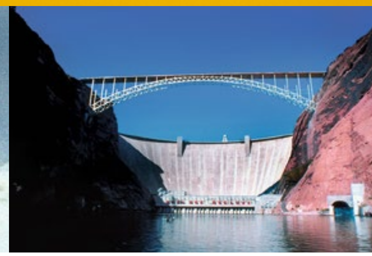
Kevin Sene





Hydro-meteorology

Forecasting and Applications

Second Edition

Springer

Hydrometeorology

Kevin Sene

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Preface to the Second Edition

In addition to the many practical applications, one of the most interesting aspects of hydrometeorology is how quickly techniques change.

Since publication of the first edition, some of the main steps forward have been in meteorology. In particular, high-resolution convection-permitting numerical models are now used operationally by several meteorological services, improving the ability to forecast convective storms. With typical horizontal scales of 1–2 km, the outputs are of interest in a wide range of hydrological applications. Data assimilation techniques have also been developed further to make more use of higher-resolution observations such as those provided by weather radars and wind profilers.

Regarding weather radar, the most significant development has been the dual-polarisation upgrades that are underway or have been completed in several countries. Compared to Doppler techniques, this approach improves the ability to distinguish between types of precipitation together with several other advantages, with corresponding improvements in the accuracy of precipitation estimates. The Core Observatory satellite for the international Global Precipitation Measurement mission was also launched in 2014 and offers the potential for a step-change in the accuracy and global coverage of satellite precipitation estimates.

At catchment scale, the reliability of water quality sensors continues to improve allowing continuous monitoring of an ever-widening range of contaminants. Some typical applications include real-time water quality and ecosystem forecasting systems and investigations into the sources of diffuse pollution. More generally probabilistic forecasting techniques are being used in an increasing number of water resources, flood and other applications. For example, seasonal flow forecasts are necessarily probabilistic in nature and are increasingly used in reservoir management and agricultural operations.

However, a forecast on its own is of little value, and developments in cell phone and smartphone technologies continue to open up new approaches to issuing alerts and guidance to end users. Web-based information services and multimedia dissemination systems are now well-established, and many national services now use social media to keep people informed during emergencies. Taken together these developments allow forecasts and warnings to be issued more effectively than was possible even just a few years ago.

This revised version of the book provides an introduction to these various topics as well as to other longer-established techniques. It follows the same structure as before with an initial section that focusses on observation and forecasting techniques and how forecasts contribute to decision-making. A second section then discusses a range of practical applications in the areas of floods, droughts, flow control, environmental impacts and water resources. Many chapters have been significantly revised, and the previous chapters on monitoring and floods have been split into two parts, covering meteorological and catchment monitoring techniques and riverine and flash floods. This has allowed more detail to be provided on topics such as weather radar, debris flows and surface water flooding.

As before the text is generally at an introductory level, and each chapter contains extensive lists of references for further reading on the more technical aspects and mathematical background. This includes references to a number of excellent guidelines that have been published since the first edition; for example, as part of the WMO/GWP Associated Programme on Flood Management. Several new 'text-boxes' and tables are included which in some cases are updated versions of descriptions which first appeared in a book on flash floods: an area in which there is perhaps the greatest need for collaboration between meteorologists and hydrologists.

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Preface to the First Edition

This book provides an introduction to recent developments in the area of hydrometeorological forecasting, with a focus on water-related applications of meteorological observation and forecasting techniques.

The Encylopaedia Britannica defines hydrometeorology as a 'branch of meteorology that deals with problems involving the hydrologic cycle, the water budget and the rainfall statistics of storms… (*continued*)'. The topic spans a wide range of disciplines, including raingauge, weather radar, satellite, river and other monitoring techniques, rainfall-runoff, flow routing and hydraulic models, and nowcasting and numerical weather prediction techniques. Applications include flood forecasting, drought forecasting, climate change impact assessments, reservoir management, and water resources and water quality studies.

The emphasis in this book is on hydrometeorological forecasting techniques, which are usually distinguished from prediction or simulation studies in that estimates are provided for a specific time or period in the future, rather than for typical past, current or future conditions. Often this requires the use of real-time observations and/or forecasts of meteorological conditions as inputs to hydrological models. The availability of information on current conditions also means that – particularly for short lead times – data assimilation techniques can be used to improve model outputs, typically by adjusting the model inputs, states or parameters or by post-processing the outputs based on the differences between observed and forecast values up to the time of the forecast.

Recent developments in meteorological forecasting techniques have significantly improved the lead times and spatial resolution of forecasts, with single-valued (deterministic) forecasts typically showing skill several days or more ahead and probabilistic forecasts sometimes providing useful information for periods of weeks ahead or longer. An improved understanding of large-scale oceanic and atmospheric features, such as the El Niño-Southern Oscillation (ENSO), is also improving the skill of forecasts at longer lead times.

These improvements are increasingly reflected in the performance of the operational hydrological models used for forecasting the impacts of floods, droughts and other environmental hazards. Of course, at lead times from a few days ahead or more, it may only be possible to provide an indication of the location and timing of events, and this inherent uncertainty is discussed in several chapters. In particular, ensemble forecasting techniques are increasingly used in hydrological forecasting and have been standard practice in meteorological forecasting for more than a decade.

Another key consideration with hydrometeorological forecasts is that the information provided is usually used for operational decision-making. This can range from decisions within the next few hours on whether to evacuate people from properties at risk from flooding through to longer-term decisions such as on when to plant and harvest crops or to impose water-use restrictions during a drought event. Forecasting models are therefore often embedded in early warning and decision support systems, which may include detection, warning dissemination and emergency response components. Several examples are provided for flood forecasting, drought forecasting and water supply, irrigation and hydropower applications, with techniques ranging from simple threshold-based approaches, such as issuing a flood warning when river levels pass a predefined value, through to probabilistic systems which attempt to provide optimal solutions subject to a range of operational, technical, economic and other constraints.

The book is presented in two main sections as follows:

- Part I – Techniques – which discusses a range of observation and forecasting techniques in meteorology and hydrology, together with methods for demand forecasting and decision-making
- Part II – Selected Applications – which discusses a range of applications in forecasting for floods, drought, flow control, environmental impacts and water resources

A glossary provides a reference to the terminology which is used and gives alternative names where the usage differs between countries (e.g. catchments, river basins, drainage basins and watersheds).

The forecasting techniques which are discussed include nowcasting; numerical weather prediction and statistical approaches; conceptual, distributed and data-driven rainfall-runoff models; and hydraulic models for forecasting the response of rivers, reservoirs and lakes. In some applications, demand forecasts are also required, such as the water requirements for water supply, irrigation and hydropower generation, and methods are discussed for a range of timescales, from short-term hydropower scheduling through to long-term assessments of water requirements for investment planning. A wide range of detection techniques is also discussed, although specific brands of software and instrumentation and other types of equipment are generally not considered.

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Acknowledgments

This book has benefited from discussions with many people. Following some time working in fluid mechanics, I moved to the Centre for Ecology and Hydrology in Wallingford in the United Kingdom. There, I had the opportunity to work on a wide range of research and consultancy projects, with much of this work overseas. Subsequently, as a part of a large engineering consultancy, my focus turned to real-time applications, including areas such as probabilistic forecasting and flood warning.

As a part of project and research work, discussions with colleagues have been invaluable and there are far too many people to mention individually. Many organizations now also place the findings from research and project work in the public domain, which has proved to be a valuable resource. Throughout, the publisher and myself have tried to determine the original source of material and to provide appropriate citations, although we apologise if there have been any unintentional errors.

In writing this book, a number of people have helped with providing permission to use figures and/or to include a discussion of their projects or systems. Most chapters include short case studies in the form of text boxes, and the following people have helped by providing comments on the text and permission to use the associated figures (Box numbers are shown in brackets): K. Beven (3.1), G. Charchun (6.2), M. Cranston (8.1, 9.3), A. Gobena and G. West (13.1), A. Green (2.3), R. Hartman (1.3, 11.1), G. Huffman and R. Gran (2.2), C. McPhail (12.3), G. Munoz (6.1), P. Schlatter (2.4), E. Sprokkereef (8.2), J. van Steenwijk and G. Stroomberg (12.2), N. Tuteja (13.2) and B. Vincendon (4.2).

As in the first edition I would also like to thank Clive Pierce for providing a significant re-write (and subsequent update) of Box 4.1, and Frank Weber for the description on which Box 13.1 is based. Reiterating thanks from the first edition, other people who allowed figures to be used (with the figure numbers shown in brackets) include B. Davey and M. Keeling (1.4), K. Stewart (3.8, 3.9) and M. Brown (Table 10.5). Heiki Walk also provided the text on short-term load forecasting in Box 6.2. Finally, from Springer, I am grateful to Robert Doe and Naomi Portnoy for their help and advice throughout the process of writing and publishing the book.

Where figures are from external sources, such as publications, conference presentations and websites, this is acknowledged in the figure captions. However, for completeness, the following list summarises the sources of the figures which are included:

BC Hydro (Box 6.2, 13.1; Figs. 6.7, 6.8, 13.3, 13.4, 13.5)
Bureau of Meteorology (Box 13.2, Figs. 4.5, 13.6, 13.7)
Cabinet Office (Fig. 4.3)
Defra (Figs. 9.8 (*part*), 9.9)
Environment Agency (Figs. 7.1, 11.8)
European Centre for Medium-Range Weather Forecasts (Figs. 4.1, 4.7, 4.8, 4.12)
Food and Agriculture Organization (Box 6.1, Figs. 6.2, 6.4, 6.5)
International Commission for the Hydrology of the Rhine Basin (Fig. 12.3)
Joint Research Center (Fig. 10.3)
Lancaster Environment Centre (Box 3.1; Figs. 3.5, 12.4)
Met Office (Box 2.3, 4.1; Figs. 1.6, 1.14, 2.5, 2.6, 2.7, 3.6, 4.2, 4.3, 4.5, 4.6, 9.6)
Météo France (Box 4.2; Figs. 4.9, 4.10, 4.11)
NASA (Box 2.2)
National Drought Mitigation Center (Figs. 1.2, 10.1)
National Oceanography Centre (Figs. 5.6, 8.12)
NOAA/Great Lakes Environmental Research Laboratory (Figs. 3.4, 11.4, 12.5, 12.6, 12.7; Table 12.3)
NOAA/National Weather Service (Box 1.3, 2.4, 11.1; Figs. 1.3, 1.5, 1.7, 1.8, 1.10, 1.11, 1.12, 1.13, 2.8, 5.11, 7.3, 7.6, 9.1, 9.7, 11.5, 11.6)
Office of Science and Technology (Fig. 8.5)
Open University (Fig. 1.4)
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Scottish Environment Protection Agency (Box 8.1, 9.3, 12.3; Figs. 8.4, 9.10, 9.11, 12.8)
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Tennessee Valley Authority (Fig. 6.6)
Urban Drainage and Flood Control District (Figs. 3.8, 3.9)
U.S. Army Corps of Engineers (Fig. 9.13)
U.S. Environmental Protection Agency (Fig. 11.9)
U.S. Geological Survey (Figs. 3.3 (*part*), 5.4, 6.1, 9.12)
U.S. National Parks (Fig. 9.14 (*part*))
World Meteorological Organisation (Figs. 1.7, 1.9, 2.1, 2.2, 3.7, 5.2, 7.3, 8.1, 9.2, 10.2, 11.3, 13.8)

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Chapter 1
Introduction

Abstract Hydrometeorological forecasts are used in a wide range of applications such as early warning systems, reservoir operations, pollution control and river basin management. Typically meteorological observations and forecasts are used as inputs to hydrological models, whose outputs are then processed into a range of products tailored to operational needs. Increasingly this includes estimates for the uncertainty in forecasts, based on probabilistic techniques. This chapter presents a general introduction to these topics including developing areas such as seasonal forecasting and risk-based approaches to decision-making.

Keywords Hydrometeorology • Meteorology • Hydrology • Hydrologic • Demand Forecast • Lead time • Decision-support • Risk based • Probabilistic • Ensemble

1.1 Forecasting Applications

1.1.1 Basic Concepts

The main purpose of a hydrological forecasting system is usually to provide estimates for future conditions based on observations and meteorological forecasts. Some typical applications include providing warnings of impending floods, forecasting the onset and progression of droughts and assisting with water supply, irrigation and hydropower operations. Longer-term uses include river basin planning and climate change impact assessments.

For example, a meteorological service might issue a forecast that 150 mm of rainfall is expected in the next 24 hours or that there is a 45 % chance that rainfall will be below normal in the next 3 months. A hydrological service would then interpret this information in terms of the likely impacts such as a threat of flooding in the next few days or of low reservoir levels in coming months.

One key consideration is the lead time provided, which the World Meteorological Organisation (WMO 2012a) defines as the 'Interval of time between the issuing of a forecast (warning) and the expected occurrence of the forecast event'. Figure 1.1 shows a simple example for the case of an isolated storm leading to a rapid rise in river levels. Here the flood risk is assessed by comparing the forecast levels with a predefined flood alert value which, in this

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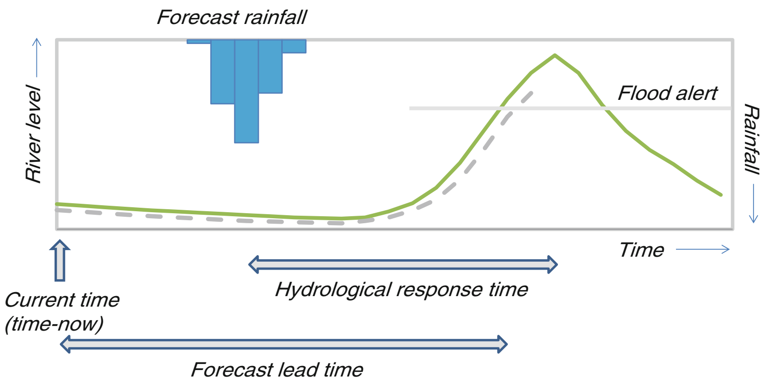

Fig. 1.1 Example of the lead time available from a hydrological model using rainfall forecasts as inputs for a simple flash flood scenario. The river-level forecast – issued at ‘time now’ – is shown as a dotted line together with the river levels that were subsequently observed; in reality these would of course not be available at the time of the forecast

case, is anticipated to be exceeded. However, in practice many factors need to be considered even for this simple situation; for example, how accurate was the rainfall forecast, does the hydrological model consistently underestimate levels and would organisational procedures allow a warning to be issued on the basis of a forecast alone? These more general issues of forecast interpretation and forecast verification are discussed in later sections and chapters.

In practice early warnings are typically escalated as parameters such as river levels rise or water quality deteriorates. Warning codes and messages vary widely between organisations although three- or four-stage alerts are typical in flood and tropical cyclone warning systems, for example, using terms such as alert, advisory, watch and warning.

Rapidly developing situations such as flash floods are some of the most demanding forecasting problems due to the limited time available to receive observations, run models and issue warnings. In contrast, for some reservoir and river basin management applications, projections are required for months to years ahead. Although the boundaries are not clear-cut, some typical lead-time requirements for the applications discussed in later chapters include:

- Minutes to weeks ahead – flood warning, hydropower scheduling, irrigation scheduling, water supply operations, pollution control and predictive control for urban drainage systems
- Weeks to months ahead – drought forecasting, planting/harvesting of crops and annual snowmelt forecasts
- Months to years ahead – river basin planning, climate change impact assessments and the operation of reservoir systems with large over-year storage

The terms seasonal and intra-annual are sometimes used to describe within-year variations and interannual for longer-term variations.

Table 1.1 provides more background information on typical lead-time requirements together with an indication of typical spatial scales. Here a sub-catchment is that part of the catchment above the point at which a forecast is required, which is normally called a forecast or forecasting point. However, as discussed in later chapters, due to technical limitations it is not always feasible to meet these requirements. Note that some alternative names for a catchment include river basin and watershed.

1.1.2 Technical Aspects

Table 1.2 illustrates the various components which are typically included in an operational flow forecasting system. However, the extent to which these are required depends on the application and, in particular, on the lead times, spatial scales and flow ranges of interest. For example, in a large river catchment, sufficient advance warning of flooding may be possible simply from using observations of river flows from a gauge further upstream; however, for a small upland catchment the only feasible way to obtain indications of flooding potential in time to act might be to rely on rainfall forecasts. Similarly, whilst demand forecasts are often a key input for drought and water resources applications, they are often less relevant to flood forecasting applications.

Flow forecasting systems are normally operated by national hydrological services and sometimes other organisations such as reservoir operators, river basin authorities and water supply utilities. In some countries the national meteorological and hydrological services are combined, although one survey (WMO 2008a) suggested that this was the case in less than half of the 139 countries considered. However, a common alternative is to establish a joint operations or forecasting centre at a national level to facilitate cooperation between meteorologists, hydrologists and disaster risk managers.

As indicated in Table 1.2, river and rainfall observations are usually some of the key inputs to a forecasting system. In many countries the first routine observations began in the late nineteenth or early twentieth century, and values would typically be recorded manually by paid or volunteer observers at set times each day. The record sheets would then be posted to (or collected by) regional or national centres at regular intervals for further processing; indeed, many hydrological services have archives of such records dating back several decades. During emergencies values would be relayed more frequently by phone or radio. This general approach is still widely used nowadays either as a backup to automated approaches or as the primary approach where budgets do not allow more automated systems.

The first public weather forecasting services began in the nineteenth century as did remote transmission of data, using telegraphy systems. River flow forecasting services were first introduced early in the twentieth century, and one of the first

Table 1.1 Some examples of typical user requirements for a range of forecasting applications, subject to technical feasibility

Application	Typical spatial scale	Typical lead-time requirements
Drought early warning	Water supply scheme, regional, national or continental	Varies widely depending on the application, with types of drought including meteorological, hydrological, groundwater, soil moisture and socioeconomic, ranging from hours to days ahead for real-time operation to seasonal and longer timescales for severe droughts (see Chap. 10)
Ecosystem forecasting	Field, lake, reservoir, catchment or lake basin; coastal waters	A wide range of timescales varying from hours to days ahead for pollution incidents, days to weeks ahead for harmful algal blooms and longer term for ecosystem impacts (see Chap. 12)
Famine early warning	Regional, national or continental	Ideally seasonal or better, with information available before the start of the main crop growing season(s) (see Chap. 10)
Flood warning	Sub-catchment, catchment or regional	Can vary from a few minutes to hours ahead for flash floods and related phenomena such as debris flows, urban flooding, dam breaks and ice jam floods, through to hours or days ahead for low-lying areas in large river catchments (see Chaps. 8 and 9)
Hydropower operations	Hydropower scheme, catchment or regional	Minutes to hourly or daily for production scheduling; daily to seasonal or longer for water resources management; longer term for investment planning (see Chaps. 6, 11 and 13)
Irrigation scheduling	Irrigation scheme, catchment or regional	Hours to days ahead for crop water allocation; intra-seasonal for operational decisions (e.g. fertilisation, pest control); seasonal for planting/ harvesting decisions; longer range for investment decisions (see Chaps. 6 and 10)
Navigation	River reaches, canals, lakes or reservoirs	Hours to days or months ahead for river traffic control and navigation warnings, including (as appropriate) estimates for water levels, flow velocities, wave heights, ice formation, ice break-up and other hazards (see Chap. 8)
Pollution Incidents	Sub-catchment, river reach, catchment or lake basin	From minutes to hours or days ahead for chemical, biological, radiation, etc. incidents, through to longer term for general water quality and ecological applications (see Chap. 12)
Water resources	Sub-catchment, catchment, regional or continental	From hours to days ahead for operational management to weeks, years or decades ahead for river basin management, integrated water resources management and climate change impact assessments (see Chaps. 10 and 13)
Water supply	Water supply scheme, sub-catchment, catchment or regional	Varies from minutes or hours to days ahead for tactical decision-making regarding pumping, treatment etc. to days or months ahead for operational planning and years ahead for investment decisions (see Chaps. 6, 10, 11 and 13)

Table 1.2 Illustration of some typical technical aspects of a flow forecasting service

Component	Description
Meteorological observations	Observation techniques include raingauges, weather stations, weather radar, satellite precipitation estimates and multisensor products; see Chap. 2
Catchment monitoring	Monitoring techniques include river gauges, reservoir gauges, tide gauges, soil moisture sensors, snow pillows, water quality sensors and satellite-based observations; see Chap. 3
Meteorological forecasting	Forecasting techniques include nowcasting, numerical weather prediction and statistical methods, plus statistical, weather-matching and dynamic post-processing techniques; see Chap. 4
Hydrological forecasting	Forecasting techniques include statistical methods, water-balance approaches, rainfall-runoff models, hydrological and hydrodynamic river flow routing models and a range of approaches for individual features of a catchment, such as urban drainage networks, snowmelt, reservoirs, lake storage, water quality and ecosystems; see Chaps. 5, 8, 9, 10, 11, 12 and 13
Demand forecasting	Forecasting techniques include empirical, statistical and microcomponent-based approaches for estimating withdrawals (abstractions) for water supply, irrigation, hydropower and other applications; see Chap. 6
Forecast interpretation	Approaches include risk-based and threshold-based techniques and decision-support systems, including the use of probabilistic forecasts and software tools for post-processing outputs into the required formats; see Chaps. 7, 8, 9, 10, 11, 12 and 13

rainfall-runoff modelling techniques (the unit hydrograph) was developed in the 1930s although is rarely used in forecasting applications nowadays. The first general-purpose computer came into use in the 1940s and some other significant developments since then – in general terms – include:

- Weather radar – the introduction of ground-based radar stations in the 1950s for remote monitoring of rainfall, typically with upgrades to Doppler systems in the 1990s and dual-polarisation capability since about 2010 (see Chap. 2)
- Satellite observations – the launch of the first earth-observing satellites in the 1960s, since then used for an ever-increasing range of applications, including the launch of the first spaceborne precipitation radar in the 1990s (see Chap. 2)
- Telecommunications – development of satellite, broadband and cell phone-based data transmission systems starting in the 1970s (for geostationary satellites) and accelerating in recent years, as alternatives to existing radio or landline-based systems (see Chap. 3)
- Numerical Weather Prediction – the introduction of numerical weather forecasting models into operational use in the 1950s with routine use of ensemble techniques starting in the late 1980s/early 1990s (see Chap. 4)

Another significant development has been the rapid adoption of cell phone, smartphone and web-based technologies, and this has revolutionised the options available for issuing warnings and forecasts, including in some of the poorest parts of the world, albeit with some caveats about reliability which are discussed in later chapters.

A modern-day forecasting system normally makes use of many sources of data and types of model and provides information that underpins a wide range of forecasting products and services. Hydrological forecasting centres are usually staffed year round with additional staff on call during emergencies during which time operations are typically around the clock (24/7). During normal times, training, system development and other activities are usually a full-time occupation; for example, in a flood forecasting service, WMO (2011a) notes that some typical staff duties include operational activities (e.g. making forecasts), modelling (model calibration), hydrometry (e.g. data collection, transmission, management and quality control) and informatics (e.g. equipment and system operation, providing appropriate output formats).

However, despite these advances, it is important to note that there remain wide variations in forecasting capability and, in one survey (WMO 2006a), only about one-third of the 86 member states surveyed reported well-established national flood forecasting and warning services, with the remainder reporting intermediate, basic, insufficient or no services. Where there were problems this was for a range of reasons including a lack of observational data or technical issues or a lack of institutional capacity.

These types of issues are not just specific to flood forecasting applications and can potentially impact upon all aspects of the forecasting chain. Manually based systems are therefore still widely used, and even in more automated systems, it is still vital to regularly visit gauges to download data loggers and check calibrations and for maintenance and repairs. Indeed, many hydrological services continue to employ gauge readers at automatic sites – at least on a part-time basis – for site maintenance and site security and to provide backup in case instruments fail.

1.1.3 Disaster Risk Reduction

The terminology surrounding early warning systems, natural hazards and contingency planning varies between countries but one concept that is widely used is the disaster risk management cycle. This takes many forms and Fig. 1.2 shows an example for the case of droughts, and Table 1.3 lists some typical aspects for flood warning applications. More generally UN/ISDR (2006) notes that for early warning systems, the following four elements need to be considered:

- Risk knowledge – are the hazards and the vulnerabilities well known? What are the patterns and trends in these factors? Are risk maps and data widely available?
- Monitoring and warning service – are the right parameters being monitored? Is there a sound scientific basis for making forecasts? Can accurate and timely warnings be generated?

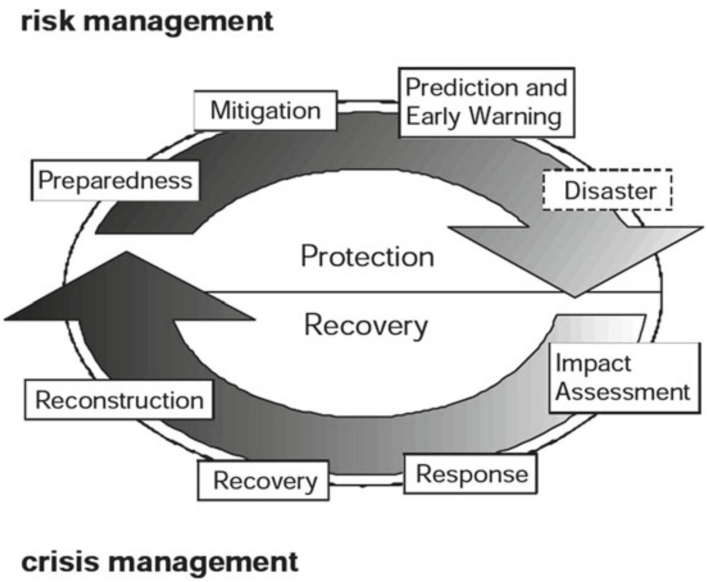

Fig. 1.2 The cycle of disaster management (National Drought Mitigation Center, University of Nebraska-Lincoln; Wilhite and Svoboda 2005)

Table 1.3 Some typical examples of activities within the disaster risk management cycle for flood warning applications

Item	Examples
Preparedness	Lesson-learned/post-event reviews, contingency planning, flood risk assessment, flood modelling, community engagement, public-awareness/outreach activities, media liaison, tabletop, functional and full-scale emergency response exercises, training, capacity building, forecast verification studies, improving monitoring and forecasting systems, research and development, financial/investment planning
Monitoring and forecasting	Monitoring meteorological and catchment conditions, running forecasting models, gathering information from staff on site regarding the flood threat and impacts and from the public and volunteer 'spotters'; for example, sending images and reports to base using smartphones and text messages
Warning	Interpreting the available observations and forecasts and then if appropriate issuing a flood watch or warning in collaboration with civil protection authorities, the emergency services and community leaders
Response	Search and rescue, evacuation of areas at risk, flood-fighting measures to try to reduce the extent of flooding such as raising temporary barriers or using sandbags, lowering (drawing down) reservoir levels, diverting flows
Recovery	Restoration of water, power and other essential services, medical treatment/monitoring, emergency repairs to critical infrastructure, shelter management and logistics
Mitigation	Longer-term measures to repair damage to properties and critical infrastructure, restore livelihoods and help to reduce the future risks from flooding

- Dissemination and communication – do warnings reach all of those at risk? Are the risks and warnings understood? Is the warning information clear and useable?
- Response capability – are response plans up to date and tested? Are local capacities and knowledge made use of? Are people prepared and ready to react to warnings?

Response plans – often called contingency plans – are a key aspect and amongst other objectives serve to clarify the legislative framework, the roles and responsibilities of organisations and the criteria for issuing warnings. Typically in a well-developed contingency planning framework, all relevant government departments, emergency response agencies and local authorities will have plans in place, together with critical infrastructure operators, businesses and the communities at risk. However, as with the technical aspects of a forecasting system, the extent to which this is possible in part depends on institutional capacity, funding and the legislative environment (e.g. Table 1.4).

An important development in recent years has been a move towards disaster risk reduction rather than crisis management. For example, most national governments were signatories to the UN/ISDR Hyogo Framework in 2005, and some key priorities for action for its successor, the Sendai Framework for Disaster Risk Reduction (UN 2015) from 2015–2030, are:

- Understanding disaster risk
- Strengthening disaster risk governance to manage disaster risk
- Investing in disaster risk reduction for resilience
- Enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation and reconstruction

More generally a community-based or people-centred approach is widely advocated in which those affected play a key role in the design and operation of warning systems (e.g. Basher 2006, Drabek 2000, UN/ISDR 2006, APFM 2006, WMO 2005, 2006b, Parker and Priest 2012). This is sometimes called an end-to-end forecasting and warning system (e.g. WMO 2012b) or one which ensures last-mile connectivity. Neglecting these aspects is often a significant factor in warning systems not performing as expected; for example, in the context of flood warning, FCDMC (1997) notes that:

Table 1.4 Comparative examples of disaster reduction capacities in richer and poorer countries (DFID 2004)

Richer countries	Poorer countries
Have regulatory frameworks to minimise disaster risk which are enforced	Regulatory frameworks are weak or absent, and/or the capacity to enforce them is lacking
Have effective early warning and information mechanisms in place to minimise loss of life	Lack comprehensive information systems linked to pre-emptive response
Have highly developed emergency response and medical care systems	Divert funds from development programs to emergency assistance and recovery
Insurance schemes spread the burden of property losses	Those affected bear full burden of property losses and may lose livelihoods

A common frustration among operators of flood warning systems is the difficulty in evolving from a data collection and monitoring system to one that saves lives and property from flood threat

In that regard, national flood warning guidelines for Australia (Australian Government 2009) note that 'the critical issues in developing and maintaining such a system are:

- it must recognise and satisfy the warning needs of the flood-liable community by ensuring the community is involved in system design and development
- it must incorporate all relevant organisations and be integrated with floodplain and emergency management arrangements
- it must be capable of operating for both 'routine' and severe flood events, and
- each agency involved in the system must accept ownership of it and work co-operatively with other agencies to improve its operation'

Similar considerations apply to other types of disaster, such as droughts and pollution incidents. In particular, the vulnerability of specific groups needs to be considered and typically depends on a range of physical, social, economic and environmental factors; for example, one definition is that vulnerability relates to 'the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard' (UN/ISDR 2009).

Chapters 7, 8, 9, 10, 11, 12 and 13 include some further discussion of these issues for specific applications, whilst the remainder of this chapter provides an introduction to the technical aspects of operational forecasting (Sect. 1.2) and forecast interpretation (Sect. 1.3). Box 1.1 also provides an introduction to one of the key concepts in hydrological modelling, namely, the hydrological cycle.

Box 1.1: The Hydrological Cycle

Hydrometeorology is often defined in terms of the hydrological cycle (or hydrologic cycle in North American terminology) as illustrated by the following examples and Fig. 1.3:

- *[Hydrometeorology is]* an interdisciplinary science involving the study and analysis of the interrelationships between the atmospheric and land phases of water as it moves through the hydrologic cycle (NOAA 2015)
- *[Hydrometeorology is the]* study of the atmospheric and land phases of the hydrological cycle, with emphasis on the interrelationships involved (WMO 2012a)

Rainfall is usually the main influence on river flows although spring flows from aquifers and snowmelt in mountain regions play a role in some river basins. Other key components in the water balance include infiltration and percolation to deeper soil layers and artificial influences from abstractions and discharges; for example, for water supply, irrigation or hydropower operations. Typically river flows reach the sea over timescales of hours to weeks, although in some cases water remains in storage for months or more such as in aquifers, snowpack or large lakes and reservoirs.

(continued)

Box 1.1 (continued)

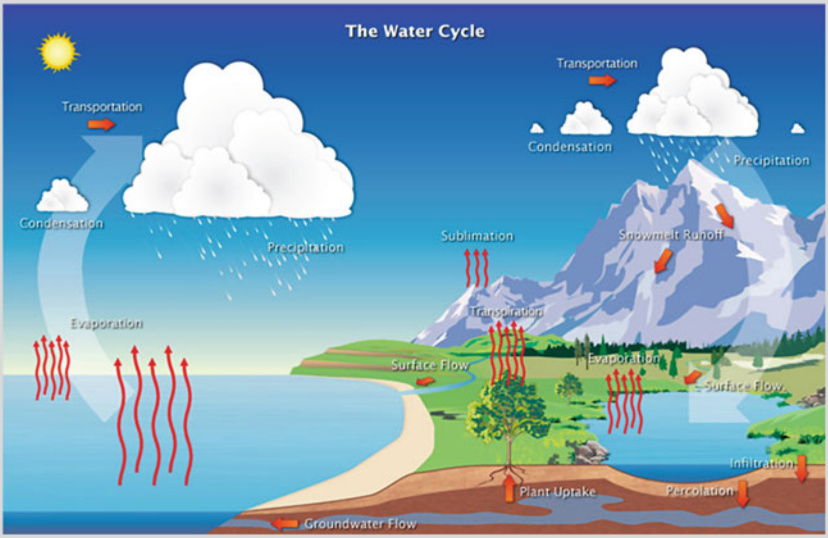

Fig. 1.3 Illustration of Earth's water cycle (Source: NOAA/National Weather Service JetStream – Online School for Weather)

The main driver of this process is solar radiation and the resulting atmospheric circulation. This causes water vapour to return to the atmosphere via evaporation from open water surfaces and evapotranspiration from crops, forests and natural vegetation. Clouds form and the cycle is then repeated as rainfall and other types of precipitation occur, where the term precipitation is used to describe water in its solid and liquid states, such as rainfall, snow or hail. Convective and orographic effects are often key factors in the formation of clouds due to the uplift caused by heating of the land surface and as air flows over hills and mountain ranges.

Chapter 5 provides more background on the surface water and groundwater aspects of the hydrological cycle. The importance of each component depends on a range of factors including geological formations, soil types, artificial influences and the local climate. For example, Fig. 1.4 shows some typical rainfall regimes around the world. These range from high-latitude regions with permanent snow cover to desert regions with little or no annual rainfall, together with mountain regions where the annual snowmelt is a significant contributor to regional water resources.

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Box 1.1 (continued)

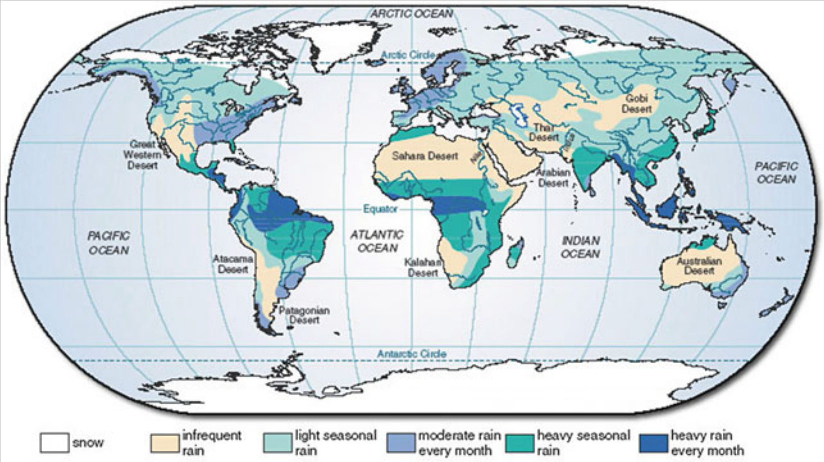

Fig. 1.4 Map showing world rainfall (© Open University, Halliday and Davey (2007), http://www.open.edu)

Internationally the highest annual total rainfall probably occurs in the Cherrapunji area in India where the mean value is about 11–12 m/year and values have exceeded 26 m (e.g. WMO 2009). These extremes are linked to the annual monsoon on the Indian subcontinent which is caused by variations in the prevailing winds driven by temperature (and hence air pressure) differences between the oceans and land surfaces, resulting in increased rainfall during the period when winds are onshore.

1.2 Operational Forecasting

1.2.1 Meteorological Forecasting

Table 1.5 summarises the main modelling techniques which are used in meteorological forecasting applications. Although definitions vary, forecasts are often described as short-range for lead times up to 3 days ahead and as medium-range for 3–10 days ahead, whilst extended and long-range forecasts extend to seasonal and longer time periods (WMO 2012c).

Nowcasting was one of the earliest approaches, although the original manually based techniques have largely been replaced by automated systems, at least for precipitation forecasts. At longer lead times, similar techniques are used to forecast the track and landfall of tropical cyclones, which are known as hurricanes in coastal waters off the Americas and typhoons in east and southeast Asia (e.g. Fig. 1.5). Similarly statistical methods are well established with the first applications dating back to the 1920s; typically these make use of the linkages (or ‘teleconnections’)

Table 1.5 Summary of some key meteorological forecasting techniques

Technique	Typical maximum lead time	Basis of method
Nowcasting	Up to several hours ahead	Extrapolation of the motion of weather radar and/or satellite-based rainfall intensity observations, increasingly guided by, or blended with, the outputs from numerical weather prediction models. Also, manual or automated extrapolation of other parameters such as fog
Numerical Weather Prediction (NWP)	Days to months ahead	Three-dimensional modelling of the atmosphere on a horizontal grid and vertical layer basis, accounting for mass, momentum and energy transport and transfer at the land and (in some cases) the ocean surfaces and initialised using observations from a wide range of land-based (weather radar, weather station, etc.), oceanographic (weather stations on buoys, boats, etc.), atmospheric (aircraft, radiosonde, wind profiler, etc.) and satellite-based observation systems
Statistical techniques	Weeks to months ahead	Multiple regression and other statistical techniques linking future weather to indicators or predictors representing the strength of oceanic and atmospheric phenomena such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO)

See Chap. 4 for further details

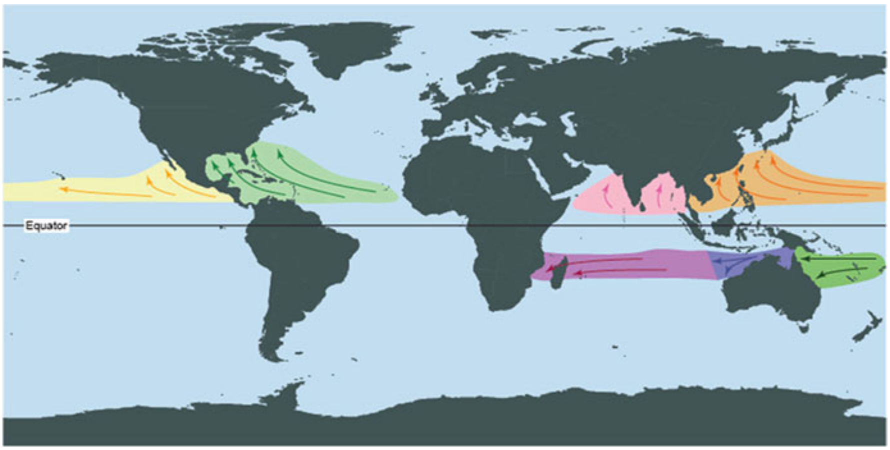

Fig. 1.5 Typical cyclone tracks (Source: NOAA, National Oceanic and Atmospheric Administration)

which are thought to exist between some atmospheric phenomena and ocean conditions, as discussed further in Box 1.2.

However, numerical weather prediction is perhaps the most important approach of all, although it is important to note that not all national meteorological services or centres (NMCs) have the capability to operate these types of model. For this reason under the auspices of WMO, several regional and global centres have been designated which share model outputs with other member states through WMO and other channels. Initiatives such as the Severe Weather Forecasting Demonstration Project (WMO 2010) provide another way of sharing expertise, and the stated objective is to 'improve severe weather forecasting services in countries where sophisticated model outputs are not currently used' through the following general approach:

- global NWP centres to provide available NWP products, including in the form of probabilities
- regional centres to interpret information received from global NWP centres, run limited-area models to refine products, liaise with the participating NMCs
- NMCs to issue alerts, advisories, severe weather warnings; to liaise and collaborate with Media, and disaster management and civil protection authorities; and to contribute to the evaluation of the project

The first project began in Southern Africa in 2006 with subsequent projects in Eastern Africa, the Southwest Pacific Islands and Southeast Asia, with others at the planning stage. For example, in Southern Africa, this has included implementation of a high-resolution model across the region as part of a collaboration between the South African Weather Service, national meteorological services and the UK Met Office.

The term 'limited-area model' here refers to a model which is typically of national or regional extent. In operational use this then requires lateral boundary conditions to be provided by a coarser-scale regional or global model, as illustrated in Fig. 1.6. For each model run a set of initial conditions is required, which is usually based on the outputs from the previous model run and recent observations. This initialisation stage – called data assimilation – is a complex task which normally accounts for a significant proportion of the time between each forecast run. Due to the complexities of this process, and of the models themselves, the most advanced meteorological services use some of the most powerful supercomputers available.

In recent years, ensemble forecasting techniques have become standard practice in numerical weather prediction. The aim is to assess the uncertainty in forecasts due to uncertainties in initial conditions and – in some cases – other factors such as the model parameterisation schemes. Typically about 10–50 ensemble members are generated alongside the deterministic model run, and the outputs are available to forecasters using a variety of map-based and graphical formats.

These types of outputs are increasingly used in hydrological applications as discussed in Sect. 1.3 and later chapters. However, values are often post-processed first to provide a better representation of conditions at the locations and scales of interest. The main techniques include dynamic downscaling, statistical post-processing and weather-matching or analogue techniques (see Chap. 4). For example, statistical post-processing techniques have been used in the National Weather Service in the USA for decades, and many meteorological services and private-sector forecasters use these types of techniques to provide tailor-made (or 'added-value') forecast products for specific users such as airport or wind farm operators.

Due to computational limitations, there is usually a trade-off between the horizontal grid scale, the forecast length (maximum lead time), the number of ensemble members and the model run interval. In the early days, the grid resolutions were such that only the largest-scale features of the atmosphere could be predicted with any confidence. Even in the 1990s the typical grid scales in local or regional models were still about 10–20 km which was often too coarse for hydrological applications.

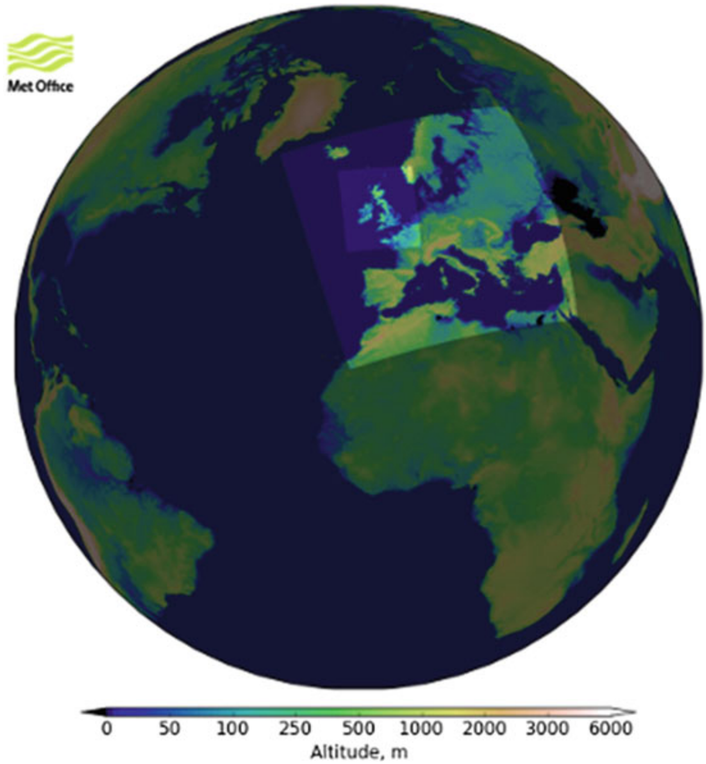

Fig. 1.6 A number of numerical weather prediction models are run at the Met Office (© the Met Office 2015, Contains public sector information licensed under the Open Government Licence v1.0)

However, in recent years, there have been step-changes in resolution meaning that models are now much better able to represent smaller-scale effects such as convectively driven rainfall. Some other key developments have included improvements to data assimilation schemes to make use of a wider range of types of observation systems – such as weather radar observations – and improvements in the representation of land-atmosphere processes. The latest short-range models typically use grid scales in the range 1–2 km and often form part of a suite of models for different domains and lead times, as illustrated in Table 1.6. Here GCMs are normally used for modelling the impacts of climate change for years to decades ahead and consider additional processes which are important at these timescales such as the carbon cycle and the influences of land-use changes.

Whilst using a hierarchy of models has been the general approach for 2–3 decades or more, a long-term aim in many meteorological services is to develop so-called ‘seamless’ forecasting systems and products as illustrated in Fig. 1.7 (e.g. Seo and Demargne 2008; WMO 2011b). For example, the Met Office (Met Office 2015) notes that some benefits of a seamless forecasting system *include*:

Table 1.6 Hypothetical example of a suite of models operated by a national meteorological service (2010–2015 approximately)

Model	Description
Nowcasting model	15 min estimates on a 1–2 km grid to lead times of 6–8 h (20–50 ensemble members)
Limited area model	1–3 hourly runs on a 1–2 km grid to lead times of 24–36 h (10–20 ensemble members)
Regional model	6 hourly runs on a 10–20 km grid to lead times of 5 days (20–50 ensemble members)
Global model	6–12 hourly runs on a 20–40 km grid to lead times of 15 days (20–50 ensemble members)
Seasonal model	Weekly or monthly runs of the global model for lead times of several months (20–50 ensemble members)
General Circulation Model (GCM)	A global-scale model operated on demand on a 50–300 km grid for run lengths of years to decades (20–50 ensemble members)

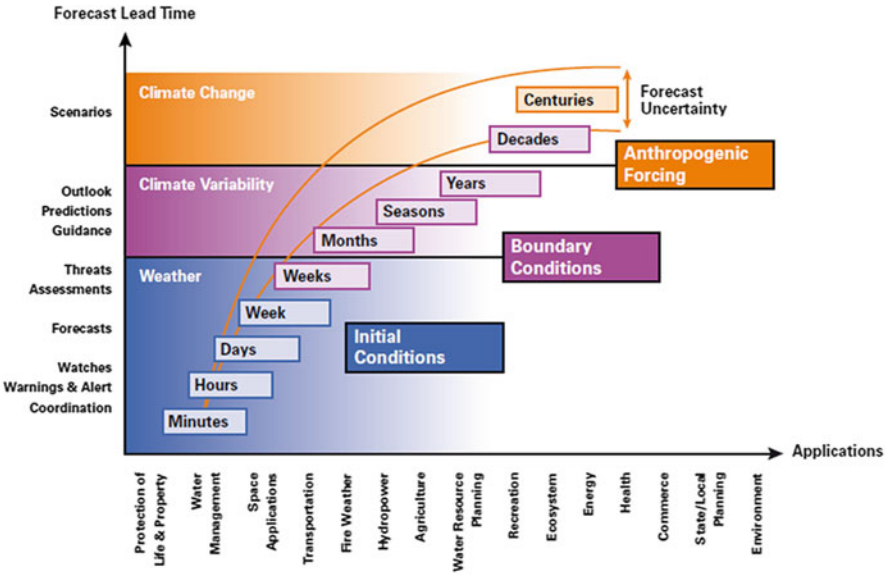

Fig. 1.7 Schematic diagram showing the challenges of developing 'seamless' products and services and the available climate information and gaps (Source: National Oceanic and Atmospheric Administration; in WMO 2011b, courtesy of WMO)

- Efficiency – by developing only one system, duplicated effort is reduced
- Understanding – a seamless system allows us to learn about climate model performance and error growth from well constrained, observed and initialised shorter-range predictions
- Confidence – using the same model at different resolutions gives us confidence that the driving mechanisms within models are consistent with each other

- Synergy – advances in climate science can improve weather forecasts and vice versa

Several meteorological services have already made significant progress towards these objectives (e.g. Brown et al. 2012), and Chap. 4 discusses this topic further and provides more detail on modelling techniques and related areas such as forecast verification and post-processing.

Box 1.2: Regional and Global-Scale Features

In many parts of the world, there are distinct seasonal patterns and large-scale features of the atmosphere and oceans which are, in principle, predictable, even if only to provide a general indication of the timing and location of events, in probabilistic terms. Some key influences include seasonal variations in surface heating, variations in ocean temperatures and phenomena such as jet streams. Most atmospheric features evolve over timescales of days to weeks (at most), but the oceans respond more slowly and the heat capacity is larger, which raises the possibility of forecasting atmospheric changes over longer timescales. The investigation of these phenomena (or 'teleconnections') is a key area for research in meteorology, and Table 1.7 describes some key mechanisms which have been identified as either primary or secondary driving factors.

Table 1.7 Summary of some large-scale features of the atmosphere and oceans

Feature	Location	Typical timescales	Description
Atmospheric rivers	Pacific Ocean, Indian Ocean, Atlantic	Days or more	"…narrow corridors of water vapour transport in the lower atmosphere several hundred kilometres wide and extending for thousands of kilometres, sometimes across entire ocean basins…" (Ralph and Dettinger 2011). Typically they result from fast-moving low-level jets (e.g. Neiman et al. 2008) and can cause extreme rainfall and flooding where they make landfall
El Niño-Southern Oscillation (ENSO)	Eastern and central Pacific	2–7 years	El Niño events relate to abnormal increases in sea surface temperatures (SST) for durations typically of a few months or more in the central and eastern Pacific; this is related to a breakdown of the normal situation in which easterly trade winds push warmer surface waters westwards, with the resulting circulation causing cooler waters to upwell to the east. In contrast when the westerly flow strengthens this is called a La Niña event and the normal pattern is stronger than usual. The term Southern Oscillation describes the irregular oscillation in atmospheric pressure differences between the east and west Pacific which results from these effects (e.g. Palmer and Hagedorn 2006; Troccoli et al. 2008)

(continued)

Box 1.2 (continued)

Table 1.7 (continued)

Feature	Location	Typical timescales	Description
Inter Tropical Convergence Zone (ITCZ)	Equatorial regions; typically ±10° N/S, but as much as 45° N in southeast Asia	Seasonal	The convergence zone between the trade winds in the northern and southern hemispheres which results in an uplift of air and generation of heavy rainfall and thunderstorms in equatorial regions. Over land, the north-south position follows a meandering path linked to the zenith of the sun, with widths of hundreds of kilometres. In the absence of local factors this usually leads to two wet seasons each year in areas near the equator (e.g. the 'long' and 'short' rains) but a single main rainfall season at the northern and southern limits
Madden Julian Oscillation (MJO)	Indian Ocean to western Pacific, and to a lesser extent the Atlantic Ocean	Variously described as 30–60 days or 40–50 days	Intra-seasonal patterns of atmospheric circulation and enhanced and suppressed tropical rainfall which progress eastwards from the Indian Ocean into the western Pacific Ocean, and to a lesser extent the Atlantic Ocean with strong variations from year to year. Areas affected include the western USA, the Pacific Northwest and southeast Asia, with impacts on the Indian and Australian monsoons (Madden and Julian 1994)
North Atlantic Oscillation (NAO)	North Atlantic	Several years	A phenomenon linked to ocean surface conditions, which appears as an oscillation which can persist for several years in the relative positions and strengths of the permanent high pressure region around the subtropical Atlantic (the Azores High) and the low pressure in Arctic regions (the Iceland Low). This affects the strength and tracks of storms across the Atlantic and across Europe (particularly in winter), with influences on air temperatures and rainfall from a region extending from North Africa to northern Europe; the locations depending on current conditions in the Atlantic (e.g. Hurrell et al. 2003; Scaife 2014)

The influences of El Niño are perhaps the most widespread (e.g. Fig. 1.8); for example, the 1982–1983 and 1997–1998 events affected rainfall in countries in Africa, Asia and South America, and in the USA (e.g. Hoerling and Kumar 2003; NDMC 2009). The Indian Ocean Dipole is a similar – possibly related – type of phenomenon and occurs in the Indian Ocean, extending between Australia and Indonesia and the African coastline (e.g. Saji et al. 1999; Manatsa et al. 2011). Longer-term signals have also been identified such as the Pacific Decadal Oscillation which is an oscillation in surface temperatures over 2–3 decades in the midlatitudes of the Pacific Ocean (Mantua et al. 1997).

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Box 1.2 (continued)

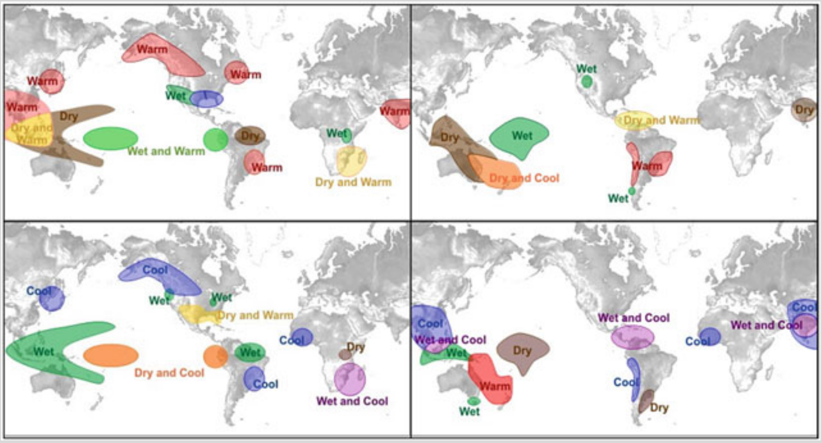

Fig. 1.8 The regions where the greatest impacts occur due to the shift in the jet stream as a result of ENSO. *Top row*: El Niño effect during December to February (*left*) and June to August (*right*), *lower row*: La Niña effect during December to February (*left*) and June to August (*right*) (Source: NOAA, National Oceanic and Atmospheric Administration)

The usual approaches to seasonal forecasting are to use long-range numerical prediction model runs and statistical techniques, either separately or in combination, as described in Chaps. 4, 5 and 13. Publicly available bulletins on the progression of El Niño events include the WMO El Niño/La Niña updates issued through a collaborative effort between WMO and the International Research Institute for Climate and Society (IRI) (http://www.wmo.ch/) and the weekly and monthly updates issued by the NOAA/National Weather Service Climate Prediction Center in the USA (http://www.cpc.noaa.gov/).

Satellite observations of sea surface temperatures are widely used to help with detecting the onset of El Niño events. Also, since the 1980s an ever-growing network of moored buoy-mounted weather stations has been operated in equatorial regions as part of initiatives such as the US/Japanese TAO-TRITON programme. In addition, more than 3000 freely drifting buoys, again equipped with satellite telemetry, have been deployed since 2000 to record ocean currents plus temperatures and salinity as part of the multinational Argo programme. These are designed to rise and descend following a programmed schedule, sampling conditions over a range of depths from the surface to about 2000 m below.

1.2.2 Hydrological Forecasting

There are many approaches to generating hydrological forecasts, ranging from simple empirical techniques to real-time hydrodynamic models. Integrated catchment models are also widely used in which rainfall-runoff models provide the inputs to flow routing models for the river network. For water resources applications, simpler water-balance approaches sometimes suffice although often include sophisticated algorithms to guide users towards an optimum balance between water supply and demand. At a catchment or regional scale, distributed (grid-based) rainfall-runoff models are increasingly used in real-time applications.

Later chapters present examples of these and other approaches, and – as part of the model design – it is often useful to assess the relative magnitudes of the terms in the water balance; for example, using the type of conceptualisation shown in Fig. 1.9 which considers the following modelling components (WMO 2012d):

- Land surface and soil water store: primarily water in surface soil layers, wetlands, bogs and shallow surface depressions
- Surface water store: water in rivers, lakes, canals, dams and storage reservoirs
- Groundwater store: water in underground storage though typically only the volumes above some datum considered as the lowest practical variation or limit of extraction are considered
- Water supply system: water in service reservoirs, tanks, pipes and treatment works

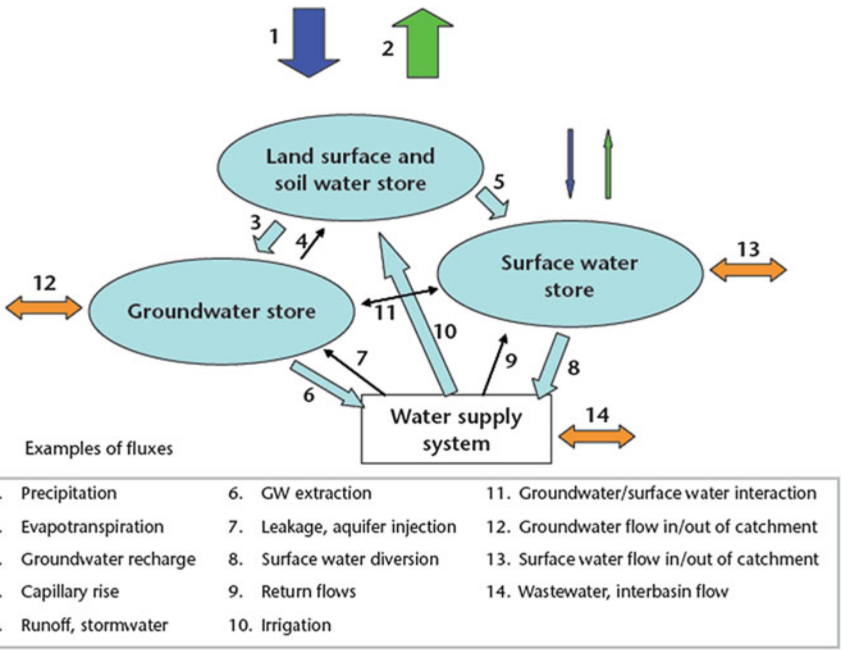

Fig. 1.9 Conceptual diagram of sub-catchment water-balance framework (WMO 2012d, courtesy of WMO)

The extent to which these types of components and linkages are required depends on the application, and this topic is discussed in Chaps. 5, 8, 9, 10, 11, 12 and 13. Given the various modelling uncertainties, data assimilation is widely used to help to improve forecast outputs, and, as in meteorology, this often involves initialising the model states based on recent observations and/or post-processing the model outputs (see Chaps. 5 and 8).

As in meteorological forecasting applications the maximum useful lead time provided is an important consideration, and short-term hydrological forecasts are generally considered to extend 2 days from issue of the forecast, whilst medium-term forecasts extend from 2 to 10 days, long-term forecasts beyond 10 days and seasonal forecasts for several months (WMO 2008b). The maximum achievable lead time for a given system – at which a forecast shows skill – depends on a range of factors, such as rainfall forecast accuracy, catchment response times and any artificial influences on flows. For example, this might range from a few hours for a flash flood application to weeks or months ahead when forecasting water supply due to seasonal snowmelt.

Although models are sometimes optimised for specific applications, such as flood or low flow forecasting, there are often considerable advantages to an integrated approach covering multiple uses, rather than models which are only operated at certain times of the year. This allows the latest developments to be shared between applications, and other potential benefits include:

- Opportunities for cost sharing between organisations
- Reducing duplication in monitoring networks, with increased data sharing
- Providing a common information platform
- Helping to maintain staff skills and training year round
- Earlier detection of monitoring and telemetry issues

The wider range of products and services offered also potentially benefits more users and raises the profile of the forecasting service and opportunities for future funding.

One key area for data sharing is between meteorological and hydrological services, and Table 1.8 illustrates some of the variables which may be required (see WMO 2012e and Box 1.3 also). Here surge is a short-term change in sea levels due to atmospheric pressure and wind influences and is discussed further in Chap. 8.

Variations in meteorological conditions also affect the demand for water, and some typical influences include the linkages between air temperature and drinking water demand and rainfall and irrigation requirements. For hydropower generation there is the additional complication that electrical demand needs to be taken into account, such as the increased use of heating in cold weather or of air conditioners in hot weather (see Chap. 6).

Although it is possible to operate hydrological models on demand, it is often more practicable to use a computer-based forecasting system, particularly for short-term applications. Systems of this type usually have the facility to manage real-time inputs, run models – including any ensemble or data assimilation component – and then post-process the outputs into a range of map-based, graphical and report-based formats. Some typical examples of the types of inputs which may need to be considered, depending on the application, include:

- Meteorological forecasts – nowcasts, numerical weather prediction model outputs and statistical forecasts
- Meteorological observations – raingauge, weather station and weather radar observations and satellite precipitation estimates
- Hydrological observations – river-level, river flow, gate setting, soil moisture, snow cover and reservoir level observations

In particular the automation of basic tasks related to data processing and validation leaves forecasters with more time to interpret model outputs and discuss potential impacts with end users. However, as discussed in Chap. 5, the resilience to power supply, telemetry and other failures is an important factor to consider in system design. The interval at which model runs are performed varies between applications but might range from every 5–15 min in flash flood applications to daily operations or more in some water resources applications.

Table 1.8 Some examples of the use of meteorological inputs in hydrological forecasting applications

Parameter	Typical hydrological components influenced by this parameter
Rainfall	River flows, surface runoff, reservoir and lake levels, urban drainage, groundwater levels, snowmelt
Snow	Snow cover, snow depth, snow density, snow water equivalent
Air temperature	Snowmelt, evaporation, evapotranspiration
Humidity	Evaporation, evapotranspiration
Radiation	Evaporation, evapotranspiration, snowmelt, ice break-up
Surge	Water levels in estuaries and large lakes
Windspeed	Wave heights on lakes and reservoirs, surge in estuaries and large lakes, evaporation, evapotranspiration, snowmelt
Wind direction	Wave directions on lakes and reservoirs and in estuaries

Box 1.3: California-Nevada River Forecast Center (CNRFC)
The California-Nevada River Forecast Center (CNRFC) is one of 13 River Forecast Centers (Fig. 1.10) in NOAA's US National Weather Service (NWS), whose main functions are (Hartman and Schaake 2014):

- Continuous hydrometeorological data assimilation, river basin modelling and hydrologic forecast preparation
- Technical support and interaction with supported and supporting NWS offices
- Technical support and interaction with outside water management agencies and users
- Applied research, development and technological implementation to facilitate and support the above functions

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Box 1.3 (continued)

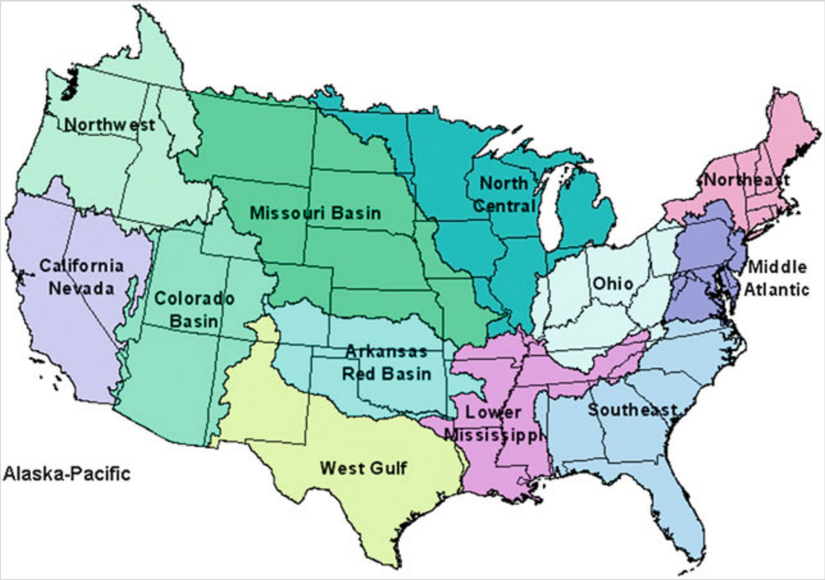

Fig. 1.10 National Weather Service River Forecast Centers in the United States (http://www.weather.gov/ahps/rfc/rfc.php)

The head office is in Sacramento in California and responsibilities include providing forecasts for flood management, reservoir management, water supply, irrigation, recreation, spring snowmelt and flash flooding. Forecasts are provided for a range of timescales, from short-term flash flood forecasts through to long-term forecasts for water resources applications for the weeks and months ahead.

The CNRFC works in partnership with a number of federal, state and local organisations, including the US Army Corps of Engineers (USACE), the US Bureau of Reclamation (USBR), the California Department of Water Resources, the US Geological Survey (USGS) and various irrigation and water authorities. Support is also provided to approximately 30 local flood warning agencies operated by cities and counties in California and Nevada which use ALERT (Automated Local Evaluation in Real Time) river and rain gauge telemetry systems.

The combined telemetry network in California and Nevada across these organisations includes more than 1,450 rain gauges, 750 air temperature sensors, 750 river gauges and 120 reservoir level gauges. The majority of river gauges are operated by the USGS under the National Streamflow Information Program. Information is also available on a range of other variables, including wind speed, wind direction, relative humidity, barometric pressure

(continued)

Box 1.3 (continued)
and actual and scheduled releases from reservoir operators. Remote sensing data from the NEXRAD network of weather radars, and from geostationary (GOES) and polar orbiting satellites, round out the observation portfolio. For ground-based stations, the telemetry systems used include radio, microwave, satellite, telephone and meteorburst approaches. Meteorological forecast information is provided by ten NWS Weather Forecast Offices in California, Nevada and Oregon, and the NWS National Centers for Environmental Protection (NCEP). A team of meteorologists within the CNRFC integrate forecast guidance and numerical weather prediction model outlooks to provide estimates of watershed-scale precipitation, snow levels and air temperature for up to 6 days ahead.

The area covered by CNRFC is approximately 627,000 km^2, and catchment models have been developed for 275+ river basins, with forecasts provided for approximately 95 Flood Forecast Points, 70+ Reservoir Inflow Points and 50+ traditional Water Supply Points. Forecasts are derived for a range of timescales, as illustrated in Fig. 1.11.

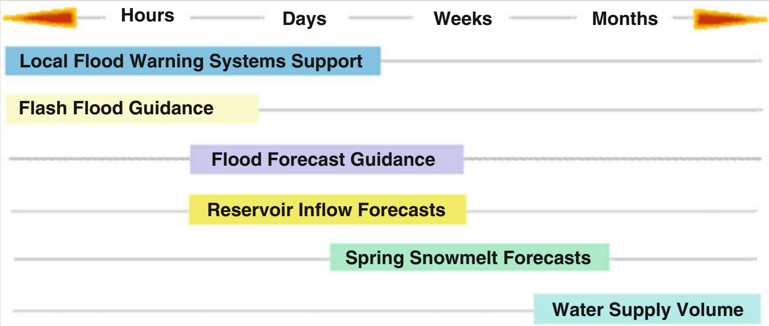

Fig. 1.11 Typical applications of flow forecasts for a range of timescales (California-Nevada River Forecast Center, http://www.cnrfc.noaa.gov/)

Models are operated through a real-time forecasting system called the Community Hydrologic Prediction System (CHPS). CHPS is based on the Delft-FEWS system developed in the Netherlands with enhancements and extensions to meet US National Weather Service requirements. The types of models which are used include the Sacramento Soil Moisture Accounting (SAC-SMA) conceptual rainfall-runoff model (Burnash 1995), the SNOW-17 snowmelt model (Anderson 1968), unit hydrograph techniques, hydrologic and hydrodynamic flow routing models, reservoir operation models and arithmetic transformations. A suite of adjustment algorithms allow operational hydrologists to perform real-time data assimilation.

(continued)

Box 1.3 (continued)

Long-term flow forecasts are derived by leveraging the spatial and temporal coherence of historical rainfall and air temperature records using the Ensemble Streamflow Prediction approach (Day 1985). These estimates are used in conjunction with multiple regression approaches which relate likely seasonal flow volumes to snow water equivalent, precipitation and other types of data, including indices which may reflect future conditions (e.g. relating to the El Niño-Southern Oscillation). These types of estimates are particularly useful for reservoir management, such as during the extended drought which began in California in 2013. The CNRFC provides a range of other forecast products to different users, including 5-day reservoir inflow forecasts to water management agencies (e.g. Fig. 1.12) and Flash Flood Guidance based on current watershed conditions.

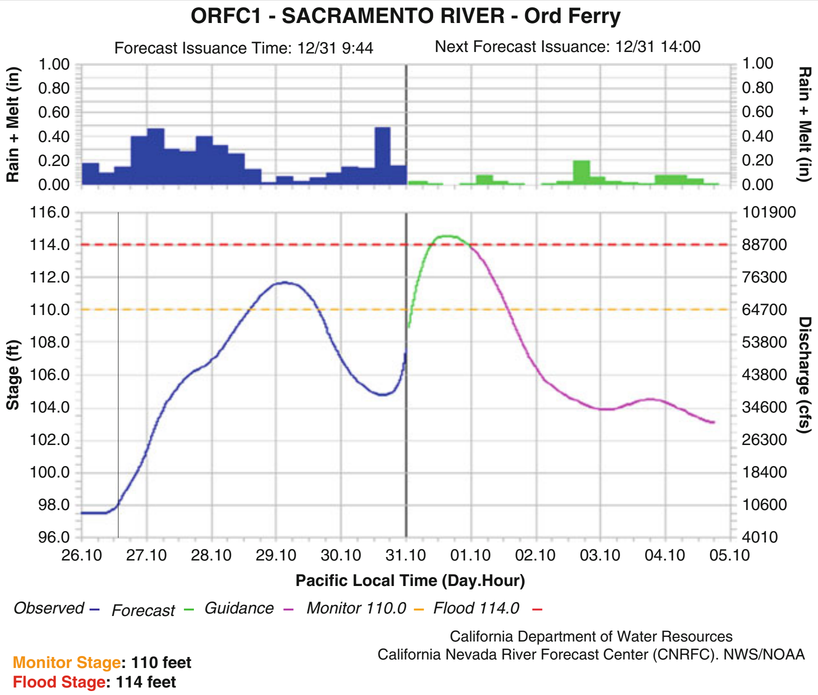

Fig. 1.12 Illustration of a deterministic river stage forecast guidance for Ord Ferry on the Sacramento River (California-Nevada River Forecast Center, http://www.cnrfc.noaa.gov/)

During flood events, the center is staffed 24 hours a day, 7 days per week. Forecasts are disseminated via a range of media, including a comprehensive set of tabulated, graphical and map-based products which are available on the CNRFC website (http://www.cnrfc.noaa.gov).

(continued)

Box 1.3 (continued)

One recent development has been implementation of the Hydrologic Ensemble Forecast System (HEFS). This system, which operates within the CHPS framework, allows short- to medium-range ensemble rainfall and air temperature forecasts from numerical weather prediction models to be used as model inputs (Demargne et al. 2014). Post-processing components are included for both the meteorological and hydrological forecast outputs to help to correct for systematic bias and other issues, plus an ensemble verification component (Fig. 1.13). The resulting probabilistic flow and stage estimates and longer range forecasts allow a more risk-based approach to decision-making and some applications in CNRFC include (Hartman et al. 2013):

- Short-range (hours to days) – Watch and warning program, local emergency management activities, reservoir and flood control system management
- Medium-range (days to weeks) – Reservoir management, local emergency management preparedness, snowmelt runoff management
- Long-range (weeks to months) – Water supply planning, reservoir management

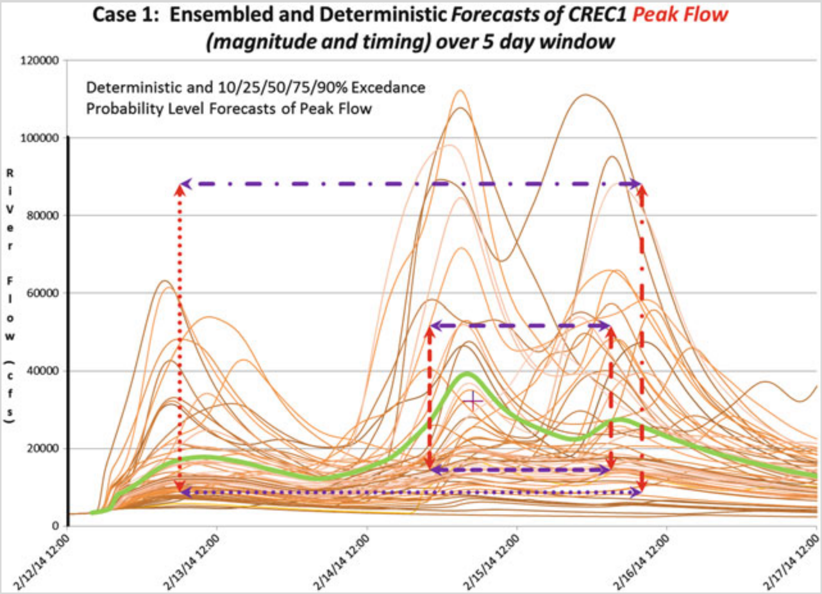

Fig. 1.13 Experimental ensemble river stage forecast product (NOAA/NWS 2014)

(continued)

Box 1.3 (continued)

As a part of HEFS implementation, the CNRFC began generating short, medium, and long-range ensemble-based products on a daily basis, 365 days/year. These products include the raw model ensembles for each location as well as a "build your own" interface where users can generate information specific to their decision application.

Some other areas for development include wider use of distributed rainfall-runoff models and extension of model applications further into low flow and drought forecasting and for smaller fast response catchments. Interagency efforts are also underway to leverage the information in probabilistic short-term (up to 2 weeks) streamflow forecasts for improved reservoir management. Forecast Informed Reservoir Operations (FIRO) has the potential to improve the capacity of certain reservoir systems for both water resources and flood protection benefits.

1.3 Forecast Interpretation

The raw outputs from a hydrological forecasting model usually consist of a set of numerical values at the selected forecasting points, along a river reach or on a gridded basis. Some specialist users such as reservoir, hydropower or tidal barrier operators may be able to make direct use of the outputs in this form; for example, as inputs to decision-support systems. However, usually some further post-processing is required into more user-friendly formats such as maps, graphs or tables and interpretation in terms of the likely impacts or consequences. Some typical ways of issuing forecasts include via situation reports, bulletins and web pages and other routes such as text messages, smartphone applications and briefings to the media.

For any given forecasting application, the optimum approach to use is best developed as a collaborative effort between forecasters and end users (e.g. Rogers et al. 2007). The approach adopted usually depends on a range of factors including:

- Model run frequency – how often model runs are performed and when forecast outputs are available for delivery
- User requirements – user-specific requirements such as preferred forecast delivery times and formats
- Dissemination routes – the preferred approaches or channels to use for issuing forecasts and warnings to users
- Risk tolerance – the risk profiles of end users, such as tolerance to false alarms and the consequences of a missed forecast or warning
- Technical skills – the familiarity of users with using the types of information conveyed, particularly regarding probabilistic information

For example, in a flood warning application, civil protection authorities normally require as much information as possible from the earliest signs of a threat including map-based displays showing the potential timing, locations and magnitude of flooding. Normally this includes the option to discuss the situation directly with forecasters such as by conference calls or web-based discussion forums or in person at a multi-agency command centre. In contrast in a seasonal forecasting application, a subsistence farmer might require a much greater level of certainty before considering changing crop types or planting schedules.

As noted earlier, the increasing availability of Internet access and cell phones has greatly increased the options for displaying information and for dissemination of warnings rapidly to large numbers of people, including in remote areas. These approaches and related developments such as social media are increasingly used alongside more traditional techniques. Chapter 7 discusses some of the advantages and potential drawbacks of the methods available; for example, the risk of communication networks failing in storm conditions and the general issue that not everyone has Internet access. For early warning systems it is therefore usual to use a range of direct, indirect and community-based approaches to provide multiple communication routes, both for resilience and to help to ensure that warnings reach as many people as possible.

For a meteorological service, many different products and services are usually offered to a range of users. In some cases these are generated automatically, such as feeds of model outputs to website pages, whilst others require expert inputs from forecasting staff. For example, within the WMO Severe Weather Forecasting Demonstration Project discussed earlier, the recommended products (WMO 2010) for a regional centre to distribute to national meteorological and hydrological services (NMHSs) include:

- charts to depict the large-scale flow (e.g. 500 hPa, 700 hPa, 850 hPa geopotential height, 850 hPa temperature, tropopause height, upper air winds, MSLP (*Mean Sea Level Pressure*))
- surface weather elements (e.g. 6-hour accumulated precipitation, surface (10m) windspeed and gusts (if available), 2m temperature, 850 hPa specific humidity)
- maps of vertical motion, potential vorticity or height of specified PV surface
- maps of convective indices such as CAPE, Lifting Index, helicity…
- relevant satellite images (where NMHSs do not have satellite receiving capability)
- special products derived from satellite images (e.g. derived precipitation or images annotated with guidance notes)

In practice a range of additional products is normally provided particularly for regions affected by tropical cyclones.

Typically when possible the outputs from several forecasting centres are considered before deciding on the information to convey, together with recent observations and the views of colleagues. Similarly, at longer timescales, 'consensus' forecasts are one of the key outputs from the WMO-led Regional Climate Outlook Forums which are active in several parts of the world. These are held before the start of each main rainfall season and provide information to support contingency planning for floods, droughts and other natural hazards in the months ahead.

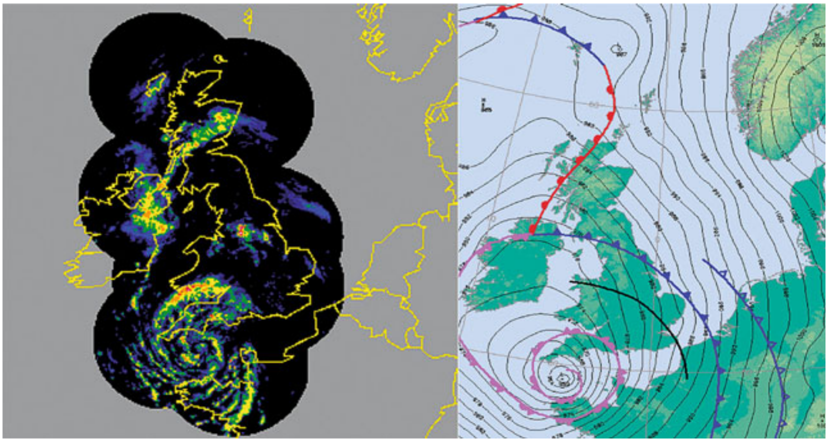

Fig. 1.14 Example of the weather radar output and corresponding surface pressure chart (55 min earlier) produced by the UK Met Office for a day in December 2005 in which a deep low-pressure region was approaching the UK and which illustrates how closely the rainfall was linked to the atmospheric circulation in this event (Met Office 2013; Contains public sector information licensed under the Open Government Licence v1.0)

More generally some examples of the types of products relevant to hydrological applications include severe weather warnings, surge and wave forecasts and seasonal rainfall and air temperature forecasts. In particular, weather radar images are an important tool for flood forecasting, and Fig. 1.14 shows an example of this type of output from the Met Office in the UK, together with the corresponding surface pressure chart.

Similarly hydrological forecast products need to be tailored to end user's needs, and later chapters present examples for a range of flood, drought, water resources and environmental applications. However, the amount of interpretation required varies; for example, regarding river-level observations, many hydrological services display these in near real time on websites, and these are typically included in products for specific users, such as weekly bulletins for irrigation scheme operators. In some countries, such as the USA, this extends to the facility for users to register their own threshold settings via a website, so that text message alerts are sent whenever the criteria are met; however, this is normally an information-only service, and users must decide how best to make use of any information provided.

Most hydrological services also offer a formal early warning service, covering floods, droughts and a range of other hazards. Typically this consists of issuing warnings for a range of alert levels via personal contacts, websites and text messages and with the help of the media and professional partners. Automated messaging services are also increasingly used, as discussed in Chap. 7. Often Internet-based alerts are accompanied by maps showing the extent of the risk, and civil protection authorities normally have access to a range of additional information such as contact lists for critical infrastructure operators.

Generally, though, it is important to note that hydrological observations and forecasts are often only one part of a wider decision-making process (e.g. Pagano et al. 2014; Hartman and Schaake 2014). For example, regarding meteorological forecasting, Persson (2013) notes that:

> Weather forecasting has never been primarily about getting it "right" or "wrong", as in some quiz show, but, rather, about providing information for decision-making, maximizing advantages and minimizing disadvantages.
>
> It is here, in the decision-making process, that professional weather forecasters can really "add value", thanks to their education, their unique position in the centre of the information flow and their experience in the skill and characteristics of different forecast systems.

Similarly, for hydrological applications, many different factors need to be considered, and Table 1.9 shows some examples related to flood warning, with the precise mix depending on the facilities available and forecaster expertise.

Table 1.9 Some examples of the types of information which may be considered when deciding whether to issue a flood warning

Item	Description
Decision-support tools	Map-based computer systems to display on-the-ground information from telemetry and observers together with rainfall and flood forecasts; see Chap. 7
Forecast outputs	Both deterministic and ensemble river flow or level forecasts (if available) and the outputs from simpler correlation and other models (if available), in some cases displaying the outputs from recent model runs for comparison
Forecast discussions	Discussions with colleagues and others involved in the flood warning and emergency response process regarding their views on how the situation will develop; for example, operational staff, meteorologists, civil protection staff and emergency responders
Local knowledge	Experience of the types of conditions which lead to extreme weather and flooding in a catchment, taking account of topography, reservoir operations and other factors and of model performance in those conditions. Also a knowledge of potential locations with a significant risk from flooding making use of flood risk maps developed from hydrological and hydrodynamic modelling studies
Observations	Recent river, rainfall and other observations and – if relevant – reports from staff on site such as flood patrols and volunteer 'spotters', plus information from the public and others received by phone, social media and other sources
Risk tolerance	Attitudes to risk both at an organisational level and in specific communities based on consultations and lessons learned from previous flood events, particularly regarding lead times, missed warnings, late warnings, false alarms, near misses and how frequently warning updates are required
User requirements	The lead times and message formats ideally required by emergency responders, civil protection authorities, communities and others, particularly for warnings likely to lead to evacuation of properties and impacts on critical infrastructure, in some cases considering factors such as the time of day (or night) and meteorological conditions (e.g. air temperature, 'wind-chill'). Also the need to provide a consistent message when possible, even if forecast outputs are varying widely between model runs

Adapted from Sene (2013)

Regarding risk tolerance, risk is usually defined as the combination of probability and consequence; for example, in pollution incidents this could be based on the chances of contaminants exceeding harmful values and the likely number of people who could be affected. Box 1.4 provides a brief introduction to the role of risk-based techniques in decision-making, and later chapters illustrate a range of applications.

Box 1.4: Risk-Based Decision-Making

One of the potential advantages of probabilistic forecasting techniques is that risk-based assessments can be made as an event unfolds. This has the potential to lead to better decision-making in flow control, drought, environmental and flood warning applications. Whilst the emphasis is often on quantifying the uncertainty arising from rainfall inputs, other factors which are increasingly considered include the uncertainties arising from model parameters and observations. Alternatively estimates for the overall uncertainty are obtained using statistical or data assimilation techniques without attempting to disaggregate the individual sources (see Chap. 5).

Regarding overall objectives, probabilistic techniques are widely recommended as a way of advising users of the uncertainty in forecasts, and some potential benefits (Krzysztofowicz 2001) include:

- First, they are scientifically more 'honest' than deterministic forecasts: they allow the forecaster to admit the uncertainty and to express the degree of certitude
- Second, they enable an authority to set risk-based criteria for flood watches, flood warnings, and emergency response; and they enable the forecaster to issue watches and warnings with explicitly stated detection probabilities
- Third, they appraise the user of the uncertainty; and they provide information necessary for making rational decisions, enabling the user to take risk explicitly into account
- Fourth, they offer potential for additional economic benefits of forecasts to every rational decision maker and thereby to society as a whole

Beven (2012) also notes that in real-time operational forecasting, '….allowing for uncertainty means being right more often in terms of bracketing when warning thresholds are crossed. It also gives a more realistic representation of forecasting capability in communicating with professional partners…'

These types of approach are probably best established in reservoir operations, using either stochastic or ensemble techniques (see Chap. 11). For early warning applications, this is a developing area, but in general terms some approaches to decision-making include the use of probabilistic thresholds and techniques from decision theory, such as cost-loss approaches. As when any new technique is introduced, the implications and benefits need to be considered throughout all stages of the disaster risk management cycle. For example, some issues to consider include the potential changes in roles and responsibilities when issuing warnings using a risk-based approach, how skill in

(continued)

Box 1.4 (continued)
interpreting probabilistic information increases with familiarity with the products, and dealing with low-probability, high-impact situations.

There are also a number of wider issues to consider regarding the extent to which probabilistic and risk-based information is made available and how it should be used operationally (e.g. National Research Council 2006; Troccoli et al. 2008; WMO 2008c; Ramos et al. 2013; Pappenberger et al. 2013; Werner et al. 2013). These communication and decision-making issues are an active area for research for both meteorological and hydrological forecasting applications; for example, this is a key theme within the international Hydrologic Ensemble Prediction Experiment (HEPEX) programme (Schaake et al. 2007, http://hepex.irstea.fr/). Demargne et al. (2014) citing a range of authors also note that 'Increased collaborations between forecasters, scientists (including social and behavioral scientists), and decision makers should help to understand decision processes with uncertainty-based forecasts, develop innovative training and education activities to promote a common understanding, and, ultimately, increase the effectiveness of probabilistic forecasts'.

1.4 Summary

- Hydrometeorological forecasts provide information to help with decision-making for a wide range of flood, drought, flow control, environmental and water resources applications. Examples range from early warning systems for flash floods through to providing information to support day-to-day operations and longer-term strategic planning. However, forecasts are usually only one element in a wider decision-making process which includes information from a range of other sources such as observations and feedback on current impacts.
- Many hydrological services started out using manually based observation techniques with little or no flow forecasting capability. A typical progression was then to bring in automated transmission of river levels and simple forecasting procedures. These were then superseded by automated forecasting models, although manual approaches are still widely used where budgets are limited, particularly in community-based flood warning systems.
- Some technological developments in recent decades which have helped to improve the effectiveness of forecasting and warning systems include the introduction of weather radar and satellite-based observation systems, improved telecommunications systems for receiving observations and improved approaches to issuing warnings, such as the Internet, cell phones and social media.
- In meteorological forecasting applications, the main modelling techniques include nowcasting, numerical weather prediction and – for longer lead times – statistical techniques which typically relate atmospheric conditions to indices describing ocean and atmospheric phenomena. In recent years, the resolution and accuracy of numerical models have improved greatly allowing a wider range of hydrological applications to be considered, and ensemble forecasting approaches have become standard practice.

- In hydrological forecasting applications, rainfall-runoff and flow routing models are widely used with additional models as required to represent specific features of a catchment such as reservoirs, lakes or urban drainage systems. Rainfall forecasts provide the potential to extend lead times, albeit with greater uncertainty at longer lead times. Models are often operated on a forecasting system although are sometimes used ‘on demand’, particularly for longer lead-time applications or where budgets are limited.
- The outputs from forecasting models typically require some further processing both to improve the accuracy and to present results in a format which is more useful to end users. Forecast products should be developed in close collaboration with key users as should the decision-making criteria for issuing warnings and other types of guidance based on forecast outputs.
- Internationally it is widely recommended that an assessment of uncertainty should be included with forecasts, both to appraise users of potential issues and for input to risk-based decision-making techniques across a wide range of applications. These approaches are increasingly used operationally, and this is an active area for research with some key questions including how best to generate and calibrate forecasts and to communicate probabilistic information to end users.

References

Anderson E (1968) Development and testing of snow pack energy balance equations. Water Resources Research, 4(1): 19–37

APFM (2006) Social Aspects and Stakeholder Involvement in Integrated Flood Management. Associated Programme on Flood Management, Technical Document No. 4, Flood Management Policy Series, WMO No-1008, Geneva

Australian Government (2009) Manual 21 – Flood Warning. Australian Emergency Manuals Series. Attorney General’s Department, Canberra

Basher R (2006) Global early warning systems for natural hazards: systematic and people-centred. Philosophical Transactions of the Royal Society A, 364: 2167–2182

Beven KJ (2012) Rainfall-Runoff Modelling – the Primer, 2nd edn. Wiley-Blackwell, Chichester

Brown A, Milton S, Cullen M, Golding B, Mitchell J, Shelly A (2012) Unified Modeling and Prediction of Weather and Climate: A 25-Year Journey. Bull Am Meteorol Soc, 93:1865–1877

Burnash RJC (1995) The NWS River Forecast System – Catchment modeling. In Computer Models of Watershed Hydrology (Ed. Singh VP). Water Resources Publications, Highlands Ranch, CO

Day GN (1985) Extended Streamflow Forecasting using NWSRFS. Journal of Water Resources Planning and Management, 111(2): 157–170

Demargne J, Wu L, Regonda SK, Brown JD, Lee H, He M, Seo D-J, Hartman R, Herr HD, Fresch M, Schaake J, Zhu Y (2014) The science of NOAA’s operational Hydrologic Ensemble Forecast Service. Bulletin of the American Meteorological Society, 95: 79–98

DFID (2004) Disaster Risk Reduction: a development concern: a scoping study on links between disaster risk reduction, poverty and development. Department for International Development, London/Overseas Development Group, Norwich

Drabek TE (2000) The social factors that constrain human responses to flood warnings. In Floods (Ed. Parker DJ). Routledge, London

FCDMC (1997) Guidelines for developing a comprehensive flood warning program. Flood Control District of Maricopa County, Phoenix, Arizona

Halliday T, Davey B (2007) Water and Health in an Overcrowded World. Oxford University Press, Oxford

Hartman R, Schaake J (2014) Case Study: Decision Making for Flood Forecasting in the US National Weather Service. In Applied Uncertainty Analysis for Flood Risk Management (Eds. Beven K, Hall J), Imperial College Press, London

Hartman R, Optiz H, Stokes M (2013) NWS Water Resources Forecasting in the Western U.S. National Hydrologic Warning Council, 2013 Training Conference and Exposition, 3–6 June 2013, Ponte Vedra, Florida

Hoerling M, Kumar A (2003) The perfect ocean for drought. Science, 299(5607): 691–694

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (2003) An overview of the North Atlantic Oscillation. In The North Atlantic Oscillation: Climatic Significance and Environmental Impact (Eds. Hurrell JW, Kushnir Y, Ottersen G, Visbeck M). Geophysical Monograph Series, Vol. 134, pp. 1–35, Academic Press, London

Krzysztofowicz R (2001) The case for probabilistic forecasting in hydrology. Journal of Hydrology, 249: 2–9

Madden RA, Julian PR (1994) Observations of the 40–50 day tropical oscillation: a review. Monthly Weather Review, 122:814–836

Manatsa, D., Matarira, C.H., Mukwada, G. (2011) Relative impacts of ENSO and Indian Ocean dipole/zonal mode on east SADC rainfall. International Journal of Climatology, 31(4): 558–577

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78: 1069–1079

Met Office (2013) National Meteorological Library and Archive Factsheet 15 – Weather Radar (Version 01), Met Office, Exeter

Met Office (2015) Met Office Unified Model. http://www.metoffice.gov.uk

National Research Council (2006) Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions using Weather and Climate Forecasts. The National Academies Press, Washington

NDMC (2009) Understanding Your Risk and Impacts: Reported effects of the 1997–98 El Niño. National Drought Mitigation Center, University of Nebraska-Lincoln

Neiman PJ, Ralph FM, Wick GA, Lundquist JD, Dettinger MD (2008) Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the west coast of North America based on eight years of SSM/I satellite observations. J Hydrometeorol 9:22–47

NOAA (2015) National Weather Service (2015) Glossary http://w1.weather.gov/glossary/

Pagano TC, Wood AW, Ramos M-H, Cloke HL, Pappenberger F, Clark MP, Cranston M, Kavetski D, Mathevet T, Sorooshian S, Verkade JS (2014) Challenges of operational river forecasting. J. Hydrometeor, 15, 1692–1707

Palmer T, Hagedorn R (Eds.) (2006) Predictability of Weather and Climate. Cambridge University Press, Cambridge

Pappenberger F, Stephens E, Thielen J, Salamon P, Demeritt D, van Andel SJ, Wetterhall F, Alfieri L (2013) Visualizing probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. Hydrological Processes, 27(1): 132–146

Parker DJ, Priest SJ (2012) The fallibility of flood warning chains: can Europe's flood warnings be effective? Water Resour Manage, 26(10):2927–2950

Persson A (2013) User guide to ECMWF forecast products, Version 1.1. ECMWF, Reading

Ralph FM, Dettinger MD (2011) Storms, floods, and the science of atmospheric rivers. Eos Tran Am Geophys Union 92(32):265–272

Ramos MH, van Andel SJ, Pappenberger F (2013) Do probabilistic forecasts lead to better decisions?, Hydrol. Earth Syst.Sci., 17: 2219–2232

Rogers DP, Clarke S, Connor SJ, Dexter P, Dubus L, Guddal J, Korshunov AI, Lazo JK, Smetanina MI, Stewart B, Tang Xu, Tsirkunov VV, Ulatov SI, Whung P-Y, Wilhite DA (2007) Deriving

societal and economic benefits from meteorological and hydrological services. WMO Bulletin, 56: 15–22
Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401: 360–363
Scaife AA (2014) Skillful long-range prediction of European and North American winters. Geophysical Research Letters, 41(7): 2514–2519
Schaake JC, Hamill TM, Buizza R, Clark M (2007) HEPEX The Hydrological Ensemble Prediction Experiment. Bull Am Meteorol Soc, 88(10):1541–1547
Sene (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht, 386pp
Seo D-J, Demargne J (2008) Use of ensembles in operational hydrologic forecasting in NWS. The 4th NCEP/NWS Ensemble User Workshop, Washington, 13–15 May 2008
Troccoli A, Harrison M, Anderson D L T, Mason SJ (2008) Seasonal Climate: Forecasting and Managing Risk. NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht
UN/ISDR (2006) Developing early warning systems: a checklist. EWC III Third International Conference on Early Warning from Concept to Action, 27–29 March 2006, Bonn, Germany
UN/ISDR (2009) Risk and poverty in a changing climate: invest today for a safer tomorrow. 2009 Global Assessment Report on Disaster Risk Reduction. International Strategy for Disaster Reduction, United Nations, Geneva
UN (2015) Sendai Framework for Disaster Risk Reduction 2015–2030. Third United Nations World Conference on Disaster Risk Reduction, Sendai, Japan, 14–18 March 2015
Werner K, Avery K, Owen G (2013) River Forecast Application for Water Management: Oil and Water?. Wea. Climate Soc., 5, 244–253
Wilhite DA, Svoboda MD (2005) Drought Early Warning Systems in the Context of Drought Preparedness and Mitigation. In (Eds. Wilhite DA, Sivakumar MVK, Wood DA) Early Warning Systems for Drought Preparedness and Drought Management. Proceedings of an Expert Group Meeting held September 5–7 2000 in Lisbon, Portugal
WMO (2005) Guidelines on Integrating Severe Weather Warnings into Disaster Risk Management. WMO/TD-No.1292
WMO (2006a) Strategy and Action Plan for the Enhancement of Cooperation between National Meteorological and Hydrological Services for Improved Flood Forecasting. WMO, Geneva
WMO (2006b) Preventing and Mitigating Natural Disasters. WMO-No. 993, Geneva
WMO (2008a) Capacity assessment of National Meteorological and Hydrological Services in support of Disaster Risk Reduction: Analysis of the 2006 WMO Disaster Risk Reduction Country-level Survey, Geneva
WMO (2008b) Technical Regulations – Volume III – Hydrology. 2006 ed., Suppl. No. 1 (I.2008), Geneva
WMO (2008c) Guidelines on Communicating Forecast Uncertainty. WMO/TD No. 1422, Geneva
WMO (2009) Guide to Hydrological Practices, 6th edn. WMO-No. 168, Geneva
WMO (2010) Severe Weather Forecasting Demonstration Project (SWFDP): Guidebook on planning regional subprojects, World Meteorological Organisation, Geneva
WMO (2011a) Manual on Flood Forecasting and Warning. WMO-No.1072, Geneva
WMO (2011b) WMO Strategic Plan 2012–2015. WMO-No. 1069, Geneva
WMO (2012a) WMO/UNESCO International Glossary of Hydrology, WMO-No. 385, Geneva
WMO (2012b) Management of Flash Floods. WMO/GWP Associated Programme on Flood Management, Integrated Flood Management Tools Series No.16
WMO (2012c) Manual on the Global Data-processing and Forecasting System, Volume I - Global Aspects. WMO-No. 485, Geneva
WMO (2012d) Technical Material for Water Resources Assessment. Technical Report Series No. 2, WMO-No. 1095, Geneva
WMO (2012e) Climate and Meteorological Information Requirements for Water Management: A review of issues. WMO-No. 1094, Geneva

Part I
Techniques

Chapter 2
Meteorological Observations

Abstract Meteorological observations play a key role in many flood, drought, environmental and water resources applications. Whilst rainfall observations are most widely used, other parameters of interest include air temperatures, humidity and wind speeds. The main measurement techniques include raingauges, weather stations and weather radar, with satellite precipitation estimates playing an important role in data-sparse regions. This chapter discusses these approaches and some of their strengths and limitations for hydrological applications. This includes a discussion of multisensor techniques which seek to combine the best features from several different observation systems.

Keywords Raingauge • Weather station • Weather radar • Satellite precipitation estimate • Multisensor precipitation estimate • Meteorological observations

2.1 Introduction

Observations of rainfall and atmospheric variables are widely used in hydrometeorological applications. Some typical uses, which are discussed in later chapters, include:

- Demand forecasts – estimating the impacts of air temperatures on water demand for water supply, irrigation and hydropower applications
- Drought indices – using rainfall observations to derive indicators of drought risk to help with deciding whether to issue alerts
- Flash flood alerts – using observations of rainfall amounts (depths) over a range of time periods (durations) as indicators of the risk of flooding
- Flood forecasting – providing an automated feed of rainfall observations to rainfall-runoff models to estimate flood flows
- Snowmelt forecasts – providing estimates for the magnitude and timing of snowmelt-driven runoff based on rainfall and air temperature observations
- Water resources – providing inputs to the rainfall-runoff and reservoir components in water supply models

In most countries, the national meteorological service operates a core network of raingauges, weather stations and – where budgets allow – weather radars, plus a range of more specialised instrumentation (see Table 2.1). However, separate

K. Sene, *Hydrometeorology*, DOI 10.1007/978-3-319-23546-2_2

Table 2.1 Some examples of observation techniques used in weather forecasting applications

Technique	Description
Aircraft and shipborne instruments	Automated equipment for monitoring key atmospheric parameters for transmission by radio or satellite telemetry; for example, for aircraft, typically reporting on wind speed and direction, air temperature, altitude, atmospheric turbulence (indirectly) and the aircraft position. Several thousand aircraft and ships are included in these long-established voluntary programmes (WMO 2013). As necessary, some organisations, such as NOAA, operate flights into oncoming tropical cyclones and hurricanes to gather additional data from on-board instruments and using radio-equipped dropsondes
Ground-based GPS	The use of specialised GPS devices in conjunction with surface pressure observations to estimate the atmospheric precipitable water or integrated water vapour in the vicinity of the instrument. The estimates are based on the time delay of the signal between satellite and ground, expressed in terms of ionospheric and hydrostatic and 'wet' or water vapour-related components. This technique is useful both to assist with thunderstorm forecasting and data assimilation in atmospheric models and has been used by meteorological services since the 1990s; the precipitable water is an estimate of the depth of water which would result if all of the water vapour in an imaginary column of air over a given location was to fall as precipitation
Lightning detection systems	Ground-based networks for detecting the locations of lightning flashes, inferred from the differences in time of travel to each sensor of electromagnetic waves in the lower atmosphere. These low-frequency emissions sometimes propagate for hundreds of kilometres. These observations are increasingly used as part of the data assimilation process in atmospheric models and in thunderstorm forecasting
Radiosondes	Expendable air pressure, air temperature and humidity sensors for providing upper-air observations and vertical profiles within the atmosphere; these are launched on hydrogen- or helium-filled weather balloons, with a transmitter to relay data. More than 1,000 are launched twice each day internationally as part of a coordinated effort within the WMO World Weather Watch Programme, and heights of up to 20–35 km are reached. Rawinsondes in addition provide information on wind speed and direction via on-board GPS sensors or tracking from the ground. In the past, balloons were launched manually, but automated launchers are increasingly used, particularly in remote locations
Wind profilers	Ground-based vertically pointing radar instruments for continuously measuring the vertical wind profile in the lower atmosphere, and sometimes equipped with radio-acoustic sounding systems for estimating air temperature profiles. For example, in one approach, wind speeds at different levels are deduced from the frequency shifts and time of travel for several beams transmitted vertically and at an angle to the vertical resulting from backscattering due to variations in refractivity. Profilers provide the advantage of continuous monitoring of wind speed and, in some cases, air temperature profiles and have been widely used since the 1990s

Adapted from Sene (2013)

networks of raingauges and weather stations are often operated by other organisations such as hydrological services, agricultural research institutes, water supply utilities and hydropower companies. Some meteorological services also support active networks of volunteer observers or 'spotters'.

Internationally, there are networks of raingauges and weather stations in most countries, at least to some extent. However, due to the expense and specialised knowledge required, some other types of instrumentation are used to a lesser extent. For example, weather radar coverage ranges from being almost complete in most of the USA, Canada, Europe and parts of Asia to very limited in parts of Africa.

Satellite systems differ in that these are normally operated by space agencies such as NASA in the USA, EUMETSAT in Europe or JAXA in Japan. There is also increasing private sector involvement, such as for telecommunications networks and the public/private partnerships for some types of earth observation satellites. For meteorological applications, some of the earliest systems were the Meteosat series of geostationary satellites in Europe and the GOES series in the USA, and further examples are presented later.

For national meteorological services, a key driver for data collection is to support the operation of weather forecasting models. Most national services are members of the World Meteorological Organisation – which is a specialised United Nations agency – and so have access to information via the WMO Global Observing System. Figure 2.1 illustrates the typical flow of data to a national centre.

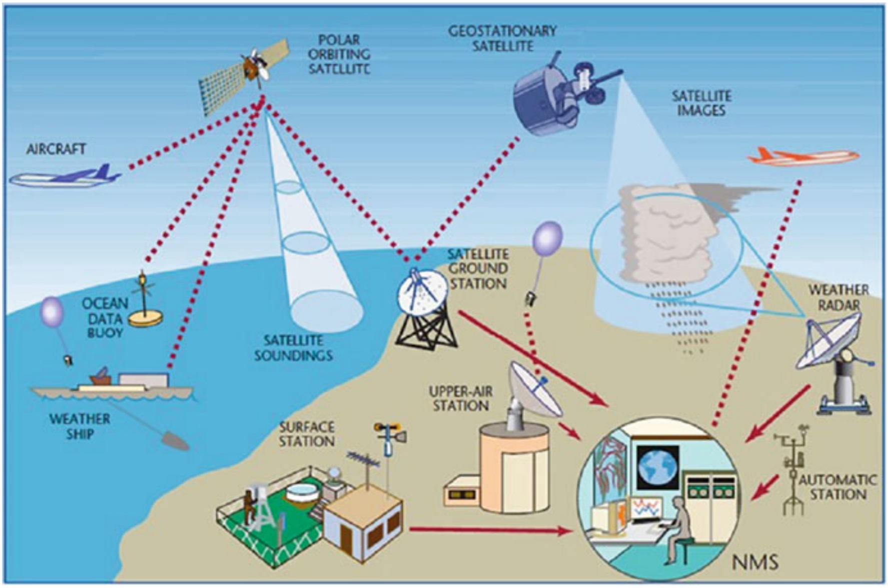

Fig. 2.1 Illustration of the WMO Global Observing System, which is a fundamental component of World Meteorological Organisation (WMO) programmes and services. Data are collected from satellites, hundreds of ocean buoys, aircraft, ships and some 10,000 land-based stations. Within countries, the National Weather Service makes observations using manned and automatic instruments of temperature, precipitation, wind speed and direction, atmospheric pressure and other characteristics of the 'weather'. The observations, forecasts and products developed from these data are sent around the world every day, using the Global Telecommunication System (WMO 2006, courtesy of WMO)

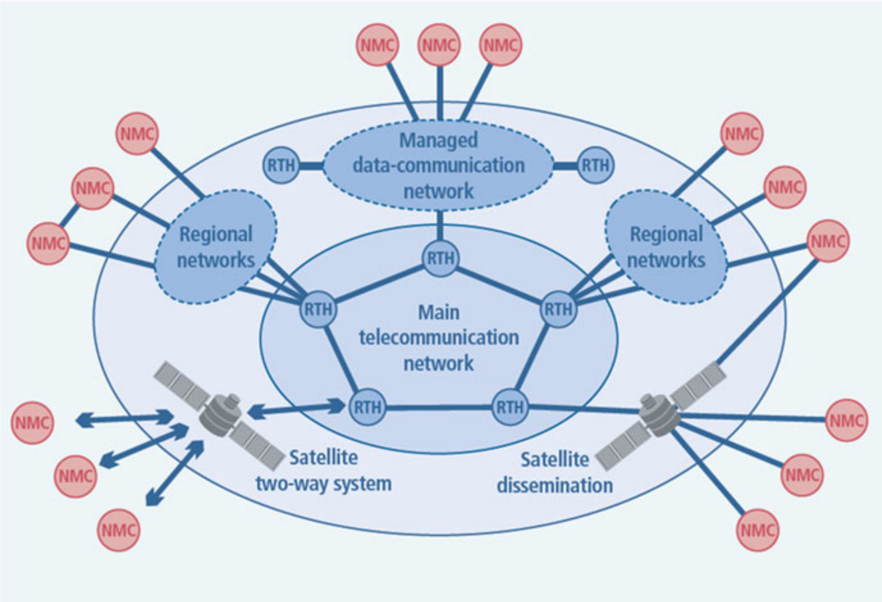

Fig. 2.2 Structure of WMO's Global Telecommunication System (*NMC* National Meteorological Centre) (WMO 2006, courtesy of WMO)

The main routes for data exchange are links within the WMO Global Telecommunication System (GTS) and those provided by national or international space agencies. Figure 2.2 shows the structure of the GTS, and as noted in WMO (2006), this is:

> a dedicated network of telecommunication facilities and centres, using leased lines, satellite-based systems, the Internet, and data networks, that is implemented and operated by the National Meteorological and Hydrological Services of WMO Member countries…

for which some key functions are:

> to facilitate the rapid, reliable collection and exchange of all meteorological and related data and for the distribution of weather, climate and water analyses, forecasts and warnings produced by the Global Producing Centres, Regional Specialized Meteorological Centres and National Meteorological and Hydrological Services. The System also supports the exchange of certain other data, such as seismic data.

Due to the need to share data between time zones, values are usually reported using the UTC (Coordinated Universal Time) time standard, based on standard (synoptic) intervals of every 6 h starting from midnight (00:00) each day and, where possible, 3-hourly intermediate intervals. In practice values are usually recorded more frequently at automatic stations. The term synoptic here means that observations are intended to provide a simultaneous view of current conditions over a wide area.

In many cases, observations are shared with hydrological services, which often operate their own telemetry networks, as discussed in Chap. 3. Although it is difficult to generalise, for hydrological applications ground-based observations – including weather radar – are usually preferred due to their greater accuracy and higher resolution; however, where networks are sparse or a wider spatial view is required, then satellite-based estimates are sometimes a better choice, or the only option. Later sections and chapters discuss these issues in more detail, but in general terms some key technical factors to consider in choosing which techniques to use include:

- Sampling frequency – In some cases, there are constraints on how often observations can be provided, a classic example being with polar-orbiting satellites which usually only overfly a given area every few hours or days.
- Signal processing – Some observation systems such as raingauges provide direct estimates for the parameter(s) of interest, whereas others, such as weather radars and satellites, require some assumptions and further post-processing to infer the values required.
- Spatial resolution – All observation systems have limitations such as the network densities for raingauges and the grid scale and maximum useful range for weather radars, a key question being how these relate to the hydrological scales of interest.
- Transmission times (or latency) – For most observation systems, there is a delay of minutes or more between the time at which an observation is made and its receipt, plus completion of any post-processing required.

For example, for fast-developing situations such as flash floods, ideally sub-hourly rainfall observations would be available at a fine level of detail, which tends to rule out the use of satellite-based observations. In contrast, droughts usually develop over periods of weeks or months over a wide area so that daily or longer transmission intervals are sometimes sufficient.

The following sections describe these various techniques in more detail. Further information is provided in the many books, technical standards and guidelines on these topics including WMO (2000, 2007, 2008a), Strangeways (2007), Michaelides (2008) and Testik and Gebremichael (2010). Multisensor approaches are also increasingly used as discussed in Box 2.1.

Box 2.1: Multisensor Precipitation Estimates

In recent years, there has been increasing interest in the use of multisensor products based on the outputs from several types of sensor. The main aim is to overcome some of the limitations in individual observation systems and hence to reduce the uncertainty in the overall estimates. Some alternative names include data fusion or multiparameter techniques.

One particular application has been for precipitation estimates due to the difficulties in observations; for example, relating to the wide spatial and temporal variations in rainfall in most storms. Indeed the following two techniques are well established as discussed in later sections:

(continued)

Box 2.1 (continued)

- Weather radar – adjustment of outputs using real-time raingauge observations
- Satellites – combining the outputs from multiple satellite systems and – in some cases – recent raingauge observations

These types of analyses are increasingly guided by, or merged with, the outputs from Numerical Weather Prediction (NWP) models, such as estimates for the vertical profiles of temperature and humidity.

A more recent development has been to include information from additional sources such as lightning detection systems, wind profilers, radiosondes and GPS-based humidity estimates. In particular, increases in lightning activity and humidity are often signs of convective activity and thunderstorms. One such example is the Multiple Radar Multiple Sensor System which is under development in the USA by a consortium of organisations (http://mrms.ou.edu/); the website notes that, in addition to weather forecasting and aviation, some other potential applications include flood warning and support for hydrological and ecosystem modelling. This general approach is also used in some nowcasting systems as discussed in Chapter 4.

More generally, some necessary capabilities for this type of approach include (Vasiloff et al. 2007):

- Real-time processing of radar, rain/snow gauge, satellite, lightning and NWP output data
- Quality control tools for input datasets
- Variable resolution and formatting of input data and output products
- Long-term retrospective analysis, that is, reanalysis
- Robust verification and assessment tools
- Integration of externally derived precipitation products
- High-bandwidth servers for product generation and dissemination

Here reanalysis is the generation of long-term time series based on current algorithms and sensor networks; that is, the aim is to derive a best estimate for what might have been observed in the past if present-day systems had been available. Analyses of this type are increasingly becoming available for multisensor, satellite precipitation and weather radar systems, in some cases with the analyses extending back several decades. As discussed in Chaps. 4 and 5, these outputs have many potential uses in model calibration and verification studies for both meteorological and hydrological applications (e.g. Moulin et al. 2009; Krajewski et al. 2010; Nelson et al. 2010).

2.2 Satellites

2.2.1 Introduction

Since the Sputnik 1 satellite was launched in 1957, satellites have been increasingly used for communications, earth observation and a range of other applications. Estimates vary, but it seems likely that more than one thousand are operational at any one time.

One of the main distinguishing features between satellite systems is the orbital height, for which the three main categories are geostationary, polar and low-earth orbit (LEO). Geostationary satellites are placed above the equator at an altitude of approximately 36,000 km, whilst the altitudes for polar and low-earth orbiting satellites are typically in the ranges 700–1,000 km and 300–800 km.

For geostationary satellites, the orbit is chosen so that they appear to remain fixed relative to a given point on the earth. Images are typically provided every 15–30 min in the visible, water vapour and infrared bands at a spatial resolution of 1–4 km. In contrast, satellites in lower orbits may only pass near to a given location every few hours or days but due to the shorter range can use a wider range of sensors, such as microwave sensors. To improve the spatial coverage, this has led some operators to launch constellations of satellites, and some telecommunications systems contain more than 50 low-earth orbit satellites. For meteorological applications, however, polar-orbiting satellites are usually operated in pairs using sun-synchronous orbits which ensure that a given location on the equator is overflown at about the same time each day.

Table 2.2 provides some examples of the satellite systems used in meteorological and earth observations. Many of these form part of long-term programmes in which a series of satellites has been launched under the same general name but with successive improvements to sensors, communications and the satellite platform (spacecraft). Examples include the long-running US, European and Japanese geostationary satellite programmes which – along with satellites operated by Russia, China and several other countries – form part of the WMO Integrated Global Observing System (WIGOS). Other examples of international collaborations include those between the MetOp and NOAA-N programmes and the multi-national GPM programme.

Most satellites carry a range of sensors and communications equipment and sometimes secondary payloads such as for search and rescue operations. Some long-established types of sensor with applications in meteorology include the Special Sensor Microwave Imager Sounder (SSMIS; successor to SSM/I), Advanced Microwave Sounding Unit (AMSU), Microwave Humidity Sounder (MHS) and – for visible and infrared observations – the Advanced Very High Resolution Radiometer (AVHRR). Here a sounder is designed to detect radiation in frequencies typical of the atmosphere, whilst passive imagers focus on those typical of the ground or sea surface and/or cloud cover (and active devices in addition exclude typical surface and cloud emission frequencies). There are of course many newer types than the few listed here.

Table 2.2 Some satellite systems of interest to hydrometeorological forecasting applications

Name	Country/operator	Orbit	First launch	Typical hydrometeorological applications
Geostationary Operational Environmental Satellite (GOES)	National Oceanic and Atmospheric Administration (NOAA)	G	1975	Weather forecasting, earth observation; three operational satellites provide near global coverage
Global Precipitation Measurement (GPM) mission	International/ multi-agency	LEO, P	2014	Precipitation measurement by active weather radar and other instruments
Himawari (formerly MTSAT/GMS)	Japan Meteorological Agency (JMA)	G	1977	Weather forecasting, earth observation, with two satellites positioned over East Asia and the Western Pacific
Joint Polar Satellite System (JPSS); formerly NOAA-N	National Oceanic and Atmospheric Administration (NOAA)	P	1978	Operational meteorology; NOAA-19 launched in 2009; Suomi in 2011; more planned
Landsat	National Aeronautics and Space Administration (NASA)/USGS	P	1972	Earth observation of vegetation, land use, flood extents, etc.
MetOp	EUMETSAT (Europe)	P	2006	Operational meteorology. with the first two satellites launched in 2006 and 2012, with more planned
Meteosat Second Generation (MSG)	EUMETSAT (Europe)	G	1977	Meteorological observations using three operational satellites
RadarSat	Canadian Space Agency, private sector	P	1995	Earth observation by Synthetic Aperture Radar (SAR)
SENTINEL	European Space Agency	LEO	2014	Earth observation including Synthetic Aperture Radar (SAR); several satellites planned
SPOT	Public/private sector (France/Sweden/ Belgium)	P	1986	Earth observations including the SPOT VEGETATION product

G geostationary orbit, *P* polar orbit, *LEO* low-earth orbit

In addition to the types of sensor and wavelengths recorded, as indicated above another distinguishing feature is whether sensors are passive or active. Here, passive sensors record the radiation received from the atmosphere, land surface and oceans, whereas active systems transmit a signal into the atmosphere and record the returns. Synthetic Aperture Radar (SAR) is an example of an active sensing approach and combines successive images along the satellite track to simulate an extremely large high-resolution radar antenna; for example, to generate digital elevation models of the earth's surface. Using these various approaches, some quantities which can be measured or inferred in the atmosphere and oceans include (WMO 2008a):

(a) The temperature profile and the temperature at the cloud top and at the surface of the sea and land
(b) The humidity profile
(c) The wind at cloud level and at the ocean surface
(d) Liquid and total water and precipitation rate
(e) Net radiation and albedo
(f) Cloud type and height of cloud top
(g) Total ozone
(h) The coverage and the edge of ice and snow

Table 2.3 illustrates some of the types of satellite data products which are produced. Quantities such as wind and humidity profiles, or the underlying radiances, are of great interest in weather forecasting, and, as discussed in Chap. 4, satellite observations play a vital role in numerical weather prediction, with obvious benefits for hydrological applications.

However, for hydrometeorological applications, the suitability of products needs to be evaluated on a case-by-case basis. Some important considerations include the time intervals and resolution at which products are available, the cost and means of delivery plus of course the performance of the algorithms used to infer (retrieve) the parameters of interest from the raw radiance observations.

For example, polar-orbiting satellites typically record data along a track with a width (swath) of a few 100 km and orbit the earth every 100 min or so. Hence, a given area such as a river catchment may only be observed every few hours or more, so that the outputs are only of limited use for some applications. By contrast, geostationary satellites remain within sight of a given point on the ground at all times but, due to their much greater altitude, have some limitations on the products available. In some systems, there are also significant time delays between observations and receipt of the processed values.

Table 2.3 Some examples of the types of satellite-based products used in meteorological applications in addition to radiance and imagery products (Adapted from Sene 2013); the categories are based on WMO (2007)

Category	Typical sensor inputs	Examples of derived/inferred outputs
Cloud characteristics	Visible, infrared	Cloud top temperatures, types, heights, masks, etc.
Atmospheric temperature and humidity soundings	Infrared, microwave	Vertical profiles of air temperature and humidity
Atmospheric motion winds	Sequences of cloud, water vapour or ozone images or fields	Estimates for wind speeds and directions at various levels
Land and sea-surface temperatures	Infrared (cloud-free), microwave (sea temperatures)	Estimates with various spatial resolutions and coverages
Snow and ice	Visible, infrared, microwave	Spatial coverage, plus snow depth estimates for active microwave instruments
Vegetation	Visible, infrared	Vegetation type and growth, leaf area index
Ocean surface	Microwave (active), scatterometer	Sea level (altimetry), significant wave height, wind intensity

Mission websites normally publish these key aspects of performance for the range of products offered with links to detailed technical documentation. Despite these limitations, satellite systems are widely used in hydrology, and some examples include data transmission for hydrological data (Chap. 3), snow cover detection for flood forecasting applications (Chap. 8), estimating drought indices in famine early warning systems (Chap. 10) and monitoring the spread of Harmful Algal Blooms (Chap. 12). More generally, estimates of soil moisture, land use and vegetation cover are of value in many applications, as are satellite precipitation estimates as discussed in the following section.

2.2.2 Satellite Precipitation Estimates

Although satellite images show cloud formations, quantitative estimates of precipitation at the ground surface need to be inferred, and estimates are often based on the outputs from several sensors.

Estimates of this type have been available since the 1970s, but historically one limitation for hydrological forecasting applications has been the accuracy and resolution of the products, with the possible exception of some large river basins. As noted earlier, the need for constant surveillance also rules out individual polar and low-earth orbiting satellites for some applications, such as flash flood warning. However, the outputs continue to improve, and several practical applications are discussed in later chapters. The Global Precipitation Measurement mission also offers great potential for the future and is discussed further in Box 2.2.

Box 2.2: Global Precipitation Measurement Mission

Spaceborne weather radars provide more accurate estimates of precipitation than passive infrared or microwave sensors can support. The first such instrument to be flown was as part of the joint US/Japanese Tropical Rainfall Measuring Mission (TRMM). The satellite was launched in 1997 into a low-Earth orbit which covered much of the tropics, with an altitude of about 400 km.

The principles of operation for spaceborne radar are similar to those for ground-based installations; however, some key constraints include weight limitations and the time delays between each overpass of the satellite. Nevertheless – despite these constraints on the observations – these were used as a key input in generating three-hourly estimates of rainfall in the tropics for nearly two decades, and this led to numerous scientific papers and several operational applications. The satellite operated long beyond its planned initial lifetime, and it was not until 2014 that it ran out of fuel.

The successor to TRMM is the Global Precipitation Measurement (GPM) mission. This is again led by NASA and JAXA and builds on the experience gained from the TRMM (Hou et al. 2014). The GPS Core Observatory satellite was launched in 2014, and the two primary instruments are a 13-channel microwave imager and a dual-frequency precipitation radar. The radar operates

(continued)

Box 2.2 (continued)
in the Ku and Ka bands with wavelengths of ~2 and ~0.8 cm, respectively, and has a spatial resolution of approximately 5 km. The radar and microwave systems are complimentary, with the imager more sensitive to light rain and snowfall than the radar, whilst the radar is better able to detect moderate to heavy rainfall. The two frequencies used in the radar also allow drop size distributions to be estimated.

However, another key function of the Core Observatory is to act as a reference for the microwave sensors carried on board a number of other satellites. The aim is to provide a consistent framework for intercalibration of the outputs so that combined products can be produced with a greater spatial and temporal resolution than is possible from the Core Observatory alone.

The partners for this constellation of satellites include operators of existing satellites in the USA, Japan, India and Europe (and more are expected to be launched in future). Research institutions from more than a dozen countries are participating in the scientific aspects of the mission, and an extensive network of ground-based monitoring stations has been set up in Europe, the Americas, Asia and Africa to assist with validating the outputs. Some potential applications of the combined outputs include flood monitoring, crop forecasting, water management and landslide risk assessments, whilst the core scientific objectives for the overall programme are:

- Advancing precipitation measurement from space
- Improving knowledge of precipitation systems, water-cycle variability and freshwater availability
- Improving climate modelling and prediction
- Improving weather forecasting and 4-D climate reanalysis
- Improving hydrological modelling and prediction

Here, reanalysis is the construction of uniformly gridded meteorological data fields, and the fourth dimension referred to is time. Some particular advances envisaged (http://pmm.nasa.gov/) in the area of precipitation estimation include the capability to:

- Provide retrievals of microphysical properties and vertical structure information using active remote-sensing techniques over a broad spectral range
- Estimate snow and lighter rain rates through the use of high-frequency passive microwave radiometry
- Improve passive microwave retrieval (PWR) algorithms over land
- Improve precipitation retrievals in mid and high latitudes during cold seasons

For individual sensor products, one key objective is to make precipitation products routinely available with near global coverage at 3-hourly intervals or better, within three hours of observation (and combined products will be interpolated to finer timescales). Planning is also underway for additional spaceborne radar missions with Doppler capability.

Some of the first operational approaches were so-called Cold Cloud Duration techniques, based on geostationary satellite observations. This technique is particularly useful in data-sparse regions (e.g. Tarnavsky et al. 2014), and the underlying assumption is that deeper cloud formations are more likely to lead to intense rainfall and so will tend to have lower temperatures at their upper limit. The inputs typically include both visible and multichannel infrared observations of cloud cover and cloud top temperatures. The precipitation at the ground surface is normally inferred using empirical relationships calibrated from historical raingauge or weather radar. In some products, the outputs are guided by wind field and humidity estimates from Numerical Weather Prediction models such as in the widely used NOAA Hydroestimator product (Scofield and Kuligowski 2003). More generally, both cloud-indexing (single image) and life-history (successive image) approaches are used (WMO 2000).

Another long-established approach is to use the outputs from microwave sensors on board polar-orbiting satellites. The basis of the method is to detect cloud emissions due to water vapour and hence to infer the water and ice content of cloud formations. Over the oceans, there is generally a sharp contrast with the background levels of radiation, whilst over land, the presence of clouds can be inferred from reductions in brightness temperatures.

Cold Cloud Duration techniques are generally most suitable for deep convective layers in areas such as the tropics but often have limitations for stratiform and orographic cloud. In contrast, microwave-based techniques generally work best when there are significant amounts of cloud ice particles present and less well for warmer orographic cloud. For a given location on the ground, the best temporal and spatial resolutions achieved are about 15 min/4 km for geostationary satellite-based precipitation products and 3–6 h/15 km for passive microwave-based products (Vasiloff et al. 2007) although resolutions continue to improve (see Box 2.2). However, the performance depends on a number of factors including the choice of sensors, the signal processing algorithms, and atmospheric conditions (e.g. Sorooshian et al. 2011).

Given these differing measurement characteristics, another development has been to produce products based on a combination of these techniques. For example, in the NOAA CMORPH approach (Joyce et al. 2004), microwave precipitation estimates from a number of polar-orbiting satellites are combined and propagated during the periods between satellite overpasses based on infrared observations from geostationary satellites. In contrast, the Rainfall Estimation (RFE) Algorithm (Xie and Arkin 1996; NOAA 2009) combines precipitation estimates from the following sources:

- Rainfall amounts from up to 1,000 raingauges across Africa, quality controlled using maximum/minimum range checks and plausibility checks against the satellite estimates
- Precipitation estimates from the Special Sensor Microwave/Imagery (SSM/I) microwave sensors on the Defense Meteorological Satellite Program polar-orbiting satellites, which are available up to 4 times per day at a resolution of approximately 25 km (Ferraro and Marks 1995)

- Precipitation estimates from the Advanced Microwave Sounding Unit (AMSU) aboard NOAA-N series polar-orbiting satellites, at a similar spatial and temporal resolution to SSM/I (Zhao et al. 2000)
- Precipitation estimates based on Meteosat infrared cloud top temperature measurements using the GOES Precipitation Index at half hourly intervals and a resolution of 4 km (Arkin and Meisner 1987)

These outputs are merged using predetermined weighting coefficients based on a maximum likelihood approach and an inverse weighting scheme. The single combined value is then adjusted using the raingauge data, again using an inverse weighting scheme.

Some other examples include PERSIANN (Hsu and Sorooshian 2008) which combines multiple inputs using artificial neural network techniques and the EUMETSAT Multi-sensor Precipitation Estimate (MPE) product (Kidd et al.; 2008) which blends geostationary and polar-orbiting infrared and microwave observations. As discussed previously, the decision on which technique(s) to use depends on a number of factors including the performance at the study location and the frequency and latency of observations.

Regarding performance, Chap. 4 discusses forecast verification techniques for rainfall forecasts, and similar techniques are used to help to assess the accuracy of satellite precipitation estimates. In particular, since 2001 the CGMS/WMO International Precipitation Working Group has provided a focus for the development and comparison of satellite-based precipitation measurement techniques (e.g. Turk et al. 2008). For example, a general finding, based on comparisons of nine satellite precipitation products and the outputs from four Numerical Weather Prediction (NWP) models (Ebert et al. 2007), was that, for daily values over land at ~25 km spatial scales:

> Satellite estimates of rainfall occurrence and amount are most accurate during summer and at lower latitudes, while the NWP models show greatest skill during winter and at higher latitudes. Generally speaking, the more the precipitation regime tends toward deep convection, the more (less) accurate the satellite (model) estimates are.

More generally, some priorities for research include (e.g. Turk et al. 2008; Sorooshian et al. 2011):

- Quantification of the uncertainty in individual sensors and precipitation products
- Optimisation of algorithms for different climate regions, storm regimes, surface conditions, seasons and altitudes
- Further development of error or performance metrics

2.3 Raingauges

Raingauge networks are operated for a range of purposes, including agricultural, flood warning and water resources applications.

Manually operated gauges collect rainfall in a purpose-made container. At a fixed time each day (or other period), an observer then empties the accumulated water into a graduated measure to record the rainfall since the last reading. These are often called storage or non-recording gauges. The records are then usually either sent to regional or national headquarters on a regular basis or collected during routine visits.

Volunteer observers also play an important role in some countries; for example, in the UK reporting observations from several thousand gauges. The Community Collaborative Rain, Hail and Snow (CoCoRaHS) network in the USA operates on a similar principle (http://www.cocorahs.org/). A similar number of volunteers report on weather conditions, snowfall and other parameters in the National Weather Service Cooperative Observer Program (http://www.nws.noaa.gov/om/coop/). These networks provide a valuable additional source of information, and web-based tools are increasingly available to share data more widely.

A key advantage of automated gauges is the option to report observations on a more frequent basis, in some cases as frequently as every 1 to 5 min. These are often called autographic or recording gauges and are widely used in flood warning systems and water resources applications. Perhaps, the most common type is the tipping bucket raingauge (e.g. Fig. 2.3) in which rainfall is collected in a receptacle which is divided into two sections and mounted on a lever arm. Once a certain weight of water has been collected, the arm tips emptying that side of the container so that its counterpart rises up to take its place. Each tip is recorded on a data logger and – for gauges with telemetry – either reported immediately or accumulated

Fig. 2.3 Examples of raingauges sited at a weather station in the UK (*left*) and an IFLOWS installation in the USA (*right*). Integrated Flood Observing and Warning Systems (IFLOWS) are widely used in flood warning applications in the eastern USA and have similar origins to the ALERT systems discussed in Chap. 3; here, the gauge is situated at the top of the structure, which also houses a data logger and telemetry equipment (Sene 2013)

to be sent at the next transmission time. The rainfall depths recorded per tip are one of the choices available on purchase and are typically in the range 0.2–2.0 mm. Larger sizes are often more appropriate for high rainfall locations, and many organisations standardise on a single size; for example, 0.2 mm or 0.5 mm gauges are often – but not exclusively – used for flood warning applications in temperate regions.

More generally, some other ways of automatically recording rainfall include:

- Drop-counting raingauges – which use optical detectors, electrodes or piezoelectric sensors to infer the size and numbers of individual droplets and hence the rainfall rate
- Hot-plate types – which estimate rainfall intensity or snowfall from the additional power required for evaporation from an electrically heated plate
- Weighing raingauges – which measure the weight of water accumulated using load cells, strain gauges or vibrating wire techniques

Hot-plate gauges are a recent innovation in which two horizontal plates are maintained at a constant temperature and mounted one above the other (Rasmussen et al. 2011). The lowermost plate is shielded from rain and snow but exposed to a similar wind field as the upper plate, thereby allowing wind-related influences to be inferred and corrections made.

The decision on which type of gauge to use normally depends on a range of factors such as performance, cost, vendor support, power requirements and issues related to the location, such as site security and ease of access. For example, for national networks, a 2008/2009 survey suggested that tipping bucket raingauges are the most common type (Nitu and Wong 2010) followed by weighing raingauges, with 1-min or hourly reporting intervals the most common. Solid-state types such as drop-counting and hot-plate instruments provide another option, with the former a common feature in weather stations operated by highways agencies.

The likely gauge performance is usually assessed from a combination of past experience, documentation from the manufacturer and – if possible – the findings from intercomparison experiments. However, it is worth noting that some issues may relate to installation or maintenance problems rather than just technical limitations; for example, some typical problems include:

- Temporary blockages from poor maintenance (e.g. grass cuttings, fallen leaves)
- Spurious returns from splashing from the surrounding ground and other factors such as unreported gauge testing or repairs
- Evaporation of water within the instrument before it is recorded such as from wetting of the gauge funnel
- Wind effects locally around the gauge and from surrounding obstacles such as trees and buildings

Wind effects are often the main concern, and most national services have technical standards which specify the maximum heights at which instruments should be installed and the minimum clearance from surrounding obstacles (e.g. WMO 2008a; Sevruk et al. 2009; Vuerich et al. 2009). However, sometimes for reasons such as security of the equipment or the risk of flooding, it is necessary to use locations which are not ideal, such as siting gauges in confined areas or on top of the recorder kiosks at river gauging stations.

Some common ways to reduce wind effects are to use wind shields to break up the airflow around the gauge and/or to give the gauge sides a more aerodynamic profile. In some cases, observations are adjusted using empirically based correction factors (e.g. WMO 2009). Where accurate observations are particularly important, reference gauges are sometimes installed in which the gauge is located in a large pit with the opening at ground level and surrounded by a mesh screen. This helps to reduce wind effects and splashing, and these types of installations are often used in intercomparison studies and in deriving correction factors for other types of gauge. For some locations, snowfall is another consideration, and mitigation options include the use of shields to help to reduce wind drift and the addition of electrical heaters to gauges. However, there are better ways to record snow depth and snow water equivalent, and Chapter 3 describes some examples.

For many hydrological applications, area-averaged estimates of rainfall are required, such as catchment-average values. Table 2.4 summarises several of the most common techniques, and some examples of their application are provided by Creutin and Obled (1982), Tabios and Salas (1985), Seo (1998), Goovaerts (2000), Daly (2006) and Zhang et al. (2011), amongst others. Map-based (GIS) analyses and digital terrain models are often used in deriving the weights and other factors to apply.

As indicated, secondary or auxiliary variables are considered in some approaches, such as the elevation or aspect at the gauge location, or the recorded mean annual rainfall. Some approaches such as geostatistical techniques also provide an estimate for the uncertainty in estimates as part of the calculation procedure (e.g. McMillan et al. 2012).

Table 2.4 Some examples of approaches to catchment averaging of raingauge observations

User-defined weights	The total rainfall consists of a weighted sum where the weights are derived by trial and error, using expert judgement, or consideration of factors such as the elevation and mean annual rainfall for each gauge. The simplest approach is to use equal weights which provide an arithmetic mean
Thiessen Polygons	A weighted sum, with the weights based on the proportion of the catchment area attributed to each raingauge, based on polygons constructed from lines connecting the mid-points between gauges
Inverse distance	A weighted sum, with the weights dependent on functions of the inverse of the distance of gauges (e.g. the inverse square) from grid points or other locations of interest, perhaps including elevation in the relationship, and sometimes with a cut-off beyond a certain distance
Isohyetal	Derivation of lines of equal rainfall and hence catchment rainfall estimates using expert judgement and/or automated procedures
Surface fitting	Other types of surface-fitting approach, such as spline interpolation, multiquadric and triangular plane (TIN) methods
Geostatistical techniques	Methods based on the covariance structure of observations, seeking to minimise the variance in estimates, sometimes bringing in other factors such as elevation using a co-Kriging approach

Most methods are suitable for automation within a forecasting system although for isohyetal techniques expert input is normally preferred. In real-time operation, individual gauge values need to be checked automatically before use, and some typical approaches include checks on unusually high values and comparisons with nearby gauges, plus maintaining a list of currently suspect gauges to exclude pending further investigation. However, particularly for flood warning applications, it is important that the validation algorithms do not inadvertently remove valid extreme values.

For sub-daily recording intervals, the simpler types of averaging techniques are generally better suited to low-lying areas, and where widespread, relatively uniform rainfall is the usual feature of interest, such as frontal events. However, where topographic influences on rainfall are important, such as elevation, aspect and slope, more complex techniques are normally preferred. Similar considerations apply at longer timescales such as daily or monthly values, although the influences of spatial variability are typically less pronounced. Some approaches to help with developing and calibrating averaging schemes include:

- Examination of historical sequences of weather radar and/or satellite time series data and images to see if there are any typical storm paths and types in a catchment
- Climatological studies to assess local meteorological influences such as rain shadow effects, elevation dependence (e.g. seasonal inversion layers) and coastal influences
- The use of stochastic sampling techniques to assess the performance of a large number of possible choices of parameter values
- Evaluating the proposed choice of scheme(s) in terms of the impacts on flow forecasts by using the rainfall estimates as inputs to hydrological models

Another key consideration is the gauge network density. The requirement often depends on the application, and this topic is discussed further in later chapters; however, some general points worth noting are:

- Gauge performance – In some cases, it may be better to exclude some raingauges in a region from the analysis due to issues with their performance, for example, as identified from double mass and time series comparisons with the records for nearby gauges
- Spatial representation – Due to difficulties of access, site security issues or operational needs, raingauges tend to be sited in or near population centres and often in the lowermost parts of a catchment, away from the main runoff generating areas

However, each situation needs to be considered on a case-by-case basis. For example, in temperate regions, a common issue is for there to be few raingauges in the higher elevation, headwater parts of a catchment. In contrast, in semiarid regions, the highest population concentrations are sometimes in the highest rainfall areas such as plateau regions inland and along coastal margins.

Where budgets allow, experimental studies using dense networks of raingauges can help to decide on optimum network densities. A process of successive degradation of the network (data denial) can then be used when evaluating different averaging schemes. Although in many applications the key requirement is to use real-time observations, it is worth noting that manually recorded observations should not be overlooked when deriving catchment-averaging schemes. This is because there are often many more instruments of this type in a region and historical records are typically available for much longer periods than for automated gauges. The key limitation of course is that usually only daily or monthly values are available or 10-day values in some agricultural applications. However, these can still provide an indication of factors such as elevation influences and typical storm directions, even when sub-daily values are the main interest.

Although raingauges are by far the most common in situ approach to measuring rainfall, another type of instrument which is widely used in meteorological applications is the disdrometer. These rely on interruption of a laser or ultrasound beam thereby providing information on drop sizes and distributions as well as rainfall intensity, and one use is in weather radar calibration studies. At a larger scale, microwave techniques offer the potential to measure path-averaged rainfall rates over distances of a kilometre or more (e.g. Ruf et al. 1996; Rahimi et al. 2003). Some factors which affect the signal attenuation include the rainfall extent, drop size distributions and moisture on the antennas. One factor which has led to increasing interest in this approach is the potential to make use of the tower-to-tower (backhaul) signals used by cell phone network providers (e.g. Leijnse et al. 2007; Zinevich et al. 2010; Overeem et al. 2013). Given the number of cell phone towers installed worldwide, this offers the chance to widen rainfall observation networks with little additional expenditure, particularly for urban areas. Some key areas for research include how best to interpret observations since the operating frequencies and tower placements were not originally designed with rainfall measurement in mind, and how to take account of factors such as wetting of antennas.

2.4 Weather Stations

Weather stations record a wide range of meteorological parameters and are used both on land and at sea, such as on ocean buoys, ships and oil rigs. Most meteorological services operate core networks for synoptic and longer-term climate observations, and other major users include the agricultural sector, road network and airport operators, and some reservoir operators and national hydrological services.

At most sites, the standard set of parameters recorded includes air temperature, humidity, wind speed and direction, atmospheric pressure and solar radiation. Although in practice networks are often more extensive than this, at a national level, WMO Member States are required to maintain two basic types of networks (WMO 2013) depending on the requirements laid down by WMO regional associations:

- Regional Basic Synoptic Networks – providing observations at synoptic intervals and intermediate times
- Regional Basic Climatological Networks – long-term stations (established for at least 10 years) including at least one reference climatological station

Some examples of additional application-specific variables then include:

- Aeronautical meteorological stations – runway visual range, atmospheric pressure (QNH and/or QFE)
- Agricultural meteorological stations – soil temperatures and soil water (volumetric content) at various depths, phenological observations

As for raingauges, instrument siting is an important consideration with regard to the surrounding terrain and local exposure. More generally, web-based services provide the opportunity to share data amongst many users and introduce common data validation and metadata standards (e.g. Box 2.3).

For manually operated sites, observations are usually made either once per day or at set times each day, such as at 3- or 6-hourly intervals, and more frequently in some applications, such as at airports. Instruments are normally installed in a fenced enclosure with a so-called Stevenson Screen to house those which need to be shielded, such as wet and dry bulb thermometers. This type of housing consists of a white-painted box, mounted above ground level, with louvered sides to allow ventilation. For synoptic stations, one feature is usually a tall mast to allow wind observations to be made at the standard height of 10 m; however, different heights are often used for other applications (WMO 2008a, b). Some types of observations such as present weather rely on the observer's experience or make use of secondary information such as cloud base reports from aircraft. Other types of instrument normally installed include a sunshine recorder and a raingauge.

Some of the longest continuous daily records are from Sweden, and these date back to 1722 in one case (Bergström and Moberg 2002). Manually operated stations are still widely used although increasingly at least some of the instruments are automated (e.g. Fig. 2.4). Nowadays, electronic sensors are available for most parameters, and examples include hygrometers (for humidity), radiometers (for radiation), ultrasonic anemometers (for wind speed), visiometers (for visibility), ceilometers (for cloud base) and thermistors (for temperatures). For example, ceilometers or cloud base recorders use an upwards pointing laser light source transmitted for fractions of a second, and the height of the cloud base is then deduced from the time taken for the reflected signal to be received. Installation options for automated sensors include the traditional meteorological enclosure or mounting all key instruments on a single mast. In some designs, several sensors are combined into a single solid-state unit.

Fig. 2.4 Example of a weather station in the UK with a Stevenson Screen in the foreground and a mast with a cup anemometer and wind vane; the inset image shows the top of the mast in more detail

Box 2.3: Weather Observations Website

In recent years, automatic weather stations have become widely used by weather enthusiasts, schools and small businesses. Manufacturers often provide the facility to display values on a website, and these outputs can potentially help to provide a wider view of current conditions than that available from synoptic networks alone. This is particularly the case for severe weather applications due to the extra detail provided at local level, even if the measurement techniques do not necessarily meet national or WMO standards.

To help to aggregate these types of observations, in 2011 the UK Met Office launched the Weather Observations Website, or WOW for short (http://wow.metoffice.gov.uk). The aim was to provide a common platform for displaying weather observations for use by amateur observers, schools and other potential users. Development of the site was supported by the Department for Education and the Royal Meteorological Society, and a similar site was later launched in Australia in partnership with the Bureau of Meteorology (http://www.bom.gov.au).

(continued)

Box 2.3 (continued)

In the first year of operations, observations were loaded from more than two thousand sites in over 150 countries, and the total now exceeds 5000. The site is free to use, and measurements can be added manually or loaded automatically from computer files. Some simple range checks are performed on data entry, and registered users can flag values which seem suspect; if multiple users highlight issues with a station, then further data entry is blocked until the owner has resolved the problem.

Importantly, when a site is created on the system – in addition to location, reporting intervals and other basic information – users are requested to enter key metadata relating to the site characteristics. The factors to enter include ratings (scores) describing the overall site exposure plus individual ratings for the quality of air temperature, rainfall and wind observations; for example, Table 2.5 shows the exposure categories relating to rainfall and air temperature observations. The WMO Urban Climate Zone Index (UCZ) also describes the degree of urbanisation at the site. An overall site rating is then calculated on a scale of 1* to 5* based on these values with additional quality ratings for the rainfall and air temperature instruments. There is also the option to include photographs of the site and surrounding area.

Measurements can be displayed as graphs (e.g. Fig. 2.5) or tables and on maps showing the spatial distribution of observations. The choice of output variables includes air temperatures, rainfall rate, present weather, wind speed/direction, humidity, atmospheric pressure, snowfall and soil moisture. Ad hoc information on weather impacts can also be entered and displayed on the maps; for example, using scores on a scale of 1–4 to summarise the level of travel, utility and business disruption and property damage. Free-text descriptions and photographs can also be added if users wish to provide this information.

Local observations such as these are increasingly used in early warning applications for both severe weather and other hazards, such as flash floods. The outputs can also be viewed on smartphones, and crowdsourcing techniques are under development, based on social media reports of weather impacts. Programming tools are available to allow third parties to develop custom-made applications, and a forum allows users to share information and to request help and assistance. Research is also underway to develop statistical techniques for automated validation of data entries, with a view to using these types of observations as part of the data assimilation process in numerical weather prediction models.

(continued)

Box 2.3 (continued)

Table 2.5 Summary of exposure category entries relating to rainfall and air temperature observations

No.	Exposure	Description
5	Very open exposure	No obstructions within 10 h or more of temperature or rainfall instruments
4	Open exposure	Most obstructions/heated buildings 5 h or more from temperature or rainfall instruments, none within 2 h
3	Standard exposure	No significant obstructions or heated buildings within 2 h of temperature or rainfall instruments
2	Restricted exposure	Most obstructions/heated buildings >2 h from temperature or rainfall instruments, none within 1 h
1	Sheltered exposure	Significant obstructions or heated buildings within 1 h of temperature or rainfall instruments
0	Very sheltered exposure	Site obstructions or sensor exposure severely limit exposure to sunshine, wind, rainfall
R	Rooftop site	Rooftop sites for temperature and rainfall sensors should be avoided where possible
T	Traffic site	Equipment sited adjacent to public highway
U	–	Exposure unknown or not stated

h is height of the obstruction above the sensor height

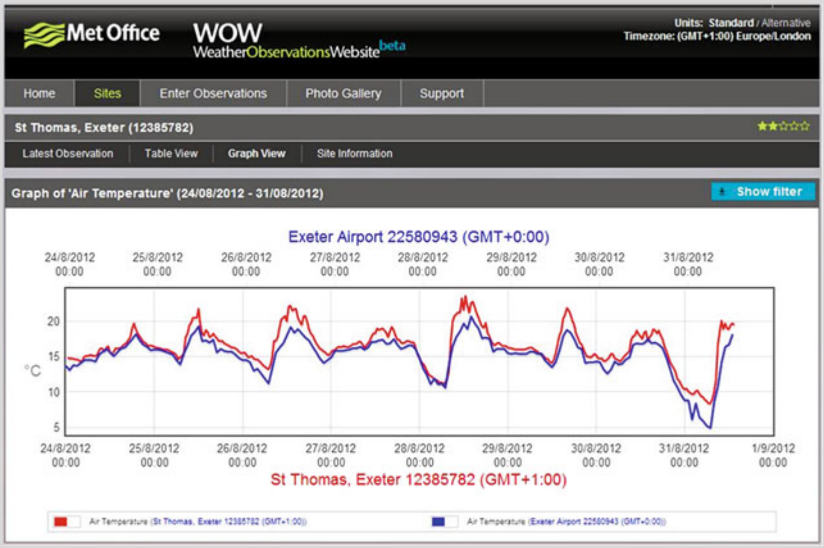

Fig. 2.5 Example of graphical output from the Weather Observation Website comparing air temperature observations for two sites (Green 2012; Contains public sector information licenced under the Open Government Licence v1.0)

2.5 Weather Radar

When aircraft-tracking radar networks were introduced in the late 1930s and 1940s, one early problem was interference from rainfall, snow and hail. However, the potential applications in meteorology were soon recognised, and the first operational weather radar networks were established in the 1950s.

The main meteorological applications of weather radar are for nowcasting and in the data assimilation process for Numerical Weather Prediction models (see Chap. 4). The outputs are also used for flood, drought, water quality and water resources applications. In some cases, this is mainly in a qualitative way to visualise the progression of storms, but the direct use as inputs to real-time hydrological models is increasingly commonplace as discussed in later chapters.

A weather radar installation usually consists of the radar dish, a radome to protect the dish and a building or housing which contains the computer and electrical equipment (e.g. Fig. 2.6). The dish is typically turned at several revolutions per minute. For meteorological applications, devices usually operate at wavelengths of about 3, 5 or 10 cm, which fall within the X-band, C-band and S-band, respectively. The attenuation of the signal is greater at shorter wavelengths, and hence the range (or optimal coverage) is shorter; however, the sensitivity to light rainfall is higher and smaller dishes are required. Most operational weather radar systems are C- or S-band devices although X-band radars are increasingly used to fill in gaps in national networks in mountain regions and/or near to high-risk locations, such as in Japan (Maki et al. 2010), Denmark (Pedersen et al. 2010) and France (see Box 4.2).

In most radar systems, the principle of operation is to transmit a rotating pulsed electromagnetic (microwave) beam and then record the strength of the backscattered

Fig. 2.6 View of the internal workings of a weather radar and the Chenies Radar in the UK (Met Office 2013; Contains public sector information licensed under the Open Government Licence v1.0)

signal and the time taken for it to return. This provides a measure of precipitation amounts and the distance from the radar. The ‘listening’ time is normally far greater than the time spent transmitting the signal. Normally, the beam is inclined upwards at a shallow angle, and several angles are used during each full volume scan. Many permutations exist of this basic configuration such as scans below the horizon in mountain areas and use of a range of pre-programmed sequences for beam inclination and rate of rotation which can be selected depending on the prevailing meteorological conditions. In some cases, this includes slower volume scans for wind profiling in clear-air conditions.

The WMO Radar Database shows that there are more than 800 operational radars worldwide, and the associated website (http://wrd.mgm.gov.tr/) includes technical details for each instrument and photographs for a selection of installations. However, due to cost it is often difficult to provide a full national coverage, although this ideal is approached in locations such as the USA, New Zealand, Japan, South Korea and much of Europe. In the USA, for example, there are about 160 radars in the national network (http://radar.weather.gov/), and the total number in Europe exceeds 200 (http://www.eumetnet.eu/radar-network). Where a full national coverage is not feasible or required, another option is to focus on installing instruments near to high-risk locations such as major population centres. In contrast, some national meteorological services in Africa and other parts of the world do not yet operate any weather radars (e.g. Sireci et al. 2010).

Many factors need to be considered in the siting and choice of equipment including the local climate, cost, site access and security, potential obstructions and the overall network design (e.g. Leone et al. 1989; WMO 2008a). Regarding climate, field observations are often made both during feasibility studies and calibration to better understand typical storm types and characteristics. There is also the intrinsic limitation that at long range the power of the reflected signal is reduced by the spread of the beam and attenuation. In addition, the curvature of the earth has a progressively greater effect on beam height with increasing distance from the radar.

Some typical maximum useful ranges for C-band radars might be 100–250 km, with products generated at a resolution of 5 km, although typically with a higher resolution possible for outputs close to the radar (e.g. 1 km). In some cases, the useful range of S-band instruments extends to 300–400 km, whilst maximum ranges for X-band instruments are typically in the range 30–60 km. However, the outputs from individual radars (single-site outputs) are often combined into a composite or mosaic image to derive products with greater spatial coverage (see Chap. 1 for example).

Until recently, Doppler instruments were probably the common type worldwide, but in many national services, these are being upgraded (or have been upgraded) to dual-polarisation capability. In Doppler instruments, energy is transmitted in a single plane (usually horizontal), and the change in frequency of the reflected signal provides a measure of the speed and direction of hydrometeors (rain drops, snowflakes, etc.) and helps with identifying ground clutter. In dual-polarisation devices, both horizontal and vertical pulses are transmitted improving the ability to classify types of hydrometeors and providing a range of other benefits (e.g. Box 2.4).

For all types, one key approach to interpreting the reflected signal is to use empirically based equations that express the relationships between range, drop size distribution – expressed in terms of a radar reflectivity factor (Z) – and rainfall intensity or rate (R). These so-called Z-R relationships are often calibrated for typical local conditions so may over- or underestimate rainfall under very light or extremely heavy rainfall conditions, and in some systems alternate values can be selected if required. Box 2.4 discusses some of the additional techniques used in processing dual polarisation observations. Rainfall intensities are usually processed to 5-min, 15-min or hourly values for delivery to end users, and other types of products often include wind profiles, cloud top heights and hydrometeor characteristics. Outputs are usually made available both as grid-based data files and as a real-time feed for display on purpose-made graphical user interfaces either developed by the manufacturer or a third-party supplier.

Some typical stages in signal processing include quality control, hydrometeor classification and product generation. An essential initial stage is to correct for a number of non-meteorological factors such as radome wetting and anomalous echoes when the beam encounters hills and other obstacles, which are often called ground clutter. As part of the calibration process, line of sight analyses using spatial analysis tools and digital terrain models are widely used to help with deciding how to interpret the reflected signal. In operational use, long-term average values of outputs can also provide more insights into these types of issues.

During operation, some factors which may affect the accuracy of measurements include rainfall at low levels beneath the beam and anomalous propagation. In the latter case, this is due to density variations in the atmosphere and can cause the beam to strike the ground; this is often called 'anaprop'. Spurious signals from flocks of birds or swarms of insects are another potential issue. Table 2.6 and Fig. 2.7 summarise these and some other issues which can occur; however, most weather radar signal processing systems attempt to correct for these various factors. For example, one common approach is to assume typical profiles for the vertical variations in reflectivity (the Vertical Profile of Reflectivity) to allow measurements to be adjusted to better represent precipitation at the ground surface and account for bright-band influences. In some cases, profiles are estimated with the help of supplementary sources of information such as estimates for wind fields and freezing levels from numerical weather prediction models.

Compared to raingauge observations, a key advantage of weather radar observations is the spatial view of precipitation although the rainfall at the ground surface must be inferred. In contrast, raingauge networks only provide point values, and network densities are sometimes too low to assess spatial variations in rainfall in any detail. A natural development has therefore been to devise schemes to combine these two complementary types of observations in the form of raingauge-adjusted radar products. Some examples of these approaches include Bayesian, Kalman filter, multiquadric and surface-fitting techniques (e.g. Wilson and Brandes 1979; Todini 2001, 2005; Seo and Breidenbach 2002; Moore et al. 2004). Simpler bias correction approaches are sometimes used as well or instead based on weekly or longer rainfall accumulations. Careful quality control of raingauge observations is required to avoid erroneous values affecting the combined product.

A typical characteristic with these types of approach is that the spatial sampling error 'decreases with increasing area size, increasing time period, increasing gage density, and increasing rainfall amount' (Wilson and Brandes 1979, reported by

Table 2.6 Some examples of sources of weather-related uncertainties in weather radar observations of precipitation

Item	Influence on rainfall (if uncorrected)	Description
Overshooting	Underestimate	Radar beam above the precipitation at long ranges
Evaporation	Overestimate	Precipitation detected at high levels may evaporate as it falls to the ground
Orographic enhancement	Underestimate	Increase in rainfall on into-wind slopes due to topographic influences
Bright band	Overestimate	Strong echoes from melting snow flakes with large, wet reflective surfaces
Drop size distribution / precipitation type	Various	Smaller drop sizes (e.g. as in drizzle) or larger drop sizes (e.g. as in heavy showers) than used in calibrating reflectivity relationships; plus issues with snow and hail
Anaprop	Various	Diversion of the beam into the ground due to density variations in the atmosphere

e.g. Collier (1996), Bringi and Chandrasekar (2001), Meischner (2004), WMO (2008a), Villarini and Krajewski (2010), Hong and Gourley (2014)

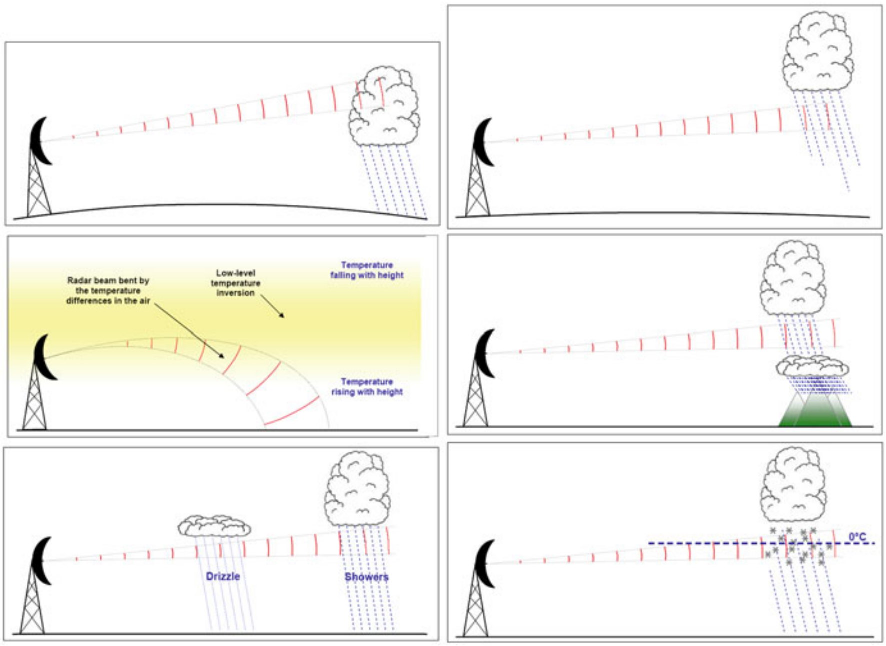

Fig. 2.7 Meteorological causes of errors in weather radar observations. From *top left* clockwise: (**a**) radar beam above the precipitation at long distances, (**b**) evaporation of rainfall at low levels beneath the beam, (**c**) orographic enhancement of rainfall at low levels, (**d**) bright band, (**e**) varying drop sizes of precipitation, (**f**) anomalous propagation (anaprop) (Met Office 2013; Contains public sector information licensed under the Open Government Licence v1.0)

Box 2.4: Dual Polarization Weather Surveillance Radar, USA

The National Weather Service has operated a network of weather surveillance radars since the 1940s, and Table 2.7 summarises some key historical developments (NOAA 2010). The most recent change is the upgrade to dual polarization (dual-pol or polarimetric) capability which was completed in 2013 (Zrnic et al. 2014).

The basis of the technique is that microwave pulses are transmitted in both the horizontal and vertical polarisation planes, rather than just the horizontal. Modifications to the existing fleet of 160 radars were made to the antenna hardware and by providing additional signal and post-processing software, without affecting the existing scanning strategies, data resolution or reflectivity and velocity algorithms.

The availability of reflected power and phase information in two planes allows several new parameters to be calculated in addition to the reflectivity factor for horizontal polarisation Z_h. These include (Ryzhkov et al. 2005; Scharfenberg et al. 2005; Schlatter 2010; Kumjian 2013):

- The differential reflectivity (Z_{DR}) which is a measure of the log of the ratio of the reflected horizontal to vertical power returns. Z_{DR} is approximately zero dB for spherical hydrometeors and becomes positive when these are horizontally oriented and – much less frequently – negative when vertically oriented (e.g. in an electrical field). It provides an indication of the presence of hail and of the median rain drop shape and hence size
- The specific differential phase (K_{DP}) which is the mean rate of change of the differential phase per kilometre, where the differential phase is a measure of the shifts (or lag) between horizontal and vertical phases; for

Table 2.7 Some key developments in the weather surveillance radar network in the USA

Date	Description
1947	US Basic Radar Network started, based on converted airborne radars from World War 2
1959	S-Band Weather Radar Surveillance network started (WSR-57 radars)
1971	First Doppler radar installed at the National Severe Storms Laboratory (NSSL)
1976	Installation of local C-band radars (WSR-74C) and additional S-band radars (WSR-74S)
1976–1979	Field tests of 4 Doppler radars as part of the Joint Doppler Operational Project
1984	First research trials of dual polarization radar at NSSL
1990–1997	Installation of the NEXRAD network of 159 S-Band Doppler radars (WSR-88D)
2002–2003	Joint POLarisation Experiment at NSSL on dual polarization techniques (JPOLE)
2011–2013	Upgrade completed of 160 weather radars to dual polarization

(continued)

Box 2.4 (continued)

example, due to passing through rainfall. The differential phase is near zero for spherical objects and higher for horizontally oriented objects, with the magnitude of the change also increasing with particle concentration. It is useful for distinguishing between precipitation and other echoes, for identifying regions of high liquid content even in the presence of hail and for estimating rain rate

- The correlation coefficient (CC or ρ_{HV}) between horizontally and vertically polarised power returns. This is typically higher (close to 1.0; perfect correlation) for meteorological echoes that are fairly uniform in shape and size, such as rain and snow, and lower for more irregular shapes, such as clear-air returns (blooms) caused by concentrations of birds and insects and ground clutter. It is extremely useful for differentiation of precipitation vs. non-precipitation targets and for identifying melting layers, giant hail and airborne tornadic debris

In particular, some advantages of using the differential phase parameter include its immunity to radar calibration errors, attenuation in precipitation and partial blockage of the radar beam (Ryzhkov et al. 2005). Various other correlation parameters can also be estimated between transmitted and reflected components although their relationship to precipitation characteristics is less well understood.

Based on extensive field trials (Ryzhkov et al. 2005; Scharfenberg et al. 2005), some key benefits which have been found include significant improvements to radar data quality and rainfall estimates and an improved ability to distinguish rainfall echoes from other types of return, such as those caused by anomalous propagation and non-hydrometeors. For example Zrnic and Ryzhkov (1999) and Kumjian (2013) note that polarimetry has the potential to:

- Improve quantitative precipitation estimation
- Discriminate hail from rain and better estimate hail size
- Identify precipitation type in winter storms (dry/wet snow, sleet, rain)
- Identify electrically active storms
- Identify biological scatterers (birds, insects) and their effects on wind measurements
- Identify the presence of chaff and other non-meteorological targets and their effects on precipitation measurements

Other benefits include the ability to identify airborne tornadic debris and to provide qualitative improvements in precipitation estimates. For the NEXRAD dual polarization upgrades, in addition to the three base products described above, three new algorithms were made available (e.g. Fig. 2.8):

(continued)

Box 2.4 (continued)

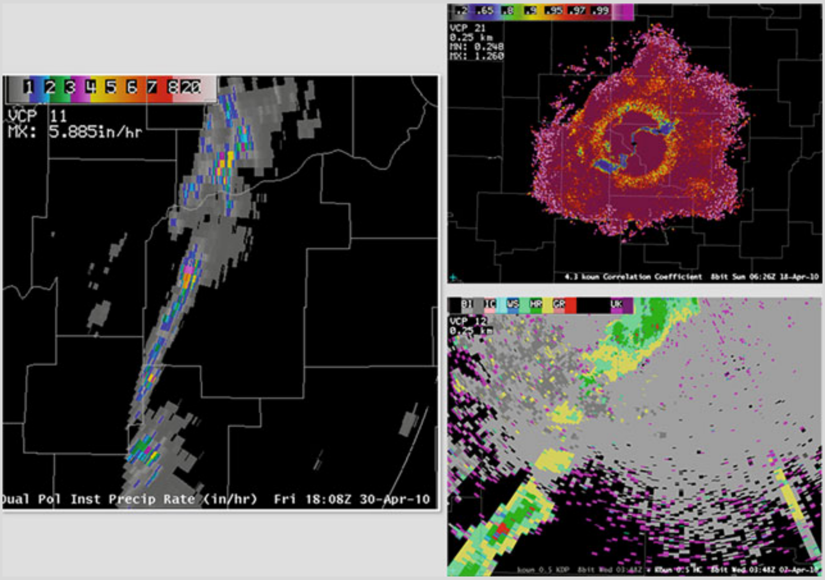

Fig. 2.8 Some examples of outputs from a dual polarization radar in Oklahoma. From the *top right clockwise*: Melting Layer Detection Algorithm outputs clearly showing a bright-band 'ring'; Hydrometeor Classification Algorithm outputs (*HR* heavy rain, *GR* graupel, *WS* wet snow, *IC* Ice Crystals, *UK* Unknown); Dual-Pol QPE outputs showing the instantaneous precipitation rate in inches/hour (NOAA/National Weather Service; Schlatter 2010)

- Melting Layer Detection Algorithm – which detects the melting layer based on reduced values for the correlation coefficient CC
- Hydrometeor Classification Algorithm – which makes a best guess of the dominant hydrometeor type for every beam elevation angle, using the following classification scheme: light/moderate rain, heavy rain, hail, 'big drops', graupel, ice crystals, dry snow, wet snow, unknown
- Dual-Pol QPE – an advanced precipitation estimation algorithm making use of dual polarization parameters

Text adapted from Sene (2013)

Krajewski et al. 2010). Often the choice of approach to use is based on performance comparisons for a calibration period, in some cases considering the impacts on flows or other factors relevant to the application; for example, assessing the differences in rainfall-runoff model outputs using raingauge-based or radar-rainfall estimates as inputs (see Chapter 5).

Many meteorological services have archives of historical weather radar observations to assist in this type of work, although there may have been a number of changes in hardware, instruments and signal processing techniques in the period available. This has led to the increasing use of reanalysis techniques which aim to reconstruct the values which would have been recorded with the current radar network (e.g. Delrieu et al. 2009; Moulin et al. 2009; Krajewski et al. 2010). As noted earlier, these types of analyses are potentially a valuable tool in calibrating hydrological models. More generally, estimates of the uncertainty in observations are increasingly provided either as ensemble values (e.g. Germann et al. 2009) or in the form of quality indices (e.g. Norman et al. 2010). This can help both with assessing the suitability of the outputs for use in a given application and, when estimates are available in real time, with adopting more of a risk-based approach to decision-making, combining probability and consequence (see Chapter 7).

For the future, it is worth noting that a major research effort is underway in the USA, Japan and elsewhere to develop phased-array weather radars (e.g. Meischner et al. 1997; McLaughlin et al. 2009). These are solid-state devices in which the scanning is performed electronically rather than with a rotating dish. This approach offers the potential to produce devices which are more reliable than current systems and perform volume scans more quickly and in a more targeted way. For example, Heinselman et al. (2008) note that this could 'provide the high temporal resolution data needed to facilitate earlier detection of significant storm development, convergence, microburst precursors, wind shear, and hail signatures'. In addition to developing replacements for existing radar systems, another major area for research, again with prototypes already developed, is in the use of much smaller flat-plate X-band devices. For example, networks of these instruments could potentially be mounted on buildings in urban areas to help to detect rainfall likely to lead to surface water flooding, using agile or adaptive scanning strategies to focus observations on areas of rapid storm development (e.g. McLaughlin et al. 2009).

2.6 Summary

- For hydrological applications, the main types of meteorological observations of interest include precipitation (rainfall, snow), air temperatures and additional parameters to assist with the estimation of evaporation and water demand. The main techniques include raingauges, weather stations, weather radar and satellite observations. Additional types of sensor used in meteorological applications include wind profilers, radiosondes and lightning detection systems.
- Regarding satellite observations, geostationary satellites have the advantage of a fixed field of view, whilst low-earth and polar-orbiting satellites are able to make use of shorter-range sensors such as spaceborne radar and microwave imagers. Satellite precipitation estimates are perhaps the key product of interest for hydrological applications, and these are often based on the observations from a range of sensors on board geostationary and polar-orbiting satellites. In some

cases, near real-time raingauge observations and the outputs from numerical weather prediction models are used to help with deriving values. The resulting estimates are particularly useful where raingauge networks are sparse and/or there are is no weather radar coverage available; the Global Precipitation Measurement Mission also offers great potential for the future.

- Tipping bucket raingauges are perhaps the most widely used type, followed by weighing raingauges. Solid-state devices are a common feature in road weather information systems, and hot-plate devices are a promising new development. Area-averaging techniques range from simple averaging of values to complex geostatistical methods, and some key factors which affect the accuracy of the estimates include the gauge network density and topographic influences.
- Weather stations usually include at least one raingauge and provide other outputs of interest for hydrological applications such as air temperatures, humidity, wind speeds, snow depth and soil moisture. They are used in a range of meteorological, agricultural and aviation applications and by some hydrological services. Web-based services provide a means to integrate observations from a large number of sources with associated metadata management and data validation.
- Weather radars provide a spatial view of precipitation. In many countries, existing Doppler networks are being (or have recently been) upgraded to dual-polarisation capability, allowing more precise identification of hydrometeors and a range of other advantages. S-band instruments have the longest range and together with C-band devices are the usual types in national networks. Shorter-range X-band instruments are increasingly used for gap filling in national networks. For all types, the observations need to be post-processed to help to compensate for hardware issues, ground clutter and event-specific factors, often making use of raingauge observations and in some cases the outputs from numerical weather prediction models.
- Each type of observation system has its own strengths and limitations in terms of accuracy and the spatial resolution and frequency of observations. The approach to use in a given situation normally depends on a range of factors including the operational requirement, budgets, existing instrumentation, staff skills and resources and the potential benefits. There is increasing interest in multisensor systems which seek to combine the best aspects of each approach.

References

Arkin PA, Meisner BN (1987) The relationship between large-scale convective rainfall and cold cloud over the western hemisphere during 1982–84. Monthly Weather Review, 115(1): 51–74

Bergström H, Moberg A (2002) Daily air temperature and pressure series for Uppsala (1722–1998). Climatic Change, 53: 213–252

Bringi VN, Chandrasekar V (2001) Polarimetric Doppler weather radar: principles and applications. Cambridge University Press, Cambridge

Collier CG (1996) Applications of Weather Radar Systems: A Guide to Uses of Radar Data in Meteorology and Hydrology (2nd ed.). Wiley, Chichester

Creutin JD, Obled C (1982) Objective analyses and mapping techniques for rainfall fields: an objective comparison. Water Resources Research, 18(2): 413–431

Daly C (2006) Guidelines for assessing the suitability of spatial climate data sets. Int J Climat 26:707–721

Delrieu G, Braud I, Borga M, Boudevillain B, Fabry F, Freer J, Gaume E, Nakakita E, Seed A, Tabary P, Uijlenhoet R (2009) Weather radar and hydrology. Adv Water Resour 32:969–974

Ebert E E, Janowiak J E, Kidd C (2007) Comparison of near real-time precipitation estimates from satellite observations and numerical models. Bulletin of the American Meteorological Society, 88(1): 47–64

Ferraro RR, Marks GF (1995) The development of SSM/I rain rate retrieval algorithms using ground-based radar measurements. Journal of Atmospheric and Oceanic Technology, 12: 755–770

Germann U, Berenguer M, Sempere-Torres D, Zappa M (2009) REAL – ensemble radar precipitation estimation for hydrology in a mountainous region. Q J R Meteorol Soc 135:445–456

Goovaerts P (2000) Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. Journal of Hydrology, 228:113–129

Green A (2012) Introducing the Weather Observations Website (WOW) WMO Technical Conference on Meteorological and Environmental Instruments, Brussels, 16–18 October 2012

Heinselman PL, Priegnitz DL, Manross KL, Smith TM, Adams RW (2008) Rapid sampling of severe storms by the National Weather Radar Testbed phased array radar. Weather Forecast 23:808–824

Hong Y, Gourley J (2014) Radar Hydrology: Principles, Models, and Applications. CRC Press

Hou AY, Kakar RK, Neeck S, Azarbarzin AA, Kummerow CD, Kojima M, Oki R, Nakamura K, Iguchi T (2014) The Global Precipitation Measurement Mission. Bull. Amer. Meteor. Soc., 95:701–722

Hsu K-L, Sorooshian S (2008) Satellite-based precipitation measurement using PERSIANN System. In Hydrological Modelling and the Water Cycle (Eds. Sorooshian S, Hsu K, Coppola E, Tomassetti B, Verdecchia M, Visconti G), Springer, Dordrecht

Joyce RJ, Janowiak JE, Arkin PA, Xie P (2004) A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. Journal of Hydrometeorology, 5(3): 487–503

Kidd C, Heinemann T, Levizzani V, Kniveton DR (2008) International Precipitation Working Group (IPWG): Inter-comparison of regional precipitation products. 2008 EUMETSAT Meteorological Satellite Conference, Darmstadt, Germany, 8–12 September 2008

Krajewski WF, Villarini G, Smith JA (2010) Radar-rainfall uncertainties: where are we after thirty years of effort? Bull Am Meteorol Soc 91(1):87–94

Kumjian MR (2013) Principles and applications of dual-polarization weather radar. Part I: Description of the polarimetric radar variables; Part II: Warm- and cold-season applications; Part III: Artifacts. J. Operational Meteor., 1(19), 226–242

Leijnse H, Uijlenhoet R, Stricker JNM (2007) Rainfall measurement using radio links from cellular communication networks. Water Resour Res 43:W03201

Leone DA, Endlich RM, Petričeks J, Collis RTH, Porter JR (1989) Meteorological considerations used in planning the NEXRAD network. Bull Am Meteorol Soc 70(1):4–13

Maki M, Maesaka T, Kato A, Shimizu S, Kim D-S, Iwanami K, Tsuchiya S, Kato T, Kikumori T, Kieda K (2010) X-band polarimetric radar networks in urban areas. ERAD 2010 – 6th European conference on radar in meteorology and hydrology, Sibiu, 6–10 September 2010

McLaughlin D, Pepyne D, Chandrasekar V, Philips B, Kurose J, Zink M, Droegemeier K, Cruz-Pol S, Junyent F, Brotzge J, Westbrook D, Bharadwaj N, Wang Y, Lyons E, Hondl K, Liu Y, Knapp E, Xue M, Hopf A, Kloesel K, DeFonzo A, Kollias P, Brewster K, Contreras R, Dolan B, Djaferis T, Insanic E, Frasier S, Carr F (2009) Short-wavelength technology and the potential for distributed networks of small radar systems. Bull Am Meteorol Soc 90(12):1797–1817

McMillan H, Krueger T, Freer J (2012) Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality. Hydrological Processes 26(26):4078–4111

Meischner P, Collier C, Illingworth A, Joss J, Randeu W (1997) Advanced weather radar systems in Europe: the COST 75 action. Bull Am Meteorol Soc 78:1411–143

Meischner P (2004) Weather radar: principles and advanced applications, Series: Physics of Earth and Space Environments. Springer, New York

Met Office (2013) National Meteorological Library and Archive Factsheet 15 – Weather Radar (Version 01), Met Office, Exeter

Michaelides S (ed) (2008) Precipitation: advances in measurement, estimation and prediction. Springer, Dordrecht

Moore RJ, Jones AE, Jones DA, Black KB, Bell VA (2004) Weather radar for flood forecasting: some UK experiences. Sixth International Symposium on Hydrological Applications of Weather Radar, Melbourne, Australia, 2–4 February 2004

Moulin L, Tabary P, Parent du Châtelet J, Gueguen C, Laurantin O, Soubeyroux J-M, Dupuy P, L'Hénaff G, Andréassian V, Loumagne C, Andrieu H, Delrieu G (2009) The French Community Quantitative Precipitation Estimation (QPE) Re-analysis project: Establishment of a reference multi-year, multi-source, nation-wide, hourly QPE data base for hydrology and climate change studies. American Meteorological Society 34th Conference on Radar Meteorology, Williamsburg, 5–9 October 2009

Nelson BR, Seo D-J, Kim D (2010) Multisensor precipitation reanalysis. J Hydrometeorol 11:666–682

Nitu R, Wong K (2010) CIMO Survey on national summaries of methods and instruments for solid precipitation measurement at automatic weather stations. Instruments and observing methods Report No. 102, WMO/TD No.1544, Geneva

NOAA (2009) The NOAA Climate Prediction Center African Rainfall Estimation Algorithm Version 2.0

NOAA (2010) An historical look at NEXRAD. NEXRAD Now, 20: 31–35

Norman K, Gaussiat N, Harrison D, Scovell R, Boscacci M (2010) A quality index scheme to support the exchange of volume radar reflectivity in Europe. ERAD 2010 – the sixth European Conference on Radar in Meteorology and Hydrology, Sibiu, 6–10 September 2010

Overeem H, Leijnse R, Uijlenhoet (2013) Country-wide rainfall maps from cellular communication networks. Proc. National Academy of Sciences of the United States of America, 110: 2741–2745

Pedersen L, Jensen NE, Madsen H (2010) Calibration of local area weather radar - identifying significant factors affecting the calibration. Atmos Res 97(1–2):129–14

Rahimi AR, Holt AR, Upton GJG, Cummings RJ (2003) Use of dual-frequency microwave links for measuring path-averaged rainfall. Journal of Geophysical Research, 108(D15): 4467

Rasmussen RM, Hallett J, Purcell R, Landolt SD, Cole J (2011) The hotplate precipitation gauge. J Atmos Oceanic Technol 28:148–164

Ruf CS, Aydin K, Mathur S, Bobak JP (1996) 35-GHz dual-polarization propagation link for rain-rate estimation. J Atmos Ocean Technol 13:419–425

Ryzhkov AV, Schuur TJ, Burgess DW, Heinselman PL, Giangrande SE, Zrnic DS (2005) The Joint Polarization Experiment. Polarimetric Rainfall Measurements and Hydrometeor Classification. Bull Am Meteorol Soc 86(6):809–824

Scharfenberg KA, Miller DJ, Schuur TJ, Schlatter PT, Giangrande SE, Melnikov VM, Burgess DW, Andra DL, Foster MP, Krause JM (2005) The Joint Polarization Experiment: polarimetric radar in forecasting and warning decision making. Weather Forecast 20:775–788

Schlatter P (2010) The dual polarization radar technology update. Eastern Region Flash Flood Conference, Wilkes-Barre, 2–4 June 2010

Scofield RA, Kuligowski RJ (2003) Status and outlook of operational satellite precipitation algorithms for extreme precipitation events. Weather Forecasting, 18:1037–1051

Sene (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht

Seo D-J (1998) Real-time estimation of rainfall fields using rain gage data under fractional coverage conditions. J Hydrol 208(1–2):25–36

Seo D-J. Breidenbach J P (2002) Real-time correction of spatially nonuniform bias in radar rainfall data using rain gauge measurements. Journal of Hydrometeorology, 3: 93–111

Sevruk B, Ondrás M, Chvílac B (2009) The WMO Precipitation Measurement Intercomparison. Atmos Res, 92(3):376–380

Sireci O, Joe P, Eminoglu S, Akyildiz K (2010) A comprehensive worldwide web-based weather radar database. TECO 2010 WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, Helsinki, 30 August-1 September 2010

Sorooshian S, AghaKouchak A, Arkin P, Eylander J, Foufoula-Georgiou E, Harmon R, Hendrickx JMH, Imam B, Kuligowski R, Skahill B, Skofronick-Jackson G (2011) Advancing the remote sensing of precipitation. Bull Am Meteorol Soc 92(10):1271–1272

Strangeways I (2007) Precipitation: Theory, Measurement and Distribution. Cambridge University Press, Cambridge

Tabios GQ, Salas JD (eds) (1985) A comparative analysis of techniques for spatial interpolation of precipitation. J Am Water Resour Ass 21(3):365–380

Tarnavsky E, Grimes D, Maidment R, Black E, Allan RP, Stringer M, Chadwick R, Kayitakire F (2014) Extension of the TAMSAT Satellite-Based Rainfall Monitoring over Africa and from 1983 to Present. J. Appl. Meteor. Climatol., 53: 2805–2822

Testik FY, Gebremichael M (2010) Rainfall: State of the Science, Vol 191. American Geophysical Union, Geophysical Monograph Series, Washington, DC

Todini E (2001) A Bayesian technique for conditioning radar precipitation estimates to raingauge measurements. Hydrology and Earth System Science, 5(2):187–199

Todini E (2005) Present operational flood forecasting systems and possible improvements. In River Basin Modelling for Flood Risk Mitigation (Eds. Knight DW, Shamseldin AY). Taylor and Francis, Boca Raton, FL

Turk FJ, Arkin P, Ebert EE, Sapiano MRP (2008) Evaluating High-Resolution Precipitation Products. Bull Am Meteorol Soc 89(12):1911–1916

Vasiloff SV, Seo D-J, Howard KW, Zhang J, Kitzmiller DH, Mullusky MG, Krajewski WF, Brandes EA, Rabin RM, Berkowitz DS, Brooks HE, McGinley JA, Kuligowski RJ, Brown BG (2007) Improving QPE and very short term QPF: an initiative for a community-wide integrated approach. Bull Am Meteorol Soc 88(12):1899–1911

Villarini G, Krajewski WF (2010) Review of the different sources of uncertainty in single polarization radar-based estimates of rainfall. Surv Geophys 31(1):107–129

Vuerich E, Monesi C, Lanza LG, Stagi G, Lanzinger E (2009) WMO field intercomparison of rainfall intensity gauges (Vigna di Valle, Italy) October 2007 – April 2009. Instruments and Observing Methods Report No. 99, WMO TD-1504, Geneva

Wilson JW, Brandes EA (1979) Radar measurement of rainfall – a summary. Bull Am Meteorol Soc 60(9):1048–1058

WMO (2000) Precipitation Estimation and Forecasting. Operational Hydrology Report No. 46, Geneva

WMO (2006) Preventing and Mitigating Natural Disasters. WMO- No. 993, Geneva

WMO (2007) Guide to the Global Observing System. WMO-No. 488, Geneva (plus 2013 update)

WMO (2008a) Guide to Meteorological Instruments and Methods of Observation. WMO-No. 8, Geneva (plus 2010 update)

WMO (2008b) Technical Regulations – Volume III – Hydrology. 2006 ed., Suppl. No. 1 (I.2008), Geneva

WMO (2009) Guide to Hydrological Practices, 6th edn. WMO No-168, Geneva

WMO (2013) Manual on the Global Observing System – Volume 1: Global Aspects. WMO-No. 544, Geneva

Xie P, Arkin PA (1996) Analyses of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions. Journal of Climate, 9: 840–858

Zhang J, Howard K, Langston C, Vasiloff S, Kaney B, Arthur A, Van Cooten S, Kelleher K, Kitzmiller D, Ding F, Seo D-J, Wells E, Dempsey C (2011) National Mosaic and Multi-sensor QPE (NMQ) System – description, results and future plans. Bull Am Meteorol Soc 92(10): 1321–1338

Zhao L, Ferraro R, Moore D (2000) Validation of NOAA-15 AMSU-A rain rate algorithms. The 10th Conference on Satellite Meteorology, 9–14 January 2000, Long Beach, CA

Zinevich A, Messer H, Alpert P (2010) Prediction of rainfall intensity measurement errors using commercial microwave communication links. Atmos Meas Tech 3:1385–1402

Zrnic DS, Ryzhkov AV (1999) Polarimetry for weather surveillance radars. Bull Am Meteorol Soc 80(3):389–406

Zrnic D, Lee R, Boettcher JB (2014) Polarimetric WSR-88D network, observation highlights. ERAD 2014, Garmisch-Partenkirchen 1–5 September 2014

Chapter 3
Catchment Monitoring

Abstract Observations of catchment conditions are essential for many forecasting applications. Examples include measurements of water levels in rivers, lakes and reservoirs and estimates for evapotranspiration, snow cover and soil moisture at a catchment scale. Additional information may be required for water quality applications. This chapter discusses some of the main techniques used and the related issues of hydrometric data management and telemetry systems. This includes a discussion of river flow estimation using stage-discharge relationships and some basic considerations regarding the design of monitoring networks.

Keywords River level • River flow • Hydrometry • Stage-discharge relationship • Soil moisture • Snow conditions • Evaporation • Water quality • Telemetry • Hydrometric data management • Gauge networks

3.1 Introduction

Water level, river flow and catchment-scale observations underpin many applications in hydrometeorology. These are often called hydrometric observations where one definition (WMO 2015) for the term 'hydrometry' is that it is the:

> Science of the measurement and analysis of the water cycle including methods, techniques and instrumentation used in hydrology

Some examples of applications which are described in later chapters include:

- Drought indices – using satellite-based techniques to provide early warnings of risks to crop yield at a regional scale due to soil moisture deficits
- Flood forecasting – providing a real-time feed of river level and flow observations for input to real-time forecasting models
- Flood warning – using river level observations as the basis for issuing alerts once critical threshold values are exceeded
- Pollution incidents – tracking contaminants following an accidental spill and issuing warnings if critical thresholds are exceeded
- Water resources – providing real-time inflow, water level and outflow information to help with reservoir operations

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Data collection authorities include national hydrological services plus a range of other organisations which – depending on the country – might include river basin commissions, water supply utilities, hydropower operators, state agencies, irrigation scheme operators and community-based flood warning schemes.

A key requirement is often to monitor river levels and flows and the usual approach is to record levels and then convert these to flows using an empirically based stage-discharge relationship, which is often called a rating curve. However, more direct approaches include ultrasonic gauges and river gauging structures. Some other locations where water level observations may be required include in reservoirs, lakes and wetlands and the tidal reaches of estuaries. Both manual and automated observation techniques are used, in the latter case with values recorded to a data logger and in many cases transmitted to a central location via a telemetry system. Due to recent developments in sensor technologies, similar techniques are increasingly used in water quality applications, allowing continuous monitoring of parameters such as water temperatures, pH, dissolved oxygen and chlorophyll a.

At a catchment scale the main choices are usually between satellite-based estimates and in situ (point) values, which are sometimes called land-surface observations. For satellite products, historically one limitation has been the rather coarse resolution of outputs compared to the scales of hydrological interest. This has tended to restrict applications to large river basins or regional studies, primarily for spatially extensive and/or slowly varying parameters such as snow cover, land use and vegetation types. However, resolutions continue to improve, although for hydrological applications it is important to understand the limitations on spatial resolution and sampling frequencies. Of course, the other main choice, of using site-specific values, also has limitations due to the wide spatial variations that often occur in parameters such as soil moisture and snow depth. As a result, when catchment-wide estimates are required, these approaches are often combined, with the satellite products providing the spatial view and the in situ observations the local detail.

This chapter describes these various techniques and some of their strengths and limitations. This includes a brief discussion of approaches to designing hydrometric monitoring networks and to the related topics of hydrometric data management and telemetry systems. Further information is provided in the references cited and in the many guidelines and technical standards on these topics, such as the examples shown in Table 3.1. Later chapters discuss some more specialised techniques for specific applications such as for debris flow detection (Chap. 9), geotechnical monitoring (Chap. 9) and environmental monitoring (Chap. 12).

Table 3.1 Some examples of guidelines and technical standards issued by the International Organisation for Standardization (ISO) and the World Meteorological Organisation (WMO)

Organisation	Topic	Year	Description
ISO	River gauging	Various	A series of standards on topics such as velocity-area methods, flow gauging structures, data management and sediment transport and groundwater observations (http://www.iso.org/)
WMO	General, network design	(2008a)	*Guide to Hydrological Practices, Volume I: Hydrology – From Measurement to Hydrological Information*
	Standards	(2008b)	*Technical Regulations, Volume III: Hydrology*
	River gauging	(2010)	*Manual on Stream Gauging* (2 volumes)
	Water quality	(2013)	Planning of water quality monitoring systems

3.2 River Gauging Stations

3.2.1 Water Levels

Water levels often need to be monitored in rivers, lakes, reservoirs, wetlands and estuaries. Most national hydrological services maintain extensive networks of recording sites, sometimes with thousands of gauges, as in the USA, for example. The first modern-day sites were established in the nineteenth century such as in the 1880s on the Rio Grande in the USA and the 1890s on Lake Malawi and Lake Victoria in Africa, although a recording site on the River Nile near Cairo (the Roda gauge) predates these by centuries.

For rivers the classical approach is to use a staff gauge or gauge board which is essentially a large vertically mounted graduated scale or ruler. These are typically 1 m in length and are mounted on structures such as bridge piers or on free-standing supports set into river banks, with a sufficient number to cover the likely range in levels. Observations are then made manually by an observer, typically 2–3 times per day, and written on record sheets to be collected by hydrometry staff or sent by post to regional or national centres. However, if a flood threat develops then readings are made more frequently and reported at the time of observation, typically by landline, cell phone or radio. Painted scales on bridge piers or metal rods provide a cheaper alternative in some community-based flood warning systems. Some alternative names for observers include gauge readers or watchmen, who are usually either government employees or local residents paid a small salary to supplement their normal income.

This approach is still widely used in local warning systems – where observers are often volunteers – and in some national services where budgets are limited. However, the more usual approach nowadays is to use automated systems in which readings are recorded locally to a data logger and sent via telemetry for automated loading into a hydrometric data management system. As discussed later the main options for data transmission include radio, cell phone, landline, meteor burst or satellite-based approaches.

Even in a telemetry-based system, though, this does not preclude the need to visit sites on a regular basis for calibration and maintenance of equipment and to download data loggers. Indeed part of the reason for using a logger is to allow data to be downloaded if the telemetry link fails. A staff gauge is normally included to allow instruments to be checked and for water levels to be recorded by an observer if the electrical equipment fails; indeed part-time observers are often retained for this reason, particularly if there are also site-security issues.

One of the first approaches to automatic recording was to use clockwork-driven chart recorders with float-and-pulley devices. The rise and fall of water levels – suitably reduced by a gear mechanism – would then be traced by a pen onto a paper chart mounted on a rotating drum. However, batteries are normally used nowadays, which are either replaced during site visits or kept charged by a solar panel. The recording techniques used for rivers, reservoirs, lakes, boreholes and estuaries are similar although with different installation challenges. Table 3.2 summarises the most common types of sensors and Fig. 3.1 shows two examples of pressure transducer installations; the first for a river location with landline-based telemetry and the second for a reservoir location with radio-based telemetry.

For critical installations, such as in dam or tidal barrier applications, full-time observers or operators are sometimes employed with on-site accommodation and

Table 3.2 Summary of some techniques for monitoring water levels (Adapted from Sene 2013)

Type	Principle of operation	Some operational considerations
Bubbler or pneumatic	Release of compressed air or nitrogen through a submerged nozzle; the water depth is then inferred from the operating pressure	Requires a small pump or compressor or regular recharge of a compressed gas cylinder. The gas supply line to the nozzle is sometimes vulnerable to damage by debris or blockage by sediment
Float in stilling well	A float suspended by wire or tape from a pulley; the water depth is then inferred from the number of turns of the pulley. The float mechanism is installed inside a stilling well suspended in the water or in a downshaft in the river bank connected to the water by an underground pipe or culvert. Alternative names include float gauge and float-and-pulley instruments	There is a risk of the float jamming and the wire or tape breaking or dropping off the pulley. There are sometimes access and confined-space working issues with stilling wells and downshafts and the risk of blockages by debris or sediment. The maximum level which can be recorded is limited by the elevation of the pulley
Pressure transducer	A solid-state submerged pressure-sensing device, with the depth proportional to the pressure recorded	The electrical cable to the sensor is potentially vulnerable to damage. Sensors often had a relatively short operating life in the early days although are now hugely improved
Ultrasonic or radar	Downward-looking ‘non-contact’ devices usually mounted on a bridge or mast; the level and hence the depth are then inferred from the time of travel for the reflected signal	The reflected signal may be degraded or interrupted by debris on the water surface and other factors; ultrasonic gauges usually require air temperature corrections

Fig. 3.1 Examples of pressure transducer installations in an urban river and in a reservoir (with associated gauge boards)

communications equipment. Whilst bridges and flood walls provide perhaps the most convenient locations to install gauges, as indicated in Table 3.2 another approach is to install the electrical equipment on a river bank with an underground conduit to the river bed. Staff gauges are usually installed either so that the zero value corresponds approximately to zero flows or so that a small positive value is maintained at all times. However, in practice changes often occur due to shifting river beds and sedimentation, which can also block stilling wells and conduits and cover the lower sections of staff gauges.

On installation the zero value for the site should be – but is not always – levelled into a local benchmark which is tied into the national system. This then allows levels to be converted to values relative to the national datum for use in applications such as flood modelling and for comparisons between gauges at different sites. When gauges are replaced due to flood damage or other issues, these therefore need to be tied into previous datum values, and failure to do this is a common source of problems when interpreting historical records of river levels.

In some cases, particularly in less prosperous and/or remote areas, theft and vandalism are key concerns and Table 3.3 shows some measures which are sometimes considered as a way of reducing these risks. However, each approach needs to be considered within the local context considering whether it would help with or exacerbate problems, plus of course whether it is technically feasible. Regarding solar panels, these are often a particular target, although the need to use these may reduce in future with some suppliers now claiming a battery life of several years for some types of instrument.

Another consideration is that the overall installation should be engineered to withstand likely flood flows and any associated debris, with key electrical equipment located above likely flood levels. This approach is sometimes called flood hardening and some typical choices for the minimum installation elevation include the highest recorded flood level or – preferably – estimates for the levels likely to be

Table 3.3 Some examples of approaches for potentially improving gauge sustainability

Item	Description
Access to data	Providing community leaders and local farmers, anglers, boat users and others with near real-time access to the data via community message boards, text messages and/or websites or smartphone applications
Community engagement	Involving local civil protection or disaster risk management committee members and other local representatives in choosing where to locate gauges and in site maintenance and gauge reading
Education/ public-awareness activities	Involving local schools and colleges both in the initial installation work and via follow-up educational opportunities, such as site visits and research projects, and raising awareness of the community benefits of gauges for flood warning or other purposes, in some cases placing information boards at the site
Local employment	Employing local contractors and suppliers for the engineering works associated with gauge installation and subsequent site maintenance
Observers	Employing observers for additional duties (in addition to gauge reading) such as site upkeep, security and outreach to local communities
Security	Using protective fences and/or locating gauges at sites with a full-time security presence for other reasons such as at border crossings, on major bridges or near police stations; bonding solar panels to structures where this would not affect their performance
Visibility	Reducing the visual impact of gauge installations (size, colour, etc.) and if feasible avoiding the need to use solar panels

experienced in an extreme flood of a given return period derived from a hydrodynamic modelling study, with an appropriate margin for error added in each case. For safety-critical applications such as tidal barriers or flood warning systems in major cities, sometimes several gauges are installed to provide both more detail on local water levels and resilience in case of gauge failures; in the latter case often with on-site patrols to read staff gauges in case of telemetry failures and to check for local flooding problems.

It is also worth noting that satellite observations provide another possible approach to measuring water levels, although the main applications to date have been in sea level observations for ocean forecasting applications. The key limitations are on the resolution of observations in both the horizontal and vertical planes. However, the approach shows potential for large rivers, lakes and reservoirs (e.g. Benveniste and Berry 2004, Xu et al. 2004, Zakharova et al. 2005), particularly where due to remoteness or cost water levels cannot be recorded by other means, such as on some glacial lakes.

Another recent development is the increasing use of voluntary observers or spotters by national hydrological services, in a similar way to meteorological applications (see Chap. 2). For example, one option that has been trialled is to invite members of the public to send staff gauge readings by text from sites located at popular river access points; the values are then displayed on a publicly available website (Lowry and Fienen 2013). Another possibility is to make smartphone applications available to allow users to send details of flood impacts, as discussed further in Chaps. 7, 8, and 9.

3.2.2 River Flows

Whilst water level observations are directly useful in some applications, such as reservoir operations or flood warning, in many cases it is more useful to have information on river flows. Examples include the calibration and operation of rainfall-runoff and flow routing models and as one of the inputs to lake, reservoir and wetland water balance models. Some direct approaches to monitoring flows in a river channel include:

- Electromagnetic devices – in which a coil buried in the river bed generates a signal whose strength depends on the water velocity as it passes through the electromagnetic field generated by the instrument and which is detected by electrodes in the river bank
- Ultrasonic (hydroacoustic) devices – fixed installations in which flow velocities are estimated at one or more depths from the differences in transmission times for ultrasonic pulses transmitted in an upstream and downstream direction (with the time differences arising from the river flow velocity)

Of these two types, ultrasonic devices are by far the most common although, due to cost, neither approach is widely used (and in some countries not at all). There are also some limitations regarding the maximum width of river channel which it is practical to consider and potential site-specific issues; for example, the signal from ultrasonic devices is sometimes affected when sediment loads are high, whilst nearby electronic signals can affect electromagnetic devices.

Another option is to install a purpose-made structure in the river such as a weir or a flume. Some examples of types designed specifically for river gauging include thin-plate weirs, Crump weirs and broad-crested weirs. The basis of the approach is to record river levels and then to convert these to flows using an empirical or theoretical relationship, appropriate to the type of structure. The optimum locations to record levels depend on the type of structure and sometimes both upstream and downstream records are required. In some cases, it is possible to calibrate existing river structures built for other purposes, such as for water level management; however, if flows are complex, this may require a hydrodynamic modelling study or laboratory tests using a scale model of the structure.

Once in operational use, the level-flow relationship needs to be checked, particularly if based on theoretical values. Normally this is done through an initial intense observation campaign followed by regular spot checks thereafter, particularly for structures likely to be affected by erosion or seasonal weed growth. Downstream influences can also be a factor, particularly when river flows are high, causing so-called non-modular flows to develop in which there is no longer a unique relationship between levels and flows. This is particularly a risk in river channels with shallow slopes since backwater influences sometimes extend over considerable distances; for example, from tidal influences or other structures further downstream. In some cases the solution is to install one or more level sensors downstream of the gauge to allow corrections to be made for these factors.

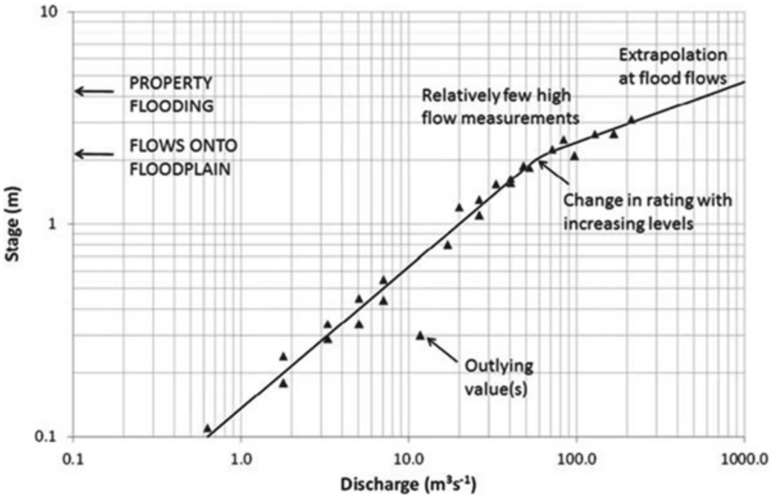

Fig. 3.2 Illustration of a power law stage-discharge relationship and some of the calibration issues which sometimes arise, particularly for high flows; note that for simplicity the zero stage and discharge values are assumed to coincide, which is often not the case in practice (Adapted from Sene 2013)

Although gauging structures are widely used, perhaps the most common approach of all is to estimate flows from the levels recorded in a natural river section, making use of a stage-discharge relationship (e.g. Fig. 3.2). Ideally gauges need to be sited in locations where there is a consistent relationship between levels and flows and there are many guidelines on the criteria for selecting suitable sites, such as those listed in Table 3.1. The level-flow relationship is usually established from both routine measurements of flows (e.g. every month) and more frequent observations during floods and low flow periods. Once sufficient so-called discharge measurements are available, the rating curve is estimated and then used operationally to convert levels to flows.

Discharge measurements are usually made by making concurrent observations of velocities and water depths across the river cross section. The traditional approach is to use a propeller-driven current meter to sample velocities at predetermined locations across the channel, typically at one or two depths. The meter is suspended by a cable from a cableway, bridge or boat or carried by an observer across the river when levels are low (e.g. Fig. 3.3). Velocities are then estimated from the number of revolutions of the propeller in a given time, as recorded by an electronic counter. Corrections are sometimes made to allow for water drag on the cable and meter (except for wading approaches) and other factors such as the change in river levels whilst observations are being made. However, this can be a time-consuming way to measure flows, sometimes taking several hours or more for a single discharge measurement on large rivers.

Fig. 3.3 Low flow gauging with a current meter (*left*) and an acoustic Doppler used to record measurements on Wild Rice River, North Dakota, during 2010 flood (*right*, US Geological Survey/ photo by Don Becker http://gallery.usgs.gov/)

A more modern approach is to use an Acoustic Doppler Current Profiler (ADCP) device (e.g. Fig. 3.3). With this technique, the depth-integrated velocity is inferred from the changes in frequency (or phase) of a Doppler ultrasound signal due to reflections from particles in the water. These devices are usually mounted on a floating platform which is towed across the river, suspended from a bridge or – for self-powered units – controlled remotely from the river bank or a boat. In addition to the speed of operation, measurements are made continuously during the traverse and can automatically detect reverse flows. So, as well as being quicker to make, the resulting flow estimates are potentially more accurate than those obtained with a current meter, especially in unsteady or recirculating flows.

In recent years, ADCP devices have increasingly superseded current meters as the usual approach for making discharge measurements. Table 3.4 also summarises some other techniques which have more specialist applications. Where surface or in-channel velocities are measured, these are normally related to flows using empirical formulae, graphs or look-up tables derived on the basis of previous river cross-section surveys and – in many cases – spot gauging measurements. Often the form of these relationships is guided by hydraulic modelling studies or formulae. The velocity-index approach in particular provides a cheaper option than a full ultrasonic installation whilst retaining the advantages of continuous monitoring of velocities. Recirculating or reverse flows can also be considered although with some compromises on the accuracy of the flow estimates compared to a full installation.

Of the other approaches dilution gauging is typically used in research studies and intensive measurement campaigns related to specific low flow issues. There are of course some potential environmental issues which need to be considered related to the choice of tracer. In contrast, float methods provide a relatively cheap and fast way to estimate flows – particularly in flood conditions – although are probably the least accurate of all of these approaches. If purpose-made floats are not available, then any floating object may suffice such as debris already on the water surface.

Table 3.4 Some examples of other flow and/or velocity measurement techniques

Method	Basis of approach
Dilution gauging	A tracer (typically a fluorescent dye) is released into the river and the concentration measured further downstream, with the flow then estimated using theoretical formulae; this technique is more suited to low flows rather than high flows
Float methods	Purpose-made floats are dropped into the river at a number of locations across the channel and the surface velocities estimated from the time taken to travel through two or more cross sections
Large-scale Particle Image Velocimetry (LSPIV)	Naturally occurring tracers on the water surfaces, such as bubbles, eddies or foam, are tracked using digital imaging techniques (e.g. Creutin et al. 2003; Muste et al. 2008; Le Coz et al. 2010; Fujita and Muste 2011). Images can be taken from bridges, river banks, vehicles or helicopters. Velocities are then estimated using statistical pattern-matching techniques
Radar velocimetry	A technique which relies on detecting the time delay between transmitting a UHF or microwave signal and receiving the reflection (e.g. Costa et al. 2006); surface velocities are then related to flows using empirical relationships
Slope-area methods	The slope of the water surface is estimated by recording water levels at several locations along a river reach over a distance of – typically – a few hundred metres, and the flow is then estimated from empirical relationships
Velocity-index approaches	Single or small numbers of ultrasonic transmitters/receivers are installed on a river bed or in the river banks to provide continuous estimates of velocity at one or more locations, which are related to flows using empirical relationships

Regarding LSPIV and radar velocimetry techniques, these have long been used in research studies, but operational applications are starting to become more common, particularly in situations where measurements need to be made quickly and there are increased safety risks, such as during flash floods. Another potential use of particle image velocimetry is to visualise and map surface velocities to help with developing hydrodynamic models of complex flows. In contrast slope-area methods provide a single approximate flow estimate and are particularly useful during post-flood assessments to derive estimates for the maximum flows reached, based on evidence of maximum water levels such as debris left at the high-water mark and damaged vegetation.

3.2.3 Stage-Discharge Relationships

For techniques which require use of a stage-discharge relationship, many factors need to be considered. Typically a power law equation is used with multipart curves if the river channel cross section changes significantly with depth or other influences come into play. However, polynomial relationships are sometimes used instead although can perform poorly when extrapolated beyond the range of observations.

Once established, curves must then be regularly checked and updated, particularly following major flood events when river flow paths can change and other problems arise. Some other potential issues include the influences of weed growth, dredging, natural shifts in river beds, ice cover and replacements to gauge boards and sensors. Also, due to hydraulic influences, some gauges exhibit looped ratings (or hysteresis) in which the form of the relationship varies depending on whether river levels are rising or falling.

The work of establishing and maintaining rating curves is a major and ongoing task for most hydrological services and is described in more detail in many textbooks and guidelines (e.g. Herschy 1999, Boiten 2008, ISO 1996, 2010, WMO 2008a). High flow performance is usually a particular concern for flood-related applications; however, measurement conditions are often at their most challenging, and Table 3.5 illustrates some of the issues which can occur. Regarding safety, as part of long-term planning, and before each site visit, detailed risk assessments are normally performed and appropriate mitigation measures adopted.

Whilst direct observations are preferred, as noted earlier slope-area methods provide another option for estimating maximum flood flows following the event. In locations with a high flood risk, maximum-level (or crest-stage) gages or recorders are sometimes installed to support these types of calculations; these typically consist of a metal tube in which a cork insert moves, which jams at the highest level reached due to the expansion which occurs on contact with water. At some sites, there is the option to make high flow measurements at locations further upstream or downstream for reasons of safety or because a higher proportion of the flow can be gauged; examples include bridges that are suitable for making observations and locations where the river channel is more confined. Flows at the surrogate location then need to be scaled to those likely to have occurred at the gauge site.

However, despite the best efforts of staff, there is usually still a need to extend rating curves beyond the highest observation ever made. In addition to simple

Table 3.5 Some examples of potential issues in high flow gauging

Item	Examples of potential issues
Access	Roads and footpaths blocked by floodwaters
Debris	Damage to equipment or cables snagged by debris
Floodplain flows	Rivers out of bank affecting travel and communications, with other priorities such as search and rescue
Gauges	River levels above the maximum which can be recorded
Night-time operations	Flood peaks occurring outside daylight hours
Flash floods	Flood flows already subsided before reaching the site or high flow velocities with large debris content
Remote sites	Difficulties in reaching the site in time to make useful observations
Rapid flow changes	Large changes in river levels during the time of the observations
Storm conditions	The risks of heavy rainfall and/or strong winds
Safety	Flood risks from all of the above, particularly when using current meters

extrapolation of values, some potentially more accurate techniques (e.g. Herschy 1999, ISO 2010, WMO 2008a) include:

- Velocity-area approaches – based on curves relating levels to mean velocities and cross-section areas, which in principle can be extrapolated with more confidence than stage-discharge relationships. The extrapolated velocities and areas are then combined to provide an estimate of flow
- Hydrodynamic approaches – which range from conveyance-slope techniques based on hydraulic formulae to the use of hydrodynamic models for the river reach to allow more complex situations to be considered such as non-modular flows and gauges which are bypassed by floodplain flows

With the exception of simple extrapolation, the accuracy of these approaches depends on the information available for calibration. For example, hydrodynamic models may need to represent both floodplain flows and features such as bridges, pipe crossings and culverts which could potentially become submerged at high flows. This requires both river channel and floodplain survey data extending some way upstream and downstream of the gauging station and more detailed survey for any structures which are likely to be affected.

Often it is useful to provide an estimate of the uncertainty in values to assist with interpreting the accuracy of the estimates. For example, confidence intervals for stage-discharge relationships are usually estimated assuming a transformed Gaussian (Normal) distribution; however, other approaches include decomposition of the individual sources of errors and Monte Carlo or Bayesian techniques (e.g. Sauer and Meyer 1992, Pappenberger et al. 2006, Petersen-Øverleir et al. 2008, McMillan et al. 2012, Le Coz et al. 2014). Depending on organisational policy, rating curves are sometimes truncated beyond the levels at which the uncertainty is thought to be too large and/or any flow estimates derived beyond those values are flagged to indicate potential problems. When developing flow forecasting models, a review of rating curves is therefore usually one of the essential first steps when assessing the accuracy of the flow data available for model calibration.

3.3 Water Quality

Water quality observations are often required for environmental and ecological forecasting applications. Parameters can be continuously monitored or recorded manually in the field or samples sent to a laboratory for further analysis.

Traditionally water quality sampling was a fairly labour-intensive process based on occasional samples taken at the sites of interest. This could mean that short-lived incidents were missed such as flushing of contaminants during floods. In particular for short-term forecasting applications, it is desirable for observations to be available in near real time.

Historically the main barriers to the use of more automated or ‘continuous sampling’ approaches were the high cost and poor reliability of sensors. However, these issues are increasingly falling away with the latest types of instrumentation, at least for the most commonly monitored parameters. Indeed some vendors offer multiparameter devices which are able to record several parameters with a single unit.

With a continuous sampling approach, values are typically recorded on a data logger and sent to a base station by telemetry. For example, Fig. 3.4 illustrates a type of multisensor observatory used as part of the Great Lakes Observing System in which the instruments provide continuous monitoring of vertical profiles of parameters such as currents, temperature, turbidity and dissolved oxygen content to a wide range of users (NOAA/GLERL 2015).

Another consideration is the large number of parameters which potentially need to be monitored (e.g. Table 3.6). For example, the United Nations Global Environment Monitoring System Water Programme recommends more than 60 core

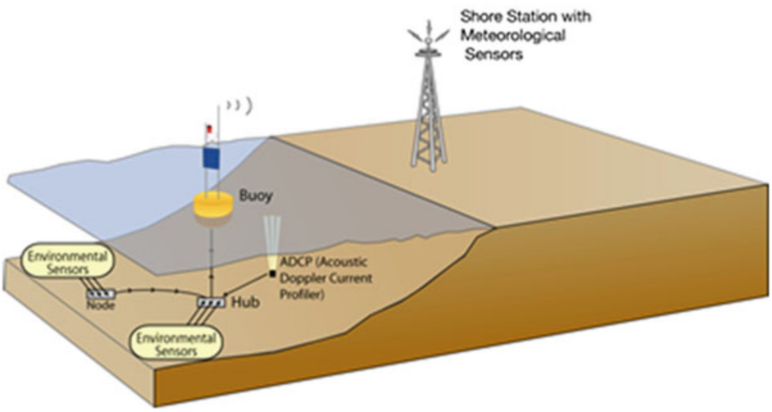

Fig. 3.4 Example of principles of operation for an observation buoy (Image courtesy of NOAA, Great Lakes Environmental Research Laboratory)

Table 3.6 Some examples of typical indicators of water quality

Type	Typical sources	Examples of typical indicators or contaminants
Fuels/hydrocarbons	Oil industry, road vehicles	Depends on compounds
Heavy metals	Industry, mining	Cadmium, mercury, copper, zinc, lead
Nutrients	Fertilisers	Nitrogen, phosphorus
Organics	Industry, mining, farming	Many possible chemical substances including herbicides and pesticides
Pathogens	Agriculture, Combined Sewer Overflows	Coliforms, streptococci, enterococci, salmonella
Solvents	Industry/mining	Depends on compounds
Suspended solids	Farming, forestry, construction	Sediment load, transparency, turbidity
Thermal pollution	Power stations	Water temperatures

water quality variables to collect if possible and identifies the following issues at global and/or regional or subregional levels (UNEP 2005):

- Organic wastes from municipal sewage discharges and agro-industrial effluents
- Eutrophication of surface waters as a result of point and non-point input of nutrients and organics
- Irrigation areas which are threatened by salinisation and polluted irrigation return waters
- Agrochemical use, fertilisers and pesticides leading to surface and groundwater contamination
- Industrial effluents containing a variety of toxic organics and inorganics
- Mining effluents and leachates from mine tailings affecting surface and groundwaters on a large scale
- Acidification of lakes, rivers and groundwaters, resulting from the long-term atmospheric transport of pollutants

In addition, WMO (2008b) defines the following 'Basic Parameters' to monitor, depending on whether a river, lake or groundwater source is being considered: temperature, pH, electrical conductivity, dissolved oxygen, nitrate, nitrite, ammonia, calcium, magnesium, sodium, potassium, chloride, sulphate, alkalinity, BOD, chlorophyll a, orthophosphate and total phosphorus (unfiltered).

The choice of what to measure depends on the application; however, many national hydrological services and reservoir operators have traditionally monitored at least the quantities illustrated in Table 3.7. Chapter 12 discusses several other examples including the use of biomonitors as near real-time indicators of the hazards from herbicides and pesticides, and Box 3.1 provides some further examples of the latest techniques.

Table 3.7 Summary of some widely monitored parameters for rivers, lakes and reservoirs (e.g. WMO 2008a, b; UNEP/WHO 1996; Hargesheimer et al. 2002)

Parameter	Typical monitoring techniques
Conductivity/ specific conductance	This provides a measure of the ionised chemical content and total dissolved solids and salinity and is usually measured by applying an alternating voltage between two immersed electrodes and recording the electrical resistance of the sample. Values are normally reported in units of microsiemens/centimetre and depend on water temperature so are usually referenced to a standard value. Direct estimates of dissolved solids are usually obtained by filtration, evaporation and weighing of water samples in a laboratory
Dissolved oxygen	When performed manually, sampling typically involves adding one reagent to fix the oxygen sample and then adding another until a colour change occurs. A typical automated approach is to measure the electrical current generated by the dissolved oxygen as it reacts with the coating on the cathode in an electrode system. Values are usually reported in units of milligrams per litre or parts per million and depend strongly on water temperature (and to a lesser extent atmospheric pressure)

(continued)

Table 3.7 (continued)

Parameter	Typical monitoring techniques
Faecal coliforms, Streptococcus	Laboratory tests for these and other pathogens typically involve membrane filtration with particular pore sizes to separate out the organisms and then cultivation of the organisms on a petri dish to determine concentrations. Values are then reported as the number of colonies per 100 ml
pH	This is a measure of the concentration of hydrogen ions and hence of acidity and alkalinity. Values are measured manually using indicators whose colour depends on the pH or electronically by measuring the potential generated between an electrode immersed in the sample and a reference electrode. Values are reported on a numerical scale from 0 to 14, with 7 indicating a neutral solution
Suspended solids	Some aspects of interest include the concentration of solids, water transparency and turbidity. Measurement techniques include: (a) filtering, drying and weighing a sample of the sediments from a known volume of water, (b) lowering a Secchi disc (a black and white-coloured disc of a specific design) into the water and recording the depth at which it disappears from view and then reappears on the downwards and return journeys and (c) turbidity meters which measure the scattering of light caused by the suspended sediment. Sediment loads are usually reported in milligrams per litre with more specialised units for turbidity, which is widely used as a surrogate for suspended sediment concentrations
Water temperature	Values are normally either measured manually using conventional thermometers or continuously sampled using thermistors

Box 3.1: River Eden Demonstration Test Catchment (EdenDTC)

Recent decades have seen an increasing awareness of agricultural impacts on the water quality in rivers, streams and lakes. Some potential consequences include damage to fish spawning grounds, changes in water colour and increases in algal growth.

In an effort to better understand these issues, during 2011 several demonstration catchments were established in England and Wales to explore ways to reduce the diffuse pollution from working farms (McGonigle et al. 2014). The project was initiated by the Department for Environment, Food and Rural Affairs (Defra) with funding from the Environment Agency and the Welsh Assembly Government. Some common issues between all catchments (Defra 2013) included:

- Inorganic nitrogen and phosphorus from fertiliser
- Pathogens, nitrogen, phosphorus and ammonium from animal manure or sometimes from septic tanks and urban sewage works
- Livestock accessing river banks cause poaching and soil erosion, leading to increased sediment in the water. They may also deposit urine and faeces directly into the stream
- Sediments eroded from bare farmland soil, in-stream channel banks and road verges

(continued)

Box 3.1 (continued)

Here poaching is a term used to describe the degradation of soil structure by cattle tamping leading to low-permeability saturated areas; these are not restricted to river banks and may be far from rivers but can be some of the first areas to produce runoff and sediments.

Continuous sampling equipment has been installed in each test area and was designed by the National Water Quality Instrumentation Service (NWQIS) of the Environment Agency. Sampling rates are typically every 15 min and the techniques used include:

- Automatic analysers – for phosphate, nitrate and ammonium
- Multiparameter sondes – single units to record conductivity, temperature, pH, dissolved oxygen, turbidity and chlorophyll a
- Pressure transducers and ultrasonic flow devices – for measuring river levels and river flows
- Time-integrated mass-flux samplers – to record fine sediment loads
- Tipping bucket raingauges – to record rainfall
- Turbidity probes – which record backscattered light from suspended sediment in a flow-through cell

These continuous observations are supplemented by laboratory analyses of borehole water samples, river sediment and soil samples and of ecological indicators such as algal diatoms.

The demonstration catchments are located in Cumbria, in Norfolk and along the Devon/Cornwall border. For example, the Eden catchment in Cumbria is a predominately rural area with a mixture of dairy and arable farming in the valleys and open moorland and forests on higher ground. Some techniques which are being tested as ways to reduce farm pollution include (e.g. Eden Rivers Trust 2011):

- Creating wetlands, ponds and sediment traps on farms
- Rainwater harvesting to reduce water use
- Measures to reduce soil compaction such as soil aerators and subsoilers
- GPS-based software to help tractor drivers apply fertilisers more effectively
- Tree planting and fencing to act as sediment traps and keep cattle from rivers

Three sub-catchments were chosen for detailed investigation and illustrate a range of farming practices and natural processes (Owen et al. 2012). Each includes an undisturbed (control) area and an area in which mitigation measures are being tested. The research programme is being managed by Lancaster University in collaboration with Durham and Newcastle Universities, the Eden Rivers Trust, CEH Lancaster and Newton Rigg College.

(continued)

Box 3.1 (continued)

The observations have helped to show some of the complexities of flow paths and sediment delivery. For example, for the Pow catchment over a 6-month period some key conclusions (LEC 2014) regarding pollutant transfer were:

- Over 20 rainfall events occurred in the Pow catchment in spring, summer and autumn, which generated streamflow responses transferring sediment, phosphorus and nitrate through Pow Beck
- More than 90 % of sediment and 75 % of phosphorus in the stream were transferred in high flows
- The majority of nitrate was also transferred in high flows, with medium flows also important, accounting for around 40 %

Figure 3.5 shows the variations in nitrate, phosphorus and sediment concentrations over this period together with the observed rainfall and river discharges. Insights such as these will help with deciding on the best advice to give to farmers and land owners and with devising catchment and nutrient management strategies.

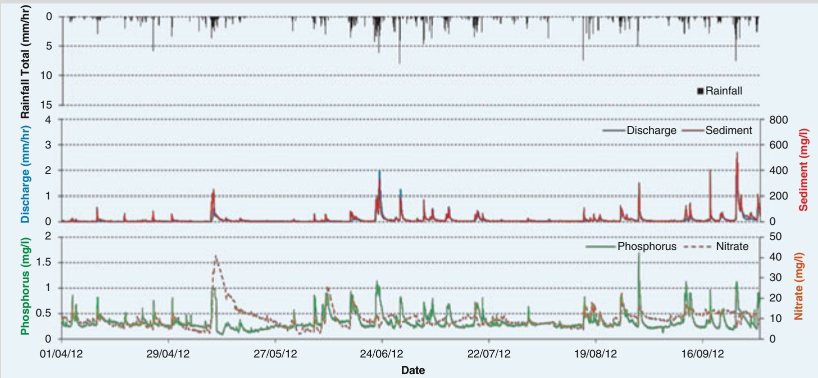

Fig. 3.5 Hourly data for the Pow catchment outlet for April to September 2012, showing flow and pollutant responses to rainfall (LEC 2014)

3.4 Catchment Conditions

In addition to observations of land use and vegetation cover, for forecasting applications some variables which are often useful at a catchment scale include estimates for the soil moisture, evapotranspiration and snow cover.

Satellite observations provide one possible route to estimating these values. However, as discussed in Chap. 2 there are sometimes issues relating to the frequency of observations, whether measurements are affected by cloud cover, and the spatial resolution of outputs. Nevertheless, satellite-based products are useful in

Table 3.8 Summary of some typical approaches to satellite monitoring of catchment conditions

Parameter	Basis of approach
Snow cover	Use of visible, near-infrared or infrared and/or microwave observations of snow extent, snow depth, snow water equivalent, albedo and other parameters, combined with a reflectance algorithm to distinguish between wet snow, forest, dry ground, etc. (e.g. König et al. 2001, Foster et al. 2011)
Soil moisture	Use of infrared and passive and/or active microwave measurements from polar-orbiting satellites, with algorithms to interpret the signals from different types of land surface including open areas and forest, water, ice, snow and urban areas. A general issue is that usually only a shallow surface layer, a few centimetres in depth, is sampled (e.g. Alavi et al. 2009, Wagner et al. 2007)
Vegetation cover	Use of visible, near-infrared and infrared observations with algorithms to differentiate between different types of vegetation (and to filter out other sources of radiation), often presented in the form of a Normalised Difference Vegetation Index (NDVI), based on differences in reflectance in the visible (red) and near-infrared channels

a number of applications, particularly in situations where ground-based measurements are sparse or changes only occur over timescales of days or more. Table 3.8 summarises some typical observation techniques and later chapters provide further examples. Some other applications are in the land data assimilation component of numerical weather prediction models (see Chap. 13) and in observations of seasonal variations in wetland extent and inundated areas during flood events.

For soil moisture monitoring perhaps the most advanced sensors to date were those launched on NASA's experimental Soil Moisture Active Passive (SMAP) mission from 2015 to 2018. That is, an L-band radiometer and – initially – a high-resolution synthetic aperture radar, allowing soil moisture estimates to be inferred from a combination of emission and backscatter observations. Soil freeze/thaw conditions are also detected. The intended spatial resolution of the estimates was approximately 10 km for soil moisture and 2–3 km for freeze/thaw states, with the near-polar orbit allowing global coverage to be completed every 2–3 days (http://smap.jpl.nasa.gov/). This compares with the 35–50 km resolution available from the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission from 2009 to 2017 (http://www.esa.int/).

In comparison, images of snow cover have been routinely available since the 1960s together with more recent products based on passive microwave sensors (e.g. König et al. 2001, Shunlin 2008, Armstrong and Brun 2008). However, inferring snow depth and snow water equivalent is a more challenging task and an active area for research. This includes the use of synthetic aperture radars and scatterometers and the development of multisensor products, for example, combining passive, active and scatterometer outputs (Foster et al. 2011). Vertically pointing Doppler radars provide another remote-sensing option and are used in California, for example, to estimate the elevation of the snow line (White et al. 2012).

Ground-based observations provide the main alternative to these techniques and, although generally more accurate, may not be representative of wider catchment conditions, particularly where there are significant changes in elevation or land cover. Table 3.9 summarises some of the main techniques for snow, soil moisture and evaporation observations.

Table 3.9 Examples of manual and automated ground-based observation techniques for catchment conditions (e.g. WMO 1992, 2008a)

Parameter	Method	Examples of techniques
Evaporation	Manual	Evaporation pans, in which the reduction in levels is measured in a prescribed type of container, for which various standard designs are available
	Automated	Specialised meteorological equipment, such as eddy correlation or Bowen Ratio devices, to measure evaporation; in the former case via observations of instantaneous values of horizontal and vertical wind speed and fluctuations in humidity and air temperature
Soil moisture	Manual	Sampling of the water content of soil samples using gravimetric weighting techniques
	Automated	Neutron, gamma or capacitance/dielectric constant probes, heat dissipation sensors, cosmic-ray sensors, time-domain sensors or tensiometers, installed at one or more depths in the soil. For example, heat dissipation sensors record the temperature difference at the sensor caused by a pulse of heat, whilst time-domain approaches measure the changes in a microwave signal transmitted between two or more vertical probes (e.g. WMO 2008a, 2009).
Snow depth and cover	Manual	Observations using graduated rules or ablation stakes or by weighing snow cores to estimate snow depths and/or water equivalent values either at a fixed measurement point, such as a weather station, or along a snow course; also ground-penetrating radars flown by helicopter or aircraft or pulled by snowmobile to measure snow depth, density and water equivalent values (e.g. Lundberg et al. 2008)
	Automatic	Some examples of techniques include: radioisotope or gamma radiation attenuation (gamma-ray) detectors installed at ground level to provide a measure of snow depth and water equivalent from the attenuation in the signal measured above the snow surface, downward-looking ultrasonic sensors which infer the snow depth from the time delays between transmission and receipt of the signal, and solid-state load-cell sensors (e.g. Johnson et al. 2007) or snow pillows to estimate snow depth/water equivalent from the weight of accumulated snow (snow pillows are flexible rubberised or metal containers filled with a nonfreezing fluid such as antifreeze)

For evaporation measurements, the traditional approach is to use an evaporation pan but these often show large day-to-day variations in evaporation due to local heating and wind effects. In contrast, due to the specialist knowledge needed, eddy correlation and similar techniques are mainly confined to research studies and one-off investigations over reservoirs, lakes and wetlands.

These limitations have led to the widespread use of indirect approaches in which evaporation rates are inferred rather than measured directly. Of these perhaps the most widely used are the Penman equation for open water evaporation (Penman 1948) and the Penman-Monteith approach for evapotranspiration (Monteith 1965). The main meteorological inputs required are the air temperature, wind speed, humidity and solar or net radiation, or suitable surrogate variables such as the wind run and number of sunshine hours. Here the wind run is the integral of observed wind speeds over a given period, such as a day. Penman-Monteith values are usually calculated for a reference grass surface with values for crops and natural vegetation estimated by adjusting these values using empirically based coefficients (see Chap. 6).

Similarly, there are many practical difficulties with obtaining representative measurements of soil moisture at a catchment scale, which has again led to the widespread use of indirect approaches. Typically a water balance model is used to keep account of the net changes in soil moisture arising from rainfall and evapotranspiration, in some cases allowing for spatial variations in land cover and vegetation types. For simplicity the surface runoff and groundwater components are often neglected in this type of approach.

Conceptual or distributed rainfall-runoff models provide another option particularly for flow forecasting applications where there is often a need for soil moisture values to be derived using the same estimation procedure as in the operational model. In some cases this includes the facility to update values manually to correct for any bias which develops; for example, some opportunities to do this are when due to recent weather soils are thought to be saturated or unusually dry. Another option is to use the soil moisture-related products provided by some meteorological services as one of the outputs from numerical weather prediction models (see Chaps. 4 and 13).

The key barrier to using more direct techniques is the large number of instruments required to adequately define soil moisture at a catchment scale. However, in recent years, the number of operational networks has increased. For example, the United States Department of Agriculture (USDA) operates about 200 automated stations and typically these use dielectric constant measuring devices to estimate soil moisture, in many cases with additional sensors for soil temperature, snow depth and water content, plus a weather station (e.g. Schaefer et al. 2007).

In recent years, another development has been to use cosmic-ray sensors to measure soil moisture (Zreda et al. 2012). These operate on a similar principle to neutron probes but detect naturally generated free neutrons, whose numbers at the ground surface depend mainly on soil moisture content over a surrounding area of several hundred metres. This approach therefore provides a spatial view of soil moisture not given by most in situ techniques, and networks of sensors have been established in several countries including the USA, the UK and Australia.

For snow depth and cover, the extent to which ground-based measurements are useful or practicable depends on many factors, including the local topography and economic drivers such as whether there is a local skiing industry. However, where measurements are made routinely, traditional spot measurements by observers are increasingly being supplemented by automated approaches (e.g. Røhr and Husebye 2005; WMO 1992, 2009; Egli et al. 2009; Rasmussen et al. 2010; Nitu and Wong 2010). For example, ultrasonic sensors (e.g. Fig. 3.6) are widely used together with snow pillows in some countries. In particular, these types of instrument are a key component in the SNOTEL network in the western USA which has more than 700 sites (Schaefer and Paetzold 2000; http://www.nrcs.usda.gov/). Where budgets allow, ground-penetrating radars provide another option and are sometimes installed at fixed locations over a distance of several kilometres or more. Multisensor products are also produced in some countries, such as the USA, based on available ground, airborne and satellite observations and physically-based snow models (e.g. http://www.nohrsc.noaa.gov/).

As for soil moisture estimates, another option is to estimate snow water equivalent values and snowmelt from water balance or conceptual models, and this approach is described in Chaps. 5 and 8. However, in flood forecasting systems, as

Fig. 3.6 Snow depth sensor (Met Office 2010; contains public sector information licenced under the Open Government Licence v1.0)

a precaution often at least one river gauge is installed downstream from snowmelt-prone areas to provide additional backup in case measurement systems or models fail to detect the potential for flooding.

3.5 Monitoring Networks

The design, installation and upkeep of a network of monitoring stations can be a considerable undertaking. Also, compromises are often required due to limitations on funding, site access (nearby roads, wet-season conditions etc.), power (if not using solar power or batteries) and telemetry options. Other factors which often need to be considered include permissions from land owners and the security of equipment from theft and vandalism. Budgets should also allow for the long-term operation, maintenance and repair of equipment, plus staff costs and any associated capacity building (e.g. NOAA 2010; WMO 2009, 2011).

Perhaps the most demanding requirements are for short- to medium-term flow forecasting applications. Table 3.10 summarises some of the main factors which usually need to be considered, and later chapters discuss this topic in more detail. For example, issues such as the level of risk, lead-time requirements, catchment response and network resilience are especially relevant to flood warning applications. Thus, for a major city, the risks to people and property might justify installing at least one river gauging station within each of the main areas at risk from flooding, possibly with backups in case of failure, together with additional raingauges and river gauges at locations further upstream to help to extend forecast lead times.

Table 3.10 Some typical factors to consider in network design for short- to medium-term forecasting

Item	Description
Catchment response	The features and locations in a catchment or region which have the greatest influence on hydrological conditions, such as reservoirs, lakes and wetlands, high runoff headwater catchments, river control structures and soil and groundwater conditions
Forecasting point(s)	The location(s) where forecasts are required in the catchment, considering both local influences such as those from flow control structures and influences from the catchment upstream
Lead-time requirements	The minimum lead time required for the application and the recording interval which is ideally required to resolve the evolution of a typical event as it occurs
Level of risk	The probability of occurrence of an event and the consequences in terms of financial damages, risk to life and/or intangible losses from issues such as flooding or pollution, or the loss of electricity (hydropower) or water supplies
Climate	The scale, intensity, duration and types of event likely to occur in a region such as widespread frontal events, tropical cyclones, hurricanes or localised storms such as thunderstorms
Operational requirements	The types of decisions and actions that the forecast outputs will support and associated risks, for example, related to operations of river control structures, drawdown of reservoirs, diversion or suspension of water supplies, pollution monitoring at an effluent outfall, water quality monitoring for fisheries, or evacuation of a city due to a heightened flood risk
Resilience	The consequences if an instrument or telemetry link fails in terms of the backups available (and how representative they are of the locations of interest) and the consequences for the operation of forecasting models and the loss of information for decision-making

By contrast, for longer-term drought forecasting applications, the emphasis might be more on regional monitoring of rainfall and accurate monitoring of low flows and major abstractions and discharges. Data values might only be required on an hourly or daily basis, whereas for flash flood and surface water flooding applications, recording intervals are often in range 1–15 min, However, this is not a general rule with some low flow forecasting applications requiring more frequent observations such as to support hydropower and water supply operations.

More generally both the catchment response and local climate are significant factors to consider and for flood modelling some of the most challenging issues arise in arid and semiarid regions where (WMO 2011) some typical problems ‘are:

- Highly localized rainfall, which may not be captured by raingauges, particularly if these are sparsely distributed
- Highly seasonal rivers, with a large range of discharge and level. These are difficult to measure with both structures or at rated sections by current meter, as channel conditions change during and after each flood event
- Ephemeral rivers, which exhibit considerable losses through the channel bed along lower reaches

- Major changes in the course of rivers and destruction of measuring devices by flood flows
- Problems of maintenance and performance of monitoring equipment in harsh conditions, especially dust and heat'

Various approaches have been proposed for network design considering issues such as the level of risk, climate, topography and measurement uncertainty (e.g. Andryszewski et al. 2005, WMO 1994, Mishra and Coulibaly 2009, Volkmann et al. 2010). This topic is also discussed in a number of guidelines related to flood and water resources applications (e.g. USACE 1996, WMO 2008a, 2011, NOAA 2010). In practice many networks are designed for a wide range of end users which usually leads to advantages in terms of sharing equipment and resources but also some compromises.

For example, a common problem with river gauges installed for water resources monitoring is that they are not necessarily suitable for flood warning applications. During floods some typical risks include flows bypassing gauges, backwater influences from locations further downstream and flooding of electrical equipment. Conversely, problems due to weed growth and shifting river channel beds are potentially an issue at low flows but less significant at high flows.

To help with deciding on gauge locations, in addition to site visits, some typical first steps are to assess the catchment response and site characteristics, and some techniques which are used include:

- Analyses of historical raingauge, weather radar and/or satellite observations to help with identifying typical rainfall distributions and – if relevant – storm paths
- Analyses of hydrological records to provide insights into flow response at potential gauge locations, possibly supported by hydrological and/or hydrodynamic modelling studies
- The use of digital elevation models to visualise the general terrain and setting of proposed gauge locations relative to topographic features; for example, regarding potential access, flooding or telemetry issues

If time and budgets allow, another option is to install temporary gauges to assess the suitability and security of the preferred sites, before proceeding to invest in other infrastructure. Ultimately of course, cost is often a critical factor, and cost-benefit and multi-criteria analyses are sometimes used to justify the installation of new equipment.

Another key consideration is whether gauges need to be on telemetry, and Table 3.11 summarises the main options. The approaches used vary widely; for example, at a national level, the US Geological Service largely relies on satellite telemetry for river gauges, whilst in the UK landline telephone (PSTN) telemetry is the most common approach. In more remote areas, meteor burst techniques provide another option and underpin the US Department of Agriculture Snow Telemetry (SNOTEL) network which was discussed earlier. In contrast radio telemetry is widely used in local flood warning systems in the USA, as discussed in Box 3.2.

Table 3.11 Some possible telemetry techniques for hydrometeorological data (Adapted from Sene 2013)

Method	Basis of technique
Cellular	Data transmission using GPRS or GSM technologies, in some cases with the option to send SMS text message alerts directly from gauges to cell phone subscribers. However, the facilities available and performance vary between service providers and locations, normally requiring specialised portable testing equipment to assess the suitability of individual sites for data transmission for which the requirements are more demanding than simply for voice or text communications
Landline	Transmission using the Public Switched Telephone Network (PSTN) or leased/common-carrier/dedicated lines
Meteor burst	Reflection of radio signals from the ion trails left by microscopic meteors, with data transmission feasible over distances of 1000 km or more. Information is transmitted in bursts during suitable atmospheric conditions which usually occur frequently enough to allow regular (sub-daily) communications
Radio	Direct (line-of-sight) VHF or UHF transmissions, with repeater stations as required to provide a link between the gauge site and receiving centre. There is sometimes the opportunity to install other types of instruments at repeater sites such as automatic weather stations
Satellite	Transmission using meteorological, communications or other geostationary satellites or via polar or low-earth orbit (LEO) satellites, of the types discussed in Chap. 2. Information is typically received directly via a satellite dish and associated software and/or via the Internet or other links from the service provider. Geostationary satellites have the advantage of appearing fixed in space from a given ground location, whilst some operators of polar and LEO types are able to provide almost complete global coverage by using constellations of satellites, with 50 or more in some networks. In particular meteorological geostationary satellites such as those within the NOAA GOES and EUMETSAT Meteosat programmes usually include a data collection and distribution capability for use by national meteorological and hydrological services

Figure 3.7 illustrates a satellite-based approach, in this case from the World Hydrological Cycle Observing System (WHYCOS) programme. This is a WMO initiative for which the mission is (WMO 2005):

> To strengthen the technical and institutional capacities of National Hydrological Services to collect and transmit, in real or near real time, hydrometeorological data and information of a consistent quality, thereby improving water resources assessment and management and promoting regional and international cooperation in data collection, sharing and research.

Several regional projects have been established, and as indicated satellite telemetry is widely used together with other approaches where appropriate.

Normally, in automated systems, the polling and receipt of telemetry data is controlled by specialised computer software or by a module within a forecasting or data management system. Depending on the approach adopted, additional equipment may need to be installed at the base station such as a radio mast or satellite dish. Regarding data transmission, the main options are to transmit data values at fixed time

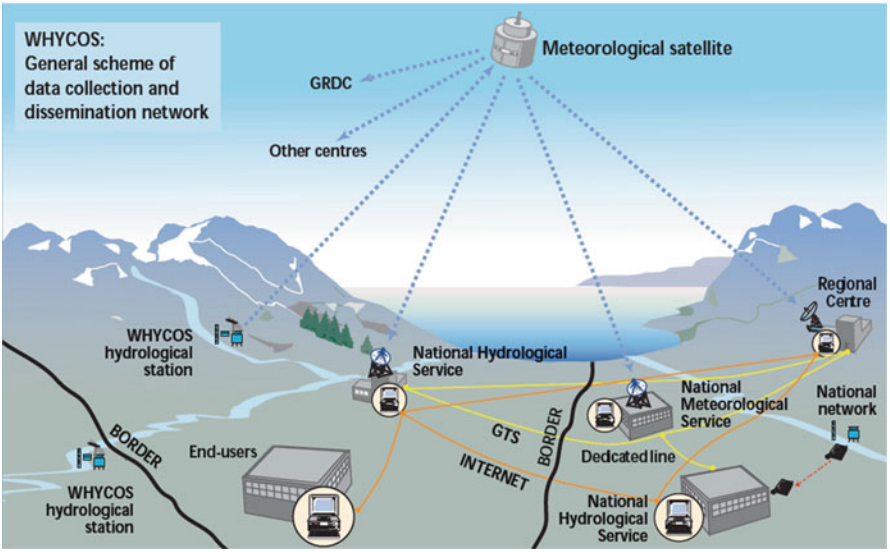

Fig. 3.7 General scheme of data collection and dissemination network in the World Hydrological Cycle Observing System (WMO 2005)

intervals, on demand or when values exceed a threshold, such as when river levels reach values likely to lead to flooding; in the latter case this is called event-based reporting. Additional diagnostic information is often transmitted relating to issues such as battery condition and the kiosk temperature.

Typically values are stored in a local database before being archived more permanently in a hydrological data management system. Table 3.12 outlines some typical functionality for systems of this type and they are often a key tool in national hydrological services and other water management organisations. As indicated, there is sometimes the facility to generate warning messages when critical threshold values are exceeded. For safety-critical applications, backup computers, power supplies and software are particularly important and in some cases extend to contingency plans to relocate operations to another site in case of flooding or other problems.

When choosing which telemetry approach to use, in addition to general considerations such as cost, power requirements, transmission distance and terrain, the limitations of individual approaches need to be considered. For example, for landline telephone links, an expensive additional run of cable and signal amplifiers may be required if there are no nearby connection points. Radio telemetry systems, by contrast, rely upon a clear line of sight for the signal and hence sometimes require repeater and booster stations to transmit the signal to the base station and in some cases suffer from radio interference. For satellite-based telemetry systems, some

Box 3.2: Automated Local Evaluation in Real Time (ALERT)

ALERT is an acronym for Automated Local Evaluation in Real Time, which is a method of using remote sensors in the field to transmit environmental data to a central computer in real time (http://www.alertsystems.org/). The most common application is to provide rainfall and streamflow data to support the operation of local flood warning systems for rivers (Fig. 3.8), although other uses include monitoring of water quality, river control structures and coastal conditions.

First introduced in the 1970s by the National Weather Service, the use of a standard protocol and software for data transmission has allowed a wide range of hardware and related software to be developed by suppliers (NOAA 2010; NOAA/NWS 2012), and the ALERT standard is widely used in the USA, Australia and elsewhere.

In the USA, ALERT systems are typically operated by city, county or state authorities, supported by the National Weather Service and with national coordination provided by the National Hydrologic Warning Council (NHWC) and regional user groups (http://hydrologicwarning.org/). When used for flood warning applications, the main components of an ALERT system normally include reporting raingauges and streamflow gauges. Other types of instrument may be used such as automatic weather stations and gauges for monitoring reservoir levels, pumping station operations, water quality and soil moisture. Power is typically provided by batteries or solar power, and data transmissions may include the current battery voltage or a daily status check. The transmission of data is by VHF or UHF radio, often with repeater stations.

Recent developments have included an enhanced ALERT2 protocol to provide faster, more reliable data transmission and the use of ever more sophisti-

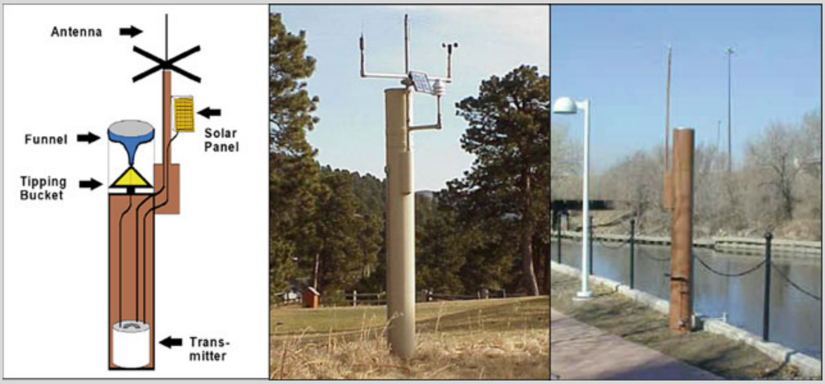

Fig. 3.8 Principles of operation of a radio-reporting raingauge (NOAA/NWS 2012) and illustration of an ALERT weather station and combined raingauge and streamflow gauge (Stewart 2009)

(continued)

Box 3.2 (continued)

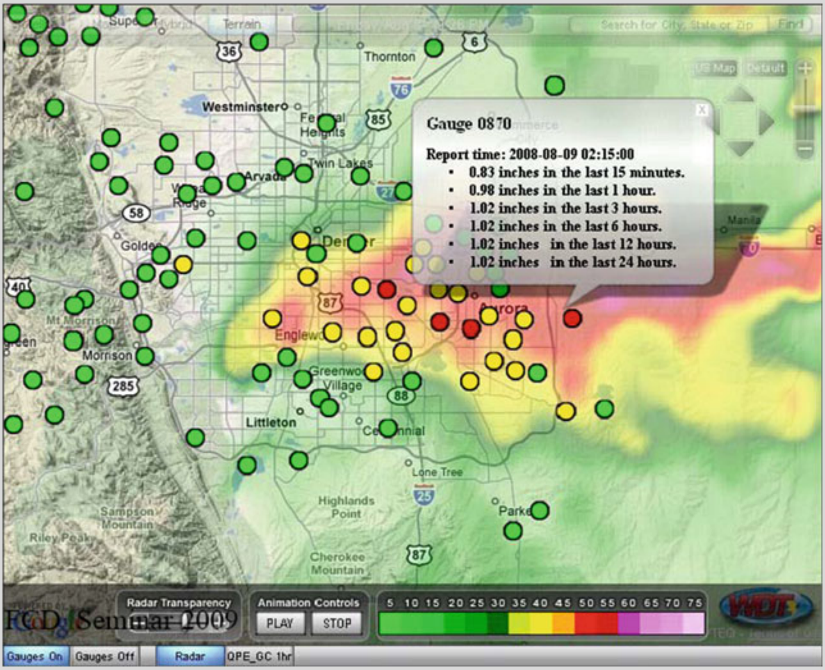

Fig. 3.9 Illustration of a combined Internet-based display of raingauge and NEXRAD weather data (Urban Drainage and Flood Control District, Denver, Colorado; Stewart 2009)

cated Internet-based tools for displaying and mapping data. For example, Fig. 3.9 shows an Internet-based display of ALERT raingauge data and NEXRAD weather radar data (at a high transparency setting) for the Denver area in Colorado, USA, including a display of rainfall for several durations over the past 15 min–24 h for the selected raingauge. The rainfall locations are colour coded according to rainfall depth-duration values, and the sequence of radar and raingauge values can be animated if required.

issues to consider include the frequency of overpasses (for polar and low-earth orbit satellites), the visibility (such as for gauges in deep valleys) and the time taken to relay observations to the base station. For meteor burst systems there are sometimes transmission delays whilst waiting for suitable atmospheric conditions.

The issue of control of the network is another consideration, and radio and meteor burst networks have the advantage that the equipment is normally owned by the operator. The disadvantage, of course, is the initial capital cost

Table 3.12 Some typical options in a hydrological data management and telemetry system (Adapted from Sene 2013)

Item	Option	Description
Data transfer	Data distribution	Automated transfer of time-series, grid-based and other data to decision support, flood forecasting and other systems, in some cases with a developer's toolkit to allow software to be developed for automated access from a user's own systems
	SCADA	Links to specialised Supervisory Control and Data Acquisition (SCADA) systems at hydropower plants, water supply reservoir and other sites
Data processing	Data quality indicators	The option to add comments and data quality flags or codes to individual values and to maintain multiple versions of individual time series (e.g. raw, checked, interpolated)
	Data validation	Graphical and automated options for quality control of incoming data, using range, threshold, persistence, rate of change and other validation criteria, including intercomparisons with other data streams (e.g. rainfall at nearby raingauges)
	Editing	Interactive editors for reviewing and changing data values and adding data quality control flags and comments, typically with password-controlled access at a range of levels (view, edit, administrator, etc.)
	Infilling	Automated and/or interactive tools for infilling data at a single site using techniques such as linear interpolation or assuming a constant value
	Metadata	Summaries of the information stored on the system following national or international metadata standards for site details, data types/units, georeferencing, etc.
Data analysis and reporting	General	A range of analysis options, for example, for base flow index, double mass, flow duration and flood frequency calculations and catchment rainfall estimates
	Multisite analyses	Tools for infilling and extending records based on data recorded at other sites (e.g. by regression, rainfall-runoff modelling)
	Rating curves	Tools for displaying, developing and applying stage-discharge and level-storage curves and for analyses of discharge measurements
	Report generation	Generation of summary 'yearbook' and other report formats for sub-daily, daily, 10-day, monthly and annual values including mean, maximum and minimum values and other statistical outputs, with the option to customise the formats and publish values to a website
	Thresholds	Definition of single-value thresholds and possibly other types, such as rate of rise or multi-criteria thresholds (possibly using a suite of programming tools)
	Alarm handling	Comparisons of real-time data with threshold values and managing the resulting alarms, including maintaining an audit trail of system outputs and user entries
	Dissemination	Automated transmission of alarms by email, text message and other options including publishing values to a website both publicly and with password-controlled access, plus links to multimedia and other warning dissemination systems

plus the need to operate and maintain the network rather than rely on a third-party/commercial service (although that too is an option); appropriate licences are usually also required. However, for some satellite and cell phone approaches, there may be significant connection and data transmission charges or restrictions on data volumes or the timing of transmission imposed by the operator. Indeed, to reduce transmission costs, some organisations use variable polling intervals; for example, initiating more frequent monitoring only when high flows seem possible.

More generally, some systems only allow one-way (simplex) transmission of data, whereas others are two way (duplex), allowing values to be requested, polling rates changed and diagnostic checks performed. It is also worth noting that many commercial networks are only provided on a best endeavours basis and run a particular risk of being overloaded during emergencies. In that regard it is particularly important to consider system resilience to storms, floods and power failures; in particular issues with cell and landline networks are often cited in lesson-learned reports following flood events.

For critical locations, dual-path systems provide an option to improve resilience by combining different approaches, such as cellular and satellite-based techniques. Indeed, in some countries, there is the option to transmit data via existing (and more robust) emergency communications networks. In some cases, a combined or hybrid approach is used, such as local communications to a nearby hub by radio, leased line, satellite or cellular transmission, with the final data transfer to regional centres by satellite telemetry or a wide area network. Another key consideration is interoperability of systems with a common example being the need for service-level agreements and robust communications links between meteorological and hydrological services (see Chaps. 4 and 5).

One other recent development worth noting is the increasing use of wireless sensor networks in environmental applications, such as water supply operations. In this so-called pervasive or grid network approach, multiple low-cost sensors with onboard software are interconnected to form networks resilient to the loss of individual sensors (e.g. Basha et al. 2008, Hoult et al. 2009). In hydrometeorology, some potential applications include flood warning (e.g. Hughes et al. 2006), monitoring conditions in storm water drainage networks (e.g. Stoianov et al. 2007) and geotechnical monitoring for debris flows, dams and levees.

3.6 Summary

- Manual observations of river levels are widely used, particularly in community-based warning schemes and as a backup to more automated approaches. Automated equipment provides the advantages of allowing more frequent observations and the option to transmit data by telemetry, but regular site visits are still required for maintenance and repair. Some typical approaches include float and pulley, pressure transducer, bubbler and ultrasonic and radar devices, and these techniques are also used for monitoring levels in reservoirs, lakes, wetlands, boreholes and estuaries.

- The most widespread approach to monitoring river flows is to record levels in a natural river channel and to convert these to flows using a stage-discharge relationship or rating curve. The discharge measurements required to establish these types of relationship are usually made using current meters or Acoustic Doppler Current Profiler (ADCP) devices. Dilution gauging, digital imaging, ultrasonic, radar, float and slope-area techniques provide other options.
- Rating curves need to be regularly reviewed and updated to account for changes over time, particularly after major flood events. Other factors such as river bed movement, seasonal weed growth and ice and backwater influences sometimes play a role. Obtaining measurements at high flows is a particular challenge and rating extension techniques include velocity-area methods and the use of hydraulic formulae or hydrodynamic models.
- Some direct techniques for flow observation include ultrasonic and electromagnetic devices, although their application is limited by the cost. Velocity-index approaches provide a simpler alternative, and gauging structures are another option. Velocimetry techniques show potential for a range of applications including flash flood gauging and visualising flow patterns to assist with calibrating hydrodynamic models.
- For water quality monitoring, although manual sampling techniques are still widely used, automated techniques are increasingly available allowing frequent (e.g. sub-hourly) sampling of parameters such as conductivity, dissolved oxygen, pH, turbidity and water temperature. If required, values can be transmitted by telemetry for input to decision support and forecasting systems.
- At a catchment scale, parameters of interest include soil moisture, snow cover and evapotranspiration. Satellite observations have the advantage of providing a catchment-wide view although in some cases lack the accuracy, frequency of observations and spatial resolutions required for hydrological applications. Nevertheless, observation techniques for snow cover, flood extent and vegetation are well established with an increasing range of options for monitoring soil moisture, snow depth and snow water equivalent values.
- In situ monitoring provides another option, and in addition to manual techniques, there are many automated approaches to monitoring catchment conditions. Examples include capacitance probes, heat dissipation sensors, ground-penetrating radar and ultrasonic sensors. However, a key issue is how representative measurements are at a catchment scale, and as a result indirect approaches are widely used such as soil moisture accounting models and Penman-based techniques for evapotranspiration. Nevertheless, monitoring networks have been established in several countries and provide operationally useful information.
- Numerous factors need to be considered when establishing a river or catchment-scale monitoring network both in terms of the operational requirements and factors such as cost, site security and site access. In addition to the types of equipment, some key decisions include the type of telemetry system to use (if any) and the type of data management system required.

- In general, but particularly for safety-critical applications such as flood warning, network resilience is an important consideration. Some options to improve resilience include dual-path telemetry systems and backup gauges and computer systems, sometimes with an alternative location for the control centre in case of emergency. Steps should also be taken to reduce the risks from theft or vandalism which are a serious problem in many countries.

References

Alavi N, Warland JS, Berg AA (2009) Assimilation of soil moisture and temperature data into land surface models: a survey. In: Park SK, Xu L (eds) Data assimilation for atmospheric, oceanic and hydrologic applications. Springer, Berlin/Heidelberg

Andryszewski A, Evans K, Haggett C, Mitchell B, Whitfield D, Harrison T (2005) Levels of service approach to flood forecasting and warning. ACTIF international conference on innovation advances and implementation of flood forecasting technology, Tromsø, Norway, 17–19 Oct 2005

Armstrong RL, Brun E (2008) Snow and Climate Physical Processes, Surface Energy Exchange and Modeling. Cambridge University Press, Cambridge

Basha EA, Ravela S, Rus D (2008) Model-based monitoring for early warning flood detection. SenSys'08, Raleigh, North Carolina, 5–7 Nov 2008

Benveniste J, Berry P (2004) Monitoring river and lake levels from space. ESA Bulletin 117 – February 2004

Boiten W (2008) Hydrometry, 3rd edn. Taylor and Francis, London

Costa JE, Cheng RT, Haeni FP, Melcher N, Spicer KR, Hayes E, Plant W, Hayes K, Teague C, Barrick D (2006) Use of radars to monitor stream discharge by noncontact methods. Water Resour Res 42:W07422

Creutin JD, Muste M, Bradley AA, Kim SC, Kruger A (2003) River gauging using PIV techniques: a proof of concept experiment on the Iowa River. J Hydrol 277:182–194

Defra (2013) Demonstrating Catchment Management: Learning from the Demonstration Test Catchments. Note No. 02, Defra, London

Eden Rivers Trust (2011) Eden Catchment Water Friendly Farming Good Practice Guide, Eden Rivers Trust, Penrith

Egli L, Jonas T, Meister R (2009) Comparison of different automatic methods for estimating snow water equivalent. Cold Reg Sci Technol 57(2–3):107–115

Foster JL, Hall DK, Eylander JB, Riggs GA, Nghiem SV, Tedesco M, Kim E, Montesano PM, Kelly REJ, Casey KA, Choudhury B (2011) A blended global snow product using visible, passive microwave and scatterometer satellite data. International Journal of Remote Sensing, 32(5): 1371–1395

Fujita I, Muste M (2011) Preface to the special issue on image velocimetry. J Hydro-environ Res 5(4):213

Hargesheimer EE, Conio O, Popovicova J (2002) Online Monitoring for Drinking Water Utilities. American Water Works Association, Denver

Herschy RW (1999) Hydrometry: Principles and Practices. Wiley, New York

Hoult N, Bennett PJ, Stoianov I, Maksimovic C, Fidler P, Middleton C, Graham N, Soga K (2009) Wireless sensor networks: creating 'smart infrastructure'. Proc Inst Civ Eng, Civ Eng 162(CE3):136–143

Hughes D, Greenwood P, Blair G, Coulson G, Pappenberger F, Smith P, Beven K (2006) An intelligent and adaptable grid-based flood monitoring and warning system. 5th UK eScience All Hands Meeting (AHM'06), Nottingham, UK

ISO (1996) Measurement of liquid flow in open channels. Part 1: Establishment and operation of a gauging station. International Organisation for Standardization, ISO 1100–1, Geneva

ISO (2010) Measurement of liquid flow in open channels. Part 2: Determination of the stage discharge relation. International Organisation for Standardization, ISO 1100–2, Geneva

Johnson J, Gelvin A, Schaefer G (2007) An engineering design study of electronic snow water equivalent sensor performance. In: 75th annual Western snow conference, Kailua-Kona, Hawaii, 16–19 Apr 2007

König M, Winther J-G, Isaksson E (2001) Measuring snow and glacier ice properties from satellite. Rev Geophys 39(1):1–27

Le Coz J, Hauet A, Pierrefeu G, Dramais G, Camenen B (2010) Performance of image-based velocimetry (LSPIV) applied to flash- flood discharge measurements in Mediterranean rivers. J Hydrol 394(1–2):42–52

Le Coz J, Renard B, Bonnifait L, Branger F, Le Boursicaud R (2014) Combining hydraulic knowledge and uncertain gaugings in the estimation of hydrometric rating curves: A Bayesian approach. Journal of Hydrology, 509: 573–587

LEC (2014) Pow Catchment Water Quality: April-September 2012. EdenDTC Info. Sheet, Lancaster Environment Centre, Lancaster

Lowry CS, Fienen MN (2013) Crowdhydrology: crowdsourcing hydrologic data and engaging citizen scientists. Groundwater 51:151–156

Lundberg A, Granlund N, Gustafsson D (2008) "Ground truth" snow measurements – Review of operational and new measurement methods for Sweden, Norway, and Finland. 65th Eastern Snow Conference, Fairlee (Lake Morey), Vermont, 28–30 May 2008

McGonigle DF, Burke SP, Collins AL, Gartner R, Haft MR, Harris RC, Haygarth PM, Hedges MC, Hiscock KM, Lovett AA (2014) Developing Demonstration Test Catchments as a platform for transdisciplinary land management research in England and Wales. Environ. Sci.: Processes Impacts, 2014 (16): 1618–1628

McMillan H, Krueger T, Freer J (2012) Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality. Hydrol Process 26(26):4078–4111

Met Office (2010) National Meteorological Library and Archive: Fact Sheet 17 – Weather observations over land (Version 01). Met Office, Exeter

Mishra AK, Coulibaly P (2009) Developments in hydrometric network design: a review. Rev Geophys 47:RG2001

Monteith J L (1965) Evaporation and Environment. In The State and Movement of Water in Living Organisms (Ed. Fogg G E), Symp. Soc. Exper. Biol., Vol. 19: 205–234, Academic Press, New York

Muste M, Fujita I, Hauet A (2008) Large-scale particle image velocimetry for measurements in riverine environments. Water Resour Res 44(W00D19). doi: 10.1029/2008WR006950

Nitu R, Wong K (2010) CIMO survey on national summaries of methods and instruments for solid precipitation measurement at automatic weather stations. Instruments and Observing Methods Report No. 102. WMO/TD No.1544, Geneva

NOAA (2010) Flash flood early warning system reference guide. University Corporation for Atmospheric Research, Denver

NOAA/GLERL (2015) Real-time Coastal Observation Network (ReCON). Information sheet, Great Lakes Environmental Research Laboratory, Ann Arbor

NOAA/NWS (2012) Flood Warning Systems Manual. National Weather Service, US Department of Commerce, Washington DC

Owen GJ, Perks MT, Benskin C McW, Wilkinson ME, Jonczyk J, Quinn PF (2012) Monitoring agricultural diffuse pollution through a dense monitoring network in the River Eden Demonstration Test Catchment, Cumbria, UK. Area, 44(4), 443–453

Pappenberger F, Matgen P, Beven KJ, Henry J-B, Pfister L, de Fraipont P (2006) Influence of uncertain boundary conditions and model structure on flood inundation predictions. Adv Water Resour 29:1430–1449

Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London, Series A, 193: 120–145

Petersen-Øverleir A, Soot A, Reitan T (2008) Bayesian rating curve inference as a streamflow data quality assessment tool. J Water Resour Manag 23(9):1835–1842

Rasmussen R, Baker B, Kochendorfer J, Myers T, Landolt S, Fisher A, Black J, Theriault J, Kucera P, Gochis D, Smith C, Nitu R, Hall M, Cristanelli S, Gutmann E (2010) The NOAA/FAA/

NCAR Winter Precipitation Test Bed: how well are we measuring snow? Paper 8-4-10, TECO-2010 - WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation, Helsinki, 30 August –1 September
Røhr PC, Husebye S (2005) Flood forecasting technology in Norway, innovation and advances. ACTIF International Conference on Innovation Advances and Implementation of Flood Forecasting Technology, Tromsø, Norway, 17–19 October 2005
Sauer VB, Meyer RW (1992) Determination of error in individual discharge measurements, USGS open file Report 92–144
Schaefer GL, Paetzold RF (2000) SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network). Paper presented at Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives, Lincoln, NB, March 2000
Schaefer GL, Cosh MH, Jackson TJ (2007) The USDA Natural Resources Conservation Service Soil Climate Analysis Network (SCAN). Journal of Atmospheric and Oceanic Technology, 24(12): 2073–2077
Sene (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht, 386pp
Shunlin L (Ed.) (2008) Advances in Land Remote Sensing System, Modeling, Inversion and Application. Springer, Dordrecht
Stewart K (2009) Trends and Developments in Stormwater & Floodplain Management. Annual UDFCD Seminar, 24 February 2009, Denver, Colorado
Stoianov I, Nachman L, Madden S (2007) PIPENET: a wireless sensor network for pipeline monitoring. 6th International Symposium on Information Processing in Sensor Networks, Cambridge, MA, 25–27 April 2007
UNEP (2005) Operational Guide for Data Submission Version 4. United Nations Environment Programme Global Environment Monitoring System/Water Programme
UNEP/WHO (1996) Water Quality Monitoring – A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes (Eds. Bartram J, Balance R). Published on behalf of United Nations Environment Programme and the World Health Organization
USACE (1996) Hydrologic aspects of flood warning-preparedness programs. US Army Corps of Engineers Report ETL 1110-2-540, Office of Chief of Engineers, Washington, DC
Volkmann THM, Lyon SW, Gupta HV, Troch PA (2010) Multicriteria design of rain gauge networks for flash flood prediction in semiarid catchments with complex terrain. Water Resour Res, 46:W11554
Wagner W, Blöschl G, Pampaloni P, Calvet J-C, Bizarri B, Wigneron J-P, Kerr Y (2007) Operational readiness of microwave remote sensing of soil moisture for hydrologic applications. Nord Hydrol 38(1):1–20
White AB, Colman B, Carter GM, Ralph FM, Webb RS, Brandon DG, King CW, Neiman PJ, Gottas DJ, Jankov I, Brill KF, Zhu Y, Cook K, Buehner HE, Opitz H, Reynolds DW, Schick LJ (2012) NOAA's rapid response to the Howard A. Hanson Dam flood risk management crisis. Bull Am Meteor Soc 93(2):189–207
WMO (1992) Snow cover measurements and areal assessment of precipitation and soil moisture. Operational Hydrology Report No. 35. WMO-No. 749, Geneva
WMO (1994) An overview of selected techniques for analysing surface water data networks, Operational Hydrology Report No. 41, WMO-No. 806, Geneva
WMO (2005) WHYCOS Guidelines: Hydrological Information Systems for Integrated Water Resources Management. WMO/TD-No. 1282, Geneva
WMO (2008a) Guide to Hydrological Practices, Volume I: Hydrology – From Measurement to Hydrological Information, WMO-No. 168, 6th edition, Geneva
WMO (2008b) Technical Regulations – Volume III – Hydrology. 2006 ed., Suppl. No. 1 (I.2008), Geneva
WMO (2009) Guide to Hydrological Practices, Volume II: Management of Water Resources and Application of Hydrological Practices, WMO-No. 168, 6th edition, Geneva

WMO (2010) Manual on Stream Gauging. Volume I – Fieldwork, Volume II – Computation of discharge. WMO-No. 1044, Geneva
WMO (2011) Manual on Flood Forecasting and Warning. WMO-No. 1072, Geneva
WMO (2013) Planning of Water Quality Monitoring Systems. WMO-No. 1113, Geneva
WMO (2015) International Glossary of Hydrology. WMO No. 385, Geneva
Xu K, Zhang J, Watanabe M, Sun C (2004) Estimating river discharge from very high-resolution satellite data: a case study in the Yangtze River, China. Hydrological Processes, 18(10): 1927–1939
Zakharova EA, Kouraev AV, Cazenave A, Seyler F (2005) Amazon discharge estimated from TOPEX/Poseidon altimetry. Comptes Rendus Geosciences, 338: 188–196
Zreda M, Shuttleworth WJ, Zeng X, Zweck C, Desilets D, Franz T, Rosolem R (2012) COSMOS: the COsmic-ray Soil Moisture Observing System. Hydrol. Earth Syst. Sci., 16: 4079–4099

Chapter 4
Meteorological Forecasting

Abstract Meteorological forecasts offer the potential to extend the time available for decision-making in hydrological applications. In addition to the general weather forecasts provided to the public, a range of more specialised products and services are usually available, including the raw forecasting model outputs if required. Examples include ensemble rainfall forecasts for flood forecasting and water supply applications, seasonal forecasts for drought and agricultural applications and air temperature forecasts for snowmelt and demand forecasting. The main meteorological forecasting techniques consist of nowcasting, Numerical Weather Prediction and statistical methods, and this chapter provides an introduction to these approaches. The related topics of data assimilation, forecast verification and post-processing of outputs are also discussed.

Keywords Quantitative Precipitation Forecasts • Nowcasting • Numerical Weather Prediction • Statistical techniques • Downscaling • Post-processing • Data assimilation • Forecast verification

4.1 Introduction

Meteorological forecasts play a key role in many aspects of the hydrological forecasting process. The types of outputs which are potentially of interest include rainfall forecasts – which are often known as Quantitative Precipitation Forecasts (QPF) – and forecasts for a range of other parameters, including air temperatures, wind speeds and humidity. The main forecasting techniques include:

- Nowcasting – short-range local or regional forecasts based on extrapolating the current motion of storms, clouds, fog and other features, typically based on weather radar or satellite observations
- Numerical Weather Prediction (NWP) – physically based models for mass, momentum and energy exchange in the atmosphere at a local (limited-area), regional or global scale; in climate studies, these are typically called General Circulation Models (GCMs)

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- Statistical Methods – techniques which use regressions and other statistical approaches to estimate future conditions, particularly for longer-range forecasts

As indicated, forecasts are often described as short-range, medium-range or long-range where, with current techniques, lead times of 0–3 days, 3–10 days (or 3–15 days) and 10–15 days or more are typically quoted. For example, the World Meteorological Organisation (WMO 2012a) defines the following meteorological forecasting ranges:

- Nowcasting (current conditions and 0–2 h)
- Very short-range (up to 12 h)
- Short-range (12–72 h)
- Medium-range (72–240 h)
- Extended-range (10–30 days)
- Long-range (30 days–2 years)

Table 4.1 lists some key characteristics for the types of atmospheric features which may need to be considered. Some relevant spatial scales include the microscale, mesoscale and macroscale, where one definition of mesoscale (AMS 2015) is that it is:

> Pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes.

In contrast, some examples of phenomena at the micro- and macro-scales include tornadoes and cloud physical processes and cyclonic and frontal systems.

A general consideration is that larger-scale features such as fronts are generally more predictable than shorter-lived smaller-scale features such as thunderstorms (e.g. Fig. 4.1). Also for a given type of phenomenon, the predictability usually decreases with increasing lead time; for example, for a thunderstorm, it may only be possible to provide meaningful estimates of rainfall an hour or so ahead.

In recent decades, one major improvement in forecasting capability has arisen from the routine use of ensemble techniques in numerical weather prediction. This approach has been developed since, due to the non-linear and chaotic nature of atmospheric processes, small differences in model initial conditions often lead to significantly different outcomes, as illustrated in Fig. 4.2. The aim is to help to assess the uncertainty in forecasts, particularly for extreme events and at longer lead times, as a guide to decision-making. For example, Inness and Dorling (2013) note that three advantages of running an ensemble…'are that:

- The ensemble mean is, on average, a more skillful forecast than any single deterministic forecast
- The ensemble spread gives an indication of the predictability of the atmosphere
- The availability of an ensemble of forecasts allows the generation of probability-based forecasts'

Indeed, it is widely held that for some types of event such as thunderstorms and in seasonal forecasting, it is only meaningful to provide information in probabilistic

Table 4.1 Some examples of atmospheric features

Feature	Description (NOAA/NWS 2015)
Extratropical cyclone	A cyclone in the middle and high latitudes often being 2000 kilometers in diameter and usually containing a cold front that extends toward the equator for hundreds of kilometers
Front	A boundary or transition zone between two air masses of different density and thus (usually) of different temperature. A moving front is named according to the advancing air mass e.g. cold front if colder air is advancing
Intertropical convergence zone (ITCZ)	The region where the northeasterly and southeasterly trade winds converge, forming an often continuous band of clouds or thunderstorms near the equator
Jet stream	Relatively strong winds concentrated in a narrow stream in the atmosphere, normally referring to horizontal, high-altitude winds. The position and orientation of jet streams vary from day to day. General weather patterns (hot/cold, wet/dry) are related closely to the position, strength and orientation of the jet stream (or jet streams). A jet stream at low levels is known as a low-level jet
Mesoscale convective system	A complex of thunderstorms which becomes organised on a scale larger than the individual thunderstorms and normally persists for several hours or more. MCSs may be round or linear in shape and include systems such as tropical cyclones, squall lines and MCCs (among others). MCS often is used to describe a cluster of thunderstorms that does not satisfy the size, shape or duration criteria of an MCC (*MCC = Mesoscale Convective Complex*)
Monsoon	A thermally driven wind arising from differential heating between a land mass and the adjacent ocean that reverses its direction seasonally
Thunderstorm	A local storm produced by a cumulonimbus cloud and accompanied by lightning and thunder
Tropical cyclone	A warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters with organised deep convection and a closed surface wind circulation about a well-defined center

terms (e.g. Troccoli et al. 2008; Stensrud et al. 2009; WMO 2012b). As noted in Chap. 1, probabilistic approaches are increasingly used in hydrological applications, often with ensemble rainfall and air temperature forecasts as inputs.

The first operational ensemble forecasting systems became available in the late 1980s and early 1990s (e.g. Molteni et al. 1996; Toth and Kalnay 1997). This approach is now standard practice both in operational weather forecasting and climate projections, and typically about 10–50 scenarios are provided for future conditions. Modelling uncertainties are also increasingly considered; for example, due to the finite model grid resolution, or uncertainties in the lateral boundary conditions and/or model parameters (e.g. Persson 2013).

Part of the value of ensemble approaches is the wide range of outputs available showing different aspects of the forecast; for example, within the WMO Severe Weather Forecasting Demonstration Project (see Chap. 1), the recommended probabilistic forecast products to be issued from global centres to other centres include (WMO 2010a):

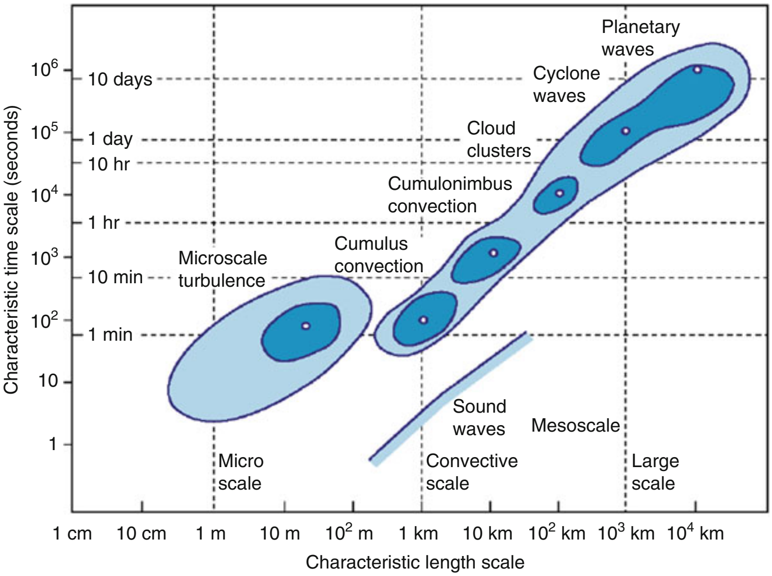

Fig. 4.1 A schematic illustration of the relationship between atmospheric scale and timescale. The typical predictability is currently approximately twice the timescale, but might ultimately be three times the timescale (Persson 2013; Source ECMWF)

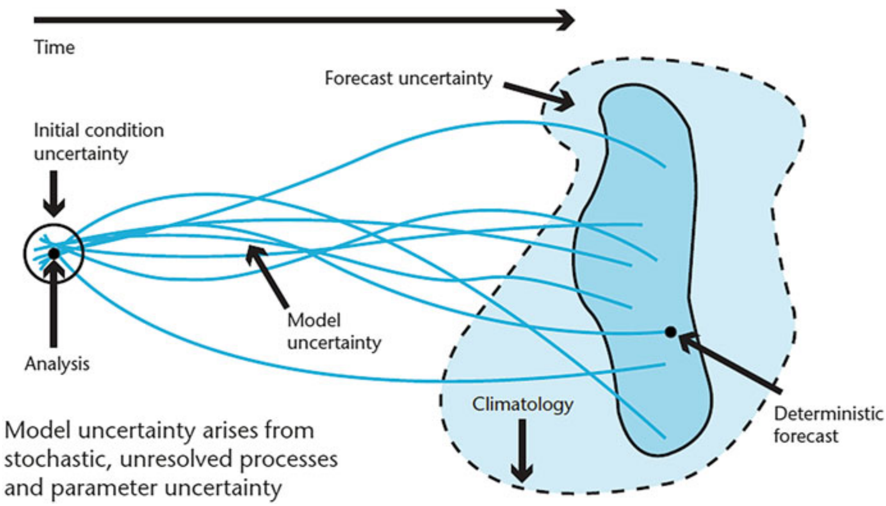

Fig. 4.2 Concept of an Ensemble Prediction System and the various sources of uncertainty that need to be represented (Met Office 2010; contains public sector information licensed under the Open Government Licence v1.0)

- Probability of severe weather events such as precipitation and wind higher than given thresholds
- 'Spaghetti' plots (e.g. 500 hPa geopotential height in extra-tropics, precipitation and wind higher than given thresholds)
- Stamp maps (e.g. streamlines in the tropics, wind speed, accumulated precipitation)
- Dispersion diagrams (plumes and EPSgrams) for weather elements at specific locations
- Representative members of a classification of weather pattern such as clustering or tubing (optional product depending on possibilities of Global Centre)
- Severe weather risk index such as Extreme Forecast Index (where available)

Here the Extreme Forecast Index is based on a comparison of the current model outputs with probability distributions based on the so-called model climatology – obtained from a reforecasting exercise – for the same location, time of year and lead time (e.g. Persson 2013). If severe weather is likely to be associated with a Tropical Cyclone, then other relevant products may be included such as charts showing the formation probability and, once formed, the position, track and strike probability.

More generally, the lead times at which forecasts show skill are constantly improving, and model resolutions are nowadays much closer to the scales of interest in hydrological forecasting. Some key contributing factors have been developments in the following areas:

- Computing Power – general increases in processor power and the use of parallel and distributed processing techniques (with some of the world's fastest supercomputers being used in operational weather forecasting)
- Model Initialisation – improved techniques for the assimilation of ground-based, upper air, satellite and ocean observations into model runs and increasing use of weather radar observations
- Atmospheric Processes – increased understanding and representation of key processes, in particular at smaller scales, and of land-atmosphere and ocean-atmosphere interactions

For example, since the 1990s, the typical horizontal grid scales for local and regional models have reduced from values of the order of 10–25 km to 1–4 km. Figure 4.3 shows an example of the benefits of these higher resolutions based on post-event simulations of a major storm in northwest England during January 2005. The improved representation of the rainfall distribution is very apparent, and a 1.5 km grid scale model has subsequently been implemented operationally for the whole of the UK.

In addition to a public weather forecasting service – delivered via television, radio, websites and other media – most meteorological services offer a range of more specialised products for specific applications. Often some post-processing is applied to adjust the outputs to better represent conditions at the site(s) of interest, typically using statistical, weather-matching or dynamical techniques. Some users may also require direct delivery of the outputs for input to their own systems which, in hydrology, might include flood forecasting systems and decision support tools to help with reservoir and hydropower operations.

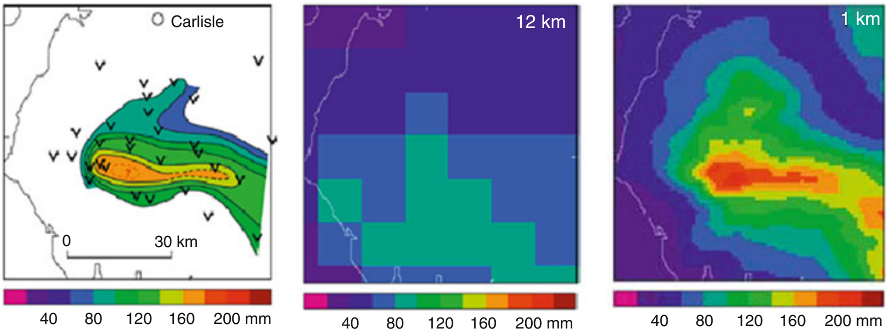

Fig. 4.3 Comparison of observed values and hindcasts at a 12 and 1 km resolution using the Met Office Unified Model for a major rainfall event in northwest England in January 2005 which resulted in flooding to almost 2,000 properties in the city of Carlisle (Cabinet Office 2008, © Crown Copyright 2008, the Met Office)

In this regard, as discussed in Chap. 1, another key development has been a move towards implementing so-called unified or seamless forecasting systems (e.g. Shapiro et al. 2010; Brown et al. 2012). These aim to provide products which are consistent across the full range of spatial scales and lead times, in both deterministic and ensemble form. For example, in some meteorological services, this has led to an increasing convergence between the dynamical cores in General Circulation Models and operational weather forecasting models.

This chapter provides a general introduction to these various topics, at an introductory level, with a focus on the types of information typically required in hydrological applications. Section 4.2 discusses the main techniques which are used operationally, and Sect. 4.3 describes a range of practical considerations such as forecast delivery mechanisms and post-processing and forecast verification techniques. More detailed information can be found in the references which are cited and in the many guidelines and books on these topics including WMO (2000), Kalnay (2002), Stensrud (2007), Troccoli et al. (2008), Markowski and Richardson (2010), Inness and Dorling (2013) and Palmer and Hagedorn (2006).

4.2 Forecasting Techniques

4.2.1 Nowcasting

Nowcasting techniques aim to extrapolate the motion of atmosphere features such as fog banks and storms based on recent observations. Although often associated with weather radar applications, similar techniques are used in satellite-based forecasting. Nowcasting was one of the earliest meteorological forecasting techniques although the original manually based approaches have largely been superseded by automated and computer-aided techniques. Compared to numerical weather prediction models, a key advantage is the reduced computing time required, allowing outputs to be updated more frequently such as every 5 or 15 min.

When based on weather radar observations, the objective is usually to estimate how areas of precipitation might move and develop in the next few hours. The lead times at which forecasts show skill depend on factors such as the type of storm, topographic influences, the calculation procedure and the underlying resolution of the radar observations, which is typically in the range 1–5 km (see Chap. 2). Maximum useful lead times of up to 6–8 h ahead are sometimes quoted for widespread storms although values are usually considerably less for convective events such as thunderstorms. Indeed, due to the challenges in thunderstorm recognition and forecasting, some systems allow forecasters to manually adjust convergence boundaries and other features to help improve model outputs (e.g. Hering et al. 2008; Deslandes et al. 2008; Halmevaara et al. 2010; Roberts et al. 2012).

The earliest approaches to radar nowcasting were based on simple advection or extrapolation of rainfall, in which areas of rainfall were translated based on current speeds and directions of travel. However, the latest techniques make use of a wide range of additional sources of information such as the outputs from numerical weather prediction models and lightning and satellite observations (e.g. Wilson et al. 2010; WMO 2010b). Probabilistic approaches are increasingly used; for example, using weather-matching (Panziera et al. 2011) or scale-decomposition techniques (see Box 4.1).

Figure 4.4 shows an idealised comparison of an extrapolation-only approach with a more detailed approach combining nowcasts with the outputs from a numerical weather prediction model. The example is for the case of a single storm cell approaching a town. The location of the storm is shown for the current time (time-now)

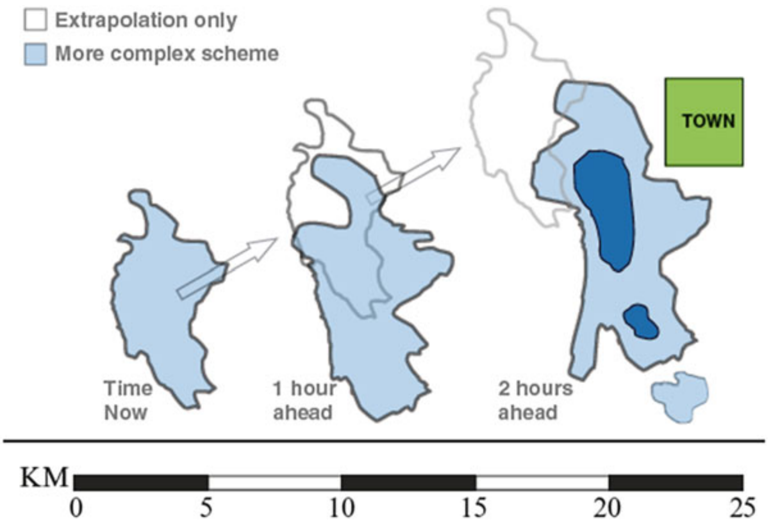

Fig. 4.4 Illustration of two approaches to nowcasting; simple extrapolation and a more complex scheme making use of Numerical Weather Prediction model outputs (Adapted from Sene 2013)

and for the forecasts for 1- and 2-h ahead. For the simplest case (advection only), only minor rainfall would be forecast, whilst the more complex approach anticipates both the change in the path of the storm as it approaches the town and the development of some more intense areas of rainfall. Of course, this is a simplification of how advection-based schemes operate, and many algorithms improve upon this simple translation of outputs using a range of statistical, cell-tracking, fuzzy logic and other approaches (e.g. Browning and Collier 1989; Wilson 2004).

When numerical weather prediction model outputs are included, most algorithms are designed so that their contribution increases at longer lead times, as the information content of the observations decreases. Indeed, nowcasting is increasingly viewed as a form of post-processing of model outputs, helping to provide more detail at short lead times than is possible with current modelling approaches. For example, Sun et al. (2014) note that:

> The use of NWP for nowcasting precipitation will experience continued rapid development in the decades to come. While the traditional nowcasting techniques will continue to be developed, they will more and more depend on the short-term high-resolution NWP that is initialized by radar observations. The combination of the two techniques….will be the key to producing seamless nowcasting that takes advantage of both techniques. With the continued improvements of high-resolution data assimilation, numerical modeling with rapid cycles, and computation efficiency, it is anticipated that the precipitation nowcasting skill by NWP will continue to be improved, giving an increased weight in the blended nowcasting. The greatest challenges are to skillfully handle the predictability issue that is scale dependent, to improve mesoscale observations especially in the lower levels, and to produce initial conditions that are dynamically balanced at the mesoscale and convective scale.

Similar techniques are used in nowcasting based on satellite observations. For example, the widely used Hydro-Nowcaster product, produced by the NOAA/NESDIS Center for Satellite Applications and Research, determines the motion of cloud clusters from consecutive infrared images and then extrapolates these areas out to lead times of 3 h at 15 min intervals (Scofield et al. 2004). Estimates for growth and decay are obtained from observations of changes in the mean temperature and minimum temperature (at a pixel level) within each cluster and changes in the extent of cloud clusters between successive images. These types of technique provide a useful addition to radar-based nowcasting products and are sometimes used for short-range rainfall forecasting in regions without weather radar networks.

Box 4.1: Short-Term Ensemble Prediction System (STEPS)

STEPS is a probabilistic nowcasting technique which was developed jointly by the Met Office in the UK and the Bureau of Meteorology in Australia (Bowler et al. 2006; Pierce et al. 2005; Seed et al. 2013). The system became operational in the UK in 2008 (for single scenario – deterministic – forecasts) and in 2009 (for ensemble forecasts) and replaced an earlier deterministic nowcasting approach (Nimrod) which had been used since the late 1990s (Golding 2000).

(continued)

Box 4.1 (continued)

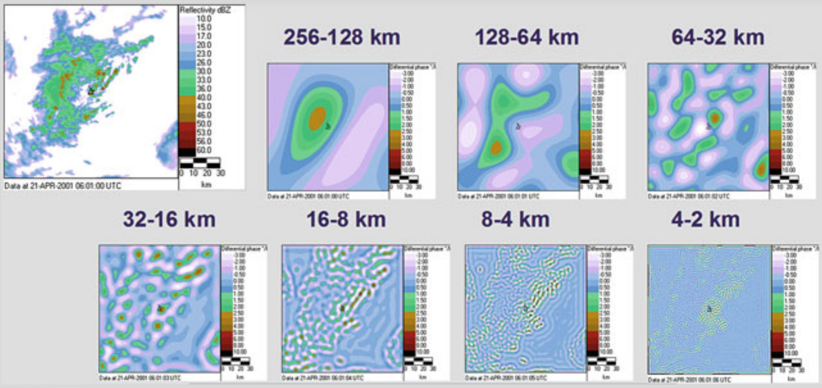

Fig. 4.5 Comparison of a STEPS cascade decomposition with the original radar inferred precipitation field (*top-left*) (© Australian Bureau of Meteorology)

Products based upon the following forecast configurations are currently generated: 2 km resolution, control member (unperturbed) nowcasts and short-range forecasts of rain rate with ranges of 7 h and 32 h, respectively, and associated 24 member ensembles. Accumulation products for a range of accumulation periods are generated from these. Nowcasts are updated on a 15-min cycle and short-range forecasts on a 6-h cycle. All configurations combine a radar-based extrapolation nowcast of rain rate with short-range, NWP-based ensemble precipitation forecasts of the same quantity. The latter are generated by a state-of-the-art, convection-permitting, dynamically downscaled configuration of the Met Office Global and Regional Ensemble Prediction System (Golding et al. 2014) known as MOGREPS-UK.

The STEPS approach acknowledges that precipitation fields exhibit scaling properties in both space and time (dynamic scaling). These imply that precipitation fields exhibit important sources of variability over a wide range of spatial scales and that the predictability of precipitation features increases non-linearly with their size. Consequently, the evolution of a field of instantaneous rain rate can be modelled effectively using a cascade framework (Fig. 4.5). Such a framework enables a field of rain rate to be decomposed into a hierarchy of component fields representing the variability in the original field over a discrete set of spatial scales. This allows STEPS to model the scale-dependent loss of predictive skill in an extrapolated radar inferred precipitation field (a nowcast) and a corresponding Numerical Weather Prediction (NWP) model forecast of precipitation. In this way, an optimal combination of these model forecast components can be produced in which

(continued)

Box 4.1 (continued)
features at scales lacking skill are replaced by synthetically generated precipitation (noise) with appropriate statistical properties.

In operational use in the UK (Fig. 4.6), STEPS blends extrapolated precipitation observations from a network of C-band weather radars (mosaic) with ensemble NWP forecasts from the Met Office's Unified Model. The model domain has horizontal dimensions of 1096 km (east–west) × 1408 km (north–south).

Unlike many operational precipitation nowcasting tools, STEPS can generate an ensemble of equally likely observation and forecast realisations by accounting for significant sources of uncertainty. These include uncertainties in the radar inferred distribution of rain rate and uncertainties in the evolution of the two model forecast components. Uncertainties in the evolution of the extrapolation nowcast are modelled by considering errors in the apparent motion and Lagrangian evolution (the evolution in a reference frame moving with the precipitation) of the radar inferred precipitation field separately.

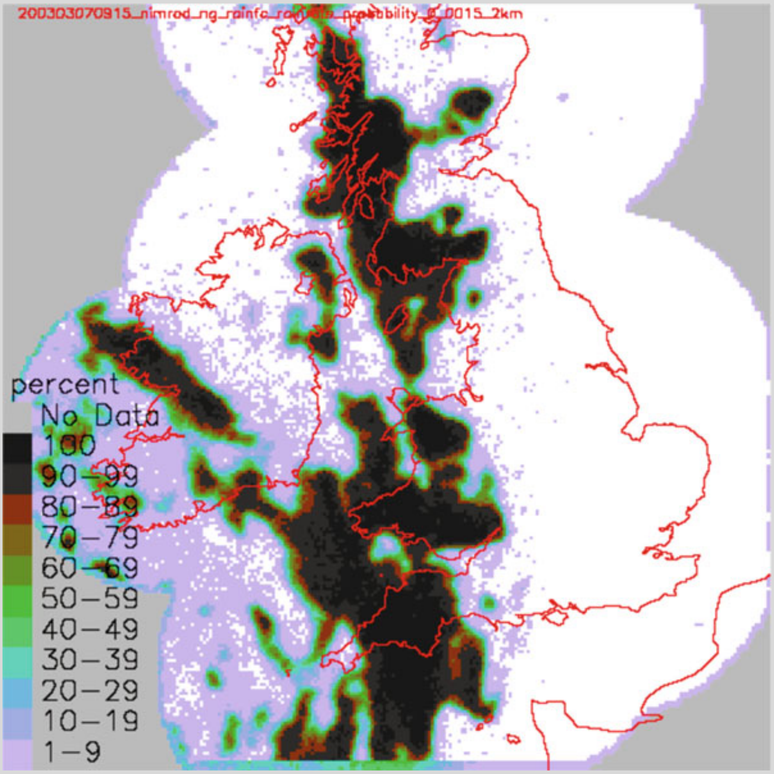

Fig. 4.6 Example of a STEPS probability of precipitation outputs; semicircular boundaries indicate the extent of coverage for the UK and Ireland weather radar network (© Crown Copyright 2009, the Met Office)

(continued)

Box 4.1 (continued)

The apparent motion of the observed precipitation is derived using an optical flow method (Bowler et al. 2004) and two time sequential fields of radar inferred precipitation. The temporal evolution of the precipitation is modelled using a hierarchy of second-order autoregressive models. Since estimates of both the apparent motion and Lagrangian temporal evolution of the observations are subject to error, the associated uncertainty is represented in the ensemble by perturbing the motion field and precipitation field with noise.

Each member of a STEPS ensemble forecast is a weighted blend of the extrapolation forecast, NWP forecast and noise. The weight assigned to the two model forecast components is based upon estimates of their skill. In the very short range, these are determined by comparison with a recent radar inferred precipitation field. Current skill estimates relax to climatological estimates based upon a 20-day rolling climatology. Since larger-scale precipitation features tend to be most predictable, the weights applied to the model forecast components will increase with increasing scale. The noise tends to dominate the convective scales after a few time steps because neither the extrapolation nowcast nor MOGREPS-UK forecast possess significant skill at these averaging scales. Noise is added to the blend to preserve the variance on each level of the cascade and ensures that the statistical properties of the blended forecasts closely follow those of the radar in the first 2 h and those of the appropriate MOGREPS-UK ensemble member thereafter.

Verification (Seed et al. 2013) suggests that the blending methodology employed to combine the extrapolation nowcast and a given NWP forecast is near optimal. Ensemble verification statistics show that STEPS ensembles exhibit skill in terms of both reliability and resolution. Current research is considering topics such as the performance for more extreme (higher rainfall rate) events, improving the matching between observed and forecast distributions of rainfall rates, and techniques for improving the representation of observation error in STEPS.

4.2.2 Numerical Weather Prediction

Numerical weather prediction models are usually operated by national meteorological services. In addition to precipitation forecasts, model outputs of hydrological interest typically include forecasts for core (prognostic) variables such as air temperature, humidity and wind speeds and secondary (diagnostic) variables such as soil moisture conditions and snow cover.

A typical configuration is to use a local or limited area model for the location of interest, nested within a lower-resolution regional- and/or global-scale model. Chapter 1 shows an example of this approach. The global-scale model provides lateral boundary conditions to the regional-scale model (if used), which in turn provides boundary conditions to the limited area model.

Although not every meteorological service has this capability, many operate limited area or regional models tailored to local needs. In contrast, global-scale models tend to be operated by a smaller number of specialised centres; for example, WMO has designated a number of Global Producing Centres (GPCs) for long-range forecasts, and these are summarised in Table 4.2.

In addition, several regional specialised meteorological centres have been established for tropical cyclone forecasting (WMO 2015). These include centres in La Réunion off the southeast coast of Africa, Fiji, Honolulu, Miami, New Delhi and Tokyo, plus tropical cyclone warning centres in Australia and New Zealand. Other activities include providing advice on raising public awareness of the risks from cyclones, the design of warning messages, performing risk and hazard assessments and on disaster risk reduction measures. These centres also allocate names to storms as they develop, based on an intentionally agreed list; some examples referred to in later chapters include Typhoon Morakot and Hurricane Katrina.

In general terms, each run of a numerical weather prediction model usually involves the following key steps:

- Data processing – validation and analysis of data from a wide range of sources, including ground-based stations, aircraft, ships, ocean buoys, radiosondes and satellites

Table 4.2 WMO Global Producing Centres of long-range weather forecasts (see http://www.wmo.int for the latest updates)

Country	Organisation	Location
Australia	Bureau of Meteorology	Melbourne
Brazil	Center for Weather Forecasts and Climate Studies/National Institute for Space Research	Sao Paulo
Canada	Meteorological Service of Canada	Montreal
China	China Meteorological Administration/Beijing Climate Centre	Beijing
France	Météo-France	Toulouse
Japan	Japan Meteorological Agency/Tokyo Climate Centre	Tokyo
Korea	Korea Meteorological Administration	Seoul
Russia	Hydrometeorological Centre of Russia	Moscow
South Africa	South African Weather Service	Pretoria
UK	Met Office	Exeter
USA	Climate Prediction Centre/National Oceanic and Atmospheric Administration	Washington
International	European Centre for Medium-Range Weather Forecasts (ECMWF) (supported by 34 Member States)	Reading, UK

- Data assimilation – initialisation of model runs based on recent and current observations and the outputs from the previous model run
- Model runs – operation of the model, or suite of models, often performing multiple runs to obtain an ensemble of forecasts
- Post-processing/product generation – additional processing to improve forecast outputs and generate products for end users

As discussed in Chap. 2, the WMO Global Telecommunication System (GTS) is one of the main routes for data collection together with information from satellite operators and national networks.

Given the computational requirements, a balance is usually required between the model complexity and resolution, the number of ensemble members and the frequency of model runs. Coarser grid spacings therefore tend to be used for ensemble model runs and global-scale models. From a user's perspective, some key factors relating to model runs include the following items:

- Forecast production cycle – how often model runs are performed and the times, or intervals, at which products are made available
- Forecast length or range – the maximum lead time for which forecast outputs are provided for each product
- Forecast output intervals – the averaging periods or model output times included within each forecast product
- Ensemble outputs – the number of ensemble members

For example, a medium-range global-scale forecasting model might typically be operated every 6–12 h providing 20–50 ensemble members for up to 5–15 days ahead. In contrast, some of the latest high-resolution local models are operated every 1–3 h providing 10–20 ensemble members for up to 24–36 h ahead (e.g. Box 4.2).

Grid scales of 1–4 km are typical nowadays at a local or regional scale. In contrast, values of 10–20 km or more are typical for global-scale models (and 30–70 km for ensemble forms) and perhaps 50–200 km or more for the models used for decadal (10-year) or longer-term climate projections (see Chap. 13). Typically, the smallest atmospheric features which can be resolved without attenuation have wavelengths of the order of 3–5 grid lengths (e.g. Lean and Clark 2003; Persson 2013). In the vertical direction, between 20 and 100 layers are typical, usually with closer (terrain-following) spacing near to the land surface.

Although not visible to the user, most models run at a much more frequent internal model time step than that for which outputs are available. This is typically of the order of minutes both to ensure numerical stability and to represent the diurnal variations in conditions. It is also worth noting that spectral solution schemes are used in some global-scale models rather than a finite-difference approach. In this case, horizontal resolutions are described in terms of spectral harmonics; for example, a T799L91 model would have 91 vertical levels and 799 harmonics.

For the atmospheric component, a range of sub-grid processes normally needs to be represented as illustrated in Fig. 4.7 and Table 4.3. Parameterisation schemes are typically based on the findings from atmospheric special observation campaigns, simulations using process-based models and mathematical studies to derive approximate solutions. Generally, schemes need to be tuned to be consistent with the model resolution, and it may be possible to ‘switch off’ some components at smaller grid spacings if processes are modelled directly. For example, one significant development in recent years has been the introduction of non-hydrostatic models with grid scales of the order 1–2 km. This greatly improves the ability to model deep convective processes and topographic influences, and this type of model is often called a convection-permitting or convective-scale model.

The approach used for data assimilation is another distinguishing feature between models (e.g. Kalnay 2002; Park and Liang 2009), and Schlatter (2000) notes that ‘the four main challenges are:

- to generate an initial state for a computer forecast that has the same mass-wind balance as the assimilating model
- to deal with the common problem of highly non-uniform distribution of observations
- to exploit the value of proxy observations (of parameters that are not carried explicitly in the model)
- to determine the statistical error properties of observing systems and numerical model alike so as to give each information source the proper weight’

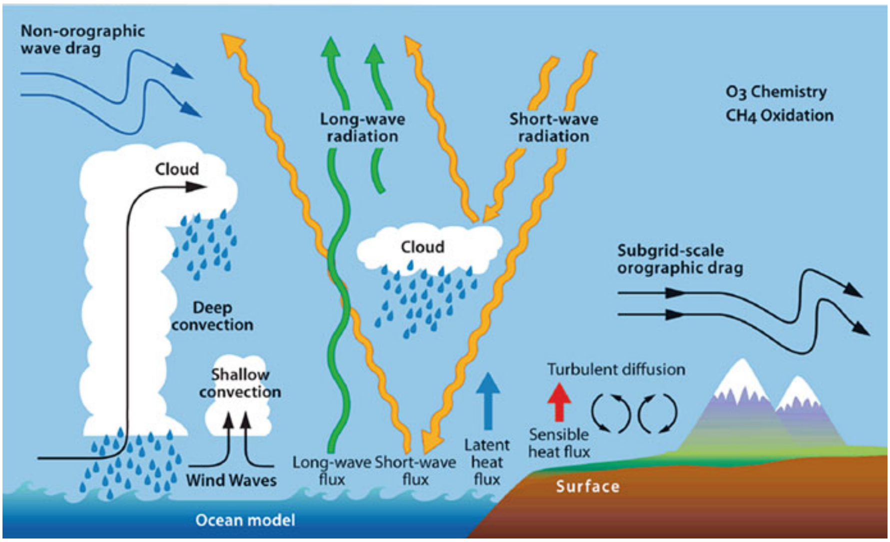

Fig. 4.7 Main physical processes represented in the ECMWF model (Source: ECMWF)

Table 4.3 Illustration of some typical sub-components in an atmospheric model

Item	Description
Cloud physics/ convection	Simplified models to represent – to varying degrees – processes such as uplift and descent, boundary layer turbulence, cloud top entrainment, precipitation (rainfall, snow, hail, ice), evaporation, radiative heat transfer, etc., typically distinguishing between different types of cloud, fog and precipitating and non-precipitating cloud and sometimes considering the influence of aerosols on radiation and heat transfer
Land-atmosphere interactions	Land-surface models including a mosaic of land, soil and vegetation types, often with several soil layers, and more dynamic parameters such as snow cover, linked to conceptual models for soil moisture storage and evapotranspiration processes (see Chap. 13)
Ocean-atmosphere interactions	Some models – particularly for longer-range forecasts – are coupled either fully or partially with an ocean model (which is often called a single-tier or two-tier approach). Typically in addition to representing ocean currents and heat exchange, the ocean component includes wave models to allow for the two-way interactions of the wind field and waves; for short-range forecasts, a simpler approach is to assume constant sea surface conditions for the duration of the model run
Orographic influences	Representation of topography by parameters such as orientation, aspect ratio, height, slope, etc. to estimate key influences on the wider circulation. More detailed representations are used in some local and mesoscale models
Radiative transfer	Models for influences at the land surface, absorption by aerosols, etc., and in particular the influence of water vapour and clouds on the radiation balance. Processes such as absorption, emissions and scattering of radiation are usually represented
Turbulence	First-order closure (eddy diffusivity) schemes, with separate advective treatment for convective clouds, which are increasingly being superseded by higher-order schemes and combined methods

Figure 4.8 illustrates the types of observations which are typically included in data assimilation schemes. Particularly in data-sparse areas, satellite observations play an increasingly important role, normally with direct assimilation of radiance values and making use of information on cloud types, extent and motion. For high-resolution models, the move to more rapid updates and smaller grid scales has also led to a need to consider new types of information such as radar reflectivity, radar refractivity, Doppler winds, GPS-based humidity and wind profiler observations (e.g. Benjamin et al. 2010; Dabberdt et al. 2005; Stensrud et al. 2009; Sun et al. 2014; Weckwerth et al. 2005).

Data assimilation is one of the most time consuming and complex aspects in operational weather forecasting and is often the limiting factor on the frequency of model runs. Extensive validation checks also need to be made on incoming data; for example, checking for temporarily blocked sites due to unreliable values and using advanced statistical techniques to compare records at nearby sites. For point observations, values also need to be distributed in a plausible way using so-called spreading and balance functions.

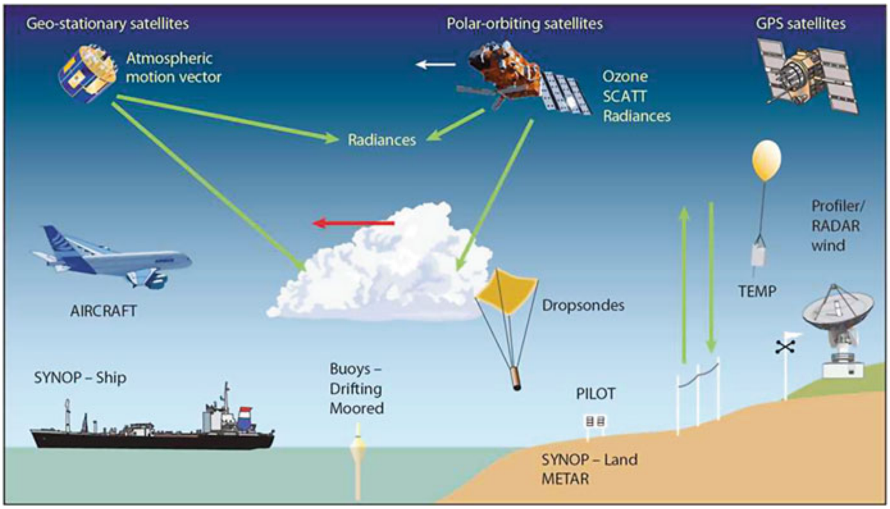

Fig. 4.8 Illustration of observations received at ECMWF for data assimilation (Source: ECMWF)

Some of the earliest operational approaches to data assimilation were optimal interpolation and then 3-D variational (3D-Var) schemes (Kalnay 2002). 3D-Var approaches are still widely used and involve the minimisation of an objective function (cost function) which takes account of the observed values and the short-range (background) forecast from the previous model run; the aim of the estimation process is being to progressively move the model state closer to the observations, without introducing spurious transient and other effects. However, this approach is increasingly being superseded by methods which allow for the differing times of observations such as the 4D-Var approach, where the 'fourth dimension' is time.

These general approaches are also used for long-range forecasting (e.g. Doblas-Reyes et al. 2005; Troccoli 2010; Troccoli et al. 2008) from weeks to months ahead. At longer timescales, the representation of ocean processes becomes more important although a general problem is usually the lack of direct information on surface and sub-surface conditions (temperature, currents, salinity, etc.) requiring more reliance on satellite observations. Forecast runs are usually performed at less frequent intervals, such as every week, so time constraints are less of an issue. This is a developing area however so these techniques are often supplemented by statistical methods, as described in the following section.

For decadal (10–30 year) and longer predictions, such as in climate change assessments, grid spacings of the order 50–200 km are typical, and again a fully coupled ocean component is essential. For this type of simulation, the functionality of the land-surface component is normally extended to represent additional mechanisms such as feedback influences between climate and vegetation. Additional or more detailed modelling components are usually included for aspects such as atmospheric chemistry and the carbon cycle. However, on account of the coarser grid scale, the representation of some atmospheric processes may be simplified, although as noted earlier there is an increasing trend to develop a seamless modelling approach across all timescales. Chapter 13 discusses climate modelling in more detail and the types of outputs obtained.

More generally, there is much debate within the meteorological research literature about where the next major steps forward in forecasting capability will come from (e.g. Shapiro et al. 2010, Brown et al. 2012). Whilst the move to convective scales has brought clear advantages and there may be benefits in further reductions in grid scale, some other options for development could include reducing the grid scales for ensemble forecasts and increasing the number of ensemble members. Other choices include improved model parameterisations, including process-based stochastic formulations, more frequent model runs, more vertical layers, and closer integration with the ocean component, particularly for short- to medium-range forecasts. Multi-model ensembles provide another option in which the outputs from several forecasting centres are combined (Park et al. 2008; Raftery et al. 2005).

The solutions are in part likely to vary depending on the features of interest and local climate. For example, whilst numerical models are increasingly good at forecasting the general circulation and track for tropical cyclones, other aspects such as the intensity and precipitation are more challenging to predict due to the strong pressure, wind and other gradients near to the core (e.g. Hamill et al. 2012; Sheng et al. 2005). This has led to the development of combined dynamical-statistical approaches which make use of the strengths of both approaches as discussed in the following section. However, rapid progress is being made in improving dynamical approaches (e.g. Gall et al. 2013) and in the use of multi-model consensus forecasts (e.g. DeMaria et al. 2014).

Box 4.2: Flash Flood Forecasting Research, Southern France

For flash flood forecasting applications, the latest generation of high-resolution Numerical Weather Prediction models offers a number of potential advantages. For example, the outputs are better able to represent features such as convective storms and orographic effects, which can strongly influence where and when flash floods occur. More detail is also provided on the spatial distribution of rainfall with outputs typically available at a grid resolution of 1–4 km.

Within Météo-France, a non-hydrostatic mesoscale model (AROME) has been used operationally since 2008 (Seity et al. 2011). In 2015, this evolved from a grid scale of 2.5 km to 1.3 km and provides hourly forecasts for lead times of up to 30 h ahead using a three hour data assimilation cycle. This forms part of an operational suite of models which includes the ARPEGE global model; the latter provides the lateral boundary conditions for the AROME model runs. In AROME, a 3D-Var mesoscale data assimilation scheme is used, including observations from radiosondes, automatic weather stations, wind profilers, weather radar (Doppler winds and reflectivity), GPS

(continued)

Box 4.2 (continued)

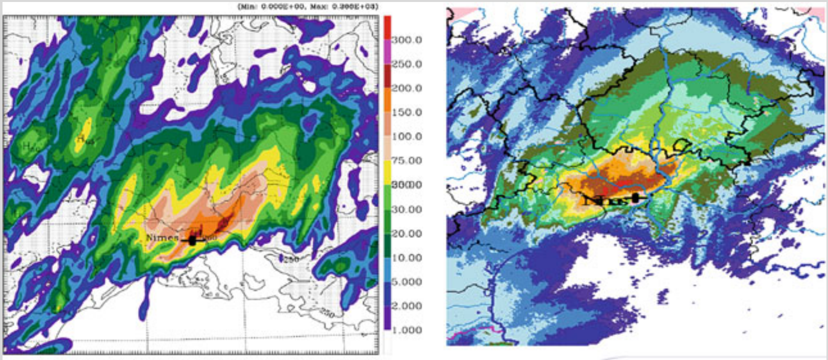

Fig. 4.9 Comparison of AROME and weather radar Quantitative Precipitation Estimates for the Gard flood event in 2002 (Carrière et al. 2011)

humidity sensors, buoys, ships, aircraft and satellites (Vincendon et al. 2011). For example, Fig. 4.9 compares observed values and hindcast estimates of rainfall for the Gard flash flood of 2002, which was one of the most catastrophic events in southern France in recent decades (Delrieu et al. 2005). A nowcasting-capable version is under development providing 12-h ahead forecasts every hour.

One particular use of AROME is for flash flood forecasting in the Cévennes-Vivarais area and the Var region of southern France. For this application, due to the uncertainties in precipitation forecasts, an ensemble forecasting approach offers a number of advantages. However, conventional approaches to the generation of ensembles are computationally intensive which can be a disadvantage in fast-evolving flash flood events. These considerations have led to the search for more computationally efficient methods which are also more focussed on the scale and types of storms likely to cause flash flooding. In particular, it is desirable to take advantage of (and preserve) the mesoscale features observed by weather radar and satellite, such as the spatial organisation of convective cells.

In one method under development in Météo-France, an object-based post-processing approach is used to identify storm cells and then to generate ensemble members based on their key characteristics. The initial stage in the procedure is to develop an error model describing the performance of the deterministic AROME model over a number of historical events in terms of the structure, location and amplitude of the precipitation field. For example, in comparisons with weather radar observations (Vincendon et al. 2011), it

(continued)

Box 4.2 (continued)

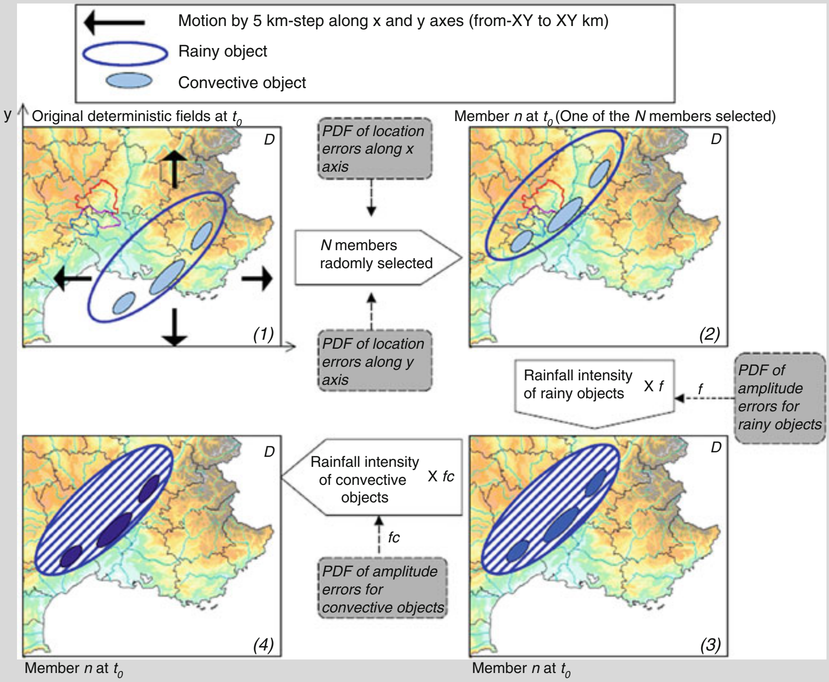

Fig. 4.10 Principle of the perturbation generation method at time *t* (Vincendon et al. 2011)

was found that thresholds of 2 and 9 mm h^{-1} could be used to delineate areas of rainfall and convective rainfall, respectively.

The ensemble members are then generated by sampling from the probability density function of location errors, with modifications for amplitude and rainfall distribution errors (Fig. 4.10); for example, generating 50-member ensembles allowing horizontal displacements of up to 50 km and amplitude factors of 0.5–1.5. A distributed hydrological modelling approach is then used to estimate flood flows. This couples the ISBA land-surface model (Noilhan and Planton 1989) and a version of TOPMODEL optimised for Mediterranean catchments (Pellarin et al. 2002); ISBA governs the overall budget among soil columns assuming more than 10 soil layers, while TOPMODEL computes the sub-surface lateral water fluxes and spatial and temporal dynamics of the saturated areas using the watershed topography (Bouilloud et al. 2010).

Hindcasting analyses for two events in southern France in 2008 (Vincendon et al. 2011) showed that the ensemble median value outperformed the flows estimated from the deterministic AROME forecasts. The object-based approach

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Box 4.2 (continued)

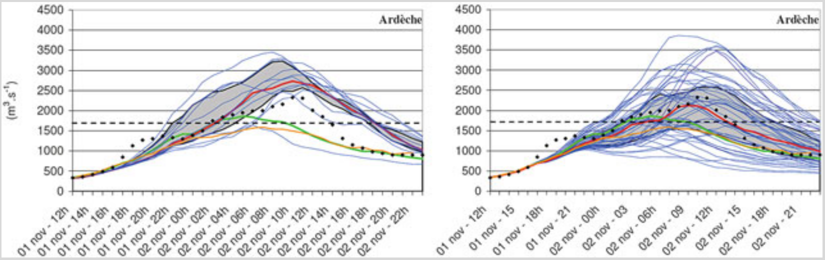

Fig. 4.11 Comparison of flood forecasts for the Ardeche at Vallon Pont d'Arc for an event on 2 November 2008 using an 11-member AROME ensemble and a 50-member ensemble derived using an object-based approach. The figures show the observed flows (*symbols*), ensemble median (*red line*), interquartile range (*shaded area*), deterministic forecast (*green line*), a forecast using radar rainfall observations (*orange line*) and the flood warning threshold level for this location (*dashed black line*) (Adapted from Vincendon et al. 2011)

also gave similar skill scores and other performance statistics to model runs using a more computationally intensive approach which takes account of the uncertainties in both initial and lateral boundary conditions (Vié et al. 2011). The ability to generate more ensemble members (50) than was possible with the more computationally intensive approach (11) also contributed to the performance improvements (e.g. Fig. 4.11). An object-oriented forecast verification technique (Wernli et al. 2008) was also used for evaluating the forecast performance in terms of the location, amplitude and structure of the precipitation field.

Current research includes evaluating the approach on more events, including observations made during special observation periods within the Hydrological Cycle in Mediterranean Experiment (HyMeX) project (Drobinski et al. 2014), also considering additional sources of uncertainty, such as in initial soil moisture conditions and the hydrological model parameters (e.g. Edouard et al. 2015). The model has also been used as a test bed for evaluating other perturbation schemes (e.g. Vie et al. 2012). Shorter-range X-band radars are also being evaluated to provide more detailed observations in areas where there are gaps in the national radar coverage and/or the data quality is poor (particularly in mountainous areas). In addition, the object-based approach is being combined into the rainfall forecasts of a convective-scale ensemble prediction system based on the AROME model (Bouttier et al. 2012; Nuissier et al. 2012) to fully sample rainfall forecasting uncertainty.

Adapted from Sene (2013)

4.2.3 Statistical Methods

Historically, the main approach to seasonal forecasting was through statistical techniques; for example, a widely cited early example is the approach developed by Sir Gilbert Walker in the early twentieth century for predicting the Indian Monsoon (Walker 1997).

The basis of these techniques is to select observed or derived parameters at the site(s) of interest such as air temperatures or cumulative rainfall and variables or indices for the phenomena believed to be the main influences. These relationships are often called teleconnections and, as might be expected, models of this type perform best in regions where it is possible to demonstrate statistically significant relationships between cause and effect. One potential limitation though is the assumption that the historical data are representative of future conditions (e.g. Goddard et al. 2001; Mason and Baddour 2008).

Statistical techniques are still widely used in long-range forecasting although as the science improves are increasingly being superseded or complemented by the outputs from numerical weather prediction models (e.g. Barnston et al. 2012; Scaife 2014; Troccoli 2010). For seasonal forecasting, predictors are often related to indices describing ocean phenomena such as the following examples:

- El Niño-Southern Oscillation (ENSO) – increases in sea surface temperatures (SST) in the eastern and central Pacific, over characteristic periods of 2–7 years, for durations of a few months or more, and cooler La Niña episodes (e.g. Barnston et al. 2012)
- Indian Ocean Dipole (IOD) – a phenomenon similar to and possibly linked to the El Niño-Southern Oscillation, with similar timescales, but occurring in the Indian Ocean from Africa to Australia and Indonesia (e.g. Manatsa et al. 2011; Saji et al. 1999)
- North Atlantic Oscillation (NAO) – a phenomenon linked to ocean surface conditions, which appears as an oscillation which can persist for several years in the relative positions and strengths of the permanent high-pressure region around the subtropical Atlantic (the Azores High) and the low pressure in Arctic regions (the Iceland Low) (e.g. Scaife 2014)

Table 4.4 lists some examples of indices relevant to these phenomena, whilst Chap. 1 provides more background on their characteristic features. Some other examples include the more complex Multivariate ENSO Index (MEI) together with indices for longer-term phenomena, such as the Pacific Decadal Oscillation (PDO).

The analyses are normally preformed using values averaged over periods of a month or more, and capital letters are often appended indicating the months used in the averaging process; for example, using 'JFM' to indicate the months of January, February and March. As in any modelling exercise, care needs to be taken to identify and correct or remove instrumental and other errors in the calibration records. Exploratory analyses using numerical weather prediction model outputs are sometimes performed to examine the likely reasons for, and likelihood of, any relationships which are hypothesised, or to derive additional (custom) indices based on model outputs.

Table 4.4 Some examples of indices used in statistical forecasting methods

Phenomenon	Abbreviation	Name	Description
El Niño-Southern Oscillation	Niño3.4	None	Averaged Pacific Sea Surface Temperature between 5°N and 5°S and 170°W and 120°W. Also the related Niño3 and Niño4 measures
	SOI	Southern Oscillation Index	Various indicators based on the normalised difference in mean sea level pressure between Tahiti and Darwen e.g. SOI, EQSOI
Indian Ocean Dipole	DMI	Dipole Mode Index	An index based on the difference in sea surface temperatures in the western and eastern Indian Ocean (50–70° E, 10°N–10°S and 90–110°E and 10°S and the equator)
North Atlantic Oscillation	NAO	North Atlantic Oscillation Index	Typically based on the normalised sea level pressure differences between observation stations in Iceland and the Azores, Lisbon or Gibraltar (or atmospheric model outputs)

In the early days, predictive equations were usually developed using single- or multiple-regression relationships. However, more advanced techniques include principal component, canonical correlation, redundancy and maximum covariance analyses. Typically, these approaches involve identifying spatial patterns or modes across the region of interest and then superimposing the outcomes to obtain the forecast (e.g. Mason and Baddour 2008). Related techniques include empirical orthogonal functions and wavelet banding approaches (e.g. Jury 2013; Van den Dool 2007; Webster and Hoyos 2004; Wilks 2011). Weather-matching or analogue techniques such as those discussed in Sect. 4.3 are sometimes used as well to help preserve the spatial consistency in outputs.

Some examples of the use of ENSO indices are presented in Chap. 13. More generally, as an illustration of the range of techniques used operationally, the following types were considered in a review of international capability in ENSO model predictions (Barnston et al. 2012): Markov, linear inverse, constructed analogue, Canonical Correlation Analysis, multiple-regression, neural network and multi-level regression models. In addition, 15 types of dynamic model were considered.

Regarding the influence of El Niño, the 1972/1973 and 1982/1983 ENSO events were probably the first to prompt major work on worldwide linkages, and development work was accelerated following the 1997/1998 event which was one of the most significant on record (see Chap. 1). Some significant findings to date (Harrison et al. 2008) are that, in general terms:

- The highest predictability of atmospheric temperatures and rainfall exists across the tropical ocean basins, in particular that of the Pacific, and over certain land areas within or immediately adjacent to those basins.
- Predictability tends to decrease further away from the Equator and from the oceans, although some areas, such as North America, are favoured in certain

seasons through enjoying higher predictability than similar regions at the same latitudes because of the manner in which teleconnections work in those areas.

- There is evidence that predictability in the global sense is higher during El Niño and La Niña events than otherwise and that in some regions, such as Europe, it may not exist at times other than during these 'window of opportunity' events (but equally may not necessarily be high during specific individual events).
- Temperature tends to be more predictable than rainfall.

As noted in the previous section, another application of statistical techniques is in tropical cyclone forecasting, such as for relating forecast intensity to other environmental variables. Outputs are usually probabilistic with, for example, the uncertainty represented by a forecast plume or cone of uncertainty for the projected track. To gain the advantages of both approaches, combined statistical-dynamical approaches are increasingly used which make use of statistical relationships linked to aspects of the model outputs in which there is more confidence, such as the large-scale circulation and storm track (e.g. DeMaria et al. 2014).

4.3 Operational Considerations

4.3.1 Forecast Delivery

Most meteorological services operate a public weather service. Forecasts are normally delivered via websites, television, radio, newspapers and – increasingly – using newer techniques such as social media and smartphone applications. Typically in larger centres, an around-the-clock service is operated with several forecasters rostered to be on duty at any one time.

Although some outputs are published automatically to websites, most products and services are based on guidance from senior forecasters. For example, Inness and Dorling (2013) note that this may 'include an overall summary of the forecast narrative, some indication of the consensus or disagreement between models from different centres and some guidance as to the uncertainty in the forecast'. Typically the factors taken into account include recent satellite, weather radar, lightning, surface and upper air observations, the views from other experts, synoptic conditions and the outputs from model runs. In some centres, particularly for thunderstorm forecasting, forecasters have the option to intervene in the forecasting process to improve the outputs.

If severe weather is forecast, then contingency arrangements are usually in place for discussions with civil protection and emergency response staff. Some typical mechanisms include phone or video conferences and web-based chat rooms, and temporary secondment of staff to multiagency control centres. Some meteorological and hydrological services have also established joint operation centres to permit closer collaboration between meteorologists and hydrologists, such as the Flood Forecasting Centre based in Exeter in the UK which is a partnership between the Met Office and the Environment Agency.

In particular, the role of the forecaster remains crucial for extreme events; for example, Persson (2013) notes that:

> The proportion of freely available, automatically generated weather forecasts has increased tremendously because of the expansion of the Internet. Such forecasts might satisfy needs during normal weather conditions but not in situations of extreme or high-impact weather. A decision to evacuate an area will never be made purely on the basis of automated NWP output nor is there, and might never be, one single source of NWP information with a concerted message, in particular in situations threatening extreme or high-impact weather.

For more specialised types of applications, bespoke products are usually developed in collaboration with key end users. At the simplest level, information might be provided in the form of situation reports, alerts or bulletins, as discussed further in Chap. 7 and later chapters. However, some meteorological services operate tools to help with interpreting impacts for given applications, with one example being the use of flash flood guidance techniques in the USA (see Chap. 9).

Increasingly, there is also a need to use forecasts directly as inputs to hydrological models in which case a real-time feed needs to be established to the hydrological service or centre. Some examples could include delivery of hourly ensemble rainfall forecasts for use in flood forecasting models or provision of nowcasts every 15 min for use in hydropower scheduling.

If this approach is adopted, some additional investment and organisational changes may be required. For example, this could include establishing a robust telecommunications link, specifying level of service agreements, and provision of training and documentation; also setting up an around-the-clock support facility, particularly to guard against the risk of power or telecommunications failures. For disaster risk management applications, increasingly this includes establishing a two-way flow of information regarding reports on current conditions from volunteers and staff on the ground; for example, via phone calls, smartphone applications, text messages and web-based tools.

If possible, a system of version control needs to be established so that users are aware of any changes in products in order to assess the impacts on the hydrological component. Forecasts usually also need to be archived for future use in model calibration, forecast verification and staff training exercises. For the latest high-resolution models with many grid squares and ensemble members, the increased data volumes may require additional data storage facilities and higher capacity communications links between national and regional centres.

Sometimes another consideration is which product or service to select for a hydrological application. For example, in some parts of the world, particularly where the national meteorological service has limited forecasting capability, the main choices may be between:

- Global-scale models – using the outputs from one or more international centres to take advantage of the latest data assimilation and modelling techniques
- Limited-area models – using a national model with less sophisticated data assimilation and modelling components but incorporating more local knowledge

- Simpler approaches – using simpler statistical techniques and conceptual forecasting models which have worked well for many years, particularly for longer-range forecasting

In contrast, in some cases – such as in mainland Europe – the location of interest may fall within the domain of the models operated by several nearby national centres, perhaps suggesting use of a multi-model approach. As noted earlier and in Chap. 1, the WMO Severe Weather Forecasting Demonstration Project is also extending regional capability in many parts of the world. These factors are all part of the model conceptualisation process which is discussed in later chapters. However, often the first step is to assess the performance of the various options available, and the following two sections discuss the related topics of forecast verification and post-processing of forecast outputs.

4.3.2 Post-processing

Numerical weather prediction models provide outputs on a gridded basis whose node points will not necessarily coincide with the locations of interest and for which the fine detail is subject to many uncertainties. In particular, whilst most global-scale models provide a good representation of the large-scale features of the atmosphere such as frontal systems and jet streams, there is generally less detail for smaller-scale phenomena.

For short- to medium-range forecasting, the latest generation of high-resolution non-hydrostatic models is starting to address many of these issues. However, for some applications, and particularly for forecasts of extreme events, it is desirable to downscale the model outputs to a finer scale and/or to calibrate the outputs based on the statistical (climatological) characteristics at the site(s) of interest. The main types of approach include:

- Statistical techniques – in which forecasts are adjusted to take account of the statistical characteristics of recent and historical observations at or near the site(s) of interest
- Weather-matching or analogue techniques – in which similar conditions are identified from historical archives as a basis for forecasting likely scenarios for parameters such as rainfall which are not necessarily captured in model outputs to the required level of detail
- Dynamic (or dynamical) downscaling – in which a more detailed local model is operated based on the boundary conditions provided by a regional or global-scale model

These types of techniques are used extensively in climate modelling; for example, Wilby and Wigley (1997) describe the following four main categories of downscaling: regression methods, weather pattern (circulation) based approaches, stochastic weather generators and limited-area climate models. Some meteorological services also offer additional, enhanced (or 'added value') services with varying amounts of post-processing and interpretation applied.

In statistical post-processing, one simple option is to apply correction factors to the model outputs based on topographic considerations; for example, using typical lapse rates for air temperature to help account for elevation effects or using air temperatures to estimate snow levels. Coastal influences might be accounted for in a similar manner, based on distance from the coast, wind direction and other factors. More generally one or more grid squares may be selected as representative of the site under consideration, taking account of local climate and using interpolation if appropriate (e.g. WMO 2012b). When observations or more detailed analyses are available for the locations of interest, some additional options include the techniques shown in Table 4.5. Typically, methods are calibrated off-line on the basis of historical data and archived forecast values, and the resulting relationships are then applied to the model outputs before delivery to end users.

Perhaps, the longest established form of statistical post-processing is the method of Model Output Statistics (MOS), which was developed by the National Weather Service in the USA and has been used in various forms since the 1970s (Antolik 2000; Glahn and Lowry 1972; Wilks 2011). This is typically based upon multiple-regression relationships derived from a national database of observations for a range of variables at several thousand stations. These typically vary with season, lead time, time of day and other factors, and non-linear relationships can be included through statistical transformations of outputs. In contrast, the use of post-processing techniques for ensemble forecasts is a relatively new area and one which is undergoing rapid development (e.g. Demargne et al. 2014; Jolliffe and Stephenson 2012; Weerts et al. 2014; Wilks 2011; WMO 2012b). Figure 4.12 shows an example of one such approach, in this case using a Kalman filter approach, and Chap. 5 discusses some of the more general issues with interpretation of ensemble rainfall forecasts when used in hydrological applications.

For deterministic forecasts, one advantage of statistical post-processing techniques is that, with some approaches, estimates are also provided for the uncertainty in the relationships. Indeed, this was once the main route to producing probabilistic

Table 4.5 Some examples of statistical post-processing techniques for Numerical Weather Prediction model outputs

Technique	Basis of approach
Multiple regression	Regression relationships between model variables and observed values. Some examples of possible model-based predictors include precipitable water, area averaged temperature, relative vorticity, wind speeds and geopotential heights. Relationships are typically developed for a range of forecast lead times, in some cases using predictors averaged or weighted across several grid squares
Time series analysis techniques	Adjustments to forecasts based on near real-time observations, such as values reported by telemetry from an automatic weather station. For example, Kalman filtering techniques are widely used. Typically, forecasts are updated using observations made over a period of days or weeks up to the present time
Ensemble post-processing techniques	Techniques to help compensate for modelling errors, the limited sample sizes and incomplete representation of sources of uncertainty in ensemble forecasts. This is a rapidly developing area, and techniques include quantile matching, distribution matching and – for multi-model ensembles – Bayesian Model Averaging

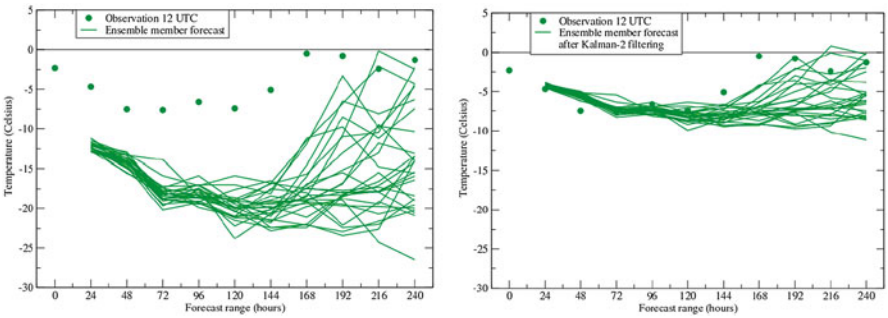

Fig. 4.12 Illustration of Kalman filter post-processing of ensemble forecast outputs. The forecast is for the 2 m air temperature for Tromsö on 12 February 2011 (*left*) and is too cold with 50–100 % probabilities of temperatures < −15 °C. After the Kalman-filtered error equation has been applied (*right*), mild forecasts have hardly been modified, whereas cold ones have been substantially warmed, leading to less spread and more realistic probabilities with, for example, 0 % probabilities for 2 m temperature < −15 °C (Persson 2013; Source ECMWF)

short- to medium-range meteorological forecasts before the introduction of ensemble forecasting techniques. There is however some effort needed in keeping the model coefficients up to date; for example, when instruments or forecasting models change. Also, for some techniques, the forecast variables may not necessarily be spatially consistent or – for a given site – mutually consistent with other variables recorded at the same location (unless parameters are modelled jointly), a factor which is important in some applications.

Another post-processing technique is that of weather-matching, for which alternative names include weather-typing or analogue techniques. The basis of the approach is to identify similar atmospheric conditions to those which are currently forecast, at the lead times of interest, by searching through an archive of historical observations. Typically this involves matching of ground-based data, such as from weather stations at different elevations, and sometimes selected atmospheric profiles obtained either from previous model runs or an archive of radiosonde ascent data.

The underlying assumption is that some aspects of the performance of numerical weather prediction models are – in principle – more predictable than others and so are more likely to be a good indicator of future conditions (e.g. Hamill et al. 2006; Obled et al. 2002; Van den Dool 2007). Some examples of parameters which often fall within this category include air temperatures, atmospheric pressures, precipitable water and geopotential heights. Having identified suitable analogues, values which are more difficult to forecast in detail such as precipitation are then extracted from an archive of stored observations, such as of weather radar observations.

One key advantage is that the spatial variability of estimates is preserved since values are extracted from the historical record. However, due to the many uncertainties in the approach, rather than choosing a single analogue, multiple candidates are usually selected and an ensemble of outputs generated. The overall performance depends on the suitability of the predictors chosen and the associated search algorithms. For example, some types of matching techniques include principal component analyses, pattern matching and more qualitative approaches such as identification of similar general classes of weather systems.

As an example, this approach has formed the basis of an operational method which has been used successfully – and successively improved – for rainfall forecasting for reservoir operations in southern France since the 1970s (Horton et al. 2012; Obled et al. 2002). In addition to the general synoptic conditions, other parameters such as humidity are considered in the search for suitable conditions. Some other applications of analogue techniques include nowcasting, as discussed earlier, and in the post-processing of ensemble forecasts (Hamill et al. 2013).

Another post-processing option is to operate a more detailed local model using boundary conditions from regional or global models. Compared to other techniques, some potential advantages of these so-called dynamical approaches are that the spatial and temporal consistency in outputs is preserved and the potential to deal with a wider range of meteorological conditions than may have occurred in the past. However, some potential barriers include the considerable technical expertise required to develop and operate models, the telecommunications infrastructure required for data assimilation and the computationally intensive nature of some approaches.

The quality of the results is also influenced by the performance of the regional- or global-scale model which provides the lateral boundary conditions. Due to the costs and complexities, this approach tends to be limited to research organisations and some private-sector weather forecast providers. However, as noted earlier as national meteorological services adopt higher-resolution models, the need to develop local models is tending to fall away except where there are specific local forecasting problems to be addressed, or more generally in climate modelling studies where this remains a valuable tool.

4.3.3 Forecast Verification

Most meteorological services routinely assess forecast performance and publish key measures on their websites and in annual reports. These can provide a guide to the value of investments and the need for future improvements and allow comparisons to be made with other forecasting services. Other aspects that are usually monitored include feedback from end users and the reliability of forecast delivery.

Regarding verification of forecast performance, many different approaches have been developed covering both deterministic and ensemble forecasts (e.g. Casati et al. 2008; Jolliffe and Stephenson 2012; Stanski et al. 1989; Wilks 2011; WMO 2008). For example, Murphy (1993) identified the following three characteristics of a good forecast:

- Consistency – the correspondence between forecasters' judgements and their forecasts

- Quality – the correspondence between the forecasts and the matching observations
- Value – the incremental economic and/or other benefits realized by decision makers through the use of forecasts

Forecast quality was defined to include the aspects of bias, association, accuracy, skill, reliability, resolution, sharpness, discrimination and uncertainty.

In verification studies, forecast outputs are typically compared with raingauge, weather station and/or weather radar observations, plus radiosonde and wind profiler observations when evaluating forecasts for upper air conditions. Some basic statistical measures of interest include the mean, cumulative values and the root mean square error; however, usually more than one measure is required to adequately describe the forecast performance, particularly for ensemble and probabilistic forecasts.

For example, skill scores such as the Brier Skill Score aim to express the skill of the forecast relative to a simpler standard or reference forecast, such as one based on climatological conditions or persistence at the site(s) of interest. Similarly, categorical statistics such as the probability of detection and false alarm ratio assess performance relative to threshold values. As model resolutions improve, there is also an increasing need to assess the spatial aspects of forecast performance rather than simply at a point or grid scale, and options include scale decomposition and object-oriented approaches (e.g. Gilleland et al. 2010; Jolliffe and Stephenson 2012; Rossa et al. 2008). For example, some features of interest typically include the shape, size, position and intensity of storms.

Chapter 5 provides some more background on how some of these measures are used within the context of hydrological forecasting. For example, regarding rainfall forecasts some key issues of interest often include:

- The forecast performance for typical basin scales, such as for catchment average rainfall
- The performance relative to critical thresholds, such as the depth and duration of rainfall which might cause flooding
- The variations in forecast performance with lead time, to provide an indication of the maximum lead time at which the forecasts show skill

It is however worth noting that meteorological performance statistics sometimes include parameters which are not routinely calculated in hydrological applications. For example, the success with forecasting non-events is often of interest; that is, when no event is forecast to occur and none happens. Some typical applications where these types of measures are relevant include deciding whether to switch on heaters in an orchard to protect the crop at night or to apply salt to a road which is at risk from icing.

For weather extremes, ideally performance should be assessed over periods long enough to include a representative sample of the types of events of interest, such as floods, droughts or rainfall seasons. In addition to requiring long-term observational records, this normally requires access to an archive of previous forecasts. One option is to use stored values from an operational model; however, for numerical weather prediction models, these may not represent a homogenous series if – as is often the case – the underlying model or data assimilation routines have been improved over the period for which values are available.

These limitations have led to increasing use of reanalysis techniques in which past conditions are simulated using current models and data assimilation procedures. Reforecasting techniques – sometimes called hindcasting – go one step beyond this to generate forecast outputs as if the model been available throughout the simulation period, typically using a simplified version due to computational limitations and using the corresponding reanalyses to initialise each run.

These types of analyses can be a major effort, and usually it is necessary to apply adjustments to allow for the fact that the instrumentation available for data assimilation will almost certainly have changed over the reanalysis period; for example, in terms of the number of land-based sites, the increasing availability of satellite-based observations and changes in recording methods and intervals. However, these techniques are increasingly becoming an intrinsic aspect of model development so that, when a major new release of a model is planned, the development effort includes provision for these types of study.

Reanalysis and – to a lesser extent – reforecasting exercises are now performed by several organisations, and there are ongoing programmes at ECMWF, NCEP in the USA, and the Japan Meteorological Agency amongst others (e.g. Dee et al. 2011; Hagedorn et al. 2012; Hamill et al. 2013). The results usually date back several decades and have a wide range of potential applications such as for calibration of hydrological forecasting models and of meteorological post-processing techniques. Indeed, Hamill et al. (2006) note that for 'many difficult problems, such as long lead forecasts, forecasts of rare events, or forecasts of surface variables with significant bias, a large training sample size afforded by reforecasts may prove especially beneficial'.

4.4 Summary

- Meteorological forecasts can assist with operational decision-making for a range of hydrological applications and are increasingly provided in ensemble form. They offer the potential to help staff to issue warnings sooner than would be possible based on observations alone and to make better decisions with regard to reservoir, water supply, irrigation and other operations. The main parameter of interest is often rainfall, but other outputs such as humidity, wind speed and air temperature are required in some applications.
- Forecast products are often distinguished by the maximum lead times for which model outputs are available. For a given lead time, it is usually easier to predict the behaviour of larger-scale features such as fronts than more localised phenomena such as thunderstorms. Forecast accuracy normally also decreases with increasing lead time and uncertainty increases.
- Nowcasting techniques provide estimates of conditions for up to a few hours ahead and are normally based on weather radar or satellite observations. Increasingly, the outputs are blended with those from numerical weather predic-

tion models, plus observations from other sources, to form merged multi-sensor products. Ensemble products are increasingly becoming available.

- Numerical weather prediction models provide forecasts for a range of timescales from a few hours ahead to seasonal and longer lead times. High-resolution convection-permitting non-hydrostatic models are increasingly being brought into operational use providing a greatly improved representation of convective processes compared to the previous generation of models. More generally there is an increasing trend to develop a unified or seamless approach common to all timescales.
- Statistical techniques provide a useful complement to numerical models, particularly for long-range forecasts. Typically, the aim is to develop multiple-regression or more complex relationships expressing the links between atmospheric variables and indices based on ocean observations such as for sea surface temperatures and/or pressures. These in turn are assumed to be indicative of phenomena such as the El Niño-Southern Oscillation, Indian Ocean Dipole and the North Atlantic Oscillation.
- Whilst forecast products such as situation reports, bulletins and warning messages suffice in many applications, in some cases it is desirable to deliver model outputs directly to end users such as flood warning agencies and reservoir operators. Often this requires some additional investment and institutional changes to allow information to be used effectively with back up facilities in case of problems. For emergency situations, it is normally essential that forecasters are involved in the wider decision-making processes that affect the emergency response.
- In many applications, some post-processing of outputs is desirable before operational use. The main techniques – largely applicable to numerical weather prediction models – are statistical methods, weather-matching techniques and dynamic downscaling. However, for short- to medium-range forecasting, the need for dynamic approaches is gradually falling away as meteorological services adopt high-resolution numerical models, although this remains a key approach for climate modelling.
- Forecast verification is a key tool for guiding model development and helping users to understand the suitability of outputs for different applications. Usually, it is advisable to consider several performance measures to explore the spatial, lead time and other characteristics of a forecast. The outputs from reanalysis and reforecasting exercises are potentially a valuable resource both for forecast verification studies and calibrating hydrological models, particularly for extreme events.

References

AMS (2015) Glossary of Meteorology. 2nd edition http://amsglossary.allenpress.com/glossary

Antolik MS (2000) An overview of the National Weather Service centralized Quantitative Precipitation Forecasts. J Hydrol, 239:306–337

Barnston AG, Tippett MK, L'Heureux ML, Li S, DeWitt DG (2012) Skill of real-time seasonal ENSO model predictions during 2002–11: Is our capability increasing? Bull. Amer. Meteor. Soc., 93: 631–651

Benjamin S, Jamison B, Moninger W, Sahm S, Schwartz B, Schlatter T (2010) Relative short-range forecast impact from aircraft, profiler, radiosonde, VAD, GPS-PW, METAR, and mesonet observations via the RUC hourly assimilation cycle. Mon Wea Rev 138:1319–1343

Bouilloud L, Chancibault K, Vincendon B, Ducrocq V, Habets F, Saulnier G, Anquetin S, Martin E, Noilhan J (2010) Coupling the ISBA land surface model and the TOPMODEL hydrological model for Mediterranean flash-flood forecasting: description, calibration, and validation. J Hydrometeorol 11:315–333

Bouttier F, Vié B, Nuissier O, Raynaud L (2012) Impact of stochastic physics in a convection permitting ensemble. Mon. Wea. Rev., 140: 3706–3721

Bowler NE, Pierce CE, Seed A (2004) Development of a precipitation nowcasting algorithm based on optical flow techniques. Journal of Hydrology, 288: 74–91

Bowler NE, Pierce CE, Seed AW (2006) STEPS: a probabilistic precipitation forecasting scheme which merges an extrapolation nowcast with downscaled NWP. Q J R Meteorol Soc 132:2127–2155

Brown A, Milton S, Cullen M, Golding B, Mitchell J, Shelly A (2012) Unified Modeling and prediction of weather and climate: A 25-Year Journey. Bull Am Meteorol Soc, 93:1865–1877

Browning KA, Collier CG (1989) Nowcasting of precipitation systems. Rev Geophys 27(3):345–370

Cabinet Office (2008) The Pitt Review: lessons learned from the 2007 floods. Cabinet Office, London

Carrière J-M, Vincendon B, Brovelli P, Tabary P (2011) Current developments for flash flood forecasting at Météo France. Workshop on flash flood and debris flow forecasting in Mediterranean areas: current advances and examples of local operational systems, Toulouse, 4 February 2011

Casati B, Wilson LJ, Stephenson DB, Nurmi P, Ghelli A, Pocernich M, Damrath U, Ebert EE, Brown BG, Mason S (2008) Forecast verification: current status and future directions. Meteorol Appl 15(1):3–18

Dabberdt W, Schlatter T, Carr F, Friday E, Jorgensen D, Koch S, Pirone M, Ralph F, Sun J, Welsh P, Wilson J, Zou X (2005) Multifunctional mesoscale observing networks. Bull Am Meteorol Soc 86(7):961–982

Dee DP et al (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc 137:553–597

Delrieu G, Ducrocq V, Gaume E, Nicol J, Payrastre O, Yates E, Kirstetter P-E, Andrieu H, Ayral P-A, Bouvier C, Creutin J-D, Livet M, Anquetin S, Lang M, Neppel L, Obled C, Parent-Du-Châtelet J, Saulnier G-M, Walpersdorf A, Wobrock W (2005) The catastrophic flash-flood event of 8–9 September 2002 in the Gard region, France: a first case study for the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory. J Hydrometeorol 6:34–52

Demargne J, Wu L, Regonda SK, Brown JD, Lee H, He M, Seo D-J, Hartman R, Herr HD, Fresch M, Schaake J, Zhu Y (2014) The science of NOAA's operational Hydrologic Ensemble Forecast Service. Bulletin of the American Meteorological Society, 95: 79–98

DeMaria M, Sampson CR, Knaff JA, Musgrave KD (2014) Is tropical cyclone intensity guidance improving? Bulletin of the American Meteorological Society, 94(3): 387–398

Deslandes R, Richter H, Bannister T (2008) The end-to-end severe thunderstorm forecasting system in Australia: overview and training issues. Aust Met Mag 57:329–343

Doblas-Reyes FJ, Hagedorn R, Palmer TN (2005) The rationale behind the success of multi-model ensembles in seasonal forecasting. Part II: Calibration and combination. Tellus-A, 57: 234–252

Drobinski et al. (34 co-authors) (2014) HYMEX: A 10-Year Multidisciplinary Program on the Mediterranean Water Cycle. Bulletin of the American Meteorological Society, 95(7): 1063–1082

Edouard S, Vincendon B, Ducrocq V (2015) Taking into account hydrological modelling uncertainty in Mediterranean flash-floods forecasting. Geophysical Research Abstracts, 17: EGU2015-1439

Gall R, Franklin J, Marks F, Rappaport EN, Toepfer F (2013) The Hurricane Forecast Improvement Project. Bulletin of the American Meteorological Society, 94(3): 329–343

Gilleland E, Ahijevych DA, Brown BG, Ebert EE (2010) Verifying forecasts spatially. Bull Am Meteorol Soc 91:1365–1373

Glahn HR, Lowry DA (1972) The use of Model Output Statistics (MOS) in objective weather forecasting. J Appl Meteorol 11:1203–1211

Goddard L, Mason SJ, Zebiak SE, Ropelewski CF, Basher R, Cane MA (2001) Review article: current approaches to seasonal to interannual climate predictions. International Journal of Climatology, 21(9): 1111–1152

Golding BW (2000) Quantitative Precipitation Forecasting in the UK. J Hydrol 239:286–305

Golding BW, Ballard SP, Mylne K, Roberts N, Saulter A, Wilson C, Agnew P, Davis LS, Trice J, Jones C, Simonin D, Li Z, Pierce C, Bennett A, Weeks M, Moseley S (2014) Forecasting capabilities for the London 2012 Olympics. Bull. Amer. Meteor. Soc., 95: 883–896

Hagedorn R, Buizza R, Hamill TM, Leutbecher M, Palmer TN (2012) Comparing TIGGE multi model forecasts with reforecast-calibrated ECMWF ensemble forecasts. Quarterly Journal of the Royal Meteorological Society, Part A, 138(668): 1814–1827

Halmevaara K, Rossi P, Mäkelä A, Koistinen J, Hasu V (2010) Supplementing convective objects with national emergency report data. ERAD 2010 – the sixth European Conference on Radar in Meteorology and Hydrology, Sibiu, 6–10 September 2010

Hamill TM, Whitaker JS, Mullen SL (2006) Reforecasts: an important dataset for improving weather predictions. Bull Am Meteorol Soc 87:33–46

Hamill TM, Brennan MJ, Brown B, DeMaria M, Rappaport EN, Toth Z (2012) NOAA'S Future ensemble-based hurricane forecast products. Bull Am Meteorol Soc 93:209–220

Hamill TM, Bates GT, Whitaker JS, Murray DR, Fiorino M, Galarneau Jr. TJ, Zhu Y, Lapenta W (2013) NOAA's Second-Generation Global Medium-Range Ensemble Reforecast Dataset. Bull. Amer. Meteor. Soc., 94: 1553–1565

Harrison M, Troccoli A, Anderson DLT, Mason SJ (2008) Introduction (Chapter 1). In Seasonal Climate: Forecasting and Managing Risk (Eds. Troccoli A, Harrison M, Anderson DLT, Mason SJ). NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht

Hering AM, Germann U, Boscacci M, Sénési S (2008) Operational nowcasting of thunderstorms in the Alps during MAP D-PHASE. ERAD 2008 – the fifth European Conference on Radar in Meteorology and Hydrology, Helsinki, 30 June-4 July 2008

Horton P, Jaboyedoff M, Metzger R, Obled C, Marty R (2012) Spatial relationship between the atmospheric circulation and the precipitation measured in the western Swiss Alps by means of the analogue method. Nat. Hazards Earth Syst. Sci., 12: 777–784

Inness PM, Dorling S (2013) Operational Weather Forecasting. Wiley-Blackwell, Chichester

Jolliffe IT, Stephenson DB (2012) Forecast verification. A practitioner's guide in atmospheric science, 2nd edn. Wiley, Chichester

Jury MR (2013) Climate prediction experiences in southern Africa 1990–2005 and key outcomes. Natural Hazards, 65: 1883–1894

Kalnay E (2002) Atmospheric modeling, data assimilation, and predictability. Cambridge University Press, Cambridge

Lean HW, Clark PA (2003) The effects of changing resolution on mesoscale modelling of line convection and slantwise circulations in FASTEX IOP16. Q J R Meteorol Soc 129(592):2255–2278

Manatsa, D., Matarira, C.H., Mukwada, G. (2011) Relative impacts of ENSO and Indian Ocean dipole/zonal mode on east SADC rainfall. International Journal of Climatology, 31(4): 558–577

Markowski P, Richardson Y (2010) Mesoscale meteorology in mid latitudes. Wiley, London

Mason SJ, Baddour O (2008) Statistical modelling (Chapter 7). In Seasonal Climate: Forecasting and Managing Risk (Eds. Troccoli A, Harrison M, Anderson DLT, Mason SJ). NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht

Met Office (2010) Met Office Science Strategy 2010–2015: unified science and modelling for unified prediction. Met Office, Exeter

Molteni F, Buizza R, Palmer TN, Petroliagis T (1996) The ECMWF Ensemble Prediction System: methodology and validation. Quarterly Journal of the Royal Meteorological Society, 122, 73–119

Murphy AH (1993) What is a good forecast? an essay on the nature of goodness in weather forecasting. Weather Forecast 8(2):281–293

NOAA/NWS (2015) National Weather Service Glossary http://weather.gov/glossary/

Noilhan J, Planton S (1989) A simple parametrization of land surface processes for meteorological models. Mon Weather Rev 117:536–549

Nuissier O, Joly B, Vié B, Ducrocq V (2012) Uncertainty of lateral boundary conditions in a convection-permitting ensemble: a strategy of selection for Mediterranean heavy precipitation events., Nat. Hazards Earth Syst. Sci., 12: 2993–3011

Obled C, Bontron G, Garcon R (2002) Quantitative Precipitation Forecasts: a statistical adaptation of model outputs through an analogues sorting approach. Atmos Res 63:303–324

Palmer T, Hagedorn R (Eds.) (2006) Predictability of Weather and Climate. Cambridge University Press, Cambridge

Panziera L, Germann U, Gabella PV, Mandapaka PV (2011) NORA–Nowcasting of Orographic Rainfall by means of Analogues. Q. J. R. Meteorol. Soc., 137(661): 2106–2123

Park SK, Liang X (eds) (2009) Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications. Springer, Dordrecht

Park Y-Y, Buizza R, Leutbecher M (2008) TIGGE: preliminary results on comparing and combining ensembles. Quarterly Journal of the Royal Meteorological Society, 134: 2029–2050

Pellarin T, Delrieu G, Saulnier GM, Andrieu H, Vignal B, Creutin JD (2002) Hydrologic visibility of weather radar systems operating in mountainous regions: case study for the Ardèche catchment (France). J Hydrometeorol 3:539–555

Persson A (2013) User guide to ECMWF forecast products, Version 1.1. ECMWF, Reading

Pierce C, Bowler N, Seed A, Jones D, Moore R (2005) Towards stochastic fluvial flood forecasting: quantification of uncertainty in very short range QPF's and its propagation through hydrological and decision making models. Second ACTIF workshop on Quantification, Reduction and Dissemination of Uncertainty in Flood Forecasting, Delft, 23–24 November 2004

Raftery AE, Gneiting T, Balabdaoui F, Polakowski M (2005) Using Bayesian model averaging to calibrate forecast ensembles. Monthly Weather Review, 133: 1155–1174

Roberts R, Anderson A, Nelson E, Brown B, Wilson J, Pocernich M, Saxen T (2012) Impacts of forecaster involvement on convective storm initiation and evolution nowcasting. Weather and Forecasting, 27: 1061–1089

Rossa A, Nurmi P, Ebert E (2008) Overview of Methods for the Verification of Quantitative Precipitation Forecasts. In: Michaelides S (ed) Precipitation: Advances in Measurement, Estimation and Prediction. Springer, Dordrecht

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401: 360–363

Scaife AA (2014) Skillful long-range prediction of European and North American winters. Geophysical Research Letters, 41(7): 2514–2519

Schlatter TW (2000) Variational assimilation of meteorological observations in the lower atmosphere: a tutorial on how it works. J Atmos Sol-Terr Phy 62(12):1057–1070

Scofield RA, Kuligowski RJ, Davenport JC (2004) The use of the Hydro-Nowcaster for mesoscale convective systems and the Tropical Rainfall Nowcaster (TRaN) for landfalling tropical systems. The 84th American Meteorological Society Meeting, Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, Seattle

Seed AW, Pierce CE, Norman K (2013) Formulation and evaluation of a scale decomposition-based stochastic precipitation nowcast scheme. Water Resources Research 49(10): 6624–6641

Seity Y, Brousseau P, Malardel S, Hello G, Bénard P, Bouttier F, Lac C, Masson V (2011) The AROME-France convective-scale operational model. Mon Wea Rev 139:976–991

Sene (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht

Shapiro M and 39 co-authors (2010) An Earth-System Prediction Initiative for the Twenty-First Century. Bull. Amer. Meteor. Soc., 91: 1377–1388

Sheng YP, Paramygin VA, Alymov V, Davis JR (2005) A real-time forecasting system for hurricane induced storm surge and coastal flooding. The 9th International Conference on Estuarine and Coastal Modeling, Charleston, SC

Stanski HR, Wilson LJ, Burrows WR (1989) Survey of common verification methods in meteorology. World Weather Watch Technical Report No. 8, WMO/TD No.358, World Meteorological Organisation, Geneva

Stensrud DJ (2007) Parameterization schemes: keys to understanding Numerical Weather Prediction models. Cambridge University Press, Cambridge

Stensrud DJ, Xue M, Wicker LJ, Kelleher KE, Foster MP, Schaefer T, Schneider RS, Benjamin SG, Weygandt SS, Ferree JT, Tuell JP (2009) Convective-scale warn-on-forecast system: a vision for 2020. Bull Am Meteorol Soc 90:1487–1499

Sun J, Xue M, Wilson JW, Zawadzki I, Ballard SP, Onvlee-Hooimeyer J, Joe P, Barker DM, Li P-W, Golding B, Xu M, Pinto J (2014) Use of NWP for nowcasting convective precipitation: Recent progress and challenges. Bulletin of the American Meteorological Society, 95:409–426

Toth Z, Kalnay E (1997) Ensemble forecasting at NCEP and the breeding method. Monthly Weather Review, 12: 3297–3319

Troccoli A (2010) Seasonal climate forecasting. Meteorological Applications, 17(3): 251–268

Troccoli A, Harrison M, Anderson DL T, Mason SJ (2008) Seasonal Climate: Forecasting and Managing Risk. NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht

Van den Dool H (2007) Empirical methods in short-term climate prediction. Oxford University Press, Oxford

Vié B, Nuissier O, Ducrocq V (2011) Cloud-resolving ensemble simulations of Mediterranean heavy precipitating events: uncertainty on initial conditions and lateral boundary conditions. Mon Weather Rev 139(2):403–423

Vié B, Molini G, Nuissier O, Vincendon B, Ducrocq V, Bouttier F, Richard E (2012) Hydro-meteorological evaluation of a convection-permitting ensemble prediction system for Mediterranean heavy precipitating events. Nat. Hazards Earth Syst. Sci., 12: 2631–2645

Vincendon B, Ducrocq V, Nuissier O, Vié B (2011) Perturbation of convection-permitting NWP forecasts for flash-flood ensemble forecasting. Nat Hazards Earth Syst Sci 11:1529–1544

Walker JW (1997) Pen portrait of Sir Gilbert Walker, CSII, MA, ScD, FRS. Weather, 52(7): 217–220

Webster PJ, Hoyos C (2004) Prediction of monsoon rainfall and river discharge on 15–30 day time scales. Bulletin of the American Meteorological Society, 85: 1745–1765

Weckwerth TM, Pettet CR, Fabry F, Park S, LeMone MA, Wilson JW (2005) Radar refractivity retrieval: validation and application to short-term forecasting. J Appl Meteorol 44:285–300

Weerts AH, Seo DJ, Werner M, Schaake J (2014) Operational hydrological ensemble forecasting. In: Beven K, Hall J (eds) Applied uncertainty analysis for flood risk management. Imperial College Press, London

Wernli H, Paulat M, Hagen M, Frei C (2008) SAL-A novel quality measure for the verification of Quantitative Precipitation Forecasts. Mon Weather Rev 136:4470–4487

Wilby RL, Wigley TM L (1997) Downscaling General Circulation Model output: a review of methods and limitations. Progress in Physical Geography, 21(4): 530–548

Wilks DS (2011) Statistical methods in the atmospheric sciences, 3rd edn. Academic Press Amsterdam

Wilson JW (2004) Precipitation nowcasting: past, present and future. In: Sixth International Symposium on Hydrological Applications of Weather Radar, Melbourne, 2–4 February 2004

Wilson JW, Feng Y, Chen M, Roberts RD (2010) Status of nowcasting convective storms. ERAD 2010 – the sixth European Conference on Radar in Meteorology and Hydrology, Sibiu, 6–10 September 2010

WMO (2000) Precipitation Estimation and Forecasting. Operational Hydrology Report No. 46, WMO No.-887 Geneva
WMO (2008) Recommendations for the verification and intercomparison of QPFs and PQPFs from operational NWP models. WMO/TD – No.1485, Revision 2, Geneva
WMO (2010a) Severe Weather Forecasting Demonstration Project (SWFDP): Guidebook on planning regional subprojects, World Meteorological Organisation, Geneva
WMO (2010b) Guidelines on Early Warning Systems and Application of Nowcasting and Warning Operations. WMO/TD No. 1559, Geneva
WMO (2012a) Manual on the Global Data-Processing and Forecasting System. Volume I – Global Aspects. WMO-No. 485, Geneva
WMO (2012b) Guidelines on Ensemble Prediction Systems and Forecasting. WMO-No. 1091, Geneva
WMO (2015) Global Guide to Tropical Cyclone Forecasting. World Meteorological Organisation, Geneva http://www.wmo.int

Chapter 5
Hydrological Forecasting

Abstract Hydrological modelling techniques include rainfall-runoff and flow routing models and simpler statistical approaches. Additional components may be required to represent specific features of a catchment such as reservoirs and lakes. For real-time use, models are typically operated within an automated forecasting system which controls the gathering of data, scheduling of model runs and data assimilation. This chapter presents an introduction to these topics and to the general issues of forecast verification and probabilistic and ensemble flow forecasting.

Keywords Rainfall-runoff • Hydrological • Hydrologic • Flow routing • Hydraulic • Hydrodynamic • Data assimilation • Forecasting system • Performance measures • Forecast verification • Forecast uncertainty • Probabilistic • Ensemble

5.1 Introduction

River flow forecasts are used in a wide range of applications including irrigation scheduling, reservoir operations and hydropower generation. The outputs can be particularly useful for flood and drought warning systems and in complex situations where river levels or flows are affected by multiple influences. Rainfall forecasts offer the potential to extend the lead times further.

Forecasting models are often based upon those developed for off-line design and planning studies. One of the first such approaches was the unit hydrograph (Sherman 1932) in which a linear relationship is assumed between the effective rainfall falling in a given time and the resulting runoff. The combined river flow hydrograph is then estimated by summing the incremental contributions corresponding to the assumed rainfall inputs. This approach is still widely used in flood estimation studies although, for real-time use, other types of rainfall-runoff models are now generally preferred.

Once water (or runoff) enters the river system, additional models are often required to translate the resulting flows to locations further downstream; a process which is called flow routing. For example, one common approach is to use an integrated catchment model in which rainfall-runoff and flow routing models are combined, as illustrated by the example in Fig. 5.1. Additional models (not shown) would normally be included to represent the unobserved (ungauged) inflows to the flow routing reaches.

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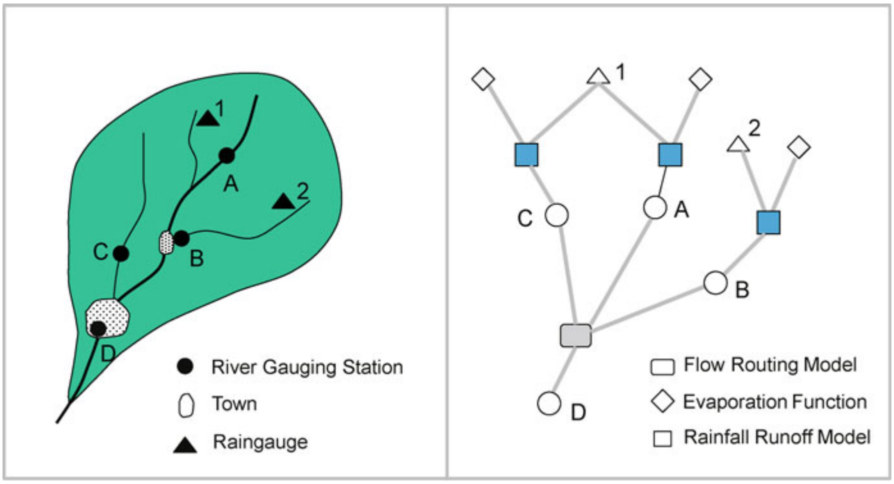

Fig. 5.1 An example of configuration of an integrated catchment model in a flood forecasting system showing the telemetered river gauges available and main locations at risk A to D *(left)* and a conceptual representation of the hydrological processes (*right)* (Adapted from Sene 2008)

When using this approach there is generally a trade-off between the greater uncertainty but longer lead times provided by rainfall-runoff models and the shorter lead times but greater precision provided by flow routing approaches. Some other modelling options, not shown here, include grid-based (distributed) representations or simpler lumped modelling approaches in which the catchment is represented as a single unit.

Model performance is normally optimised for the locations at which forecasts are required operationally. These are usually called forecasting points, and some typical examples include river gauging stations, reservoirs, control structures, river abstraction points and areas at risk from flooding. Where real-time observations are available, this provides the opportunity to update model outputs so that the forecasts are closer to the observed values. This process, called data assimilation, is also applied to distributed models, in which case the required adjustments are normally distributed over the model domain.

For rainfall-runoff models, given the complexities in how rainfall translates into runoff, a pragmatic modelling approach is often adopted in which key aspects of the response are conceptualised in terms of storage components or using time series analysis techniques. For flow routing models, in contrast, a more physically based approach is normally used in which mass and momentum are conserved to varying degrees. These types of model range from hydrological routing approaches to two- or three-dimensional hydrodynamic models. For example, in some cases, a simple routing approach may suffice for a single river reach, whilst hydrodynamic models are normally required for modelling the circulation in lakes and reservoirs and in surge forecasting for coastal waters.

If required the transport of contaminants such as pollutants can be included in the model formulation, either as passive 'tracers' or allowing for the interactions with

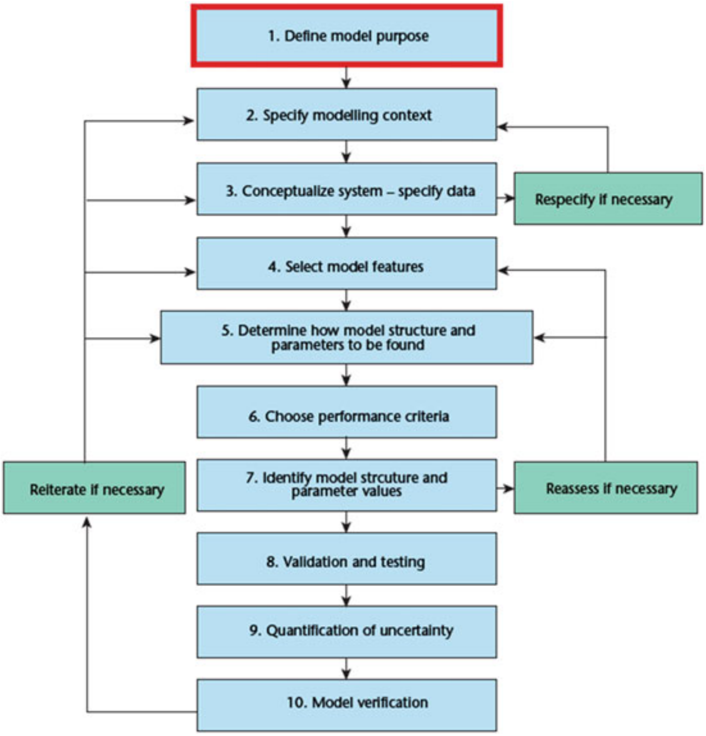

Fig. 5.2 Process for developing a flood forecasting model (WMO 2011, courtesy of WMO)

the river flow through mechanisms such as mixing, chemical reaction and biodegradation. In contrast, for some long-term planning studies, a water balance approach alone is sufficient such as in the supply-demand modelling techniques that are widely used for water resources applications and considered further in Chap. 13.

The stages in developing a real-time flow forecasting model normally include model configuration and calibration, quantification of uncertainty and testing and validation. Figure 5.2 shows an example of this process in more detail for the case of a flood forecasting model; however, similar considerations apply to other applications. Allied to this is the need to put in place a long-term plan for forecast verification and model improvements.

This chapter presents an introduction to these various techniques (Sect. 5.2) and to the related topics of forecasting systems, data assimilation, forecast verification and uncertainty estimation (Sect. 5.3). Box 5.1 also provides an introduction to statistical analysis techniques in hydrology which can often help to place model outputs into a historical context. Further information can be found in the many books and guidelines on these topics including Anderson and McDonnell (2009), Bedient et al. (2012), Beven (2012), Blöschl et al. (2013), Chanson (2004), Ji (2008), McMahon and Adeloye (2005), Shuttleworth (2012), Singh (1995) and WMO (2009, 2011, 2012a).

Box 5.1: Statistical Techniques in Hydrology

In many hydrological applications, it is useful to derive long-term indicators of river flows. In forecasting applications some typical uses include defining threshold values in early warning applications and for forecast verification studies. Some parameters of interest include:

- General – basic statistical measures such as the mean, median, maximum, minimum, variance, standard deviation and coefficient of variation, plus indicators of long-term trends
- Floods – index values such as the mean or median annual flood and estimates for flows with a given return period or annual exceedance probability such as the 1 in 100 year or 1 % values
- Droughts – measures of flow reliability such as the flow of a given duration which is exceeded for a given percentage of the time or the maximum cumulative streamflow volume (or deficit) below a threshold (or its duration)

Table 5.1 briefly describes some key analysis techniques. Some common examples of frequency distributions include the Generalised Extreme Value

Table 5.1 Some examples of statistical analysis techniques in hydrology

Technique	Description
Frequency analyses (single site)	Transformation of a sequence of high- or low-flow extreme values assuming an underlying probability distribution and then fitting a straight line to the transformed values using standard statistical techniques; examples include flood frequency growth curves based on long-term time series of annual maximum flows and low flow return period estimates based on D-day flow volume statistics for drought analyses, where D represents the averaging period for the estimates (e.g. D=7 days)
Frequency analyses (regional)	Regional or pooling group techniques are widely used in flood analyses to help to compensate for shortfalls in the data available. The basis of the approach is to select observations from a number of similar (analogue) catchments; the values are then scaled and combined before analysis. Separate statistical regression relationships are sometimes developed for index values such as the mean or median flood based on catchment characteristics such as the area and the mean annual rainfall
Flow duration analyses	Analyses of the proportion of time for which a given flow is exceeded relative to a user-defined threshold, such as the 95 % value; estimates are often written in the form Qx where x is the assumed threshold (e.g. Q95). Estimates for the cumulative flow deficits below a given threshold are also of interest and are sometimes called run-sum values
Hydrograph separation techniques	Graphically based techniques to estimate the relative contributions of sub-surface and surface runoff contributions to river flows by hypothesising what the relative split is at any one time. Both manual and semiautomated techniques are used to perform the separation, providing estimates for parameters such as the surface runoff coefficient and indices describing the baseflow contribution, such as the Base Flow Index (BFI)
Trend analyses	Some typical approaches to detecting trends in rainfall or river gauge records include regression analyses, statistical tests (e.g. Mann-Kendall), comparisons of total or mean values for different time periods and stochastic techniques in which observed values are compared with values generated using statistical assumptions regarding any underlying trends and quasi-cyclical behaviour

(continued)

Box 5.1 (continued)
and Log-Pearson type III distributions for high flows and the Weibull and log-normal distributions for low flows (e.g. Smakhtin 2001, Tallaksen and van Lanen 2004, WMO 2008a, 2009). However, internationally, the choice is large with one survey (WMO 1989) listing some 10–20 types of distributions used for flood frequency analysis alone by national hydrological services and other organisations.

Ideally these types of analyses should be based on long-term records which include a representative selection of the types of events of interest, such as floods or droughts. A particular consideration is the extent to which estimates based on past values are likely to apply in the future (e.g. Stedinger and Griffis 2011, Madsen et al. 2014). In addition to variations in climate, some other potential issues to consider include the influences of changes in land use and water demand on flow regimes.

To help to overcome limitations on record lengths, stochastic techniques are sometimes used in which synthetic time series are generated which aim to mimic the statistical characteristics of the observed flows. These methods are generally well established for records based on monthly or annual averaging periods although are more challenging to apply for shorter intervals such as daily or sub-daily values, and for multiple sites. As with any modelling approach there are also limitations when estimating extreme values outside the range of calibration. Methods range from simple random sampling of historical records through to complex statistical techniques which aim to represent the spatial and temporal characteristics of observations for many gauges in a region. So-called continuous simulation approaches provide another option, in which synthetic rainfall series are generated and then used as inputs to rainfall-runoff models in order to estimate flows.

5.2 Forecasting Techniques

5.2.1 Rainfall-Runoff Models

Rainfall-runoff or hydrologic models form a key component in many forecasting systems. The main aim is to translate observations and/or forecasts of rainfall into estimates for river flows and sometimes to represent other factors such as the influences of snowmelt. Table 5.2 summarises some of the main processes which might need to be considered when developing or calibrating a model.

The importance of each contribution depends on the application; for example, infiltration losses may be a major issue in arid and semiarid regions but minor water abstractions of little significance in a flood forecasting model.

Later chapters discuss the use of rainfall-runoff models for a range of flood, drought, environmental and water resources applications. The terminology varies but – in general terms – some distinguishing features between types of models

Table 5.2 Some of the main processes which may need to be represented in a rainfall-runoff model; see Chap. 1 for a description of the hydrological cycle

Component	Item	Description
Surface	Runoff	Runoff from the soil surface and urban areas into streams, rivers, lakes, etc.
	Interception	Interception of precipitation by vegetation
	Infiltration	Infiltration of water from the land surface into the ground
	Snowmelt	Runoff due to melting snow, as a result of solar radiation and/or an increase in air temperature and/or rainfall on snowpack (see Chap. 8)
Soil	Evaporation/ evapotranspiration	Evaporation from bare soil areas and rainfall intercepted by vegetation and losses from water bodies (e.g. reservoirs, lakes, rivers)
	Transpiration	Uptake of water from the soil for transpiration by vegetation (trees, plants, grass, etc.)
	Percolation	Percolation of water from the soil to deeper layers towards the water table/aquifer
Sub-surface	Recharge	Recharge to the water table/aquifers from deep percolation and, to a lesser extent, directly from surface flows (e.g. in karstic regions)
	Baseflow	Outflow of water into the river network from sub-surface layers, sometimes called groundwater flow or discharge
Contaminants	Point or diffuse pollution	Pollution loads from farms, urban areas, etc., particularly during and following heavy rainfall events (see Chap. 12)
Artificial influences	Abstractions	Withdrawals of water for public water supply, irrigation, energy generation, industry, etc. (see Chap. 6)
	Discharges	Discharge of treated effluents and other return flows (see Chap. 6)
	Flow control	Influences from reservoir operations and other control structures (see Chap. 11)

include the way that they represent physical processes and how they are configured at a catchment scale. Model configuration issues are discussed later, whilst the main approaches to modelling processes are:

- Physically-based models – which typically use partial differential equations to describe how rainfall is translated into runoff and are sometimes called process-based, deterministic or distributed models
- Conceptual models – which use simpler, conceptual approaches to represent the conversion of rainfall to runoff, such as stores which fill and empty in response to variations in rainfall
- Data-driven models – which use transfer functions, artificial neural networks and similar approaches to estimate river flows given the available rainfall data and are sometimes called black-box models

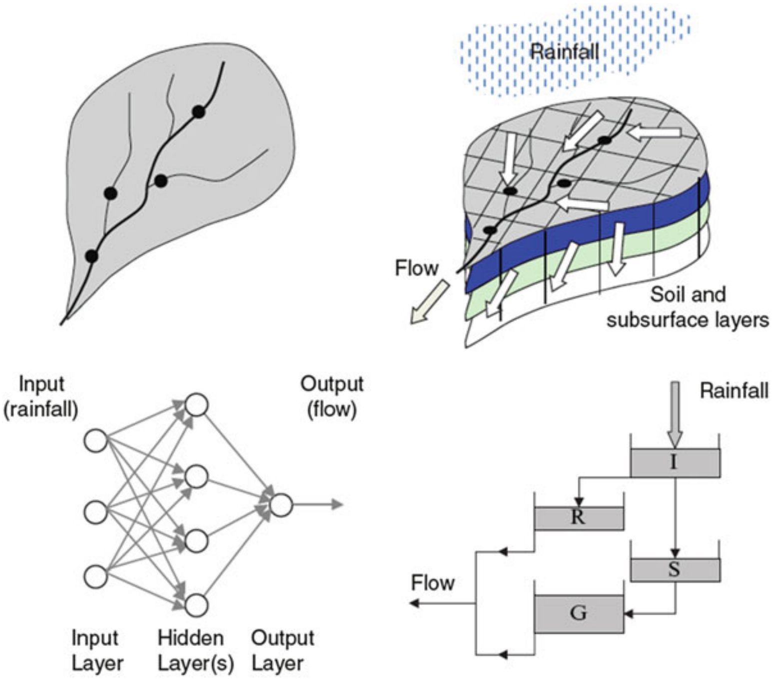

Fig. 5.3 Some simple examples of physically-based, conceptual and data-driven rainfall-runoff models, for simplicity excluding the evapotranspiration components. From *top left*, clockwise, (**a**) plan view of the catchment; (**b**) grid-based physically-based model with three soil and sub-surface layers; (**c**) conceptual model with interception, soil, surface runoff and groundwater stores; and (**d**) artificial neural network model (Adapted from Sene 2008)

Figure 5.3 provides a general illustration of these approaches. Various hybrid forms have also been developed such as distributed models which are based mainly around conceptual components and are often called physical-conceptual models and models which combine both conceptual and data-driven components.

For physically-based approaches, the catchment is usually represented on a uniform grid, although sometimes a variable grid or sub-basin approach is used. Typically several vertical layers are included representing various aspects of the soil and sub-surface processes. The estimated runoff from each cell is then routed to cells further downstream to estimate the total flows at points of interest.

This type of model is well suited for use with grid-based inputs such as satellite precipitation estimates and weather radar observations, although catchment-averaged raingauge estimates provide another option. Parameter values are typically estimated from the results of laboratory and field experiments and the values applied on other hydrologically similar catchments. The initial estimates are often based on spatial (GIS) analyses of factors such as soil types, land cover, flow pathways, geology and topography. However, usually some fine-tuning is required to calibrate outputs to gauge records, in part due to the difficulties in scaling up field-scale results to grid and catchment scales.

Whilst this type of model is widely used off-line in hydrological and water resources studies, for short- to medium-term forecasting applications simpler physical-conceptual types are the more usual approach. These still use a distributed formulation but incorporate simpler conceptual components for some or all of the key processes, such as stores of the types illustrated in Fig. 5.3. Chapter 13 discusses perhaps the most sophisticated application of this type of approach, which is for the land-atmosphere component of weather forecasting and climate models, in which the radiation and energy balances are also considered. However, simpler types are normally used for flood and water resources applications. Unlike with physically-based models, one key defining feature is often whether flows are routed between grid cells or zones, or these act in isolation. Indeed this choice is sometimes provided as a model configuration option and, as discussed in Chap. 9, the former configuration is often useful in larger river basins and the latter for flash flood applications.

For model calibration, again the aim is usually to derive initial estimates for as many parameters as possible from catchment characteristics but then to calibrate the remaining values. For conceptual models, by contrast, model parameters are usually estimated primarily from a comparison of observed and estimated flows. However, model developers often suggest typical ranges based on representative catchment characteristics or physical considerations. In some cases, automated fitting techniques are included to at least provide initial estimates for parameter values, sometimes providing a range of optimisation criteria and tools to help with calculating forecast verification statistics. This is perhaps the most common approach to rainfall-runoff modelling in flow forecasting applications, and several examples are presented in later chapters.

For data-driven models, the choice of model-fitting approach is strongly dependent on the model type. For example, for artificial neural networks, the inputs to each neuron are usually weighted and then transformed to an output using an activation or transfer function. The network is then calibrated (or ‘trained’) by adjusting the weighting factors and adding or removing neurons, using methods such as Bayesian techniques, genetic algorithms and stochastic approaches such as simulated annealing. This approach has been considered in many hydrological applications (e.g. ASCE 2000, Dawson and Wilby 1999) including demand forecasting, as discussed in Chap. 6. Similarly, for transfer function models, stochastic approaches are normally used for model identification. In some cases, the fitting process is guided by a physical interpretation of the underlying modes and timescales inherent in the catchment response, with one particular application being for flood forecasting (e.g. Young and Ratto 2009, Young et al. 2014).

There is much debate about the relative merits of each type of model with many reviews of this topic, including those by Arduino et al. 2005, Beven 2012, Sivakumar and Berndtsson 2009 and Todini 2007. Table 5.3 summarises some of the advantages which are often stated for physical-conceptual, conceptual and data-driven approaches together with references describing specific applications. Taken together these examples include applications in Australia, Brazil, Canada, China, Finland, France, the Netherlands, Sweden, the UK and the USA.

Table 5.3 Some potential advantages of different rainfall-runoff modelling approaches (Adapted from Sene 2008); the references provide examples of operational applications

Type	Description
Physical-conceptual models	Well suited to operate with spatially distributed inputs (weather radar, satellite or multisensor precipitation estimates, rainfall forecasts, multiple inflow locations, etc.)
	Can potentially represent variations in runoff with both storm direction and distribution over a catchment and events outside the calibration range
	Initial estimates for some, or all, parameter values can be related to catchment topography, soil types, channel characteristics, etc.
	Examples: Cole and Moore (2009), Collischonn et al. (2007), Cosgrove and Clark (2012), Javelle et al. (2012), Thielen et al. (2009), Vehviläinen et al. (2005), Yatheendradas et al. (2008)
Conceptual models	Fewer parameters to specify or calibrate than in physically-based approaches
	Easier to implement data assimilation than for physically-based models
	Examples: Burnash (1995), Lindström et al. (1997), Madsen (2000), Malone (1999), Moore (2007), Paquet and Garcon (2004), Quick (1995), Zhao (1992)
Data-driven models	Parsimonious, run times are fast, and models are tolerant to data loss; models are normally optimised directly for the lead times of interest
	The model-fitting or data assimilation approach automatically provides a measure of uncertainty for some types of model
	Examples: Beven (2009), Dawson and Wilby (1999), Lees et al. (1994), Yang and Han (2006), Young et al. (2014)

Intercomparison studies also provide useful insights into the strengths and limitations of specific ‘brands’ or types of model, although some care is needed in the design of the modelling experiment and interpretation of the results (e.g. Reed 1984, Clarke 2008). Some international examples include a series of studies led by the World Meteorological Organisation (WMO 1992) and the National Weather Service in the USA (Smith et al. 2004, Smith et al. 2012a) and as a component within the European Flood Forecasting System project (EFFS 2003).

Some other useful sources of information include the many papers and reports published as parts of long-term research initiatives such as the FRIEND programme and large-scale field experiments such as the Hydrological Cycle in Mediterranean Experiment (HyMeX) programme (http://www.hymex.org/) and the Hydrometeorology Testbed programme in the USA (http://hmt.noaa.gov/). Here FRIEND is a programme of research into topics such as ‘low flows, floods, variability of regimes, rainfall/runoff modelling, processes of streamflow generation, sediment transport, snow and glacier melt, climate change and variability and its uncertainties, and land-use impacts’ which since it was established in 1984 has involved more than 100 countries (http://www.unesco.org).

Depending on the type of model, the main data requirements are usually for rainfall and evaporation inputs, together with river flow observations for both model calibration and data assimilation. Some potential sources of real-time rainfall information include catchment-averaged raingauge observations, weather radar observations or satellite precipitation estimates. Rainfall forecasts also offer the potential to extend maximum useful lead times if justified by verification studies of the forecast performance. However, as discussed in Chap. 3, given the measurement difficulties evaporation or evapotranspiration estimates are often derived using indirect approaches such as the Penman or Penman-Monteith equation. Alternatively typical seasonal profiles are used in some cases. Similarly soil moisture estimates are usually derived from a water balance approach or using estimates from the previous model run. In contrast some data-driven techniques rely on more indirect measures of catchment state, such as the current river flow.

When choosing which overall modelling approach to use, in addition to a careful assessment of model performance, as discussed later some other considerations include factors such as data availability and how the model will be operated in a real-time setting. Some vendors also offer toolkit-based approaches to model development which allow components to be selected and configured according to the application. The familiarity of local modelling experts with the proposed type of model(s) also needs to be considered and, although a factor for all types of models, is a particular consideration for rainfall-runoff models due to the uncertainties in model calibration.

5.2.2 Flow Routing Models

The term flow routing normally describes the process of translating a flow hydrograph through a river network using physically-based or conceptual models. Simpler correlation models provide another option and are discussed in Box 5.2.

The main approaches are hydrological routing techniques and hydrodynamic models. Hydrological flow routing is the simpler of the two approaches, and some of the earliest methods to be developed were the Muskingum equation and reservoir routing (or level-pool) techniques. In both cases the mass balance for a river reach is expressed as a differential equation which relates the rate of change of volume to the difference between the inflows and outflows to the reach. In the reservoir routing approach, the storage is simply based on the assumed channel dimensions, whilst the Muskingum method conceptualises the flow hydrograph as consisting of rectangular (prism) and triangular (wedge) storage components.

Although empirically based, subsequent studies (Cunge 1969) have shown that, with the choice of a suitable grid length and time step, the Muskingum equation can be expressed as a simplified form of the St. Venant shallow water equations for fluid flow. These in turn are a simplification of the full Navier-Stokes equations for fluid flow which were first established in the nineteenth century and are based on conservation of both mass and momentum.

Some key parameters in the resulting Muskingum-Cunge formulation are the wave speed, which influences the time of travel in a river reach, and an attenuation parameter, which influences the timing and magnitude of flow peaks. In practice, both parameters vary with flow, particularly in situations in which the river goes out of bank onto the floodplain. Later developments have extended the method to include variable parameter values to help to allow for this effect (e.g. Price 1977, Tang et al. 1999).

Some other approximations to the St. Venant equations include the kinematic wave (e.g. Lighthill and Whitham 1955) and convection-diffusion equation approaches. Together with Muskingum-type models, these are perhaps the most widely used approaches in operational flow forecasting systems of the types described in later chapters. In the calculations, each river reach is usually divided into a number of sections, allowing other inputs such as tributary inflows and abstractions to be included at node points if required. Models are typically calibrated by trial and error or using automated optimisation routines, although some 'brands' of modelling software allow parameters such as the wave speed to be estimated from river cross-section survey data if this is available.

Hydrological routing techniques are normally formulated in terms of flows, so usually it is only possible to derive estimates for river levels at sites with stage-discharge relationships. Hydrodynamic models help to overcome this limitation and if required can account for a range of factors which normally cannot be considered when using simpler approaches, such as backwater influences and operations at weirs, gates, sluices and other control structures. Backwater effects arise when disturbances downstream of the location of interest propagate upstream, causing levels to change at that location, and are most likely to occur in rivers with a shallow slope. Some typical causes include tidal influences for rivers near to the coast and control structure operations, channel constrictions and tributary inflows at downstream locations. Other features such as floodplain flows, braided channels and flood defence structures can be included if required.

These potential advantages have led to the increasing use of hydrodynamic models in forecasting applications and computing times are nowadays less of a constraint than in the past, particularly if models are fine-tuned for real-time use. However, due to the need for topographic survey data, the development costs are often considerably higher than for hydrological routing approaches, so these types of models tend to be used mainly for higher-risk or impact applications. Some typical examples could include a flood warning system for a major city or a decision-support tool to help with managing water levels in an ecologically sensitive wetland. There is also increasing interest in coupling river forecasting models to urban drainage models to represent the interactions between surface and drainage flows (see Chaps. 9 and 11).

The main approaches to obtaining topographic survey data include depth- or echo-sounding surveys by boat and traditional ground-based surveys relative to a local benchmark. For example, river channel cross sections are typically surveyed at intervals of a few tens to hundreds of metres, depending on hydraulic characteristics and project requirements. Information on structures is ideally obtained from as-built drawings supplemented by information on current asset conditions obtained from recent site surveys. Other options include the use of Global Positioning System (GPS) devices to measure spot heights and the following remote-sensing techniques to estimate ground levels on the floodplain:

- Satellite data – using the land elevation outputs from sensors deployed as part of satellite missions, such as NASA's Terra satellite, and the Shuttle Radar Topography Mission (SRTM)

- LiDAR data – Light Detection and Ranging (LiDAR) data obtained from instruments flown on board aircraft or helicopters

LiDAR survey outputs are usually significantly more accurate than satellite-based values, with accuracies of the order of 0.1m vertically and 1m horizontally in some cases; however, there is a significant cost to collect and process the digital elevation data provided.

The usual approach to model design is to divide each river reach under consideration into a number of sections based on the channel survey data, with interpolated sections if necessary for computational reasons. Hydraulic structure characteristics, the floodplain topography and other features are added as required. Figure 5.4 illustrates a typical model configuration and forms part of an introduction to flood inundation mapping science prepared by the US Geological Survey (http://www.usgs.gov/water/).

If hydraulic structure operations are included, then these are normally represented using logical rules as discussed in Chap. 11. For flood applications, there are several possibilities for representing floodplain flows including as channels running alongside the main river, as a network of interconnected cells or reservoir units or using a fully two-dimensional modelling approach. For example, Pender and Néelz (2011) define the following types of models for use in flood inundation modelling:

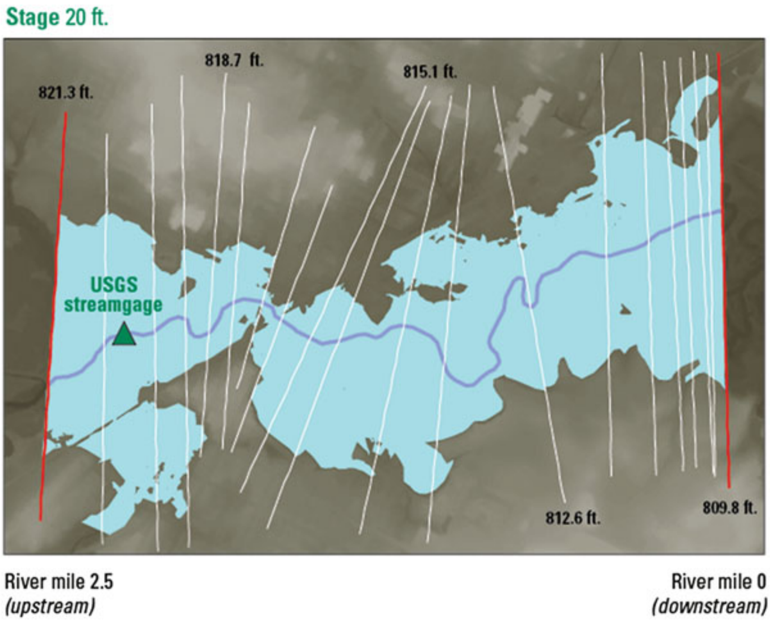

Fig. 5.4 The hydraulic model takes each individual water-surface elevation...and overlays them onto a ground-surface elevation model (the *brown*, gridded base layer) to determine how far flooding would extend (the *blue* areas). The *white lines* represent the model's perpendicular cross sections (Credit: US Geological Survey)

- Solution of the one-dimensional St. Venant equations (1D)
- 1D plus a storage cell approach to the simulation of floodplain flow (1D+)
- 2D minus the law of conservation of momentum for the floodplain flow (2D-)
- Solution of the two-dimensional shallow water equations (2D)
- 2D plus a solution for vertical velocities using continuity only (2D+)
- Solution of the three-dimensional Reynolds averaged Navier-Stokes equations (3D)

Here the numbers in brackets represent the dimensions of the model. Models are typically built by importing the available survey data into the modelling package and defining first estimates for key parameters such as loss coefficients at structures and bed roughness coefficients such as the Manning's n coefficient. Initial estimates are usually based on channel, floodplain and structure characteristics. First estimates for the contributions from any ungauged tributary inflows are also required (see later) together with conditions at the downstream boundary, which are normally based either on theoretical estimates or gauged values. Following these initial steps, the parameter values and ungauged inflow estimates are usually then fine-tuned to improve the fit between observed and forecast flows and in comparisons with any supplementary information available such as maps or satellite imagery of past flood inundation extents.

For real-time use, the main inputs usually include the gauged inflows at the upstream end of the model plus any observations available for tributary inflows. Depending on the application some other types of inputs may include:

- Control structure settings (see Chap. 11)
- Estimates for flow abstractions and discharges (see Chap. 13)
- Tide gauge observations and predictions and surge forecasts (see Chap. 8)

If model run times are an issue, then as discussed in Chap. 8, some options for reducing these include improving the model stability and convergence, removing bottlenecks to data transfer and simplifying the model at locations away from the main forecasting points (Chen et al. 2005, Werner et al. 2009).

Typically, due to computing limitations, most models currently used in short-range river forecasting applications are of the 1D or 1D+ type. In flood warning applications, these are usually used in conjunction with a suite of pre-calculated paper-based or digital flood inundation maps corresponding to different threshold levels, in some cases with GIS-based viewing software available to quickly navigate to the correct version. However, more computationally intensive approaches are increasingly becoming a feasible option for real-time use such as for floodplain inundation mapping (see Chap. 8) and surface water modelling in urban areas (see Chap. 9).

More generally in forecasting applications, it is important to check that models will continue to provide a solution even under extreme conditions and not fail due to stability or convergence issues in the numerical solution schemes. For example, this could require testing the model using synthetic inputs to represent conditions significantly beyond those experienced during the calibration period, such as unusually high flows, zero flows or rapid changes in levels, as might be caused by closing the gates in a control structure.

Box 5.2: Correlations and Transfer Functions

Correlation relationships provide another approach to estimating river levels or flows at downstream gauges from values further upstream. These are widely used as a backup to more sophisticated techniques and – despite the empirical basis – in some cases as the main approach for low-risk situations or when there are limitations on data availability or budgets. Some options for implementation include developing paper-based or spreadsheet-based charts or look-up tables and programming the coefficients into telemetry or forecasting systems.

Figure 5.5 illustrates the basis of the approach for a flood forecasting application. Here a peak-to-peak flow relationship is used to estimate flows at a downstream location from values which are measured or forecast at an upstream location. For illustration, the model has been applied to the full-flow range assuming a typical time delay to provide an estimate of the hydrograph at the downstream gauge. However, since the underlying relationships are usually based on peak values alone, this sometimes introduces attenuation-related errors on the rising and falling limb of the hydrograph so is not normally recommended.

Other factors which could potentially influence the results include any inflows or outflows between gauges, such as tributary inflows or abstractions and discharges. However, multiple sets of curves, or multiple regressions, with more than one input variable are sometimes used to attempt to account

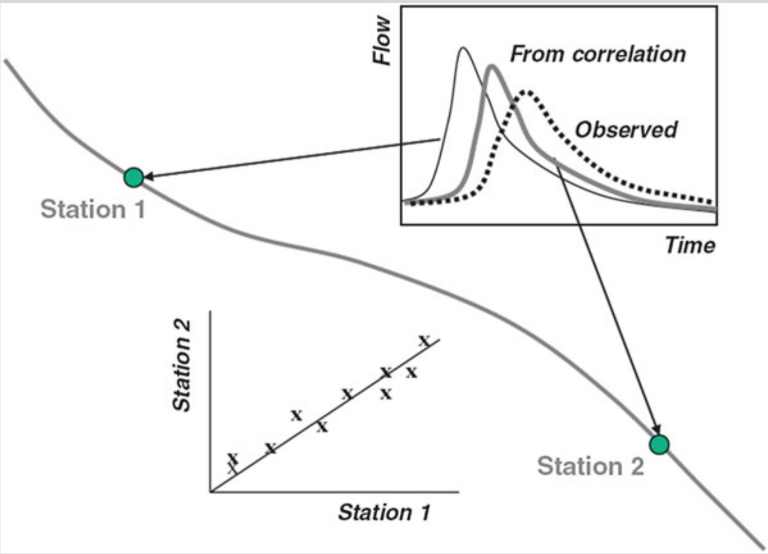

Fig. 5.5 Illustration of a peak-to-peak flow correlation relationship used to derive flows at a downstream gauge. For this example, the correlation-based forecast did not fully account for the flow attenuation which was subsequently observed

(continued)

Box 5.2 (continued)
for these effects and for other factors such as snowmelt (e.g. WMO 2009). For low flow applications, additional parameters are sometimes included such as cumulative rainfall and indices related to phenomena such as the El Niño-Southern Oscillation.

For some applications, it is desirable (or necessary) to derive regression relationships in terms of levels rather than flows; for example, for comparing peak levels with flood warning thresholds or for gauges without stage-discharge relationships. Whilst this provides a more direct approach to estimating levels, some additional factors which can affect the accuracy of the relationship include downstream (backwater) influences and hysteresis and other dynamic influences on the relationship between levels and flows (see Chap. 3).

In flood warning systems, some other simple empirical approaches include rate-of-rise triggers and time-of-travel maps. To calibrate rate-of-rise techniques, the hydrographs for several flood events at a river gauge are analysed to determine how quickly river levels rise through flood warning threshold levels. Typically both the average and worst-case values are considered operationally to predict how long it is likely to take to reach flooding thresholds. Another potential use for these estimates is to help with setting threshold levels in off-line studies to reflect the warning lead times required. A major limitation of this approach of course is the assumption that past behaviour will be repeated irrespective of other factors which come into play such as backwater influences or fast-rising floods beyond the range of calibration. Time-of-travel maps – whose purpose is to show typical time delays between flood peaks in a river network – suffer from similar limitations. Nevertheless, these types of techniques provide a useful backup to other approaches and a first indication of flooding potential.

In contrast, data-driven techniques provide a more sophisticated way to use the available observations or forecasts. Some examples include transfer functions and artificial neural networks of the types already discussed earlier in the context of rainfall-runoff modelling. Given the flexibility of these approaches, multiple inputs can be used if required of several different types, such as from raingauges and river gauges on tributaries or downstream from the location of interest, if backwater influences are a concern. For example, transfer function approaches have been used in operational flood forecasting of river levels (Lees et al. 1994, Young et al. 2014) and show promise in emulating the performance of more complex hydrodynamic models in probabilistic forecasting applications, where model run times are sometimes a constraint (e.g. Young et al. 2009).

5.2.3 Some Other Applications of Hydrodynamic Models

In addition to river modelling, hydrodynamic models are used in a range of other forecasting applications. These include modelling of reservoirs and lakes, coastal forecasting and groundwater modelling. Other examples discussed in later chapters include dam break and urban drainage models.

For reservoirs and lakes perhaps the main difference compared to river models is that main driving influences now include wind shear at the water surface and thermal effects. Indeed these factors are often more significant than the circulation driven by tributary inflows. Models are usually formulated using a three-dimensional grid with the result that run times are significantly longer than for a river application. Flow routing techniques are therefore an alternative if the main interest is in assessing inflows and volumes rather than the internal circulation.

In a full hydrodynamic model, the model grid is normally tailored in both the horizontal and vertical directions to help to capture key shoreline and depth-related processes, such as thermal stratification and surface currents. The key sources of survey data are normally bathymetric data captured by depth or acoustic sounders and digital terrain data for the shoreline. Water quality and ecological components are included as required and represented either as passive tracers or using sub-models to represent the effects of dilution, chemical reactions and the growth and decay of organisms (as appropriate). Chapter 12 discusses some examples of this approach for modelling harmful algal blooms and beach water quality problems.

For shallow water bodies, the typical approach is to use a two-dimensional model, provided that it is reasonable to assume that the water depth is small compared to horizontal length scales. In particular, this is the usual approach for coastal forecasting applications, typically using the outputs from numerical weather prediction models to provide the wind and pressure fields required at the ocean boundary. For example, Fig. 5.6 illustrates the information flow in the UK's operational storm

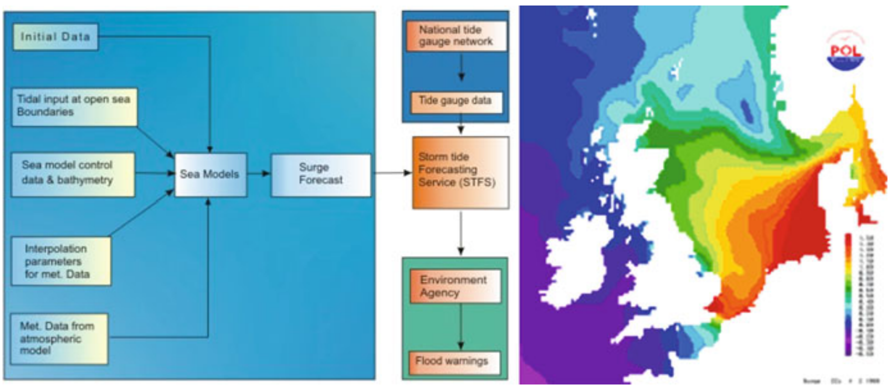

Fig. 5.6 Schematic diagram of the Surge Forecast and Flood Warning System (*left*) and predicted distribution of surge (m) at 2200 GMT 4/2/1999 from the CS3 model (*right*) (Reproduced with permission from the National Oceanography Centre; source: http://www.ntslf.org/)

tide forecasting service and an example of the output from a storm surge model for the coastline around the UK and western Europe. Chapter 8 discusses this topic in more detail in the context of flood forecasting for estuaries.

For coastal models, and some models for large lakes, wave models are included, and these typically use a phase-averaging approach which describes the key statistical characteristics of the wave climate (height, period, etc.) in the form of an energy balance equation. This normally relates the input of energy from the wind across the spectrum of wave frequencies to the dissipation of energy by factors such as wave-wave interactions, wave-current interactions and wave breaking (e.g. Komen et al. 1994, Tolman 1999).

In contrast, for groundwater modelling, the main terms to consider typically include rainfall, recharge and the outflows at springs, wells and boreholes and into the river system. Sub-surface flows are usually modelled on a two- or three-dimensional grid which is tailored to provide a higher resolution around the main features of interest such as boreholes, rivers, lakes and wetlands. Considerable detail is normally also included for the main geological controls on flows and a contaminant transport component added in water quality applications. However, simpler but considerably less accurate conceptual models are sometimes used in which groundwater flows are estimated from the sub-surface stores in a rainfall-runoff model or from a water accounting model considering the main terms in the water balance, such as recharge, abstractions and outflows.

In operational use, groundwater models can be either operated on demand or coupled to a river model to represent the interactions between surface and sub-surface flows. The timescales over which groundwater levels respond are usually considerably longer than for river flows so the main applications tend to be to support decision-making for water resources or drought applications, as discussed in Chaps. 10 and 13.

5.2.4 Model Configuration

Operational forecasting systems often include a wide range of model types such as rainfall-runoff models, flow routing models and models for specific features such as reservoirs and lakes. Due to potential bias and other issues, models should normally be calibrated using the same types of inputs as will be used in real-time, including for any data assimilation component; for example, not using raingauge observations for calibration if the model will be subsequently be operated using weather radar data as inputs.

For rainfall-runoff models, one key question is whether to use a lumped, semi-distributed or fully distributed approach, and Fig. 5.7 illustrates the differences between the first two of these approaches. In a semi-distributed model, the sub-catchment boundaries are typically defined to telemetered river or reservoir gauging stations rather than to river confluences, as they would normally be in an off-line simulation model. This is to allow the outputs to be updated in real-time via data assimilation. Lumped models in contrast are simpler to implement and may be all that is required for a small catchment or all that is justified given the data available.

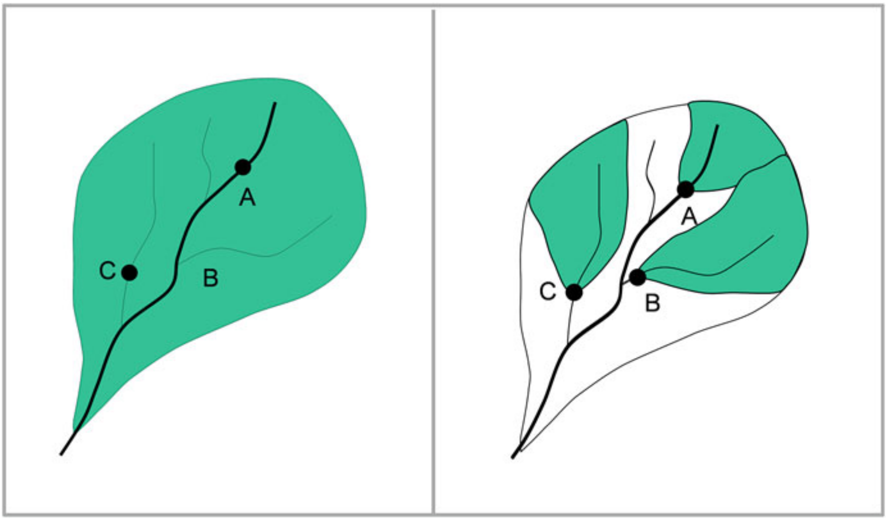

Fig. 5.7 Illustration of lumped and semi-distributed rainfall-runoff models (gauged areas shown *shaded*)

Alternatively another approach adopted in some software packages is to represent the entire catchment as a single entity within which flows are routed between representative (lumped) zones, defined based on factors such as land use, soil type and/or elevation range, or sub-basins or hydrological units

Typically, with the semi-distributed approach, rainfall-runoff and flow routing models are combined to form an integrated catchment model, perhaps using models of varying complexity; for example, a hydrodynamic approach might be required in the heavily populated lower reaches of a catchment but a simpler approach suffice for river reaches further upstream. In addition, as indicated by the unshaded areas in Fig. 5.7, estimates are usually required for the runoff from the ungauged parts of a catchment, and the main estimation techniques include:

- Parameter transfer – transferring parameter values for a model calibrated for a nearby gauged catchment with a similar hydrological response or using values from a model based on records from a river gauge upstream or downstream of the site of interest
- Regionalisation techniques – searching for regional regression or other relationships between the model parameters and catchment characteristics such as area, soil types and slope or adopting values from previous studies for that specific type of model
- Scale and lag approaches – scaling the flows measured at a telemetered gauge in a nearby catchment based on catchment area and possibly other factors such as average annual rainfall, including an appropriate time difference in the response if required

Each method has its own strengths and limitations; for example, scale and lag approaches have the advantage of using real-time data. However, this assumes that the ungauged catchment experiences the same flow response as the gauged catchment, thereby losing some of the natural variability in runoff. Parameter transfer and regionalisation techniques help to avoid this limitation but rely on the values being representative of the target catchment. Due to these uncertainties, in practice an iterative approach is often used to model calibration in which the ungauged flow contributions are treated as another source of uncertainty in the overall catchment model.

The other main rainfall-runoff modelling option is to use a grid-based distributed model, either for the entire basin or sub-catchments within it or an entire region. The grid length is normally chosen to match that of the rainfall observations that drive the model, and in some cases this may be less than the scale at which the model provides meaningful results, giving a false impression of model resolution. However, these types of issues are model dependent and need to be explored as part of calibration and verification studies. Data assimilation issues also need to be considered as discussed further in Sect. 5.3.

Another consideration, applicable to all types of rainfall-runoff model, is whether rainfall forecasts will be used as one of the inputs. This offers the potential to estimate flows at lead times beyond typical catchment response times; however, forecast uncertainty generally increases with lead time. Ideally the limitations on useful lead time would be assessed by verification studies using an archive of previous forecasts from a reforecasting exercise of the types discussed in Chap. 4.

The decision on whether to use rainfall forecasts in part links into the minimum lead times (and forecast accuracy) ideally required by end users. For example, in flood warning applications, some key timescales to consider include:

- Data transmission times – the time delay between making an observation and its receipt by telemetry (or other means) at a forecasting centre
- Model run times – the time taken to perform a model run including any pre- and post-processing tasks and multiple runs in an ensemble forecasting system
- Decision-making time – the time taken for forecasters (or other decision-makers) to interpret the information and decide whether to issuing a warning
- Warning dissemination time – the time taken to issue warnings to civil protection authorities, emergency responders and the public (as appropriate)

These delays all need to be considered as part of the model design process. One outcome of course is that user requirements, or expectations, may be unachievable with current systems, requiring further investment in models and observation systems. This topic is discussed further in later chapters including some possible options for reducing warning dissemination times.

A related issue is that of model run frequencies and output intervals. For hydrological models, the degree of user control over these quantities varies between types and ‘brands’ of model, being completely flexible in some cases but ‘hard-wired’ in others, such as to daily or monthly values alone. In contrast for hydrodynamic models, the internal model time step is usually of the order of seconds to minutes, and the output interval is a user-defined setting. However, model run times are a significant issue for some types of hydrodynamic model, influencing the frequency with which they can be operated.

For short lead-time applications, models are often required to run on the same schedule as that used for telemetry data inputs; for example, values in the range 5–15 min are typical in flash flood warning systems. In contrast for some drought forecasting applications, a daily model run may suffice and weekly or monthly runs may be sufficient in some water resources applications. These issues have some influence on the choice of model as illustrated by the example in Fig. 5.8. The values are hypothetical but help to illustrate why statistical and water balance approaches are sometimes adequate when using averaging periods of several days or more, whereas a more dynamic approach is often desirable at shorter timescales.

In addition to these configuration issues, some other factors which may influence the choice of overall modelling approach include:

- The level of expertise required to develop models
- The modelling software available
- Data availability both in real-time and for model calibration
- Additional requirements such as for topographic survey data
- The budget available for implementation
- Experience with using the model type(s) elsewhere

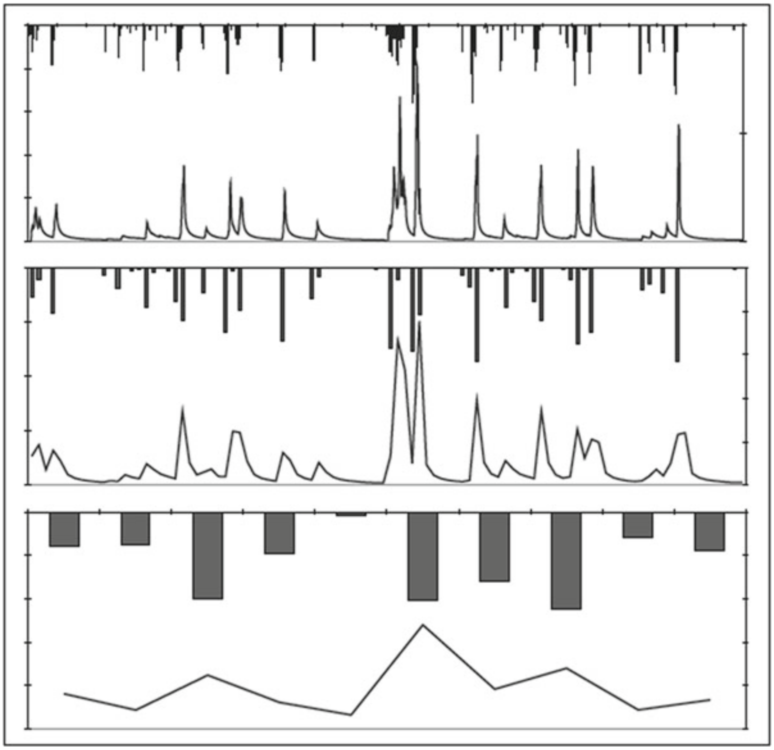

Fig. 5.8 Illustration of the relationship between rainfall and river flows for a range of averaging periods applied to the same datasets using (**a**) hourly, (**b**) daily and (**c**) 10-daily intervals (Note that 10-day values are often used in agricultural applications)

Some techniques to help decide on an approach include cost-benefit, multi-criteria and risk-based approaches. For example, in a flood warning application for a high-risk location such as a major city, an integrated catchment modelling approach could possibly be justified combining meteorological, rainfall-runoff, hydrodynamic and coastal forecasting components. In contrast, for lower-risk areas such as farmland and riverside footpaths, a simpler approach such as a correlation model could be sufficient. For higher-risk locations there may be scope to install temporary instrumentation and/or perform exploratory modelling studies to evaluate different modelling options.

Once a model has been developed, it is often operated in parallel with existing procedures before deciding whether to make the transition to operational use. Some possible outcomes could then include recognition that further development work is required and/or improved instrumentation or that the model adds value to the process and so should be implemented. In the latter case some associated requirements include staff training and deciding how to formalise the use of the model outputs in operational procedures, including any limitations on how the outputs are to be used. Chapter 7 discusses this topic further.

Another important consideration is whether it is realistic to operate the model as required (on demand) or if a forecasting system will be required. Historically, there were often limitations on the types of models which could be operated in real-time systems, although increasingly these adopt a 'plug-and-play' open-architecture approach allowing any model type which meets the required specifications to be included. The following section discusses these types of systems in more detail.

5.3 Operational Considerations

5.3.1 Flow Forecasting Systems

In operational use, a hydrological forecasting model is usually driven by inputs from a wide range of sources, including meteorological observations and forecasts and river and catchment observations. Whilst it is sometimes practicable to operate models on demand, using one-off transfers of data, often some degree of automation is useful, particularly when using telemetry and/or ensemble forecast inputs.

This normally requires use of a forecasting system, and, even for less frequent model run frequencies, this approach can help with labour-intensive tasks such as data validation and the post-processing of model outputs. This allows duty officers to focus more on interpreting forecasts and providing advice to end users and reduces the scope for data processing errors. However, there are obviously some initial costs to consider plus ongoing staff training and system support needs. Also, forecaster inputs are normally still essential, and, due to the uncertainties in model outputs, most forecasting centres require that forecasts are inspected and approved before use. The level of forecaster intervention is partly dependent on local procedures, though; for example, manual adjustments to model states are more widely used in the USA than in Europe (e.g. Liu et al. 2012, Pagano et al. 2014).

Table 5.4 lists some of the main options which are typically included in a forecasting system and Fig. 5.9 illustrates a typical overall configuration. Systems of this type are used by many organisations and several examples are discussed in later chapters. Most modern systems include a map-based interface and additional components are usually included for alarm handling and the automated dissemination of warnings. In some systems the forecasting and telemetry components are combined.

When integrating a system into operational use, in addition to developing standard operating procedures, issues such as staff training, system maintenance and performance monitoring need to be considered. In particular it is important to consider the resilience to failure of components such as computer servers and telemetry links and the possibility of model failure, such as if a hydrodynamic model run fails to converge. As discussed in Chap. 4, this may entail establishing level of service agreements with data and forecast providers, robust telecommunications links and

Table 5.4 Some examples of the functionality typically available in a flow forecasting system

Item	Description
Data gathering	Receipt of data from instruments such as raingauges and river gauging stations and possibly weather radar and satellite systems and forecasts from meteorological services
Preprocessing	Initial validation of data using checks on range, rate of change, etc., and intercomparisons with nearby records, and possibly automated infilling of short gaps, application of predefined correction factors and additional processing options, such as for estimating catchment average rainfall
Model run control	Automated scheduling of model runs, possibly with simpler alternative models selected in case of model run-time failures and alternative data sources in case of instrument or telemetry failures. Also automated re-initialisation of model states following a gap in operations
Data assimilation	Use of observations to initialise model states and/or improve the forecast inputs and outputs, and possibly model parameters, as discussed in Sect. 5.3.2, including options to view the impacts of data assimilation on forecasts
Scenario management ('what-if' scenarios)	The option for users to assess the impacts of predefined scenarios such as for flood defence breaches, dam breaks and reservoir operations. Also to consider rainfall scenarios such as 'no future rainfall' and 'rain continues as now', or replication of the rainfall corresponding to a previous event
Post-processing	Further processing of the forecast outputs into a range of map-based, graphical and tabulated formats and forecast verification statistics, and for onward transmission to other systems such as decision-support systems
Data management	Storage of key settings and both input data and forecast results for subsequent post-event reviews and analysis with replay facilities for operator training. Data models, data exchange formats, metadata standards and georeferencing systems often conform to WMO, Open Geospatial Consortium (OGC), OpenMI and other international standards
System configuration	A range of tools to assist with model calibration and configuration, plus control over other settings such as threshold values, passwords and the maps, graphs and tables visible to users; a typical distinction being between expert users, who can make configuration changes, and key users who rely on the outputs for operational decision-making

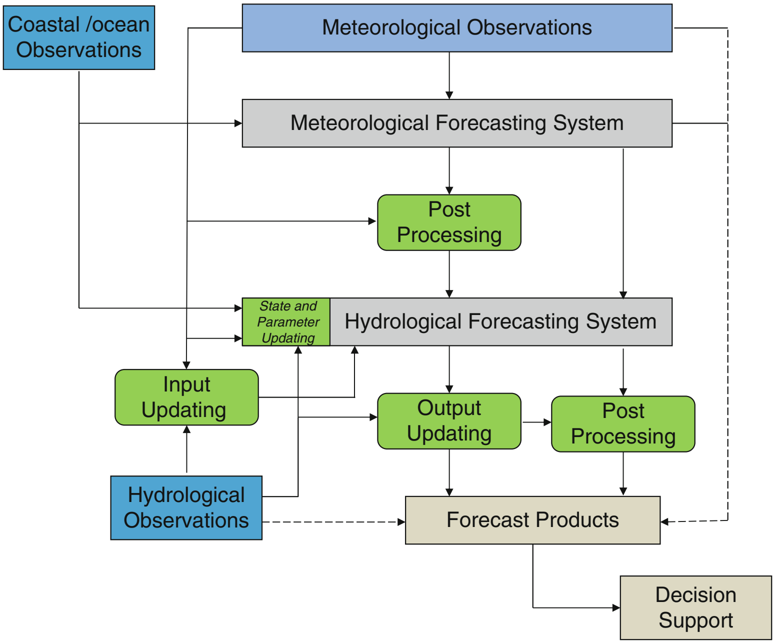

Fig. 5.9 Illustration of some typical linkages between meteorological and hydrological forecasting systems. Note that not all components and links are necessarily required; in particular normally only one approach is used for data assimilation. Similar diagrams have been produced for the data assimilation aspects by WMO (1992) and Refsgaard (1997) amongst others

around-the-clock support facilities. Additional software tools may be required for processing weather radar, satellite and other more specialised types of data inputs if these are not provided as part of the system. The nature of data-sharing agreements depends on the application, but WMO (2012b) notes that some typical aspects of any agreement are as follows:

- A high proportion of data or information items should be delivered to meet a specific time frame, e.g. any 6-h rainfall forecast should be delivered to the receiving agency within a useful time limit, say 30 min from issue time
- For any set of data delivered, the proportion of items should be consistently high, e.g. 90 % of all reporting stations
- Over an extended period of data delivery, such as 1 year, the outages should not exceed more than a small fraction of the period, e.g. 5 days in any one year and no more than 2 consecutive days
- Response time to restore data delivery from individual sites should be matched to the long-term standard of service
- Where quantitative forecasts (rainfall, temperature) are concerned, these quantities need some form of evaluation and assessment for comparison against subsequently observed values. Performance analysis is not straightforward, and suitable tolerances or limits for indicating success have to be clearly agreed between provider and user

Reliability issues are particularly important in early warning applications and some approaches to improving resilience include providing standby generators for use if power supplies fail, allowing users to enter data manually if telemetry links fail, and using dual-path telemetry systems. Simpler types of model such as correlation models are often operated in parallel to the main model both as a backup and to provide a 'reality-check' on outputs. In some systems, there is the facility to schedule several model runs within each forecast cycle both to provide additional resilience and to allow sensitivity checks to be performed; for example, using different sources of rainfall inputs such as raingauge, weather radar and satellite-based precipitation estimates.

Many systems use computer servers running in parallel, and sometimes these are located at different sites to help to guard against widespread issues such as earthquakes or flooding. Regarding models, hard copy (paper) based options such as charts and look-up tables are usually provided as a backup in case of complete system failure. As indicated in Table 5.4, another option is to allow a hierarchy of data inputs in which the system switches automatically to an alternate input if the primary source is not available. For example, for raingauge inputs alternative gauges might be designated in case a single gauge fails with predefined storm profiles or weather radar inputs available for use if all gauges fail.

Despite the advantages of a forecasting system, it is important to note that it is sometimes possible to implement quite sophisticated approaches at a lower cost which are entirely, or mainly, manually based. For example, in the early days of hydrometry, most flood warning systems relied on observers feeding information by telephone or radio (or even telegraph) to a central location for interpretation by duty officers. With a network of observers making observations at regular intervals, it is sometimes feasible to receive reports several times per day for comparison with threshold values and operation of simple forecasting models, such as correlation models. This approach is still widely used in community-based flood warning systems, as discussed further in Chap. 9, and in some national systems where resources are limited.

5.3.2 Data Assimilation

Data assimilation is the process of using recent observations to initialise models and improve forecast outputs. In hydrology it is often called real-time updating or adaptation and is a key feature which distinguishes real-time forecasting models from their off-line (simulation) counterparts. As indicated in Fig. 5.9 the main approaches are (e.g. Refsgaard 1997):

- Input updating – adjustment of the inputs to the model
- State updating – adjustment of the initial states of the model
- Parameter updating – adjustment of the model parameters
- Output updating – adjustment of the model forecasts

State updating and parameter updating routines are usually implemented internally to the model or via a bespoke interface within the forecasting system, whilst the other two methods are applied directly to the input or output values. This terminology differs slightly from that used in meteorology where the term data assimilation normally refers to state updating.

Figure 5.10 shows a simple example of output updating for a flow forecasting application. Here the forecast from the time of the most recent observation is adjusted based on the outputs from a statistical model driven by recent forecast errors, based on a comparison of observed and forecast flows. This type of updating is often called error prediction and in this example the forecast outputs are adjusted downwards since the model has been overestimating flows in the recent past.

Output updating is perhaps the most widely used approach of all and can be applied to almost any type of model, including at intermediate gauge locations within an integrated catchment model.

In contrast for state updating the main aim is to improve the initial conditions for each model run, and one widespread application is to initialise conceptual rainfall-runoff models. In contrast, for distributed rainfall-runoff models, a key challenge is that the forecast errors observed at gauge locations need to be distributed over the whole model domain. This naturally suggests making use of spatially distributed inputs such as satellite or ground-based observations of soil moisture or snow cover. Typically variational or ensemble Kalman filter techniques are used, although this is a developing area (e.g. Lee et al. 2012, Le Dimet et al. 2009, Ni-Meister 2008). As noted by Liu et al. (2012), these techniques are furthest advanced for land-surface models (LSM) of the types used in numerical weather forecasting for which:

> A major difference between LSMs and "conventional" hydrologic models is that the former include a full description of the radiation and coupled surface water and energy balance at diurnal time scales and – when coupled to an atmospheric model – are able to consider the effect of atmospheric transmissivity on sensor observations. These features make it easier to assimilate satellite land surface temperature and microwave brightness temperature observations

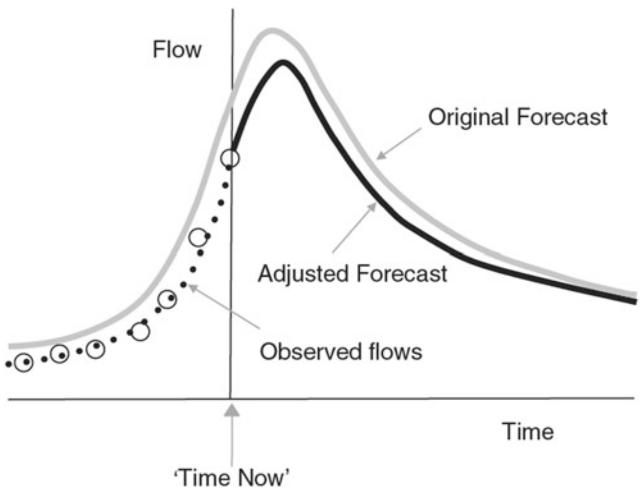

Fig. 5.10 Example of an error prediction approach to data assimilation (Adapted from Sene 2013)

and that:

> Some of the main challenges to successful assimilation of remote sensing data in hydrologic forecasting are related to the model extensions required, the mapping of observations to model variables, the specification of model and observation errors, and – for operational implementation – near-real time access to remote sensing data services and the design and configuration of operational DA systems

In contrast, for input updating techniques, the aim is to attempt to allow for uncertainties in inputs to the model. For example, this approach is sometimes used with hydrodynamic models by adjusting the inflows iteratively to obtain a better match between observed and forecast values at the key forecasting points; the main challenge being that there are usually several such points within the domain of a hydrodynamic model with the risk that adjustments will cause spurious transient effects. Post-processing modifications to meteorological forecasts are sometimes also viewed as a type of input updating or preprocessing and are discussed in Chap. 4.

Regarding parameter updating, views differ on whether it is meaningful to apply this technique to models where the parameter values describe physical processes. However, this approach is widely used with data-driven modelling techniques such as transfer function models. Another option is to restrict any adjustments to within a plausible range such as when adjusting the river channel and floodplain roughness coefficients in a hydrodynamic model.

When deciding on the approach to use, often the main constraint is the range of options offered within the modelling software or forecasting system, unless a bespoke approach is to be developed. However, increasingly a toolkit approach is offered with a range of options to choose from. More generally there have been many intercomparison studies and reviews of approaches to data assimilation including those described in the following papers and reports: Goswami et al. (2005), Liu et al. (2012), Moore (1999), O'Connell and Clarke (1981), Refsgaard (1997), Serban and Askew (1991), Weerts et al. (2014) and WMO (2009). Table 5.5 provides examples of some of the more common approaches.

Table 5.5 Some examples of data assimilation techniques used in real-time flow forecasting applications (adapted from Sene 2013)

Type	Model type	Examples
Input	Hydrodynamic	Distribution of errors into tributary inflows or the use of pseudo-inflows
State	General	Kalman filtering (including extended and ensemble versions)
	Conceptual rainfall-runoff	Adjustment of store contents
	Physical-conceptual rainfall-runoff	Variational and Kalman filter techniques
	Hydrodynamic	Ensemble Kalman filter
Parameter	Transfer function	Adjustment of model parameters
	Hydrodynamic	Adjustment of roughness coefficients
Output	General	Time series analysis techniques, adaptive gain techniques, artificial neural networks

In many cases – as shown by the example in Fig. 5.10 – a typical characteristic is for the magnitude of any changes to decrease at longer lead times, as the information content of the observations decreases. As a result, when relying on observations alone, the maximum lead time at which data assimilation is effective is typically comparable to the catchment response time at the forecasting point(s) of interest. For small catchments response times might only be of the order of a few hours or less, but for large catchments with significant storage, such as extensive winter snow cover, the dependence on initial conditions could potentially extend for many weeks or months; a topic which is discussed further in Chap. 13.

Data assimilation is widely recommended as best practice when suitable observations are available, although some potential issues to consider include (Environment Agency 2002):

- Updating does not remove the need to have a well-calibrated model, able to represent response for a wide range of types of event. In particular, some forms of updating algorithm can struggle with correcting errors in the timing of peaks
- The quality of the updated forecast will depend on the quality of the input data, and erroneous data can degrade, rather than improve, the accuracy of forecasts. Usually, it is advisable to validate data inputs either automatically or manually before they are used for data assimilation
- For real-time control applications, the use of updating needs to be factored into the system design from the start, since otherwise unwanted feedback effects can develop; for example, control gates 'hunting' for optimum settings

For example, when using a chain of models such as in an integrated catchment model, it is generally better to attempt to resolve issues at each model boundary rather than to rely on data assimilation to compensate for problems with data or the model calibration. This is particularly the case for more physically based approaches where models seek to preserve continuity of mass and possibly momentum. In addition to improving the model calibration, some examples of areas where improvements are often possible are in catchment rainfall estimates (see Chap. 2) and to stage-discharge relationships (see Chap. 3).

Before deciding whether to implement a data assimilation approach operationally, the model performance should be evaluated using a range of lead-time dependent measures such as those described in the following section. In operational use if possible the original and adjusted forecasts should be inspected before being approved for use to check for any issues. Indeed as noted earlier, in some forecasting services manually-based procedures play an important role throughout the process, particularly for medium- to long-term forecasts; for example, relating to seasonal snowmelt. Data assimilation techniques are perhaps most highly developed for flood forecasting applications, and this topic is discussed further in Chap. 8, which includes a number of additional citations. Later chapters discuss further examples in the areas of water quality forecasting (Chap. 12), snowmelt forecasting (Chaps. 8 and 13), reservoir modelling (Chap. 11) and water resources applications (Chap. 13). Section 5.3.4 also discusses probabilistic data assimilation techniques.

5.3.3 Forecast Verification

When a hydrological model is used operationally, a process is usually required to evaluate the accuracy of forecasts. In some organisations there may be a formal requirement to report on model performance both as part of routine procedures and following floods or other events. Other wider aspects of the system performance are often considered such as the success (or otherwise) with forecast delivery and user satisfaction with the service, considering issues such as whether warning messages were received and public understanding of the information conveyed. For example, WMO (2006) notes that:

> A "client focus", increased accountability (especially in the financial area), an improved service delivery system, and a requirement for comprehensive reporting on activities and outputs are just some aspects of a more demanding public sector environment

For the narrower technical issue of evaluating model performance, some particular areas of interest for early warning applications typically include success at forecasting extreme values and the crossing of thresholds. By contrast, some useful diagnostic measures for water resources applications typically include flow duration statistics, mean flows, cumulative volumes and the overall water balance. Some options for presenting results include graphical, tabulated and map-based outputs plus more advanced visualisation techniques such as animated time sequences.

The usual approach to verification is to compare observed and forecast values over a range of lead times, and some measures which are typically used include:

- The root mean square error (RMSE)
- The bias
- The R^2 efficiency (sometimes called the Nash-Sutcliffe Efficiency)
- Errors in the timing and magnitude of the peak flows

The performance for different lead times is often of interest, providing insights into the maximum time at which a forecast still adds value; examples include the error in peak flows at a 3-h lead time or the R^2 efficiency at a 12-h lead time. Indeed, some forms of data-driven model are optimised specifically for the required range of lead times as part of the model identification and calibration process. In some cases, to allow comparisons between different catchments, it is convenient to normalise values by statistical measures of the types discussed in Box 5.1; for example, using flow duration values (e.g. Q95) or flood flow estimates (e.g. the median annual flood).

When evaluating performance relative to thresholds, the usual approach is to use a contingency table, and Table 5.6 shows an example for a flood warning application. Even for this simple 2×2 example, it is possible to define a wide range of performance measures, and these include the hit rate or Probability of Detection (POD = A/(A + C)), the False Alarm Ratio (FAR = B/(A + B)) and the Critical Success Index or threat score (CSI = A/(A + B + C)). An additional quantity, useful in meteorology but perhaps less relevant in hydrological applications, is the Probability of

Table 5.6 Example of a 2 by 2 contingency table for flood warning applications; A, B, C and D are total values accumulated over a number of flood events

	Threshold crossed (observations)	Threshold not crossed (observations)
Threshold crossed (forecast)	A (*Hits*)	B *(False alarms)*
Threshold not crossed (forecast)	C *(Misses)*	D

False Detection (POFD = B/(B + D)); this is sometimes known as the false alarm rate and should be distinguished from the false alarm ratio, although the two terms are often used interchangeably.

Higher-order tables can be devised by introducing additional thresholds, such as values relating to percentile ranges.

Threshold-based measures are also used in evaluating the performance of probabilistic forecasts together with a range of other statistics. In general terms some desirable aspects of probabilistic flood forecasts include (e.g. Weerts et al. 2014):

- Reliability: the agreement between the forecast probability and the observed frequency over many cases
- Sharpness: the tendency to forecast with a concentration of large probabilities around some value, as opposed to small probabilities spread over a wide range of values
- Resolution/discrimination: the ability of the forecast to produce different probabilities of exceedance for different events/discriminate between true events and true non-events

Some examples of measures which assess these various attributes include the Brier Skill Score, the Continuous Ranked Probability Score (in continuous or discrete forms), the Reliability, and the Relative Operating Characteristic. Here a skill score assesses the added value provided by a forecast compared to a reference forecast, such as assuming the climatological mean or persistence, although the benchmark used needs to be tailored to the application (Pappenberger et al. 2015).

More generally, when considering which performance measures to use, there are various advantages and disadvantages to each approach for both deterministic and probabilistic forecasts. For example, some methods give information on the magnitude of the error, but no indication of whether this is an over- or under- prediction, whilst others are sensitive to timing errors or to outlying values.

There have been many investigations into these types of issues (e.g. Stanski et al. 1989, Demargne et al. 2009, Jolliffe and Stephenson 2011, Wilks 2011), and it is usually desirable to use several measures to assess different aspects of the model performance, and how this meets user requirements. In addition, sensitivity tests are often used to draw out different aspects of performance, such as evaluating outputs with a range of different inputs such as rainfall forecasts, catchment average rainfall derived from raingauges, and weather radar observations.

When calculating performance measures off-line, it is usually desirable to use several years or more of observations and forecasts. Long-term records are of particular importance for flood- and drought-related applications in order to sample a representative range of extreme events. This typically requires a reforecasting or hindcasting exercise similar to the meteorological examples discussed in Chap. 4. However, generally this is a less time-consuming task, although repeating runs using a hydrodynamic model is potentially computationally expensive.

Another consideration is that if possible the forecast outputs should reflect the current observational networks used to drive the model and the model in its current form. Where changes to instrumentation have been made in the hindcast period, this then requires estimates to be derived for the values which would have occurred if those changes had been in place over the whole period; for example, if new river gauges have been installed or raingauges moved to new locations. Catchment change may also need to be considered, such as the construction of reservoirs or flow diversion channels during the period of interest. For hydrological forecasting models, these types of analyses have many similarities to the types of data validation and infilling work which is routinely performed during model calibration so are not necessarily too onerous. However, as discussed earlier this is usually a considerable undertaking for any meteorological forecasting component unless reforecast values are already available – or can be commissioned – from a national meteorological service or research organisation.

5.3.4 Forecast Uncertainty

As discussed in Chap. 1, uncertainty estimates are increasingly provided with both meteorological and hydrological forecasts. Although there can be some challenges in interpretation, numerous review studies have found that many users would actively welcome more information of this type (e.g. National Research Council 2006) and also that 'over time, and with sufficient experience and user education, it is possible to improve the level of user understanding and sophistication' (WMO 2008b).

There are many different ways to visualise the outputs and several examples are presented in later chapters. For example, in the USA the uncertainty in the tracks of hurricane forecasts has been presented to the public for many years in the form of 'plumes' or 'cones of uncertainty'. In another example, many meteorological services now attach probabilities to events such as thunderstorms or heavy rainfall, such as that 'there is a 60 % or greater chance that there will be heavy rainfall in your county this afternoon'.

More specialised users often require the raw probabilistic outputs for use in their own decision-making processes. Indeed for many years, water resources managers and hydropower operators in the USA have used long-term ensemble streamflow predictions to assist in operations, particularly during the spring snowmelt season. More generally there is much development work underway in this area for a range of applications with particular interest in risk-based approaches to issuing warnings, in which decisions are made based on a combination of probability and consequence.

Chapter 7 provides a general introduction to these topics and additional examples are presented in later chapters.

Regarding the more technical issue of how to generate probabilistic flow forecasts, this is a rapidly developing area and ideas on the best approaches to use are still evolving. For example, for the Hydrologic Ensemble Forecast System (HEFS) in the USA (Fig. 5.11), some primary objectives (NOAA/NWS 2011) are that the output forecast ensembles must:

- Span lead times from one hour to one year or more (defaulting to climatology) with seamless transitions between lead-time regimes (e.g. weather to climate, short to medium to seasonal range)
- Be calibrated from a probabilistic standpoint for relevant forecast periods
- Be spatially and temporally consistent, thus linkable (routable) across RFC (*River Forecast Center*) domains
- Effectively capture the information available from current operational weather to climate forecast systems by utilizing meteorological ensemble forecasts (e.g. precipitation and temperature) that are calibrated from a probabilistic standpoint for relevant forecast periods
- Be consistent – i.e. using similar data and methods – with retrospective forecast ensembles that are used for verification and training/optimization of user decision-support tools
- Be verified via a comprehensive verification system that can generate products qualifying the expected performance of the output streamflow ensembles

In general terms, the main sources of uncertainty in model outputs arise from fundamental issues with the model design (often called model structural issues) and uncertainties in the model parameters, initial conditions and boundary conditions (e.g. Beven 2009). Sometimes these are classified as initialisation, modelling and

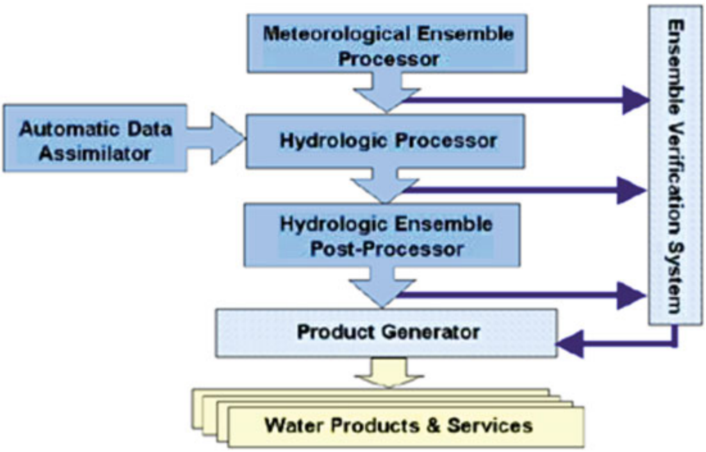

Fig. 5.11 Basic capabilities of an ensemble hydrologic forecast system (NOAA/National Weather Service 2011)

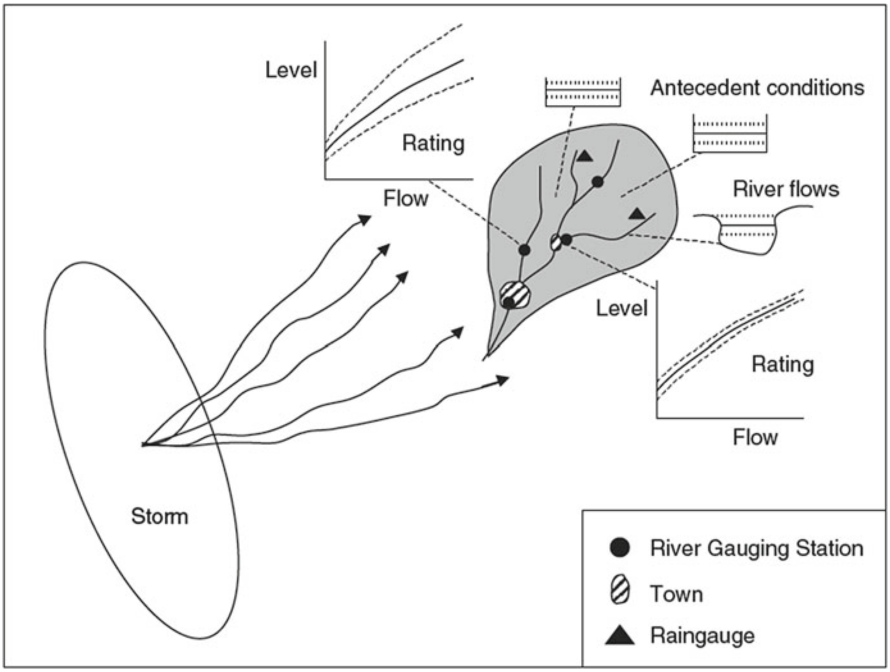

Fig. 5.12 Illustration of some sources of uncertainty for a catchment flood forecasting problem (Sene 2008)

forcing errors. Some examples include uncertainties in rainfall forecasts and in raingauge and river flow observations; uncertainty estimates are also increasingly provided with weather radar outputs and multisensor precipitation estimates (see Chap. 2).

Figure 5.12 illustrates some of the issues which typically need to be considered when using an integrated catchment model. Here, several possible scenarios are shown for the track of a storm approaching the catchment, together with indicative confidence intervals for catchment antecedent conditions and the stage-discharge relationships at river gauging stations. Ideally the uncertainties arising from these and other sources would be combined into a single estimate for the uncertainty in the resulting flow estimates, although in practice the importance of each source depends on factors such as:

- The locations of forecasting points within the catchment
- The catchment response times to those locations
- The maximum lead times ideally required for an effective operational response

For example, in a large river basin, the uncertainty in rainfall observations and forecasts typically dominates in the headwaters, whilst in the lower reaches flow routing (e.g. rating curve) uncertainty is often a key factor. Alternatively, for a given forecasting point, rainfall forecast uncertainty usually dominates at lead times greater than the catchment response time, with other sources playing a greater role at shorter lead times (e.g. Blöschl 2008, Werner et al. 2014).

Some general approaches to estimating the uncertainty in model outputs (e.g. Beven 2009) include:

- Forward uncertainty propagation – methods in which the uncertainty from individual sources is estimated. This is then propagated through the chain of model components which make up the overall model
- Probabilistic data assimilation – techniques which both reduce and provide estimates for the overall uncertainty as part of the assimilation process
- Probabilistic forecast calibration – post-processing of model outputs to estimate the probabilistic content based on a statistical model of past forecasting performance; this is sometimes called conditioning or statistical post-processing

Simpler sensitivity tests also provide a qualitative indication of the uncertainties arising from different model inputs. For example, Werner et al. (2014) describe the following examples: 'what-if' scenarios, standardised multipliers on meteorological and hydrological inputs, combinations of meteorological input products, and best guess and 5 % and 95 % confidence interval quantitative precipitation forecasts. Here, in one of the examples cited, the third of these items allows duty officers to compare flow forecasts derived using the following inputs as part of the routine system operation:

- Observed catchment rainfall
- Weather radar observations
- Weather radar-based nowcasts
- Numerical weather prediction model forecasts
- A zero rainfall profile

Time-lagged ensembles provide another simple qualitative option in which the outputs from recent forecast runs are shown together on a graph to give an idea of the consistency between model runs.

Forward uncertainty propagation techniques are usually most effective when there is one clearly identifiable source of uncertainty which dominates at the lead times of interest. At long lead times this is often from rainfall inputs, and perhaps the first approach to consider the impacts on flows was the 'Extended Streamflow Prediction' method in the USA. The basis of the technique, now usually called ensemble streamflow prediction (or ESP), is to draw samples of the historical observational records for rainfall and air temperature for use as model inputs, using the current model states as the starting point for each run (e.g. Day 1985, Ingram et al. 1998). For example, Day (1985) notes that 'The procedure was originally developed for water supply forecasting in snowmelt areas, but it can also be used to produce spring flood outlooks, forecasts for navigation, inflow hydrographs for reservoir operation, and time series needed for risk analysis during droughts'. Several examples of application of this technique are presented in later chapters, and later developments have included techniques for conditioning samples on current rainfall and air temperature forecasts and for statistical post-processing of the ensemble outputs (e.g. Demargne et al. 2007, Wood and Schaake 2008).

Since ensemble meteorological forecasts became routinely available in the 1990s, these have been increasingly used in operational flow forecasting systems (e.g. Cloke and Pappenberger 2009, Wetterhall et al. 2013, Demargne et al. 2014). Again several operational examples of this approach are discussed in later chapters. Multi-model techniques have also been considered to help to assess the uncertainty arising from model structural issues (e.g. Zappa et al. 2008) plus methods to help to assess the uncertainties arising from other areas such as high flow rating curves or catchment average rainfall estimates. However, since a separate model run is required for each ensemble member, the computing overhead can be high for some types of model, such as hydrodynamic models. Also when multiple sources of uncertainty need to be considered, these may not be fully represented and there are sometimes issues relating to parameter independence (e.g. Beven 2009).

These considerations have led to the increasing use of probabilistic data assimilation and forecast calibration techniques, and Table 5.7 shows some examples of these approaches. These have been chosen to illustrate the range of complexity of approaches, although it is important to note that this is a rapidly developing area, and many other techniques have been proposed for operational use (e.g. van Andel et al. 2013, Demargne et al. 2014). Also as noted earlier some types of data-driven

Table 5.7 Some examples of probabilistic data assimilation and forecast calibration techniques (Adapted from Sene 2013)

Type	Method	Some factors to consider
Probabilistic data assimilation	Adaptive gain (e.g. Smith et al. 2012b)	Simple to implement and applicable to any type of model output; continues to provide estimates in case of telemetry failure
	Ensemble Kalman filtering (e.g. Butts et al. 2005, Weerts and El Sarafy 2006)	Requires some assumptions about the relationship between inputs and outputs, and sometimes there are potential run-time issues due to the ensemble nature of the approach
	Particle filtering (e.g. Moradkhani et al. 2005)	As for ensemble Kalman filtering but fewer prior assumptions required (although possibly more sensitive to the assumptions made)
Probabilistic forecast calibration	Bayesian uncertainty processors (e.g. Krzysztofowicz and Kelly 2000; Todini 2008; Coccia and Todini 2011)	Bayesian approaches to estimate the predictive uncertainty given current and previous observations and current model forecasts; for example, using model conditional and hydrological uncertainty processors
	Quantile regression (e.g. Weerts et al. 2011)	A statistical approach calibrated for predefined quantile values and lead times
	ESP post-processor (Seo et al. 2006)	A statistical approach using a combination of probability matching and recursive linear regression techniques
	Bayesian Model Averaging (e.g. Raftery et al. 2005)	A technique for combining ensemble members into a single distribution, normally best used with the outputs from several different types or 'brands' of model

models automatically provide estimates for the uncertainty as part of the data assimilation approach (e.g. Young et al. 2014).

One potential advantage of data assimilation techniques is the potential to adapt – at least to some extent – to event-specific factors when they occur. However, as for their deterministic counterparts, the maximum lead times at which these types of techniques are most effective are typically comparable to the catchment response times to the forecasting point(s) of interest. In some situations, there may therefore be advantages in combining techniques (e.g. Beven 2009, Sene et al. 2014), for example using data assimilation approaches in combination with other approaches such as ensemble or statistical post-processing techniques (e.g. Moore et al. 2010, Liu et al. 2012).

Regarding the choice of approach typically a number of other factors need to be considered. In addition to the operational requirement, these include the level of risk, the catchment response time, required forecast lead times and the software, computing facilities and budgets available (e.g. Sene et al. 2014). Also long-term flow and other records are normally required to calibrate and test techniques, sometimes requiring a reforecasting or hindcasting exercise as described in the previous section. As in other aspects of flow forecasting, methods usually need to be calibrated using the same model configuration that will be used operationally, including the same data inputs and data assimilation components.

Suitable threshold values or other decision-making criteria also need to be defined, as discussed in Chap. 7 and later chapters. If an ensemble forecasting approach is used, then the outputs should be calibrated if required for anything other than visualisation or qualitative assessments, and again this is a rapidly developing area (e.g. Liu et al. 2012). Viewed more widely, there are of course additional uncertainties in the forecasting and warning chain; for example, relating to how forecasters interpret model outputs and how users interpret the warning messages or forecast guidance received.

Another consideration is whether estimates are required for complete probability density functions or selected quantiles and – as noted earlier – whether the preferred approach requires multiple runs of the forecasting model in real-time, which may lead to run-time issues in some cases, such as for hydrodynamic models. For integrated catchment models, there is also the question of where to intervene in the chain of model outputs and the potential interactions and inter-relationships between variables, and the data assimilation and post-processing routines, which is an interesting area for research.

In terms of operational implementations, uncertainty estimation techniques are perhaps most advanced for flood forecasting, water resources and reservoir operation applications, and Chaps. 8, 10 and 13 provide some additional examples. More generally as noted in Chap. 1, the international Hydrologic Ensemble Prediction EXperiment (HEPEX) is a key driver for improvements (Schaake et al. 2007; http://hepex.irstea.fr/), with the outputs including regular workshops and several special editions of journals describing the latest advances (e.g. Deidda et al. 2012, Cloke et al. 2013, Seo et al. 2014).

5.4 Summary

- Flow forecasting models are used to provide information to support decision-making in a wide range of hydrological applications, such as for reservoir operations, water resources management and in flood and drought warning systems. Meteorological forecasts can help to extend the maximum useful lead time of forecasts.
- For river flows, the main modelling options are rainfall-runoff and flow routing models. This includes lumped, semi-distributed and distributed rainfall-runoff models in conceptual, data-driven or physically-based forms and hydrological or hydrodynamic routing components. Models are often combined into integrated catchment models, and real-time distributed models are increasingly used in flood warning and water resources applications. Additional components may be required to represent the influence of reservoirs, lakes, tidal influences and other aspects of the catchment response.
- Many factors influence the choice of modelling approach. In addition to issues such as costs, the level of risk, institutional capacity and data availability, some key technical factors include the catchment characteristics, the typical response times to the forecasting points of interest and the maximum forecast lead times ideally required by users.
- Whilst manual techniques are still widely used, some potential benefits from automated forecasting systems include improvements to data management, greater flexibility in model operation and a wider range of forecast products. However, the resilience of the overall system needs to be considered as part of the design with backup procedures in place in case of failure of any component.
- A forecasting system can also facilitate the use of data assimilation techniques. These have the potential to improve forecasting performance provided that data quality or reliability issues would not degrade the model outputs. The main approaches are input, state, parameter and output updating techniques and include error prediction, Kalman filter and variational techniques.
- The main aims in forecast verification are typically to assess model performance, guide future developments and report on system performance. Some key areas of interest include the shape and timing of hydrographs, the success at forecasting the crossing of threshold values and the probabilistic content of the outputs (if applicable). Usually several measures should be considered to obtain an overall view of model performance.
- In recent years ensemble and probabilistic forecasting techniques have become standard practice in an increasing number of hydrological services, with a view to improved decision-making. This is a rapidly developing area, and probabilistic data assimilation and forecast calibration techniques are also increasingly used. In some cases, there may be advantages in using a combination of approaches.

References

Anderson MG, McDonnell JJ (Eds) (2009) Encyclopedia of Hydrological Sciences. Wiley, Chichester

Arduino G, Reggiani P, Todini E (2005) Recent advances in flood forecasting and flood risk assessment. Hydrol Earth Syst Sci 9(4): 280–284

ASCE (2000) Artificial neural networks in hydrology II: Hydrologic applications. Journal of Hydrologic Engineering, 5(2): 124–137

Bedient PB, Huber WC, Vieux BE (2012) Hydrology and Floodplain Analysis (5th ed.), Pearson

Beven KJ (2009) Environmental Modelling: An Uncertain Future. Routledge, London

Beven KJ (2012) Rainfall-Runoff Modelling – the Primer, 2nd edn. Wiley-Blackwell, Chichester

Blöschl G (2008) Flood warning–on the value of local information. Int J River Basin Manag 6(1):41–50

Blöschl G, Sivapalan M, Wagener T, Viglione A, Savenije H (Eds.) (2013) Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales. Cambridge University Press, Cambridge

Burnash RJC (1995) The NWS River Forecast System – catchment modeling. In: Singh VP (ed) Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch

Butts MB, Falk AK, Hartnack J, Madsen H, Klinting A, Van Kalken T, Cadman D, Price D (2005) Ensemble-based methods for data assimilation and uncertainty estimation in the FLOODRELIEF project. ACTIF international conference on innovation advances and implementation of flood forecasting technology, Tromsø, Norway, 17–19 October 2005

Chanson H (2004) The Hydraulics of Open Channel Flow: An Introduction, 2nd edn. Butterworth-Heinemann, Oxford

Chen Y, Sene KJ, Hearn K (2005) Converting Section 105 or SFRM hydrodynamic river models for real time forecasting applications. 40th Defra Flood and Coastal Defence Conference, York, England

Clarke RT (2008) A critique of present procedures used to compare performance of rainfall-runoff models. J Hydrol 352(3–4):379–387

Cloke HL, Pappenberger F (2009) Ensemble flood forecasting: a review. J Hydrol 375(3–4):613–626

Cloke HL, Pappenberger F, van Andel SJ, Schaake J, Thielen J, Ramos M (2013) Preface and papers. Special Issue: Hydrological Ensemble Prediction Systems (HEPS), Hydrological Processes, 27(1)

Coccia G, Todini E (2011) Recent developments in predictive uncertainty assessment based on the model conditional processor approach. Hydrol Earth Syst Sci 15:3253–3274

Cole SJ, Moore RJ (2009) Distributed hydrological modelling using weather radar in gauged and ungauged basins. Adv Water Resour 32(7):1107–1120

Collischonn W, Allasia DG, Silva BC, Tucci CEM (2007) The MGB-IPH model for large scale rainfall runoff modeling. Hydrol. Sci. J. 52(5): 878–895

Cosgrove BA, Clark E (2012) Overview and initial evaluation of the Distributed Hydrologic Model Threshold Frequency (DHM-TF) flash flood forecasting system. NOAA Tech. Report, U.S. Department of Commerce, Silver Spring

Cunge JA (1969) On the subject of a flood propagation computation method (Muskingum Method). Journal of Hydraulic Research, 7: 205–230

Dawson CW, Wilby RL (1999) A comparison of artificial neural networks used for flow forecasting. Hydrol Earth Syst Sci 3:529–540

Day GN (1985) Extended streamflow forecasting using NWSRFS. J Water Resour Plan Manage 111(2):157–170

Deidda R, Bàrdossy A, Carsteanu AA, Grossi G, Langousis A, Pappenberger F (2012) Precipitation uncertainty and variability: observations, ensemble simulation and downscaling. Hydrology and Earth System Sciences Special Edition

Demargne J, Wu L, Seo DJ, Schaake J (2007) Experimental hydrometeorological and hydrological ensemble forecasts and their verification in the US National Weather Service. Proceeding of the Symposium HS2004 at IUGG2007, Perugia, July 2007. IAHS Publication 313

Demargne J, Mullusky M, Werner K, Adams T, Lindsey S, Schwein N, Marosi W, Welles E (2009) Application of forecast verification science to operational river forecasting in the US National Weather Service. Bull Am Meteorol Soc 89:779–784

Demargne J, Wu L, Regonda SK, Brown JD, Lee H, He M, Seo D-J, Hartman R, Herr HD, Fresch M, Schaake J, Zhu Y (2014) The science of NOAA's operational Hydrologic Ensemble Forecast Service. Bulletin of the American Meteorological Society, 95: 79–98

EFFS (2003) European Flood Forecasting Systems: Final Report WP8. Deliverable 8.3, WL/Delft Hydraulics, Delft

Environment Agency (2002) Fluvial flood forecasting for flood warning – real time modelling. Defra/Environment Agency Flood and Coastal Defence R&D Programme. R&D Technical Report W5C-013/5/TR, London

Goswami M, O'Connor KM, Bhattarai KP, Shamseldin AY (2005) Assessing the performance of eight real time updating models and procedures for the Brosna river. Hydrol Earth Syst Sci 9(4):394–411

Ingram JJ, Fread DL, Larson LW (1998) Improving real-time hydrological services in the USA. Part I: Ensemble Generated Probabilistic Forecasts. Hydrology in a Changing Environment, Vol. III, British Hydrological Society, Exeter, UK

Javelle P, Pansu J, Arnaud P, Bidet Y, Janet B (2012) The AIGA method: an operational method using radar rainfall for flood warning in the South of France. Weather Radar and Hydrology (Eds. Moore RJ, Cole SJ, Illingworth AJ), IAHS Publication 351, Wallingford

Ji Z (2008) Hydrodynamics and water quality: modelling rivers, lakes and estuaries. Wiley, Chichester

Jolliffe IT, Stephenson DB (2011) Forecast verification. A practitioner's guide in atmospheric science, 2nd edn. Wiley, Chichester

Komen GJ, Cavaleri P, Donelan M, Hasselmann K, Hasselmann S, Janssen P (1994) Dynamics and Modelling of Ocean Waves. Cambridge University Press, Cambridge

Krzysztofowicz R, Kelly KS (2000) Hydrologic uncertainty processor for probabilistic river stage forecasting. Water Resour Res 36(11):3265–3277

Le Dimet F-X, Castaings W, Ngnepieba P, Vieux B (2009) Data assimilation in hydrology: variational approach. In Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications, Springer, Berlin-Heidelberg

Lee H, Seo DJ, Liu Y, Koren V, McKee P, Corby R (2012) Variational assimilation of streamflow into operational distributed hydrologic models: effect of spatiotemporal adjustment scale. Hydrol Earth Syst Sci Discuss 9:93–138

Lees M, Young PC, Ferguson S, Beven KJ, Burns J (1994) An adaptive flood warning system for the River Nith at Dumfries. In River Flood Hydraulics (Eds. White WR, Watts J), John Wiley and Sons, Chichester

Lighthill MJ, Whitham GB (1955) On kinematic waves: I – flood movement in long rivers. Proc R Soc Lond, Series A 229:281–316

Lindström G, Johannson B, Persson M, Gardelin M, Bergström S (1997) Development and test of the distributed HBV-96 hydrological model. J Hydrol 201:272–288

Liu Y, Weerts AH, Clark M, Hendricks Franssen H-J, Kumar S, Moradkhani H, Seo D-J, Schwanenberg S, Smith P, van Dijk AIJM, van Velzen N, He M, Lee H, Noh SJ, Rakovec O, Restrepo P (2012) Advancing data assimilation in operational hydrologic forecasting: progress, challenges, and emerging opportunities. Hydrol. Earth Syst. Sci. Discuss., 9: 3415–3472

Madsen H (2000) Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. J Hydrol 235(3–4):276–288

Madsen H, Lawrence D, Lang M, Martinkova M, Kjeldsen TR (2014) Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. Journal of Hydrology, 519, Part D: 3634–3650

Malone T (1999) Using URBS for real time flood modelling. Water 99: Joint Congress; 25th Hydrology & Water Resources Symposium, 2nd International Conference on Water Resources & Environment Research

McMahon TA, Adeloye AJ (2005) Water Resources Yield. Water Resources Publications LLC, Colorado

Moore RJ (1999) Real-time flood forecasting systems: perspectives and prospects. In: Casale R, Margottini C (eds) Floods and landslides: integrated risk assessment. Springer, Berlin/Heidelberg

Moore RJ (2007) The PDM rainfall runoff model. Hydrol Earth Syst Sci 11(1):483–499

Moore RJ, Robson AJ, Cole SJ, Howard PJ, Weerts A, Sene K (2010) Sources of uncertainty and probability bands for flood forecasts: an upland catchment case study. Geophysical Research Abstracts, 12, EGU2010-151609

Moradkhani H, Hsu K-L, Gupta H, Sorooshian S (2005) Uncertainty assessment of hydrologic model states and parameters: sequential data assimilation using the particle filter. Water Resour Res 41:W05012

National Research Council (2006) Completing the forecast: characterizing and communicating uncertainty for better decisions using weather and climate forecasts. National Academies Press, Washington, DC

Ni-Meister W (2008) Recent advances on soil moisture data assimilation. Phys Geogr 29(1):19–37

NOAA/NWS (2011) Hydrologic Ensemble Forecast Service – Requirements Version 4.0, June 10, 2011. Office of Hydrologic Development, Washington

O'Connell PE, Clarke RT (1981) Adaptive hydrological forecasting – a review. Hydrol Sci Bull 26(2):179–205

Pagano TC, Wood AW, Ramos M-H, Cloke HL, Pappenberger F, Clark MP, Cranston M, Kavetski D, Mathevet T, Sorooshian S, Verkade JS (2014) Challenges of Operational River Forecasting. J. Hydrometeor, 15, 1692–1707

Pappenberger F, Ramos MH, Cloke HL, Wetterhall F, Alfieri L, Bogner K, Mueller A, Salamon P (2015) How do I know if my forecasts are better? Using benchmarks in hydrological ensemble prediction. J Hydrol 522:697–713

Paquet E, Garcon R (2004) Hydrometeorological forecast at EDF-DTG MORDOR hydrological model. 4th international MOPEX workshop, Paris, July 2004

Pender G, Néelz S (2011) Flood inundation modelling to support flood risk management. In: Pender G, Faulkner H (eds) Flood risk science and management, 1st edn. John Wiley & Sons Chichester

Price RK (1977) FLOUT – A River Catchment Flood Model, Report No. IT 168, Hydraulics Research Station, Wallingford

Quick MC (1995) The UBC watershed model. In: Singh VP (ed) Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch

Raftery AE, Gneiting T, Balabdaoui F, Polakowski M (2005) Using Bayesian Model Averaging to calibrate forecast ensembles. Mon Weather Rev 133:1155–1174

Reed DW (1984) A review of British flood forecasting practice. Institute of Hydrology, Report No. 90, Wallingford

Refsgaard JC (1997) Validation and intercomparison of different updating procedures for real-time forecasting. Nord Hydrol 28(2):65–84

Schaake JC, Hamill TM, Buizza R, Clark M (2007) HEPEX: the Hydrological Ensemble Prediction Experiment. Bull Am Meteorol Soc 88:1541–1547

Sene K (2008) Flood Warning, Forecasting and Emergency Response. Springer, Dordrecht

Sene K (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht

Sene K, Weerts AH, Beven K, Moore RJ, Whitlow C, Laeger S, Cross R (2014) Uncertainty estimation in fluvial flood forecasting applications. In: Beven K, Hall J (eds) Applied Uncertainty Analysis for Flood Risk Management. Imperial College Press, London

Seo D-J, Herr HD, Schaake JC (2006) A statistical post-processor for accounting of hydrologic uncertainty in short-range ensemble streamflow prediction. Hydrol. Earth Syst. Sci. Discuss., 3: 1987–2035

Seo D-J, Liu Y, Moradkhani H, Weerts A (2014) Ensemble prediction and data assimilation for operational hydrology. Special Section: Ensemble Prediction and Data Assimilation for Operational Hydrology. Journal of Hydrology, 519(D)
Serban P, Askew AJ (1991) Hydrological forecasting and updating procedures. IAHS Publ. No. 201: 357–369
Sherman LK (1932) Streamflow from rainfall by the unit graph method. Engineering News Record, 108: 501–505
Shuttleworth WJ (2012) Terrestrial Hydrometeorology. Wiley-Blackwell, Chichester
Singh VP (ed) (1995) Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch
Sivakumar B, Berndtsson R (2009) Modeling and prediction of complex environmental systems. Editorial and 14 papers. J Stoch Environ Res Risk Assess 23(7):861–862
Smakhtin VU (2001) Low flow hydrology: a review. Journal of Hydrology, 240: 147–186
Smith MB, Seo DJ, Koren VI, Reed SM, Zhang Z, Duan Q, Moreda F, Cong S (2004) The Distributed Model lntercomparison Project (DMIP): motivation and experiment design. Journal of Hydrology, 298(1–4): 4–26
Smith MB, Koren V, Reed S, Zhang Z, Zhang Y, Moreda F, Cui D, Mizukami N, Anderson EA, Cosgrove BA (2012a) The Distributed Model Intercomparison Project – Phase 2: motivation and design of the Oklahoma experiments. J Hydrol 418–419:3–16
Smith PJ, Beven KJ, Weerts AH, Leedal D (2012b) Adaptive correction of deterministic models to produce accurate probabilistic forecasts. Hydrol Earth Syst Sci 16:2783–2799
Stanski HR.,Wilson LJ, Burrows WR (1989) Survey of common verification methods in meteorology. World Weather Watch Technical Report No.8, WMO/TD No.358. World Meteorological Organisation, Geneva
Stedinger JR, Griffis VW (2011) Getting From Here to Where? Flood Frequency Analysis and Climate. JAWRA Journal of the American Water Resources Association, 47(3): 506–513
Tallaksen LM, van Lanen HAJ (2004) Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science 48, Elsevier, Amsterdam
Tang X, Knight DW, Samuels PG (1999) Volume conservation in variable parameter Muskingum Cunge method. Journal of Hydraulic Engineering, 112: 610–620
Thielen J, Bartholmes J, Ramos M-H, de Roo A (2009) The European Flood Alert System – Part 1: concept and development. Hydrol Earth Syst Sci 13:125–140
Todini E (2007) Hydrological catchment modeling: past, present and future. Hydrol Earth Syst Sci 11(1):468–482
Todini E (2008) A model conditional processor to assess predictive uncertainty in flood forecasting. Int J River Basin Manag 6(2):123–137
Tolman HL (1999) User Manual and System Documentation of WAVEWATCH-III, Version 1.18. NOAA/NWS/NCEP/OMB Technical Note 166, National Weather Service, NOAA, US Department of Commerce
van Andel SJ, Weerts A, Schaake J, Bogner K (2013) Post-processing hydrological ensemble predictions intercomparison experiment. Hydrol. Process., 27(1); 158–161
Vehviläinen B, Huttunen M, Huttunen I (2005) Hydrological forecasting and real time monitoring in Finland: the Watershed Simulation and Forecasting System. ACTIF international conference on innovation advances and implementation of flood forecasting technology, Tromsø, Norway, 17–19 Oct 2005
Weerts AH, El Sarafy G (2006) Particle filtering and ensemble Kalman Filtering state updating with hydrological conceptual rainfall-runoff models. Water Resources Research, 42: W09403, 1–17
Weerts AH, Winsemius HC, Verkade JS (2011) Estimation of predictive hydrological uncertainty using quantile regression: examples from the National Flood Forecasting System (England and Wales). Hydrol Earth Syst Sci 15:255–265
Weerts AH, Seo DJ, Werner M, Schaake J (2014) Operational hydrological ensemble forecasting. In: Beven K, Hall J (eds) Applied Uncertainty Analysis for Flood Risk Management. Imperial College Press, London

Werner M, Cranston M, Harrison T, Whitfield D, Schellekens J (2009) Recent developments in operational flood forecasting in England, Wales and Scotland. Meteorol Appl 16(1):13–22

Werner M, Reggiani P, Weerts A (2014) Quantifying and reducing uncertainties in operational forecasting: examples from the Delft-FEWS forecasting system. In: Beven K, Hall J (eds) Applied Uncertainty Analysis for Flood Risk Management. Imperial College Press, London

Wetterhall F, Pappenberger F, Alfieri L, Cloke HL, Thielen-del Pozo J, Balabanova S, Daňhelka J, Vogelbacher A, Salamon P, Carrasco I, Cabrera-Tordera AJ, Corzo-Toscano M, Garcia-Padilla M, Garcia-Sanchez RJ, Ardilouze C, Jurela S, Terek B, Csik A, Casey J, Stankūnavičius G, Ceres V, Sprokkereef E, Stam J, Anghel E, Vladikovic D, Alionte Eklund C, Hjerdt N, Djerv H, Holmberg F, Nilsson J, Nyström K, Sušnik M, Hazlinger M, Holubecka M (2013) HESS Opinions "Forecaster priorities for improving probabilistic flood forecasts". Hydrol. Earth Syst. Sci., 17: 4389–4399

Wilks DS (2011) Statistical methods in the atmospheric sciences, 3rd edn. Academic Press, Amsterdam

WMO (1989) Statistical distributions for flood frequency analysis. Operational Hydrology Report No. 33, Geneva

WMO (1992) Simulated real time intercomparison of hydrological models. Operational Hydrology Report No. 38, WMO-No. 779, Geneva

WMO (2006) Guidelines on the Role, Operation and Management of National Hydrological Services. Operational Hydrology Report No. 49, WMO-No. 1003, Geneva

WMO (2008a) Manual on low-flow estimation and prediction. Operational Hydrology Report No. 50, WMO-No. 1029, Geneva

WMO (2008b) Guidelines on Communicating Forecast Uncertainty. WMO/TD-No. 1422, Geneva

WMO (2009) Guide to Hydrological Practices, 6th edn. WMO-No. 168, Geneva

WMO (2011) Manual on Flood Forecasting and Warning. WMO-No. 1072, Geneva

WMO (2012a) Technical Material for Water Resources Assessment. Technical Report Series No. 2, WMO-No. 1095, Geneva

WMO (2012b) Climate and Meteorological Information Requirements for Water Management: A review of issues. WMO-No. 1094, Geneva

Wood AW, Schaake JC (2008) Correcting errors in streamflow forecast ensemble mean and spread. Journal of Hydrometeorology, 9(1): 132–148

Yang Z, Han D (2006) Derivation of unit hydrograph using a transfer function approach. Water Resour Res 42(1):1–9

Yatheendradas S, Wagener T, Gupta H, Unkrich C, Goodrich D, Schaffner M, Stewart A (2008) Understanding uncertainty in distributed flash flood forecasting for semiarid regions. Water Resour Res 44:W05S19

Young PC, Ratto M (2009) A unified approach to environmental systems modeling. J Stoch Environ Res Risk Assess 23(7):1037–1057

Young P, Leedal D, Beven K (2009) Reduced order emulation of distributed hydraulic simulation models. Paper WeB7.2. The 15th IFAC Symposium on System Identification, July 6–8, 2009, Saint-Malo, France

Young PC, Romanowicz R, Beven K (2014) A data-based mechanistic modelling approach to real-time flood forecasting. In: Beven K, Hall J (eds) Applied Uncertainty Analysis for Flood Risk Management. Imperial College Press, London

Zappa M, Rotach MW, Arpagaus M, Dorninger M, Hegg C, Montani A, Ranzi R, Ament F, Germann U, Grossi G, Jaun S, Rossa A, Vogt S, Walser A, Wehrhan J, Wunram C (2008) MAP D-PHASE: real-time demonstration of hydrological ensemble prediction systems. Special Issue Article-HEPEX Workshop: Stresa, Italy, June 2007. Atmospheric Science Letters, 9(2): 80–87

Zhao R-J (1992) The Xin'anjiang model applied in China. J Hydrol 135:371–381

Chapter 6
Demand Forecasting

Abstract Estimates for water abstractions are often required in hydrological forecasting applications. In some cases, the raw or treated water is returned to the river system, whilst other demands represent a permanent loss. The main approaches used for estimating withdrawals are either to consider individual users or to aggregate values using methods such as regression relationships, econometric approaches and data-driven techniques. This chapter presents an introduction to these topics with examples in the areas of water supply, irrigation and power generation. This includes a discussion of microcomponent approaches, crop simulation models and hydro-scheduling.

Keywords Abstractions • Demands • Discharges • Demand forecast • Water use • Water supply • Irrigation • Power generation • Hydropower • Thermoelectric • Crop simulation models • Hydro-scheduling

6.1 Introduction

In many hydrological forecasting applications, it is important to consider the main abstractions and discharges in the system, particularly under low flow conditions. Typically this requires an understanding of the likely demands for water across a range of applications, including water supply, irrigation, and power generation. Return flows of treated or untreated water usually also need to be estimated. The extent to which each contribution is considered depends on the magnitude compared to river flows and the influences from other factors, such as reservoir operations.

Table 6.1 shows some examples of types of water use and the potential impacts on river flows. However, there are wide variations between countries and climate regions. For example, in England and Wales as of 2006/2007 approximately 20,000 abstraction licences were registered of which almost 50 % by volume of non-tidal abstractions were for public water supply and almost 30 % to support electricity generation (Environment Agency 2008). In contrast in the USA estimates for the year 2010 suggested that approximately 38 % of surface and groundwater withdrawals were for irrigation, 38 % were for thermoelectric power generation and 14 % were for public water supply (Maupin et al. 2014). Surface water withdrawals accounted for about 75 % of the total freshwater consumption.

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Table 6.1 Some examples of types of freshwater abstractions and discharges

Application	Typical water sources	Typical influences on river flows
Agriculture	Rivers, reservoirs, groundwater	Abstractions for farm dams, livestock watering, fish farming, etc.
Canals	Rivers, reservoirs	Minor inflows to replace water lost by evaporation and seepage and from routine canal operations, such as the flow caused by the opening and closing of lock gates
Hydropower	Rivers, reservoirs	Changes to flow regimes for reservoir and pumped storage schemes; local influences from run-of-river and micro-hydropower schemes. Losses due to seepage and evaporation from reservoirs
Industry	Rivers, reservoirs, groundwater	Abstractions for cooling and industrial processes such as in the chemical, food processing, paper, petroleum-refining and steel industries, possibly with return flows of treated or untreated water
Irrigation	Rivers, reservoirs, groundwater	Several types of use, including surface irrigation, spray irrigation and drip irrigation schemes. River flows are affected both by abstraction for irrigation and return flows from pumped or gravity drainage. Groundwater abstractions may influence river flows under low flow conditions
Mining	Rivers, reservoirs, groundwater	Some typical water uses include for cooling, conveyance, washing and flotation of mined rock and other materials and for dust control and wastewater treatment, possibly with some return of treated or contaminated flows
Thermoelectric power stations	Rivers, reservoirs	Abstractions for cooling water, which is either lost in natural or forced draft cooling systems or returned to the river system in once-through cooling systems
Water supply (potable consumption)	Rivers, reservoirs, groundwater	Abstractions to water treatment works, and possibly for interbasin transfers, plus return flows from wastewater treatment works, and sometimes minor abstractions for private industrial or domestic water supplies. Groundwater abstractions may influence river flows under low flow conditions

Figure 6.1 shows the trend in withdrawals in the USA over time. This includes saline-water abstractions which represent about 14 % of the total; for example, some common uses internationally are for desalination plants and power station cooling water systems. It is also important to distinguish between the following two types of water use:

- Consumptive – such as in irrigation schemes and water supply systems for potable water, notionally representing a permanent loss to the river system
- Non-consumptive – such as in many hydropower schemes and some types of power station cooling water systems, in which flows are returned after use

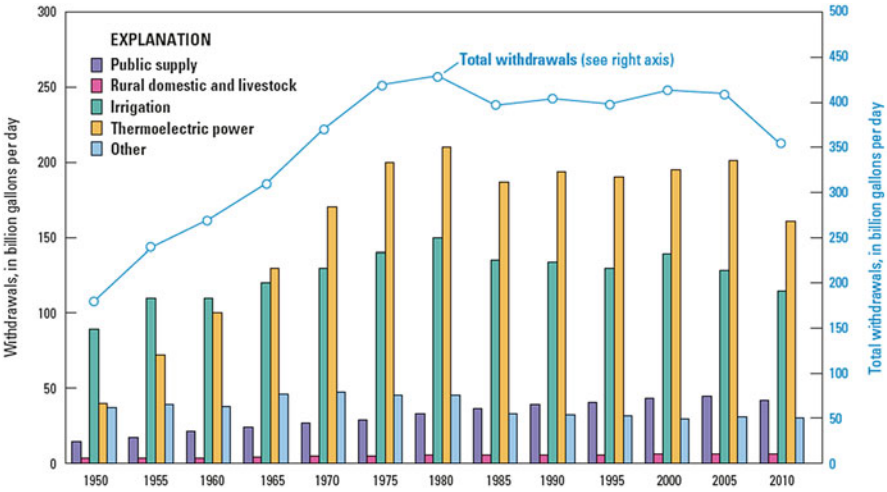

Fig. 6.1 Trends in total water withdrawals by water-use category, 1950–2010 (US Geological Survey, Maupin et al. 2014)

Of course these distinctions are not always clear-cut; for example, in consumptive schemes a proportion of the water abstracted is often returned to rivers as drainage flows or in treated form. Similarly, in non consumptive applications, there are usually some losses due to leakage, evaporation and other factors. As discussed in later chapters, the influences of changes in water temperature, sediment load and water quality may also need to be considered, together with any environmental flow requirements.

The process of estimating future water use is usually called demand forecasting. For water supply applications, users are typically classified under the general headings of residential, commercial and industrial and by sector such as 'agricultural' or 'transportation'. At short timescales, day-to-day fluctuations in demand are typically estimated on the basis of recent measurements or estimates using trend or regression analyses, artificial neural networks or time series analysis techniques. At longer timescales some examples of additional factors which often need to be considered include:

- Adaptation – how people and businesses are likely to modify their behaviour in the face of change, such as water shortages
- Climate variability – influences on water consumption from long-term variations in climate, taking account of climate change projections
- Demographic influences – projected variations in population, settlement patterns and age distributions
- Regulatory changes – possible changes in areas such as water-pricing, water-trading and competition rules, and water efficiency and leakage reduction targets
- Socioeconomic development – scenarios for changes in per capita income, employment rates, industrial development and farming practices

- Technological changes – potential reductions in water use due to developments in areas such as intelligent metering, appliance efficiencies (e.g. washing machines) and leakage detection techniques

In some cases, such as hydropower generation, a two-stage process is required, starting with the primary demand (electricity in this case) and from that determining likely water demands.

When there are many individual users to consider, aggregated demands are usually estimated for typical groups of users and/or times of year, based on the findings from sampling exercises. For example, for regional water supply to towns or cities, demand or command zones are often defined based on operational needs, although major users such as power stations usually need to be considered individually. Similarly, it is sometimes convenient to group together smaller abstractions for irrigation along a river reach, such as by smallholder farmers, whilst larger irrigation schemes need to be considered separately. These types of analysis are increasingly performed within a Geographic Information System (GIS) framework to take account of the spatial variations in demand.

In many applications, the links between weather, climate and demand need to be considered (e.g. WMO 2012a), and some possible influences include:

- Air temperatures – variations in demand for potable water and irrigation and in evaporation from irrigation schemes and reservoirs
- Rainfall – changes in demands for irrigation and lawn watering
- Solar radiation, humidity and wind speeds – some additional factors which affect both demand and evaporation in some applications

Secondary factors sometimes come into play such as increased demands for hydropower for heating in cold weather and air conditioning in hot weather.

The remainder of this chapter discusses the application of these various techniques to three specific types of water use: water supply, irrigation and power generation. Later chapters then discuss the role of demand forecasts in flow forecasting models such as for drought (Chap. 10) and water resources (Chap. 13) applications. There is an extensive literature on approaches to demand estimation and some references for further reading include: Agthe et al. 2003, Arbués et al. 2003, Butler and Memon 2006, FAO 2002, Parker and Wilby 2013, Pritchard et al. 2005 and WMO 2012b.

6.2 Water Supply

Abstractions for water supply sometimes have a significant influence on river flows. For short- to medium-term demand forecasting, multiple regression approaches are often used over timescales of up to a few hours to weeks ahead. Some typical predictors include recent water use, air temperatures and rainfall forecasts and diurnal and seasonal variations in demand. Data-driven techniques provide another option and examples include transfer functions, artificial neural networks and Kalman filter approaches. Chapter 5 discusses some of these approaches in more detail in the context of rainfall-runoff modelling and data assimilation.

Demand forecasts are also an important consideration in longer-term water resources planning studies of the types described in Chap. 13 and usually both typical and peak demands need to be considered. The main approaches at these timescales include (e.g. McMahon 1993, Wurbs 1994, Butler and Memon 2006, Parker and Wilby 2013):

- Per capita methods – multiplication of typical water uses for drinking, hygiene and sanitation, for different categories of users, by the number of users in each category
- Statistical or econometric methods – a development of per capita approaches in which multiple regression or other relationships are derived between zonal or per capita water use for different categories of users, using predictors such as climate, employment, income and price
- Microcomponent or end-user analyses – derivation of estimates for a wide range of uses taking account of factors such as the extent of ownership and frequency of use within each end-user category, with total demands estimated by aggregating this information across all users

The number of factors to consider can be large for more detailed approaches; for example, Wurbs (1994) notes that ‘water use in an urban area is dependent upon various demographic, climatic, and socioeconomic factors such as:

- resident and seasonal population
- personal income
- climate
- weather conditions
- number, market value, and types of housing units
- employment in service industries
- manufacturing employment and output
- water and wastewater prices and rate structures
- irrigated acreage in residential, commercial, and public use
- types of lawns and watering practices
- water using appliances
- demand management activities’

To limit the extent of the analyses, some level of simplification is usually introduced such as the following forms of aggregation:

- Sectoral – using categories such as residential, commercial and industrial
- Housing characteristics – using categories such as property age, value, type, size and occupancy
- Water pricing – using categories such as metered and unmetered supplies
- Spatial – grouping users spatially such as by sub-catchment, state, town, region, household, census area, city zone or command zone
- Time based – applying factors to account for the differences in water use by season or at a finer level of detail

However, as noted earlier, for some major categories of water user, such as electricity suppliers, analyses typically need to be performed individually on a case-by-case basis.

Trend and per capita approaches were the first to be developed and are still widely used for initial assessments and for small-scale schemes and when there is insufficient information available for a more complex approach. However, statistical and microcomponent techniques allow a wider range of factors to be considered and, in some cases, combinations of techniques are appropriate; for example, developing regression relationships for the frequency of use of individual micro-components for input to strategic and climate change impact studies.

For any approach, a key challenge is often to obtain sufficient data for model calibration. This has led to the widespread use of stochastic and 'what-if' approaches to assess the sensitivity of the results to the assumptions that are made. Some typical sources of information include data from household surveys, metering, billing information and research studies. However, in some cases, more approximate values may suffice; for example, based on industry guidelines or World Health Organisation standards (e.g. Butler and Memon 2006).

For more complex approaches, a wider range of information is typically required at a finer level of detail (e.g. Arbués et al. 2003, Wurbs 1994, Agthe et al. 2003, Horn et al. 2008). For example, factors which are sometimes considered include marginal prices, household incomes, net rainfall and temperature degree days. Interrelationships between variables are another potentially important factor such as the so-called elasticity of demand, which describes the relationships between demand and prices and the impact of water efficiency measures on demand. However, it is worth noting that intelligent metering systems are increasingly used and for the future offer the potential to obtain much more detail on water use at household level and for individual appliances.

6.3 Irrigation

In some countries irrigation demands represent the largest water use, particularly in more arid parts of the world. For example, figures from the Food and Agriculture Organization's AQUASTAT database show that, in some parts of Africa, Asia and South and Central America, the proportion of water withdrawn for agriculture accounts for more than half of the total (http://www.fao.org/nr/water/).

Demands are typically linked to the growing cycles of crops and tend to be seasonally dependent, although it is worth noting that in some locations it is common to plant multiple types of crops, with the planting and harvesting dates staggered throughout the year. Indeed crop rotation is one strategy for reducing the risk to crop yields from drought and other factors, such as crop disease.

The main types of irrigation scheme include (e.g. FAO 2002; Fig. 6.2):

- Surface irrigation systems – in which water is provided overland via canals and pipes and then distributed at field scale using furrow, border-strip or basin systems
- Sprinkler irrigation systems – in which water is sprayed onto the crop via fixed or mobile pressurised pipe systems (also known as spray or overhead irrigation systems)

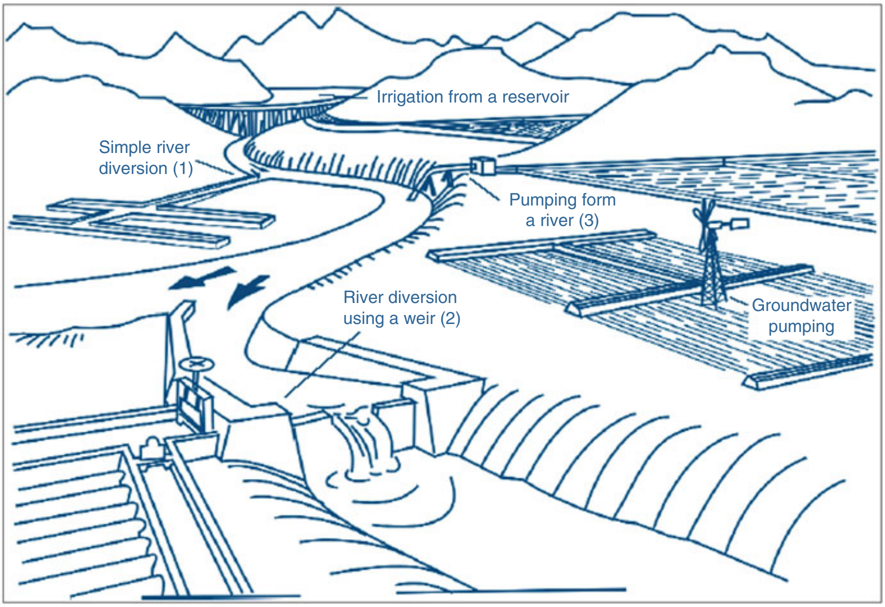

Fig. 6.2 Schemes irrigated from different sources (Food and Agriculture Organization of the United Nations; FAO 1992a, 2002; Reproduced with permission)

- Localised irrigation systems – in which water is piped under low pressure directly to the crop and delivered via drip, spray or bubbler systems
- Sub-surface irrigation systems – in which water is provided to the plant root zone at the required rate by raising or lowering the water table

The main sources of water typically include reservoirs, rivers, lakes or groundwater, using gravity-fed or pumped schemes. Pumped schemes often have higher capital and operating costs, with greater limitations on flow volumes, but allow more precision in how water is supplied and are able to operate when river levels are low. Sometimes treated wastewater or desalinated seawater is used where no other sources are readily available.

Surface irrigation schemes are the most widespread approach. In furrow and border-strip schemes, water is usually transferred to the field by gates, sluices or siphons as required, whilst, in basin schemes, the whole field is inundated. Sprinkler and localised systems allow greater precision in the timing and volumes of water applied, with lower losses to infiltration and evaporation, although are often more energy, capital and/or labour intensive.

The overall scheme efficiency, or project efficiency, depends upon the conveyance efficiencies of the main supply system and field canal system and field-application efficiencies as water moves from the source to the field to the crop. Some indicative values for field-application efficiencies might be 55–80 % for a surface water scheme, 60–85 % for sprinkler systems and 85–95 % for localised irrigation schemes

(FAO 1992a, 2002). However, these depend on a range of factors such as weather conditions, the approach to management, operation and maintenance of the scheme and other issues such as whether canals are lined, rates of sedimentation and the effectiveness of drainage systems.

The main factors which influence the water requirements for an irrigation scheme include the crop water demand, the irrigation efficiency and the effective rainfall, which is the proportion of the total rainfall available to the crop (after allowing for runoff and other losses). The simplest approach to estimating the overall demand (e.g. McMahon 1993) is to estimate a typical water demand or duty per unit area and then to multiply that value by the irrigated area. Alternative approaches include basing values on past experience or – as discussed later – a more detailed analysis based on evapotranspiration estimates and a soil (or scheme) water balance.

For long-term forecasting (e.g. WMO 2012b) some possible approaches include multiple regression and non-parametric techniques and expert systems. In regression approaches, the crop yield and other parameters of interest are typically related to predictors such as air temperature, rainfall, solar radiation, season, price and type of crop. Simpler descriptive ('non-parametric') techniques provide another option; for example, linking crop yield to indices related to the El Niño-Southern Oscillation (see Chaps. 1 and 4) or cumulative rainfall. Regarding expert systems, these typically use artificial intelligence techniques to encapsulate these types of relationships and this is an active area for development.

Crop evapotranspiration values are often estimated relative to a reference crop, which is usually taken to be short grass with specified characteristics (height, albedo, surface resistance) and a plentiful supply of water (e.g. FAO 1998). The water requirements for other crops are then expressed relative to that of the reference crop, using a crop coefficient determined from field observations. The reference crop evapotranspiration is normally estimated using the Penman-Monteith equation for which – as noted in Chap. 3 – the main meteorological input variables are air temperature, humidity, wind speed (or wind run) and solar radiation (or sunshine hours). Typically these are obtained from weather station observations, and most national meteorological services maintain networks of agricultural meteorological stations, which WMO (2013) notes 'should be located at a place that is representative of agricultural and natural conditions in the area concerned, preferably:

- At experimental stations or research institutes for agriculture, horticulture, animal husbandry, forestry, hydrobiology and soil sciences
- At agricultural and allied colleges
- In areas of present or future importance for agricultural and animal husbandry
- In forest areas
- In national parks and reserves'

For a given crop, the crop coefficient usually varies during the growing season as the height, albedo, aerodynamic properties and soil evaporation contributions change. Typically this reaches a maximum when plants reach maximum height and cover and then remains at about that value until the crop reaches the mature stage, thereafter reducing towards harvest time or full senescence. Values often vary considerably from day to day and with climate conditions, so weekly or 10-day averages are often considered; in particular, values are sensitive to the availability of water during the initial part of the growth cycle. An allowance may therefore be made for departures from ideal conditions by introducing water stress and other coefficients to allow for factors such as water shortages, waterlogging, leaching and the influence of pests and diseases. In some cases, a soil evaporation coefficient is included to allow for direct soil evaporation, such as from sparse crops with significant gaps between individual plants.

For a given type of crop, the overall irrigation scheduling requirements are then estimated from a water balance calculation which takes account of factors such as rainfall, crop evapotranspiration, irrigation efficiency, soil characteristics, plant rooting depth and plant area coverage. This approach forms the basis of the widely used FAO CROPWAT methodology, for example, which is described in Box 6.1. Irrigation scheduling calculations of this type are usually performed as part of the scheme design, using historical climate data, and in some cases are combined with real-time meteorological observations or forecasts to forecast irrigation demand. For detailed design studies, some additional complicating factors which sometimes need to be considered include influences from the water table, water use by weeds, the changes in microclimate due to the presence of the scheme, return flows from drainage and local practices such as those relating to ploughing and the application of fertilisers.

Process-based crop simulation models are also increasingly used operationally. The main applications to date have been primarily for large-scale commercial farming and for regional monitoring of drought by research organisations and national meteorological services, as discussed in Chap. 10. The starting point for the analysis is often a consideration of the water and energy balance for the crop, as illustrated by the example shown in Fig. 6.3. The net radiation depends on the solar radiation, long wave radiation and reflected and intercepted radiation at the soil surface and plant canopy. In addition to tracking of the overall water and energy balances for the soil and vegetation, models of this type typically account for a wide range of processes such as the following examples (e.g. Thornley and France 2007, WMO 2012b):

- Aerodynamic influences – representing processes such as the turbulent and diffusive transfer of water and energy within and above the plant canopy
- Soil hydrology – allowing for factors such as the influence of rainfall, irrigation, infiltration, percolation, capillary rise, evaporation, surface runoff, tillage effects and evapotranspiration by plants and weeds
- Vegetation growth – simulating processes such as photosynthesis, respiration, senescence, uptake of nutrients from fertilisers, the carbon balance, disease, weed growth, plant competition and management practices

Evapotranspiration is often represented using a Soil Vegetation Atmosphere Transfer (SVAT) modelling approach based on the concepts of aerodynamic and stomatal resistances (e.g. Shuttleworth 2007, 2012); models of this type are also a key component in the land surface schemes in numerical weather prediction models (see Chap. 13).

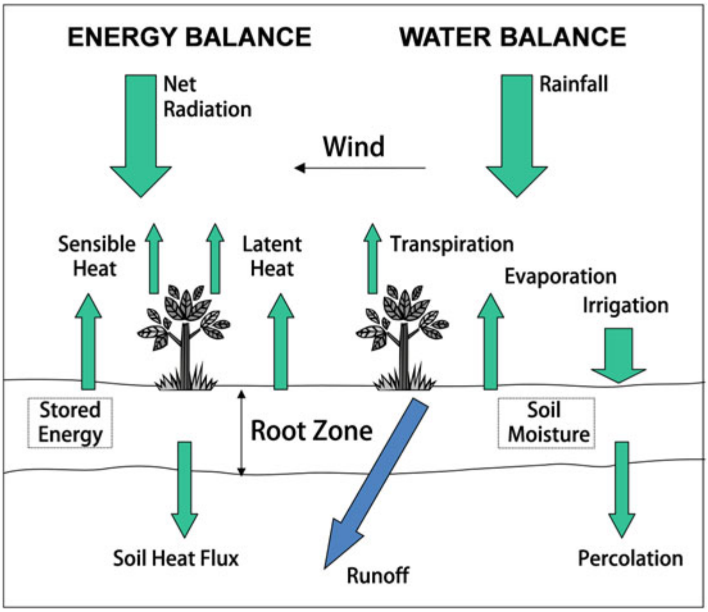

Fig. 6.3 Illustration of the water and energy balance of an irrigated sparse crop (infiltration and interception components not shown)

Crop simulation models generally have many parameters, and these are typically based on the results from laboratory and field-scale experiments. Models may be formulated at a range of scales – from plot to farm to region – depending on the application, often with a multilayer approach for the soil component. Typically, the main inputs consist of rainfall, solar radiation, air temperature, wind speed, humidity and soil moisture conditions, based on observations from ground stations (including weather radars, if available) and satellites. Some typical examples of model outputs include estimates for crop yields, soil water content and biomass.

Even more so than with simpler types of model, a key consideration is usually obtaining sufficient data for model calibration and operation, at an appropriate spatial and temporal scale (e.g. Challinor et al. 2003, Stone and Meinke 2005, Hansen et al. 2006). There may also be issues with scaling up results to the catchment or regional scale, and if meteorological forecasts are used some post-processing normally needs to be applied, as discussed in Chap. 4. Nevertheless, there are many examples of successful applications of this approach and some well-known types of models include APSIM (and Whopper Cropper), DSSAT (CERES and CROPGRO), EPIC, SIRIUS and WOFOST (e.g. Stone and Meinke 2005; Thornley and France 2007; WMO 2012b). Applications have ranged from short-term tactical decision-making, such as on when to irrigate crops or apply fertilisers, through to longer-term strategic decisions on when to plant or harvest crops and the mix of crop types to plant.

There is also increasing interest in the use of seasonal forecasts, again with a number of successful applications (e.g. Jury 2013). Chapter 13 discusses some of the technical issues relating to forecasting water availability at these timescales and – as in other applications – it is important to consider the socioeconomic aspects of forecast delivery. For example, this typically includes the risk profiles of users, the likely benefits in terms of greater yield and the financial and other consequences if the forecast is poor, particularly for subsistence farmers. There are also potential issues surrounding the communication of probabilistic information to users with a range of technical skills (e.g. Troccoli et al. 2008).

Another application for crop simulation models is in estimating the agricultural impacts related to climate change projections. Chapter 13 discusses this topic in more detail, but for the crop component, some examples of the types of factors which typically need to be considered include population growth, economic development, crop yields, adaptation strategies and changes in soil conditions due to factors such as nutrient loadings, leaching and salinisation.

Box 6.1: FAO CROPWAT Methodology

The Food and Agriculture Organization (FAO) is a United Nations agency whose mandate is to raise levels of nutrition, improve agricultural productivity, better the lives of rural populations and contribute to the growth of the world economy (http://www.fao.org). The Land and Water Division focusses on good practice in agricultural water management and efficiency and was the developer of the widely used CROPWAT decision-support tool (FAO 1992b) and – in collaboration with the Institute of Irrigation and Development Studies in the UK – the CROPWAT for Windows update (Clarke 1998) and the subsequent CROPWAT 8.0 release (FAO 2009).

CROPWAT is designed to help agrometeorologists, agronomists and irrigation engineers with the design and management of irrigation schemes. Some typical applications include calculation of crop water requirements, planning irrigation schedules, reviews of irrigation practices and studies into crop yield, under both rainfed and irrigated conditions. The approach has also been used in research studies into the extent to which seasonal rainfall and climate forecasts might help to increase crop yields during each growing season (e.g. Marica 2003).

The calculation methods are based upon the methodologies described in the following FAO Land and Water Division Irrigation and Drainage papers:

- Yield Response to Water – which provides guidance on the relationship between crop yield and water availability and on water management for optimum crop production and water efficiency (FAO 1979)
- Crop evapotranspiration: Guidelines for computing crop water requirements – which provides an updated version of the evapotranspiration estimation method in 'Crop Water Requirements' using the Penman-Monteith approach (FAO 1998)

(continued)

Box 6.1 (continued)
The main meteorological inputs which are required by CROPWAT 8.0 are either daily, 10-day (decadal) or monthly rainfall data, and climate data in terms of sunshine in hours or percentage, wind speed, humidity and maximum and minimum air temperature. These values can be entered directly or imported from the FAO CLIMWAT 2.0 database, which provides long-term monthly values for more than 5000 meteorological stations worldwide (FAO 1993 and updated in 2006). Measured values of evapotranspiration may also be used, and, if only temperature data are available, the remaining parameters can be estimated following standard meteorological procedures described in the publications mentioned above. Several options are also provided for estimating effective rainfall, including use of a fixed percentage of total rainfall, the dependable rainfall (linked to return period) or the US Soil Conservation Service approach.

Values for crop coefficients (initial, mid-season, end of season), rooting depth, yield response factors and crop height are also required and can be provided on the basis of local field experiments or using default values which are available for a wide range of crop types. To calculate water requirements for an irrigation scheme, user-supplied values are also required for the percentage of area planted, planting dates and cropping pattern/growth stages (although again default values can be used if local values are not available). Where multiple cropping patterns are used, up to 20 types of crop can be considered, with different planting dates allowed for each type (Fig. 6.4).

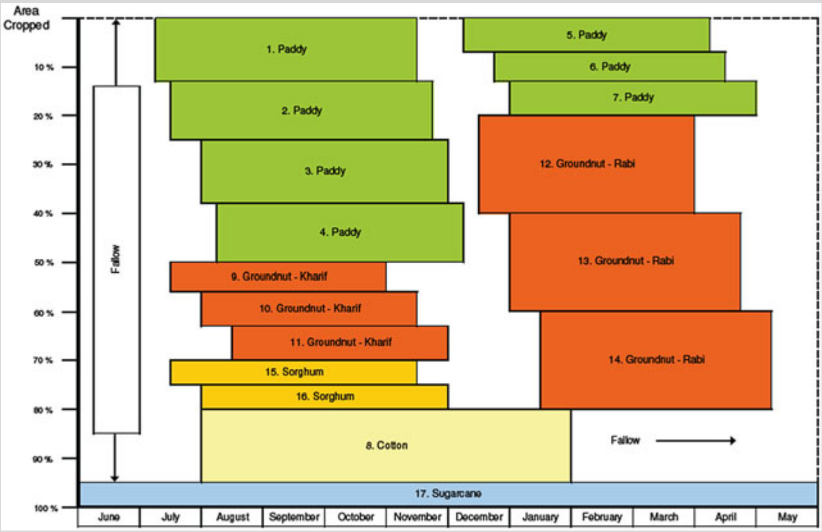

Fig. 6.4 Illustration of cropping pattern for Rajolibanda in Andhra Pradesh, India (Food and Agriculture Organization of the United Nations; FAO 2009; Reproduced with permission)

(continued)

Box 6.1 (continued)
For irrigation scheduling calculations, estimates are also required for several soil-related parameters, including the total available water, maximum infiltration rate and initial soil moisture depletion.

The irrigation scheduling module provides the following main options:

- Develop indicative irrigation schedules to improve water management
- Evaluate current irrigation practices and the associated crop water productivity
- Evaluate crop production under rainfed conditions and assess feasibility of supplementary irrigation
- Develop alternative water delivery schedules under restricted water supply conditions

Water availability and deficits are calculated using a water balance approach, in which the soil water content is estimated from values for total rainfall, crop evapotranspiration and the water supply from irrigation, where evapotranspiration is estimated from the Penman-Monteith reference values multiplied by the crop coefficient. However, no allowance is made for groundwater contributions to irrigation (Clarke 1998). Indicative irrigation schedules can be developed using user-set criteria based on the soil moisture deficit calculations, such as the requirement to return conditions to field capacity once all of the readily available moisture has been used, or to a certain percentage of the soil moisture deficit. The facility is also available to update certain parameters during the growing season to take account of observations, and examples include adjusting soil moisture values to better match field observations and the use of observed rainfall data.

The outputs from the programme include values for evapotranspiration (mm), crop yield reduction (as % of maximum), total available moisture (TAM), irrigation requirements (mm) and crop water requirements (mm) over a range of periods (e.g. daily, 10 day/decadal, monthly). Various graphs and tables are also provided to help to examine irrigation efficiency and the impact on crop yield; for example, Fig. 6.5 illustrates the estimated soil moisture deficit for a maize crop over the growing season when using an optimal irrigation schedule (upper graph) and a sub-optimal schedule (lower graph). If irrigation is available on demand, irrigation inputs are only provided when all, or a given percentage, of the readily available soil moisture (RAM) is used, and only sufficient water is provided to return the soil moisture deficit (SMD) to zero, equivalent to field capacity, or a given percentage of it specified by the user.

The latest version of CROPWAT (version 8.0) includes the option to estimate climate data in the absence of measured data (as described above), improved calculation procedures for crop water requirements, calculations for both dry crops and for paddy and upland rice, user adjustable irrigation

(continued)

Box 6.1 (continued)

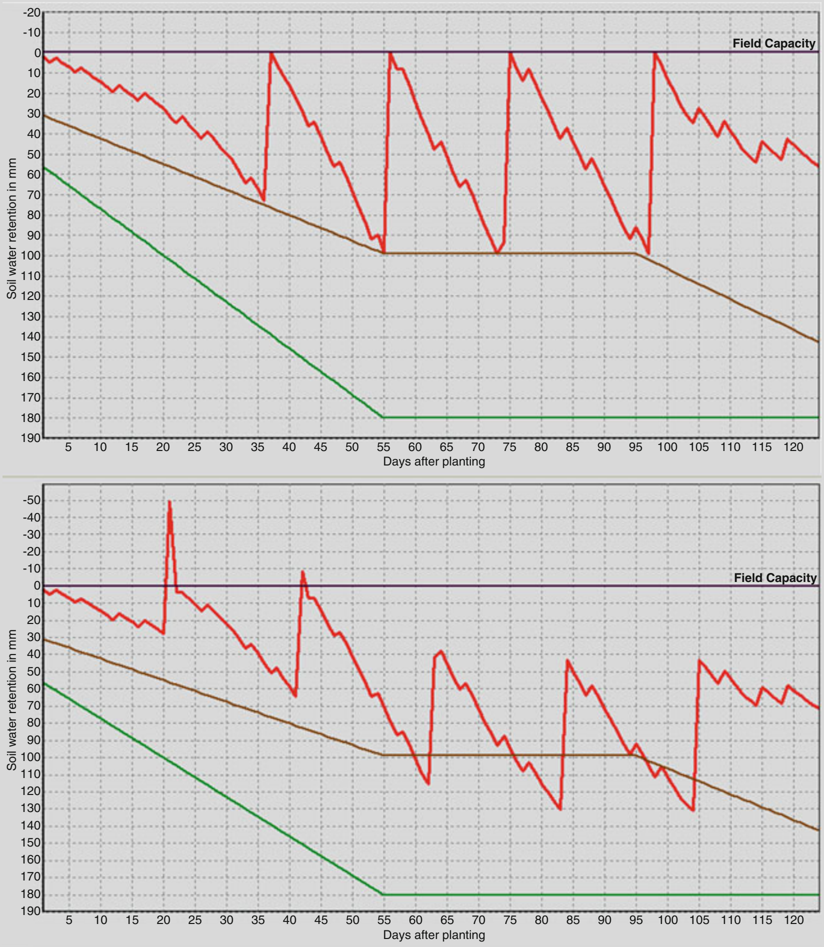

Fig. 6.5 Illustration of irrigation scheduling graph outputs from CROPWAT 8.0 for optimal and sub-optimal schedules, showing irrigation amount, RAM (*upper deficit line*) and TAM (*lower deficit line*) (Food and Agriculture Organization of the United Nations; Reproduced with permission)

schedules, the option to perform irrigation scheduling calculations at a daily time step and a range of additional facilities for the import of data and output of results. There is also considerably more flexibility in the choice of timescales, units and irrigation scheduling settings. A new rice Crop Water Requirement calculation module has been developed separating land preparation water requirements and actual crop water requirement but requiring a number of additional input parameters appropriate for paddy rice crops.

6.4 Power Generation

6.4.1 Thermoelectric Power Stations

Thermoelectric power stations typically use coal or natural gas to generate power from steam turbines, and boilers are usually cooled by pumping river or sea water through heat exchangers. The main types of cooling system are:

- Open-loop or once-through systems – which return the cooling water directly to rivers or the sea
- Closed-loop or recirculation systems – which recirculate the cooling water, typically using cooling towers or ponds to reduce the water temperature

Similar types of system are used in some types of industrial and petrochemical plants and nuclear power stations. In contrast, air-cooled (or dry-cooling) systems usually do not have any significant water requirements but only represent a small proportion of installed capacity.

The water demands for once-through systems are usually high, and, when water is withdrawn from a river, the flow needs to be sufficient to support the abstraction. Power plants which use this approach therefore tend to be located in the lower reaches of major rivers where flows are large or at the coast to provide access to seawater. However, losses are generally minor and result primarily from leakage and evaporation, so the net water use is generally low. As discussed in Chap. 12, the heating effect of the returned flows often needs to be considered for ecological reasons, with sufficient flow to dilute the thermal plume by the required amount.

By contrast, for closed-loop systems, the recirculated water needs to be cooled before reuse, and this is usually achieved by spraying the water into cooling towers. The cooling effect arises from evaporation with either natural or forced convection resulting in the familiar plume of water vapour visible above many power stations. A proportion of the cooling water is therefore lost to the atmosphere and needs to be replaced at a rate linked to the rate of power generation. This 'make-up' supply also helps to avoid the build-up of salts caused by the evaporation process. Closed-loop systems proportionally have a much higher consumption of water than direct cooling systems although avoid the thermal pollution caused by once-through systems. However, in the USA, for example, these types of system account for less than 10 % of overall river abstractions for power generation (Hutson et al. 2004; Maupin et al. 2014).

Demand forecasts for individual plants are normally derived on a case-by-case basis in collaboration with the plant owner or operator. For regional assessments, regression techniques provide another option. For example, in the USA, this approach has been used to estimate water demand at a state level (National Academy of Sciences 2002) based on predictors in the following general categories: energy generation (by method/fuel type), installed generation capacity, availability of cooling towers, weather conditions (temperature, degree days, etc.), state water law and the number of generating units.

6.4.2 Hydropower Schemes

Hydropower schemes use the flow of water through turbines to turn generators to produce electricity. Table 6.2 summarises the main types of scheme and Fig. 6.6 shows some examples. Some estimates suggest that hydropower provides almost 20 % of the world's total energy production and supplies at least 50 % of electricity production in 66 countries (International Hydropower Association 2003). Some countries in which it is a significant source of energy include Brazil, Canada, China, France, India, Japan, New Zealand, Norway, Russia, Scotland, Sweden and the USA.

For a hydropower plant, the main factors which affect the amount of power generated include the turbine efficiency, the flow rate and the net head (difference in levels). With the exception of tidal barriers, schemes therefore tend to be located in upland areas, although in lower-lying areas options include run-of-river schemes and direct placement of low-head devices within rivers, such as Archimedes screw turbines.

Depending on the mix of energy sources in a region, hydropower is either used as the primary supply of electricity or for balancing short-term fluctuations in demand which cannot easily be supplied by thermal or nuclear power stations. The ability to meet short-term loads, sometimes within minutes, is a key advantage, although a potential disadvantage is the dependence on meteorological conditions and inflows (although large reservoir storage volumes help to reduce that risk).

For reservoir storage schemes, operations need to be planned over a range of timescales, from short-term day-to-day scheduling through to medium-term management of reservoir storage and longer-term investment planning. The optimum operating strategy depends on a range of factors including the forecast inflows, outflow capacity, reservoir capacity, current storage and forecasts for future electricity demand and energy prices. Some other possible objectives include a requirement to preserve spare storage capacity to mitigate flood flows and the need to release sufficient water for a range of other purposes, such as for water supply, irrigation and fisheries. Emergency releases are sometimes also required for flood control during high flow periods.

Table 6.2 Some examples of types of hydropower scheme

Type	Description
Reservoir storage	Water is stored in a reservoir for subsequent release to meet the required electricity demand
Run of river	Water passes through a small barrage or dam without any significant storage, providing a baseload supply of electricity (e.g. see Fig. 11.2 in Chap. 11)
Pumped storage	Water is pumped from a lower reservoir to a higher reservoir during periods of low demand for electricity and then released to meet peak demands
Diversion	Water is diverted from the main river into a channel or pipe to pass through a penstock and turbine before being returned further downstream; this is a common configuration in small-scale 'micro-hydropower' schemes
Tidal barrier	Power is generated due to the head differences caused by the rise and fall of the tides (see Chap. 11)

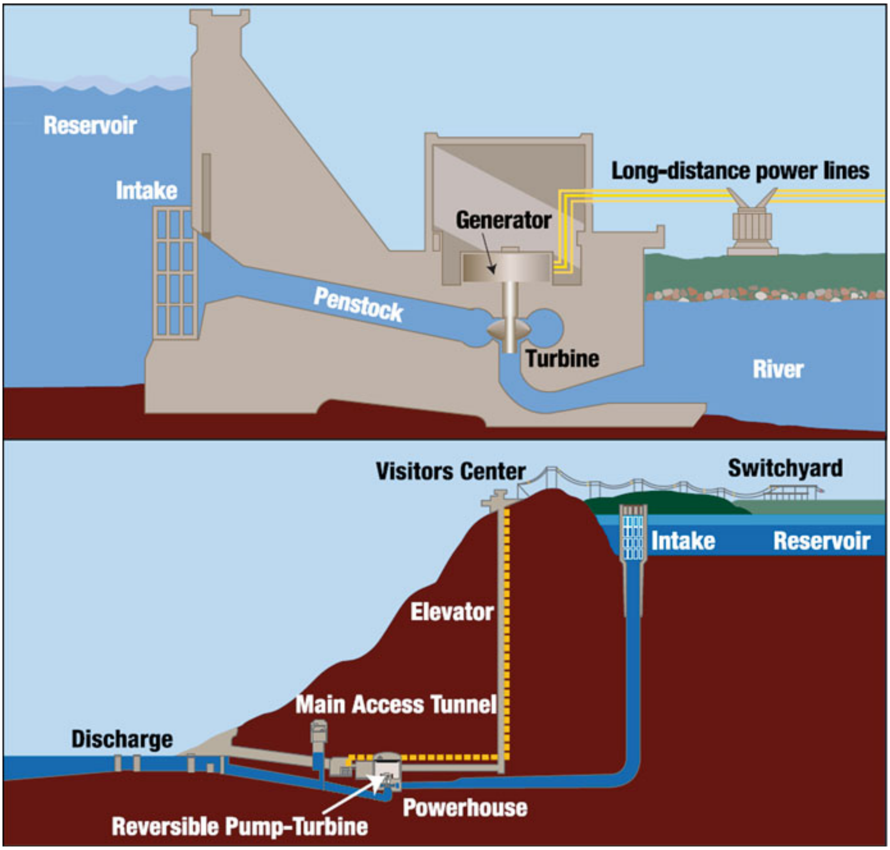

Fig. 6.6 Examples of reservoir storage and pumped storage schemes (Tennessee Valley Authority, TVA 2009)

Reservoir control or rule curves are normally defined on the basis of factors such as historical climate and river flow records and energy price forecasts. For medium- to long-term planning, linear and dynamic programming techniques (including stochastic forms) are widely used and both simulation and linear programming methods at shorter timescales (see Chap. 11). The level of detail in models is generally less at longer timescales and the time step longer, but the approaches to optimisation are normally more sophisticated and often based on stochastic simulations.

The process of operating a hydropower scheme to meet the required objectives is often called hydro-scheduling. Some possible meteorological influences on operations include:

- Rainfall – which affects river flows and provides a direct contribution at reservoir surfaces
- Air temperatures – which affect electricity demand and electrical transmission and distribution losses
- Solar radiation (or cloud cover) – which affects electricity demand

Wind speeds and humidity also potentially affect electricity demand and all of these parameters potentially influence the rates of snowmelt in regions where snow accumulates. With the possible exception of rainfall, all parameters affect evaporation at reservoir surfaces.

For forecasting inflows from hours to days ahead, semi-distributed integrated catchment models are perhaps the most common approach and typically combine rainfall-runoff, flow routing and reservoir components. Ensemble precipitation and air temperature forecasts are widely used as inputs, and several studies have shown that this potentially offers significant improvements in system performance (e.g. McCollor and Stull 2008; Boucher et al. 2012; Box 6.2). The use of long lead-time

Box 6.2: Load Forecasting in BC Hydro

BC Hydro supplies power to approximately 1.9 million customers in British Columbia (BC) including the major metropolitan areas of Vancouver and Victoria. Power is provided from 30 hydroelectric facilities and three thermal generating plants, and approximately 90 % of the power generated is from hydroelectric sources (CEA 2008). Water supply forecasts are obtained using both conceptual rainfall-runoff modelling and statistical techniques, as described in Chap. 13, and form part of a decision-making process (Fig. 6.7) which includes the following key components (Weiss 2004):

- Inputs – market prices, load forecasts, current reservoir levels, inflow forecasts
- Constraints – plant operating capacity, safety, security/reliability, compliance, environmental objectives, Columbia River Treaty
- Objectives – balance power and non-power objectives; serve domestic load; maximise profit; minimise risk and liability; comply with laws, licences, etc.; determine marginal cost of energy

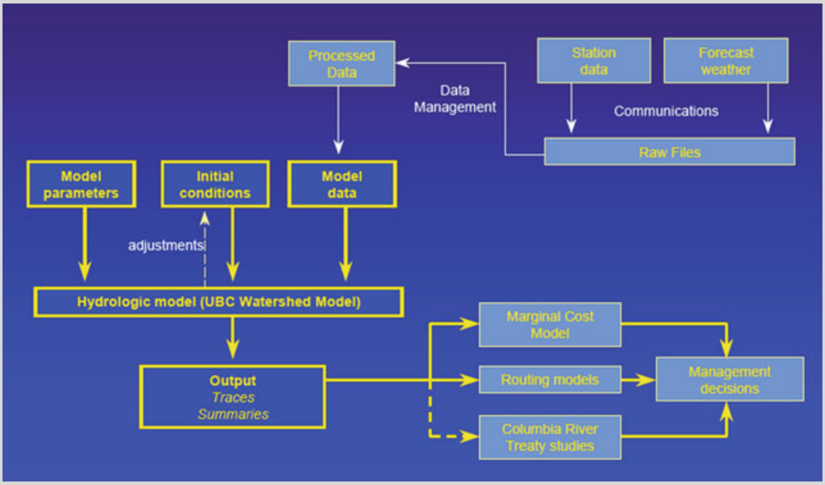

Fig. 6.7 BC Hydro Ensemble Streamflow Prediction Forecasting Process (Weiss 2004)

(continued)

Box 6.2 (continued)

Load forecasting is central to BC Hydro's long-term planning, medium-term investment and short-term operational and forecasting activities. Forecasts are based on several comprehensive end-user and econometric models that use billed sales data as historical information, combined with a wide variety of economic forecasts and inputs from internal, government and third-party sources (BC Hydro 2008).

For short-term forecasts, the time periods referred to in this context span three main time horizons: (1) the next hour load forecast from one to several hours ahead; (2) the next day forecast, usually one to two days ahead; and (3) the week ahead forecast. Each forecast time frame has specific requirements for its use:

1. The next hour load forecast, depending upon market conditions, is used to determine available energy for potential real-time exports once domestic load, environmental, system reliability and forebay management constraints are satisfied. It is also used to determine available room for imports once reliability issues and minimum generation requirements have been met. All market opportunities are assessed in conjunction with BC Hydro's marketing arm Powerex, and, once the potential trade schedules have been finalised, the optimised generation pattern for the available generation units is implemented.
2. The next day load forecast is used to assess limits for pre-schedule trading and opportunities for outage implementation along with forebay management based on daily inflow forecasts.
3. The week ahead forecast is primarily used for outage planning and reservoir management.

Short-term load forecasting for BC Hydro is carried out for three regions: (1) the total system load, (2) Vancouver Island, and (3) the Fortis BC regional load, which is a utility within the BC Hydro system area. Throughout the year, the BC Hydro system load can vary from 4000 to 10,000 MW roughly. Fortis BC load is approximately ten percent of this, and Vancouver Island is approximately one quarter of the Fortis BC load. The annual load profile is characterised by a system peak, which occurs as a result of a sustained cold temperature sequence, usually in the period from December through February. The daily load pattern varies throughout the year, varying due to day of week, meteorological conditions and sunrise-sunset times. Unexpected load curtailments by large industrial customers add to the difficulty of forecasting.

The current load forecast process uses as a first effort an Electrical Power Research Institute (EPRI) software program called ANNSTLF (Artificial Neural Network Short-Term Load Forecaster) to generate hourly load forecasts for a period of up to seven days into the future. The program, as the name implies, is comprised of two neural net programs, one of which is a temperature forecaster and the other is a load forecaster.

The forecasting process for the system load occurs as follows: using forecast temperature input from Environment Canada, which is the federal agency

(continued)

Box 6.2 (continued)
responsible for generating weather forecasts, along with historical air temperatures up to the current hour, the temperature forecaster within ANNSTLF generates a forecast temperature pattern. This pattern is adjusted based on input from a BC Hydro meteorologist, if required, and then input to the load forecaster along with historical loads up to the current hour. The neural net forecasts for each region are based on air temperatures from only one station per region. The load forecaster is then run to produce a load pattern for the next seven days. This result is then scrutinised and adjusted, if required, based on operator experience. The ANNSTLF forecaster can be run up to 35 days into the future if forecast daily high and low temperatures are input to the model. The value of operator judgement cannot be overstated as a final check on the forecast load numbers to be used for actual operation. As a check on hour-ahead forecasts, a program developed in-house, called Load Trend, is used to compare the load patterns from yesterday, a week ago and a year ago to confirm the shape of the load profile and serve as a check on ANNSTLF.

The accuracy of the forecast is generally within one percent. The largest errors occur due to unusual weather conditions, standard to daylight savings time changeover and holidays and unanticipated load curtailments. During times when the system is tight (i.e. when there is minimal spare generation), confidence limits are applied to the ANNSTLF forecasts to ensure that resources are available to meet actual loads. A number of improvements to the forecast process have been identified which include subdivision of regions, inclusion of additional meteorological variables, increasing neural net layers and or nodes and better identification of large industrial customer load patterns. Further direction in improvement in load forecasting is underway through evaluation of alternate modelling processes such as SVM (Support Vector Machines) and Genetic Expression Programming.

For longer-term planning, both deterministic and probabilistic (Monte Carlo) techniques are used, considering the main categories of residential, commercial and industrial energy demands, for which the baseline usage is about 32 %, 29 % and 37 % of total annual billed sales, respectively. Key industrial users include the pulp and paper, wood products, chemicals, metal mining and coal industries.

Some key factors considered in the forecasts are the number of customer accounts and housing starts, retail sales and employment, Gross Domestic Product (GDP) and electricity rates. The forecasts also take into account factors such as the link between temperature and energy consumption and transmission and distribution losses. For residential users, for example, load forecasts are based on projections of factors such as average efficiency trends. These trends are influenced by many variables such as the housing mix (single family, row house, apartment, etc.), heating fuel choices (electric versus non-electric), appliance penetration rates, appliance life span and changes in electricity demands for space heating, water heating, major appliances and smaller appliances. In-depth customer-specific forecasts are also performed for major transmission, commercial and industrial end users. Peak demands are also forecasted for each

(continued)

Box 6.2 (continued)
substation; these forecasts consider the likely demands from larger industrial and commercial projects that may impact substation growth.

For the Monte Carlo approach, probability distributions about the baseline trends are assumed for key drivers such as economic growth, electricity rates, weather and the response to electricity price changes (price elasticity). For example, for price elasticity, a triangular distribution is used, with a time lag included between changes in price and changes in demand. The uncertainties for temperature on demand are also included, using a beta distribution based on the number of heating degree-days per year, relative to a threshold of 18 °C. Separate impact factors are used for residential, commercial and industrial demands. The main outputs from the analyses include probability distributions for the forecast load and demand for key sectors (residential, commercial, industrial), including mean, low (90 % exceedance) and high (10 % exceedance) scenarios (e.g. Fig. 6.8).

A review of demand forecasting accuracy (BC Hydro 2008) suggested that over the period 1993–1997, the 10-years ahead demand forecasts, normalised for weather and labour disruptions, were within about 7 % of the values which were subsequently measured in the years 2003–2007.

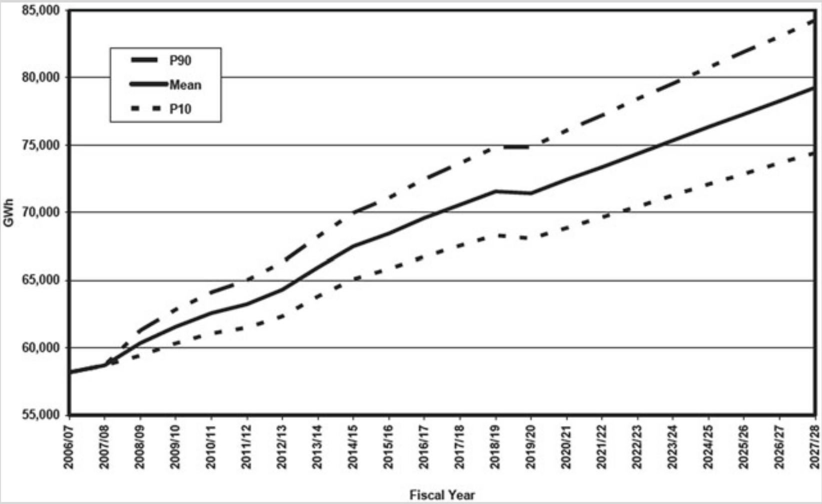

Fig. 6.8 High and Low Bands for Total Gross Load Requirements in Gigawatt-hours before Demand Side Management and Electricity Rate Impacts for the period 2007/2008 to 2027/2028 (BC Hydro 2008)

Note: the description on short-term load forecasting was provided by H. Walk, BC Hydro (personal communication), and comments on the load forecasting description were provided by G. Charchun, BC Hydro.

streamflow forecasts also potentially allows operating constraints to be relaxed in years when there is a high likelihood of ample streamflow (Hamlet et al. 2002). Chapters 7, 11 and 13 describe examples of these techniques for reservoir operation, including the use of decision-support systems for optimising the operation of multi-objective reservoir systems.

The resulting inflow forecasts are then used to help to plan day-to-day operations, and some terms which have evolved to describe hydropower generation, adapted from Hamlet et al. 2002, include:

- Firm Energy – the amount of annual energy that can be reliably supplied by a hydropower system for a given record of streamflows and a particular reservoir operating plan
- Non-firm Energy – the variable amount of energy that can be supplied over and above firm energy
- Dependable Capacity – the minimum instantaneous power available under the most adverse conditions

Firm energy is typically associated with long-term supply contracts, whilst non-firm energy is associated with shorter term contracts or interruptible power arrangements made when surplus water is available.

In many countries there is now a deregulated energy market in which suppliers bid to supply power at a range of spot prices. This contrasts with the more traditional centrally planned approach, in which prices were known for some time ahead. For daily operations, the spot price market might operate at intervals of only 30 min or 1 h, although day-ahead and longer-term contracts provide greater predictability of income. A central dispatching authority then selects the best combination of suppliers to meet the demand at the cheapest price (e.g. Pritchard et al. 2005).

Spot prices sometimes vary by an order of magnitude over a period of a few hours. Some factors which influence prices include the demand for electricity, the available generating capacity (which is linked to reservoir storage and river flows and system outages) and other factors, such as the cost of alternative sources of energy, such as from thermoelectric power stations. A price cap may be set to reduce system vulnerability and, to provide a baseload income, a proportion of capacity offered on long-term fixed price contracts. Forward and future contracts provide another way of reducing risk, in which suppliers agree to provide energy at a given time from weeks to months or years ahead.

For short-term load forecasting, in addition to typical daily, weekly and seasonal patterns of use, variations due to meteorological conditions need to be considered. Values for the next few hours to days ahead are typically estimated using artificial neural networks or time series analysis techniques. The main inputs typically include recent loads and air temperature observations and meteorological forecasts. Simpler trend or regression-based approaches provide a useful ‘reality check’ on the outputs and in some cases are used as the primary forecasting approach.

In contrast, long-term demand, or load, forecasts are typically derived from a detailed analysis of the requirements of individual end users; for example, classifying users as residential, commercial or industrial (e.g. Mazer 2007). Residential demands typically arise from many sources and examples include the requirements for lighting, heating, cooking, refrigerators and air conditioning, together with more recent developments such as electric vehicles, and computer and other types of home electronic equipment. One important consideration is the likely daily, weekend and seasonal pattern of electricity use, which is often called the load shape and expressed as a load-duration curve (which is analogous to a flow duration curve).

To simplify the analysis, one approach is to assess typical energy consumption for different types of building and heating and air conditioning systems, possibly using zones to group properties and users of a similar type. However, commercial and industrial demands are often more site specific, requiring a detailed analysis of individual components such as pumps, generators and cooling systems. Some other major users of electrical power include the transportation sector (e.g. mass transit systems) and the agricultural sector (e.g. irrigation schemes).

Some other factors which typically need to be considered include potential changes in population, gross domestic product, the links between demand and prices, employment rates and the regulatory environment; in particular regarding energy efficiency and other demand reduction measures. The potential impacts of climate variability and climate change also need be assessed and options for import or export of energy between suppliers and mixing types of energy sources. Again the overall installed generation capacity needs to be sufficient to meet typical loads over a day, season and year, together with likely peak demands. An assessment of the robustness of forecasts is often important, typically using Monte Carlo sampling techniques to assess the sensitivity of results to key factors such as assumptions about the rate of population growth, energy prices and changes in gross domestic product.

6.5 Summary

- Water demands often need to be considered in hydrological forecasting applications, particularly at low flows. Some of the most common water uses are for water supply, irrigation and power generation. Water use is often classified as consumptive or non consumptive, although the distinctions are not always clear-cut. Generally it is important to consider both typical and peak demands.
- For water supply, the main approaches for short- to medium-term forecasting include regression, artificial intelligence and time series analysis techniques. At longer timescales, options include microcomponent, econometric and more broad-brush techniques, such as per capita approaches. At these timescales, some additional factors which usually need to be considered include climate change projections, demographic and socioeconomic factors and technological and regulatory changes. A key challenge is to obtain the basic data needed to calibrate models, and often it is necessary to consider general categories of users based on spatial, water source or other considerations.

- In some countries, the greatest use of water is for irrigation, particularly in more arid parts of the world. Regression and area usage methods are widely used to forecast demands together with water balance techniques, incorporating detailed estimates for the crop evapotranspiration. Process-based crop simulation models are increasingly used and are often a key component in regional crop monitoring services.
- Water demand for power generation is another significant factor in many countries, although, in the case of hydropower schemes, and some thermoelectric plants, most of the water withdrawn is returned to the river system. Demand forecasting for hydropower schemes requires consideration of both meteorological and hydrological conditions and current and forecast power demands. Forecasting techniques include regression and artificial intelligence approaches at shorter timescales and microcomponent approaches for longer-term planning.
- For all applications, due to the uncertainties involved, sensitivity studies are widely performed to assess the robustness of estimates to the assumptions made. At longer timescales, typically this requires the use of Monte Carlo and other stochastic approaches, whilst ensemble forecasts are increasingly used in short- to medium-range and seasonal forecasting applications.

References

Agthe DE, Billings RB, Buras N (2003) Managing Urban Water Supply. Springer, Dordrecht

Arbués F, García-Valiñas MA, Martínez-Espiñeirac R (2003) Estimation of residential water demand: a state-of-the-art review. Journal of Socio-Economics, 32(1): 81–102

BC Hydro (2008) BC Hydro's Electric Load Forecast 2007/08 to 2027/28. Appendix D to BC Hydro's 2008 Long Term Acquisition Plan

Boucher M-A, Tremblay D, Delorme L, Perreault L, Anctil F (2012) Hydro-economic assessment of hydrological forecasting systems. Journal of Hydrology, 416–417: 133–144

Butler D, Memon FA (2006) Water Demand Management. IWA Publishing, London

CEA (2008) Canadian Electricity Association 2008: Electricity 08, 79(1)

Challinor AJ, Slingo JM, Wheeler TR, Craufurd PQ, Grimes DIF (2003) Toward a combined seasonal weather and crop productivity forecasting system: determination of the working spatial scale. Journal of Applied Meteorology, 42(2): 175–192

Clarke R (1998) CROPWAT for Windows User Guide. FAO, Rome, Italy

Environment Agency (2008) Water Resources in England and Wales – Current State and Future Pressures, Environment Agency, Bristol

FAO (1979) Yield Response to Water. FAO Irrigation and Drainage paper No.33, by Doorenbos J, Kassam A H, Rome, Italy

FAO (1992a) Scheme irrigation water needs and supply. Irrigation Water Management Training Manual No. 6. By Brouwer C, Hoevenaars JPM, van Boasch BE, Hatcho N, Heibloem M, Rome, Italy

FAO (1992b) CROPWAT – a computer program for irrigation planning and management. FAO Irrigation and Drainage Paper No.46, Rome, Italy

FAO (1993) CLIMWAT for CROPWAT. A climatic database for irrigation planning and management. FAO Irrigation and Drainage paper No.49, Smith, M., Rome, Italy

FAO (1998) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage paper No. 56, by Allen R G, Pereira L S, Raes D, Smith M, Rome, Italy

FAO (2002) Irrigation Manual: Planning, Development Monitoring and Evaluation of Irrigated Agriculture with Farmer Participation. Developed by Savva AP, Frenken K. Food and

Agriculture Organization of the United Nations (FAO) Sub-Regional Office for East and Southern Africa (SAFR), Harare
FAO (2009) Example of the use of CROPWAT 8.0
Hamlet AF, Huppert D, Lettenmaier DP (2002) Economic value of long-lead streamflow forecasts for Columbia River hydropower. Journal of Water Resources Planning and Management, 128: 91–101
Hansen JW, Challinor A, Ines A, Wheeler T, Moron V (2006) Translating climate forecasts into agricultural terms: advances and challenges. Climate Research, 33: 27–41
Horn MA, Moore RB, Hayes L, Flanagan SM (2008) Methods for and estimates of 2003 and projected water use in the Seacoast region, southeastern New Hampshire. US Geological Survey Scientific Investigations Report 2007–5157
Hutson SS, Barber NL, Kenny JF, Linsey KS, Lumia DS, Maupin MA (2004) Estimated use of water in the United States in 2000: Reston, Va., US Geological Survey Circular 1268
International Hydropower Association (2003) The Role of Hydropower in Sustainable Development. IHA White Paper, February 2003, UK
Jury MR (2013) Climate prediction experiences in southern Africa 1990–2005 and key outcomes. Natural Hazards, 65: 1883–1894
Marica A (2003) Application of CROPWAT Model to estimate and predict the main components of soil moisture balance based on seasonal climate forecasting. COST Action 718 – WG2: Irrigation Models. 6th MC and WG Meeting, Tjele, Denmark, 25–26 September 2003
Maupin MA, Kenny JF, Hutson SS, Lovelace JK, Barber NL, Linsey KS (2014) Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p
Mazer A (2007) Electric Power Planning for Regulated and Deregulated Markets. John Wiley & Sons, New Jersey
McCollor D, Stull R (2008) Hydrometeorological short-range ensemble forecasts in complex terrain. Part II: economic evaluation. Weather and Forecasting, 23(4): 557–574
McMahon TA (1993) Hydrologic design for water use. Chapter 27 in Handbook of Hydrology (Ed. Maidment DR), McGraw Hill, USA
National Academy of Sciences (2002) Estimating Water Use in the United States: A New Paradigm for the National Water-Use Information Program. National Academy Press, Washington, USA
Parker JM, Wilby RL (2013) Quantifying household water demand: A review of theory and practice in the UK. Water Resources Management 27(4): 981–1011
Pritchard G, Philpott AB, Neame PJ (2005) Hydroelectric reservoir optimization in a pool market. Mathematical Programming: Series A 103: 445–461
Shuttleworth WJ (2007) Putting the 'vap' into evaporation. Hydrology Earth System Science, 11(1): 210–244
Shuttleworth WJ (2012) Terrestrial Hydrometeorology. Wiley-Blackwell, Chichester
Stone, RC, Meinke H (2005) Operational seasonal forecasting of crop performance. Philosophical Transactions of the Royal Society London B: Biological Science, 360(1463): 2109–2124
Thornley J, France J (2007) Mathematical Models in Agriculture (2nd ed.). Oxford University Press, Oxford
Troccoli A, Harrison M, Anderson DLT, Mason SJ (2008) Seasonal Climate: Forecasting and Managing Risk. NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht
TVA (2009) Dams and Hydro Plants. Tennessee Valley Authority, USA
Weiss E (2004) ESP forecasting. HEPEX workshop, 8–10 March 2004, ECMWF, Reading, UK
WMO (2012a) Climate and meteorological information requirements for water management: a review of issues. WMO-No. 1094, Geneva
WMO (2012b) Guide to Agricultural Meteorological Practices (GAMP) (2010 edition – updated in 2012). WMO-No.134, Geneva
WMO (2013) Manual on the Global Observing System – Volume 1: Global Aspects. WMO-No. 544, Geneva
Wurbs RA (1994) Computer Models for Water-Resources Planning and Management. US Army Corps of Engineers, IWR Report 94-NDS-7, Alexandria, Virginia

Chapter 7
Forecast Interpretation

Abstract Ensemble and deterministic flow forecasts provide information to support decision-making in a range of applications. However, to be operationally useful, forecasts need to be presented in terms which are meaningful to the end user and delivered in time to take effective action. Some tools which are used as part of this process include thresholds, decision support systems and risk-based techniques. This chapter describes the background to these approaches and provides examples for a range of flood warning, reservoir and other applications.

Keywords Decision-making • Warning messages • Dissemination • Thresholds • Risk based • Decision Support System • Ensemble • Probabilistic • Uncertainty

7.1 Introduction

Hydrometeorological forecasts are used in a wide range of applications, and the outputs are increasingly provided in probabilistic terms, where this has the potential to lead to better decision-making.

However, usually some further interpretation is required before a warning message, hydrological bulletin or other guidance is issued. Perhaps the most common approach is to use threshold values which, once passed, indicate that a response is required; for example, to issue a predefined warning message or operate a hydraulic structure. Alternative names include triggers, alarm levels, alert levels, critical conditions and criteria.

Decision support systems provide another option. Typically, the raw forecast outputs are combined with other types of information relevant to the application, such as on food prices in famine early warning systems or the locations of properties at risk in flood warning systems. Increasingly, these types of system include algorithms to provide guidance on the optimum response although, given the many uncertainties involved, it is usually left to the user to take the final decision.

Risk-based approaches are another useful tool and, as noted in Chap. 1, are widely used in flood, drought and environmental applications (e.g. WMO 2005, 2006a; UN/ISDR 2007). Risk is usually defined in terms of the probability of an event

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occurring and the likely consequences, and Table 7.1 provides some examples of this approach.

The remainder of this chapter discusses these techniques in more detail. The focus is on the technical aspects and there are of course many wider issues relating to the interpretation (or misinterpretation) of forecasts and warnings by end users. Box 7.1 provides an introduction to this topic within the context of early warning systems, and Chaps. 1, 4 and 5 provide some further background on approaches to dealing with forecast uncertainty.

Table 7.1 Examples of risk-based approaches which are used or have been considered in hydrometeorological forecasting applications

Sector	Description	Examples
Agriculture	Crop planting and investment strategies and famine early warning systems	See Chap. 10
Droughts	Risk-based approaches to disaster preparedness and drought mitigation measures	See Chap. 10
Floods	Risk-based criteria for flood-watches, flood warnings, heavy rainfall warnings and surface water alerts	See Chaps. 8 and 9
Flow control	Daily operation of reservoir systems through to long-term planning studies	See Chap. 11
Water resources	Seasonal flow forecasting applications	See Chap. 13

Box 7.1: Dissemination of Warning Messages

In early warning applications, usually some interpretation of model outputs is required before providing guidance to end users. For example, in flood warning applications, it is usually more useful to know which locations are likely to flood rather than what the peak water level is likely to be at a nearby river gauge. A key challenge is therefore to decide how best to communicate information in a way that is meaningful and received in time to take effective action. This is particularly the case for fast-responding events such as flash floods but applies to many other types of natural hazards as well.

In practice, in addition to members of the public, warnings may need to be issued to a range of organisations, such as civil protection authorities, local and national government departments, the emergency services, community representatives and water supply companies. Typically, each group has different requirements and levels of technical understanding and familiarity with the terminology (or 'jargon') used by technical specialists. For example, in the context of flash floods, NOAA (2010) notes that 'the general public is not a homogeneous group since it involves:

- Decision makers at all levels in the community
- People with many different levels of education
- People with many different levels of financial ability and responsibility

(continued)

Box 7.1 (continued)

- People of different races and beliefs
- People with many different primary languages
- People with widely varying experience with the hazard
- People with varying levels of physical ability'

Collier et al. (2005) also note that 'we need to keep a clear distinction between the needs of hydro-meteorological services and flood emergency operations' since 'in the former case the interest is in getting the best possible forecast, whereas in the latter case the interest is in making the best possible decision'. Regarding the information conveyed, for natural hazards in general, WMO (2010) notes that:

> Effective warning messages are short, concise, understandable, and actionable, answering the questions of "what?", "where?", "when?", "why?", and "how to respond?" They should also be consistent over time. Alert messages should be tailored to the specific need of intended users. The use of plain language in simple, short sentences or phrases enhances the user's understanding of the warning. In addition, the most important information in the warning should be presented first, followed by supporting information. They should also include detailed information about the threat with recognizable or localized geographical references.

The development of predefined message templates is often emphasized so that only key details need to be added during the pressure of an event. Normally, designs should follow national or organizational standards with versions available in different languages if appropriate. Some key factors to consider include the style, content, tone, terminology and completeness of the information provided (e.g. Australian Government 2009), normally requiring extensive consultations during the design process. Often, colour codes or icons are included to provide an easily recognised visual representation of the severity of an alert, such as the coloured, triangular symbols which accompany flood warnings in the UK, as illustrated in Fig. 7.1.

Another consideration is the extent to which warnings are advisory or mandatory; for example, the difference between advising that 'there is a high probability of flooding in your neighbourhood' compared to the instruction to 'leave your property now!' or, during a developing drought, advising farmers that 'flows are expected to remain low for the next month' compared to the instruction to 'suspend spray irrigation for the next 10 days'. This is normally defined by national legislation, and a strong regulatory structure is another key component in an early warning system (e.g. UN/ISDR 2006).

As noted in Chap. 1, to help to improve the effectiveness of a warning service, a community-based or people-centred approach is widely advocated (e.g. Basher 2006; UN/ISDR 2006; WMO 2005, 2006b), and some typical outreach activities include:

- Formally involving community representatives such as by establishing emergency planning or disaster risk management committees and through active involvement in developing contingency plans

(continued)

Box 7.1 (continued)

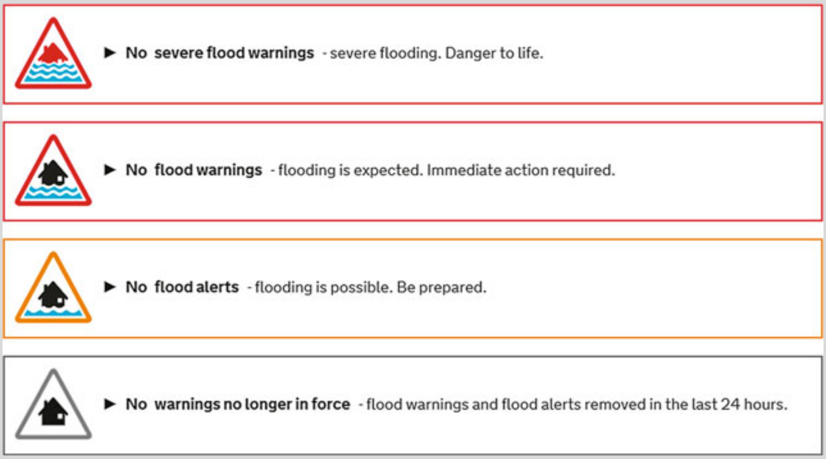


Fig. 7.1 Flood warning codes in the UK (Environment Agency 2015, © Crown Copyright 2015; Contains public sector information licensed under the Open Government Licence v3.0)

- Social research to assess satisfaction with the existing service such as the warning lead times provided in recent events and public understanding of the messages received
- Routinely running public-awareness raising campaigns such as via the media, leaflet drops, community meetings, posters and school visits, and placing flood markers in communities to indicate the water levels reached in previous flood events
- Running emergency response exercises to evaluate procedures and identify possible areas for improvements; using office-based (table-top), functional or full-scale simulation exercises

Another factor in the success of a warning service is the approach used to issue (or disseminate) warnings. Options typically include general (indirect) approaches such as newspapers, radio and television, and toll-free information lines and – particularly for short lead-time applications – more direct and community-based approaches such as cell phone or landline calls, megaphones (loud hailers), sirens, community-based radio stations church bells, mosque loudspeakers and door-knocking (e.g. Fig. 7.2). Software tools such as automated phone dialing systems and multimedia systems are also increasingly used, allowing warnings to be issued more quickly to larger numbers of people than was possible in the past. Some typical examples of the functionality provided include text to speech converters, language translators and message editing facilities, as well as a wide range of communication routes (phone, text, email, RSS, etc.).

Increasingly information is made available via websites and smartphone applications, usually with maps to provide a spatial context, and many national services

(continued)

Box 7.1 (continued)

Fig. 7.2 Example of a flood warning siren in Northeast England: the river lies between the two flood walls behind the siren (Adapted from Sene 2013)

now use social media to provide updates during emergencies and text and email alerting facilities. Each approach has its own strengths and limitations, and there is an extensive literature on this topic based on experience gained from warning systems for floods and other types of natural hazards, such as tornadoes, wildfires and earthquakes (e.g. Sorensen 2000; WMO 2002; Martini and de Roo 2007; Australian Government 2009; Coleman et al. 2011; IFRC 2012).

When developing a warning system, some examples of factors to consider include the time required to issue warnings, the needs of vulnerable groups and how to issue warnings to dispersed groups such as tourists, business travellers and vehicle drivers. Depending on the approach, some technical issues to consider include audibility in storm conditions, such as with sirens; staff safety if travelling through flooded areas, as with door-knocking; and the reliability of cell phone coverage, such as in deep river valleys.

There are also wider social issues to consider relating to the interpretation of warnings and the reasons why people do not always respond as expected (e.g. Mileti 1995; Drabek 2000; Australian Government 2009; Parker et al. 2009; Parker and Priest 2012). Some examples of potential issues include risk-taking behaviour, a lack of confidence in the authority providing the warning and of course poor message design or an inappropriate means of

(continued)

Box 7.1 (continued)
delivery. For example, WMO (2002) notes that 'It is now well recognized that if a warning program is to be successful it must strive to ensure that every person or organization at risk:

- Receives the warning
- Understands the warning
- Believes the warning is real and the contents are accurate
- Confirms the warning from other sources or people
- Personalizes the risk associated with the warning
- Decides on an appropriate course of action
- Responds in a timely manner'

Also that 'an individual's perception of risk is enhanced when:

- Warning messages before and during a particular event are issued and updated frequently
- The same warning messages are delivered by multiple credible sources
- Warning messages are consistent
- The basis for the warning is clear
- Suggested protective actions are included'

The resilience to system failure is another important consideration, and issues with cell phone, landline and radio communication networks are often cited in post-event and lessons learned reports following disasters such as floods. Generally it is therefore widely recommended to use a range of direct, indirect and community-based approaches so that messages reach as many people as possible – and in a range of formats – and as a backup in case some routes fail. For key groups such as civil protection authorities, it is also important that the methods chosen allow confirmation that messages have been received and understood.

7.2 Thresholds

Thresholds are predefined criteria for taking action and are a key decision-making tool in hydrometeorology. Typically, decisions are taken on the basis of a variable exceeding or dropping below a critical value, as illustrated by the flood-related example in Fig. 7.3 from the National Weather Service in the USA. Whilst most often associated with early warning applications, thresholds can also assist with more routine operations such as triggering the operation of flow control structures or managing reservoir releases.

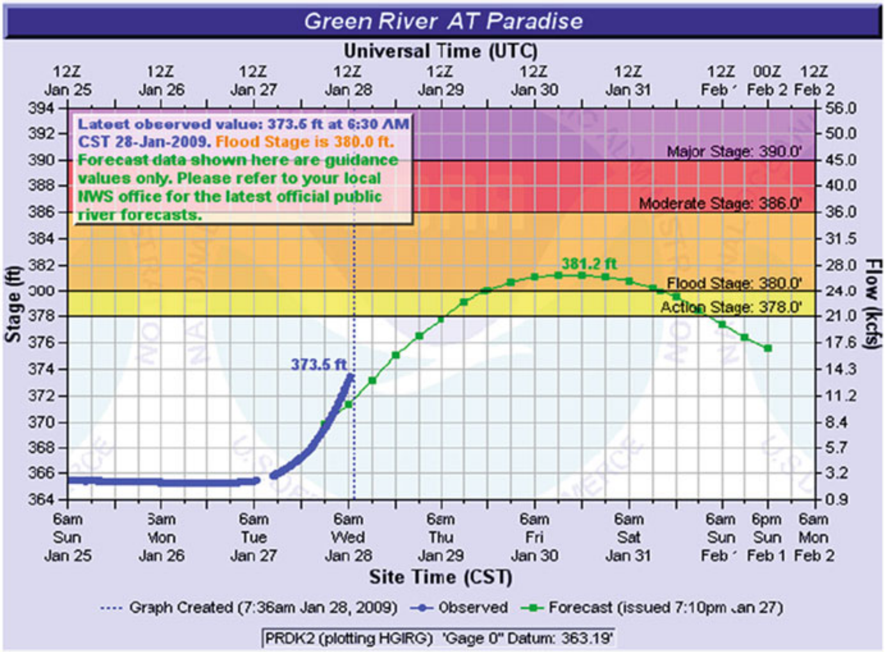


Fig. 7.3 Graphical flood forecast to T+48 h for the Green River at Paradise, Kentucky, United States (WMO 2011, courtesy of NOAA, WMO)

Threshold values can be based on a single variable or a combination of parameters, often with duration as an additional criterion. Table 7.2 presents some simple examples whilst more complex techniques include:

- Derived values – the use of cumulative flow departures and drought indices in drought warning applications, or anomalies in seasonal flow forecasting applications
- Multi-criteria thresholds – the combination of reservoir inflow and water level observations in flood warning applications, or rainfall and soil moisture conditions in flood and drought applications

Several examples of these approaches are provided in later chapters and, in many cases, these might be regarded as a simple empirical type of forecasting; for example, based on expectations about how river levels will behave in the near future and the response in similar previous events.

As already noted, in early warning applications, it is usual to have several levels of alert, and this requires separate threshold values for each stage. For example, for water quality alerts, operational and critical limits are often defined which 'can be upper limits, lower limits, a range or an "envelope" of performance measures', where 'deviations from critical limits will usually require urgent action' (WHO 2011). Similarly for natural hazards such as tropical cyclones, hurricanes and floods (WMO 2006c), a typical sequence might be:

Table 7.2 Examples of the use of thresholds in hydrometeorological applications

Parameter	Application	Basis of method
River level	Flood warning	Exceedance of threshold value
	Drought watch	Level at or below threshold value
River flow	Water resources	Flow at or below threshold value
Rainfall	Flood warning	Exceedance of depth-duration value
	Bathing water quality	Exceedance of depth-duration value
	Drought watch	Depth-duration below critical value
Reservoir levels	Flood warning	Levels exceeding critical values
Water quality	Pollution incidents	Exceedance of value

- An advisory informs people within a designated area of probable weather or hydrological conditions that could lead to hazardous situations, but they are not yet severe enough to move to the next stage of alert. People should take note of an advisory and be aware of any change in conditions
- A watch alerts the public of the possibility of a particular hazard and provides as much information as is available on its intensity and direction. Such forecasts are issued well in advance of a weather event such as a cyclone, when conditions are suitable for development of severe conditions. When a watch is announced, people should take steps to prepare to protect their lives and property. Depending on the circumstances, they may need to prepare for evacuation
- A warning is a forecast of a particular hazard or imminent danger issued when extreme conditions have developed and are occurring, or have been detected. It is time to take appropriate action

This general approach is widely used although the number of stages of alert and the message design varies widely between countries. Later chapters provide further examples.

Whilst decisions are often made on the basis of observed values, if a forecasting model is available, then the outputs can potentially help with taking decisions earlier than when based on observations alone (e.g. Box 7.2). This is sometimes called a ‘warn-on-forecast’ approach. Separate forecast thresholds are often defined both to take advantage of the additional lead time provided and to provide a safety margin due to forecast uncertainty. However, in practice, the way that forecasts are used operationally normally depends on a range of factors including confidence in the model outputs, past model performance and organizational policy.

For example, operational procedures sometimes specify that observations must have exceeded threshold values before considering taking actions based on forecast outputs. Another option is to only use forecast outputs to trigger low risk actions such as starting more frequent monitoring or providing an initial ‘heads-up’ to disaster risk management agencies. In some cases, so-called soft and hard limits are defined where duty officers have some discretion in deciding whether to issue a warning once the lower threshold is passed but must issue a warning if the second value is exceeded.

However, there are several other possible permutations, particularly for multi-criteria thresholds. Also where forecasts are routinely published to a website, additional guidance or discussion normally needs to be included regarding how to interpret the outputs, such as confidence in the values provided, or why a warning has not been issued if thresholds have been exceeded. For example, the inset on Fig. 7.3 reads 'Forecast data shown here are guidance values only. Please refer to your local NWS office for the latest official public river forecasts'.

More generally, whether using observations or forecasts, threshold values should be reviewed on a regular basis and particularly following any changes to instrumentation, models or the catchment response, such as the construction of reservoirs or levees. Measures such as hit rates and false alarm ratios are widely used for this type of analysis and are discussed in Chaps. 4 and 5. Indeed when setting threshold values, there is often a trade-off between these values and the lead times provided; for example, if a flood warning threshold is set too low, over the long term this will generally result in longer lead times and higher hit rates but more false alarms (e.g. USACE 1996). It is also important to note that the overall system performance depends on a much wider range of factors such as those relating to the dissemination, receipt and understanding of warnings, as discussed in Box 7.1, for example.

A more general consideration is how representative a chosen parameter is for the application. For example, often the first stage of alert in a flood warning system is based upon rainfall depth-duration criteria, such as 50 mm of rainfall in 6 h. However, due to the uncertainties in how rainfall translates into runoff, in many applications this would only be used to advise on the need for initial low-cost, low-impact preparatory actions rather than to issue warnings directly to members of the public. In contrast, rainfall thresholds are used more directly in some applications such as providing warnings for the risk of debris flows, surface water flooding, or of poor water quality at beaches (see Chaps. 9 and 12).

Some approaches to defining threshold values include seeking expert opinion, analyses of past events and hydrological modelling studies. Whilst the use of historical observations is generally preferred, this is not always feasible so model-based thresholds are sometimes used, such as in distributed rainfall-runoff models and Flash Flood Guidance systems (see Chap. 9). Again issues such as lead times and hit rates need to be considered as part of the calibration process. However, in some cases, such as water quality applications, it may be possible to draw on values published in national or international health or environmental guidelines. Increasingly, national services also provide users with the option to define their own values by registering entries via a website (see Chap. 1). Text message or email alerts are then provided when river levels, rainfall or water quality parameters exceed (or drop below) the specified values. It is then the responsibility of users to interpret the information received and decide on the actions to take.

More generally, and particularly for emergency applications, threshold values are usually best defined in collaboration with key stakeholders. This could include discussion of topics such as the minimum warning lead times ideally required, where this is technically feasible, and the possible impacts of false alarms. This is particularly the case for applications in which an incorrect decision would have major safety, health or financial implications such as:

- Evacuating part of a town or city in response to a flood warning
- Restricting irrigation and hydropower generation following a drought warning
- Restricting drinking water supplies due to the risk of contamination

Indeed one of the strengths of a threshold-based approach is its transparency since values can be agreed in advance and built into operational procedures, rather than trying to interpret observations and forecasts on a case-by-case basis as an event occurs. However, there are potentially many limitations since an event may unfold in different ways to that inherent in the historical information on which threshold values are based. More sophisticated risk-based and probabilistic approaches therefore have an important role to play and are described in the following sections, including the use of probabilistic thresholds.

Box 7.2: Flood Warning Thresholds

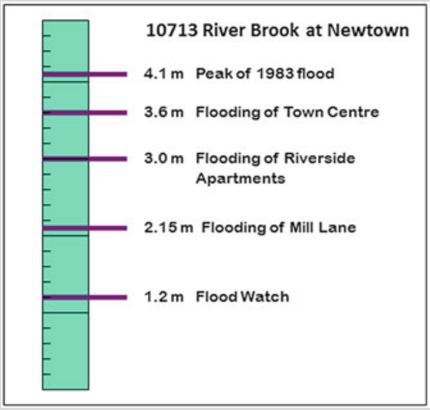
One of the most common applications of threshold-based techniques is in flood warning systems. Typically, most modern telemetry and flood forecasting systems have a map-based interface capable of displaying locations where thresholds have been exceeded, and the capability to raise email, text-based or other alerts. The raw gauge and model outputs or the information on threshold exceedances may in turn be sent on to decision-support systems and other tools such as automated phone dialing or multimedia warning dissemination systems.

For a regional or national service, the number of thresholds defined can be large, sometimes with several hundreds or thousands of values required to cover different combinations of gauges, locations at risk and stages of alert. However, paper-based procedures are still widely used where budgets are limited, particularly in community-based flood warning systems of the types described in Chap. 9. Hard copies are normally also retained as a backup in more automated approaches in case of system failure.

To provide additional resilience, threshold values are often defined for gauges upstream of locations at risk, as well as those at or near the site. These are sometimes called remote thresholds and, although providing earlier indications of a flood threat, may lead to more false alarms. Some typical sources of uncertainty include ungauged tributary inflows between the at-site and remote gauges, variations in catchment antecedent conditions, and flow control structure operations. To provide additional information to help with decision-making, these approaches are often supplemented by simple forecasting tools such as rate-of-rise triggers and correlation models of the types described in Chap. 5. Some other options include rainfall depth-duration thresholds as discussed earlier and gauges at downstream locations for sites with significant tidal or backwater influences

(continued)

Box 7.2 (continued)



Level (m)	Description
1.2	FWAT02 Flood Watch
1.8	FW021 Mill Lane
2.7	FW022 Riverside Apartments
2.9	OPS022 Close Flood Gates 1 to 4
3.2	OPS023 Loud Hailer Patrol
3.3	FW023 Town Centre
4.1	INFO23 Peak of 1983 flood
1.8 and falling	AC021 All Clear
	FWAT = Flood Watch FW = Flood Warning OPS = Operational Instruction

Fig. 7.4 Hypothetical action table showing how levels at a river level gauge correspond to flooding impacts and an associated system of flood watch, flood warning, operational and information thresholds plus an associated graphical representation of key levels (Illustrative example only; procedures vary widely between organisations)

Figure 7.4 illustrates how a system of river gauge threshold values might be presented in operational procedures. Many different formats are used, but in this example, values are summarized in a so-called action table that indicates the appropriate action(s) to take as each level is passed; to provide a visual impression of the potential impacts, a form of presentation based on a staff gauge is included (and is sometimes called a thermometer plot).

As shown in the example, additional thresholds are sometimes included that relate to operational actions such as closing a flood gate or starting loud-hailer patrols to issue warnings, together with values for information purposes such as levels reached in previous major flood events. In some applications, specific thresholds are required for critical infrastructure operators; for example, relating to power stations or water treatment works. Maps are normally included with the tables showing areas likely to be flooded for each threshold level.

If outputs are available from a forecasting system, then as noted earlier typically this requires additional threshold values to be defined. Often the values used are higher than those based on observations alone in recognition of the additional lead time provided by the forecast results. However, due to the uncertainties in model outputs, forecast thresholds normally need to be defined on the basis of performance testing, in particular to achieve a suitable compromise between lead times, hit rates and false alarm ratios. For example, it cannot necessarily be assumed that use of physically meaningful elevations will be appropriate, such as those for overtopping of a levee or the onset of property flooding.

(continued)

Box 7.2 (continued)

Given the potential safety and other implications, threshold values and any associated maps and other documentation are normally managed within the framework of a quality management system and electronic document management system. Values need to be reviewed on a regular basis and after major flood events and if changes occur in the catchment or to instrumentation; for example, the build-up of sediment in river channels due to catchment degradation is a major issue in some countries which, amongst other problems, affects threshold values.

7.3 Decision Support Systems

Decision support systems can provide useful additional information to help with decision-making including tools for visualizing and analyzing forecast outputs. One definition (NASA 2009) is that 'Decision Support Systems are a general type of computerized information system that supports business and organizational decision-making activities'. In addition to data management, validation and reporting options, some systems include:

- Simulation Models – models which use hydrometeorological observations and forecasts as inputs, such as crop simulation and reservoir operation models
- Optimisation Modules – algorithms to advise on possible response strategies such as for evacuation or deciding on reservoir releases

The two main approaches to incorporating model outputs are to integrate the model into the system or to provide automated links to import the outputs from a separate modelling environment, such as a flood forecasting system.

Table 7.3 shows some typical applications. In most cases, the outputs are for advice only, and it is left to the end user to decide on the actions to take. However, in some systems, the software is used to control actuators via a telemetry link, which in turn operate gates, valves or other components, such as in the control systems for some tidal barriers and urban drainage systems (see Chap. 11).

Historically, one of the first real-time applications was to provide guidance on reservoir operations, particularly where multiple environmental, water supply and other objectives need to be met. Urban drainage control systems are also widely used following pioneering work in the 1990s and before in Canada and the USA. Decision support systems have also been used for a number of years to support large-scale commercial farming operations and for regional food security applications. Increasingly, a probabilistic component is included in all of these examples.

Table 7.3 Examples of the use of decision support systems in hydrometeorological applications

Application	Purpose
Agricultural Risk Management Systems	The use of crop simulation models to provide information to help decide on optimum planting, harvesting and grain storage strategies and shorter-term scheduling for irrigation and fertilizer use; also famine early warning systems (see Chaps. 6 and 10) (e.g. WMO 2012)
Drought Management Systems	Providing information for use by disaster managers in deciding on optimum response strategies to food and water supply shortages (see Chap. 10) (e.g. WMO 2006a)
Flood Incident Management Systems	Providing information to assist the emergency services and others to decide on optimum evacuation, rescue, gate operation and other types of response during a flood event (see Chaps. 8 and 9 and Box 7.3)
Reservoir Operation Systems	Providing information to help reservoir operators decide on optimum reservoir release strategies to meet a range of water supply, irrigation, hydropower and other objectives subject to regulatory, environmental, economic and other constraints (see Chap. 11) (e.g. Loucks 1996)
Urban Real-Time Control Systems	Control of gates, valves and other components in urban drainage systems to minimize pollution and flooding incidents during heavy rainfall and reduce operating costs at other times (see Chap. 11) (e.g. Schilling 1989; Schütze et al. 2004)

By contrast, the use in flood incident response is a more recent development, as discussed in Box 7.3. However, for emergency management in general, some advantages of using a GIS-based approach include (MacFarlane 2005):

- Support for tasking and briefing
- Producing hard copy maps which remain a key information product for responders and planners
- Integrating data from multiple sources that may flow in during the course of an emergency
- Developing a Common Operational Picture for multi-agency staff
- Supporting two way flows of information through mobile GIS
- Assessing likely consequences and supporting forward planning
- Managing assets and resources for current and projected future demands
- Keeping the public and other affected parties informed through internet or intranet mapping systems
- Establishing one element of an audit trail
- Supporting the transition to recovery with a baseline database that also integrates a full picture of the emergency itself

There is also the option to use GPS devices to report on the locations of key assets in near real time, such as search and rescue helicopters, ambulances and mobile command units. Most modern systems include a map-based interface with the option to select from a wide range of layers such as:

- Thematic/background maps (e.g. catchment boundaries, rivers, roads, topography)
- Images (e.g. aerial photographs, satellite images)
- Application-specific information (e.g. flood warning areas, flood evacuation routes, shelter locations)
- Forecasting model outputs (e.g. flood inundation maps, maps of drought indices)

However, a common issue is that prototype systems developed as part of research projects and pilot studies are either not implemented operationally or soon fall into disuse. As with many other types of software-based system, some key factors which often influence the long-term sustainability include:

- The reliability and usability of the software and associated systems, including the level of backup provided if primary systems fail
- The degree to which the system is integrated into operational procedures and the level of technical and financial support provided over the long term
- The level of training provided to staff and the confidence that users have in the outputs
- The extent to which users were able to influence the design of the system to meet their requirements

In addition, and particularly for safety critical or high value applications, the system design needs to be extensively documented and tested, with backup procedures in place in case of system failures, loss of telemetry and other problems. For example, for the Maeslant tidal barrier in the Netherlands discussed in Chap. 11, which protects Rotterdam and surrounding areas from tidal flood risk, the design documentation for the automated decision support system consisted of several thousand pages of natural text and operation schemas and formal descriptions (Tretmans et al. 2001).

Whilst many systems focus mainly on presenting information on the current situation, as noted earlier some include algorithms to guide users towards possible solutions, and Table 7.4 provides some examples of the techniques used.

In some cases, options are formulated in financial terms to provide a common basis for making decisions across a range of possible alternatives. Examples include virtual costs such as the opportunity losses for irrigation in releasing water from a reservoir to provide flood storage, or the losses avoided (benefits) if a reservoir is operated in such a way as to reduce flooding further downstream.

However, where impacts cannot easily be expressed in financial terms, utility functions provide another option and are a concept from economics which expresses the value that a user places on an outcome, taking account of their attitude to risk (e.g. von Neumann and Morgenstern 1944; Savage 1972). These are sometimes called penalty functions. For example, in reservoir operations, overtopping of the dam wall is an unacceptable outcome so a high value would be placed on management strategies which prevent this from occurring. Similarly, for a reservoir operator, some useful metrics (to minimize) typically include the number of periods with

Table 7.4 Some examples of optimization techniques in decision support systems

Technique	Description
Artificial intelligence	Algorithms which use techniques such as artificial neural networks, fuzzy logic and genetic algorithms to develop solutions
Decision trees	An approach which identifies decision points, event points and alternative options with associated probabilities, leading to a range of outcomes from which one or more is selected
Dynamic or linear programming	Stochastic and deterministic techniques which use simplified representations of a system to iteratively arrive at an optimum solution
Expert systems	Algorithms which typically use logical or production rules to arrive at solutions using IF THEN AND OR ELSE and other constructs
Scenario analysis	Multiple runs using the full simulation model to identify an optimum based on one or more criteria, perhaps using Monte Carlo techniques

water restrictions or the cumulative water deficit. The functional forms adopted are often the subject of extensive discussions with stakeholders, and in qualitative terms, some examples of the approximate shapes of penalty curves include:

- U-shaped curves, where both low and high extreme values of the parameter – such as reservoir levels or river flows – are undesirable
- L- or J-shaped curves, which remain at low values except when the parameter is unusually low or high, at which point the penalty rises sharply (as in the overtopping example above)
- V-shaped curves, for situations where the optimum solution lies within a narrow range, such as when defining optimum flow conditions for some species

Many other forms are used and, to allow functions to be combined, values are normally expressed on a common scale such as from 0 to 1. When there are several utility functions to consider, the optimum solution is often taken to be the outcome which provides the maximum combined utility or minimum penalty (although other approaches are possible). However, sometimes outcomes are not so clear-cut, particularly when there are multiple objectives to consider. For example, for reservoir operations, it may be necessary to consider the competing requirements of water supply, hydropower, flood control, irrigation, navigation, fisheries, recreation and habitat protection. The risk tolerance of users also needs to be taken into account as discussed in the following section.

Of these various approaches, dynamic and linear programming techniques are widely used in reservoir management systems (see Chap. 11), whilst artificial intelligence techniques are used (or have been evaluated) in a number of applications, such as demand forecasting (see Chap. 6). Decision trees are also used in agricultural, hydroscheduling and bathing water pollution applications (e.g. Harrison et al. 2008, Troccoli et al. 2008 and Chaps. 6 and 12).

Box 7.3: Decision Support Systems for Flooding Incidents

During a major flood event, the emergency services and other organizations typically need to make decisions based on information from many sources, much of which is incomplete, uncertain and at times contradictory (e.g. Sorenson and Mileti 1987; Macfarlane 2005; Morss and Ralph 2007; Baumgart et al. 2008). Geographic Information Systems (GIS) and Decision Support Systems are therefore widely advocated to help to reduce this complexity and are used operationally in some countries for flood or multi-hazard applications (e.g. Fig. 7.5). The overall aim is usually to improve situational awareness and provide information to assist with deciding on priorities for response.

Table 7.5 provides some examples of the types of information which could potentially be included for presentation and analysis. In some systems, this includes tools to help with updating emergency response plans during an event and with generating web-based incident logs and situation reports; also for staff to load information remotely on the current situation from smartphone applications and other devices carried on site, such as on flooding extent or debris blockages. For flood warning applications, the safety-critical aspects are of particular importance to the design requiring detailed investigations of the resilience to failures of telemetry systems, computer equipment, power supplies and other items, with backups in place in case of failure of any one component. Access is normally also password controlled to protect confidential information.

A logical next step – although still a developing area – is to include the ability to run 'what-if' scenarios or optimization routines regarding potential flooding impacts. Flooding scenarios, such as for a dam break, are typically

Fig. 7.5 Command Unit and Water Rescue Unit used by the Greater Manchester Fire and Rescue Service in the UK during flood and other emergencies. The computer screen on the side of the command unit is used for briefing staff and shows the locations of key vehicles and other assets against a map-based background; there are additional displays in the vehicle together with computer workstations and communications equipment

(continued)

Box 7.3 (continued)

Table 7.5 Examples of the types of information which could be included in a decision support system for flood incident management

Item	Description
Base maps	Digital maps for property locations, vulnerable groups, streets and roads, railways, airports, tourist sites and flood defences (levees), together with aerial photographs, satellite images and digital terrain models
Critical infrastructure	The locations of critical assets such as power stations, pumping stations, telecommunication hubs and water and wastewater treatment works
Emergency response facilities/assets	The locations of command centres, police stations, fire stations and medical centres and of mobile assets such as vehicles and helicopters, temporary barriers, excavators, pumps and boats
Environmental risks	Potential sources of pollution, such as industrial sites, waste disposal sites and sewage treatment works
Flood forecasts	The latest model outputs for parameters such as river, reservoir and lake levels and (if the functionality is available) the anticipated flood inundation extent, plus rainfall and other meteorological forecasts if available
Flood warning and evacuation maps	Predefined maps showing areas at risk from flooding under different scenarios and potential access and evacuation routes
Hydrometeorological monitoring	Recent rainfall, weather radar, river level, reservoir level, tide gauge and other information, including aerial and satellite imagery of flooding extent if available
Shelters	The locations of emergency accommodation centres for people evacuated from their homes, access routes and the current occupancy rates and medical, food and water supplies
Traffic information	Road capacities, roadworks and information on current traffic conditions relayed by telemetry, perhaps coupled to traffic flow forecasting models

prepared off-line rather than estimated in real time; a key advantage of stored scenarios being that they can be checked and audited in advance and require minimal computing time to retrieve during an event. However, dynamic scenarios are more likely to represent current conditions, including event-specific factors, and some flood forecasting systems include this type of functionality as discussed in Chaps. 5 and 8.

Perhaps, the longest established systems with a decision support component are those developed for hurricane warning and evacuation in the USA (e.g. Wolshon et al. 2005). In addition to wind damage and tidal flooding risks, these typically include provision for assessing the risks arising from river flooding after a hurricane makes landfall. Examples include the Hurrevac system (http://www.hurrevac.com) and the Evacuation Traffic Information System. Some more recent examples related specifically to coastal or river

(continued)

Box 7.3 (continued)
flooding include systems operated in parts of the Netherlands, Germany and Switzerland (e.g. Langkamp et al. 2005; Flikweert et al. 2007; Romang et al. 2011).

More generally, there have been several research studies into the requirements for these types of systems (e.g. Lumbroso et al. 2009; Simonovic and Ahmad 2005; Van Oosterom et al. 2005). For example, one particular area of interest is in improved techniques for providing advice on emergency response, with some possible approaches including using logical rules, linguistic reasoning, fuzzy logic, Bayesian Belief Networks and artificial neural networks. These approaches are perhaps furthest advanced for evacuation planning, considering factors such as access and escape routes, current shelter occupancies and road traffic conditions. Other potential applications include prioritizing search and rescue operations and the provision of humanitarian assistance to those left stranded by a flood.

7.4 Risk-Based Approaches

One unavoidable aspect in forecasting is the uncertainty in model outputs, particularly for medium- to long-range forecasts. In particular, for some types of forecast such as seasonal forecasts, outputs are generally only considered to be meaningful in probabilistic terms. As discussed in Chap. 1, it is therefore widely recommended that the uncertainty should be taken into account in decision-making and conveyed to decision-makers (e.g. Krzysztofowicz 2001; UN/ISDR 2007; WMO 2012). This should allow users to make a better assessment of choices and adopt more of a risk-based approach to issuing warnings and operational decision-making.

For example, in flood warning applications, some users may appreciate warnings at a much lower level of probability than others since this should allow preparatory actions to be taken that would yield benefits later, if flooding does occur. Typically, this might involve actions which were already planned or can be made at relatively little cost and – in addition to activating contingency plans – could include:

- Local authorities temporarily closing riverside car parks and footpaths
- Civil protection authorities arranging emergency staff rosters and checking that key equipment is available
- Farmers moving livestock away from riverside fields
- Operational staff clearing watercourses of debris and making temporary works safe

Risk is usually defined as the combination of probability and consequence. Typically, the consequences depend not just on the exposure to a threat but on the vulnerability of individual groups as well. Vulnerability is therefore often included in definitions of risk and usually depends on a wide range of factors; for example, WMO (2006b) groups these into physical or material, constitutional or organizational and motivational or attitudinal conditions. Thus, regarding floods, some potential risk factors include:

- Social or economic factors – people with limited mobility, or visual or hearing impairments; families with young children; people without landline, cell phone, television, radio and/or Internet communications (*which could be viewed as physical or material factors*)
- Physical or material factors – underground car parks or basement apartments; housing and critical infrastructure with limited flood resilience
- Constitutional or organizational factors – a lack of clarity over roles and responsibilities for issuing flood warnings; limited or no community engagement in the design and operation of flood warning schemes
- Motivational or attitudinal factors – risk-taking behaviour by car drivers such as driving through flood waters; a lack of confidence in the agency issuing the warnings; newcomers to an area with no previous experience of flooding in that location

Regarding the probability dimension of risk, Table 7.6 illustrates some of the ways that probabilistic forecasts are used operationally, and several examples are provided in later chapters.

Given the wealth of information available, visualization techniques often have a powerful role to play (e.g. Pappenberger et al. 2013) and provide the option to view information at different lead times and spatial scales and in a range of formats. For example, Fig. 7.6 shows one of the forecast products available from the National Weather Service in the USA, which gives 'the probability or chance of the maximum stage, flow or volume at a point on a river exceeding a particular value for consecutive 7-day periods in a 90-day interval'.

As indicated in Table 7.6, another option for making quantitative use of probabilistic forecasts is to define thresholds in probabilistic terms; for example, based on a given percentage of ensemble members exceeding that value at the lead time of interest. Some studies have also shown that considering the persistence in consecutive forecasts can help to reduce the number of false alarms (e.g. Bartholmes et al. 2009)

Table 7.6 Some examples of techniques for making use of probabilistic forecasts

Technique	Description
Visualisation techniques	Spaghetti plots, plumes, histograms, box-and-whisker plots, stamp plots (i.e. multiple maps on a single page), time-lagged ensembles and other outputs showing different aspects of the forecast such as confidence intervals, clustering/tubing of ensembles, probability distributions and spatial variations
Probabilistic thresholds	The definition of threshold values in probabilistic terms, such as to provide a warning if there is more than a 60 % probability of rainfall exceeding 50 mm in 2 h
Decision theory	Evaluation of the costs and losses (or utility) of different probabilistic or ensemble scenarios to help to identify optimum solutions and the use of more complex techniques (see below)

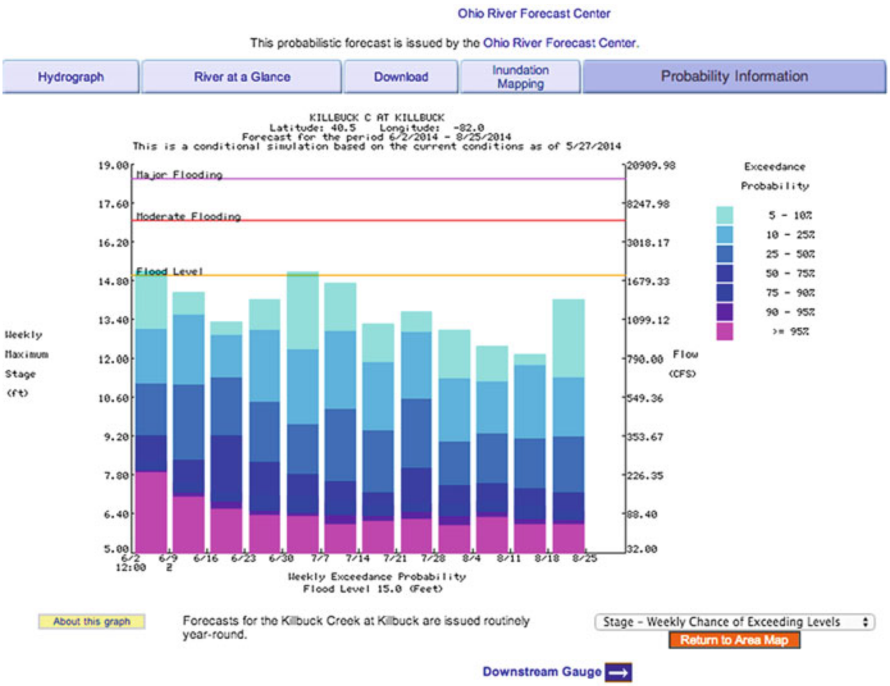


Fig. 7.6 Sample weekly chance of exceeding levels product (NOAA/NWS 2014)

and that the consistency or 'jumpiness' between successive forecast runs provides useful additional insights (e.g. Pappenberger et al. 2011; Persson 2013).

Some approaches to setting probabilistic thresholds include analyses of past forecast performance (see Chap. 5), use of model-based 'threshold-frequency' estimates (see Chap. 9) and techniques from decision theory. As discussed in Chap. 5, a reforecasting exercise is often required to generate outputs for use in calibration together with some additional post-processing to account for model bias and other issues. As for deterministic thresholds, values should normally be defined in collaboration with key stakeholders.

For example, cost-loss approaches provide one approach to setting threshold values and consider the cost of acting upon a forecast compared to the losses which would occur if no action is taken. As illustrated by the simple example in Table 7.7, these choices are normally summarized in a contingency table (or expense table) similar to those used in forecast verification (see Chaps. 4 and 5).

Over a number of events, mitigating actions would be cost effective in this case if taken whenever the probability of an event occurring exceeds the cost-loss ratio C/L (e.g. Katz and Murphy 1997). To take a simple example, on the basis of a river level forecast, temporary barriers might be installed at a riverside car park incurring staff and other costs (C). If the levels subsequently exceed the flooding threshold

Table 7.7 Example of a 2×2 expense table

	Event occurs	No event occurs
Mitigating action	Cost (C)	Cost (C)
No mitigating action	Loss (L)	No cost

and the barriers prevent flooding, then there would be no loss (L). Over the long term, it would then be advantageous to install the barriers whenever the exceedance probability for river levels is higher than the cost-loss ratio.

This approach can be extended to consider a range of other factors such as only partial mitigation of losses, variations in losses with lead times and the risk tolerance of end users (e.g. Roulston and Smith 2004; Roulin 2007; Martina and Todini 2009). In some cases, the analysis is formulated in terms of utility functions when key factors cannot be expressed in monetary terms (see Sect. 7.3). Another refinement (Richardson 2012) is to consider the economic value of the forecast to users relative to the idealized situations of having perfect foresight of an event and of only knowing the long-term average conditions (or climatology) or using a persistence-based forecast. Using these types of approach, there is then the option to tailor probability thresholds to individual groups or users depending on their risk profiles (e.g. risk averse) and the potential costs and losses over a number of events.

One application of these types of approach is in reservoir management (see Chap. 11) although with many challenges and issues to consider (e.g. McCollor and Stull 2008; Muluye 2011; Werner et al. 2013). In particular for complex multipurpose reservoir systems, a more dynamic approach may be required (e.g. Addor et al. 2011). Cost loss and risk-based techniques have also been evaluated for a range of flood-related applications such as flood warning and tidal barrier operations (e.g. Roulin 2007; Dale et al. 2014).

However, a distinction needs to be made between decisions which are taken frequently and only have minor consequences and less frequent decisions where the consequences or risks are severe, such as in a major flood event or pollution incident. Some examples of the first situation could include day-to-day decisions on irrigation scheduling or a hydropower operator deciding on the generation plan for the next few days: the defining feature here being that risk-based techniques are applied consistently over many events in a relatively short period of time.

For extreme events, some other potential issues include a lack of representative events in historical records for model calibration and that there may be social and stress-related changes in response when organizations and individuals are faced with forecasts of high impact or catastrophic events (e.g. Haimes 2009; Morss et al. 2010). As for deterministic forecasts, the model outputs are also just one component in a wider decision-making chain with many other factors which could potentially influence the extent to which warnings are heeded. In that regard, Bayesian uncertainty frameworks provide a possible approach to considering overall system performance and have been evaluated for use in flood warning applications (Krzysztofowicz et al. 1994).

Some other areas in decision theory which have potential, such as in climate forecasting applications (e.g. Rubas et al. 2006), include:

- Game theory – which considers how actions by one group affect others
- General equilibrium modelling – which accounts for overall supply and demand of resources
- Mechanism design theory – which allows for adaptation of institutional and economic behaviour

Prospect theory is another approach which is used in some scientific fields and considers the response of individuals to gains and losses rather than to absolute values (Tversky and Kahneman 1992).

Another technique, perhaps best suited to long-term planning studies, is that of Bayesian Belief Networks. These allow observed data to be combined with less precise or uncertain information, expressed in the form of probability distributions, including subjective judgements by key users. The earliest practical applications were in the 1980s in areas such as medicine and software fault diagnosis, but the method has since been applied in a wide range of industrial, financial, transport and environmental applications; in hydrometeorology, this includes agricultural, integrated water resources management and water quality applications (Jensen 1996; Fenton and Neil 2007). The interrelationships between parameters are typically represented graphically and revised as new information becomes available. Chapter 12 discusses this approach further in the context of environmental impacts.

7.5 Summary

- Once a forecast has been generated, the outputs typically require some further interpretation before guidance is provided to end users. Some typical requirements are to place results in a historical context, to assess the likely risk and to be able to view the outputs spatially alongside other information that is relevant to users.
- There are a number of procedural, societal and other factors to consider regarding forecast interpretation. For example, for early warning systems, this includes the methods used to disseminate warnings, the design and wording of warning messages and the resilience to system failures. Active community involvement is often a key factor in the success of a warning system.
- In threshold-based approaches, critical values are typically defined based on historical evidence, modelling and/or expert opinion. Options include the use of thresholds based on observations, forecasts or derived values such as drought indices, and multi-criteria approaches. In operational use, values need to be reviewed on a regular basis and where possible should be defined in collaboration with key stakeholders.
- Decision support systems are increasingly used to assist with the interpretation of forecasts in agricultural, drought, flood, reservoir and other applications.

These range from simple map-based displays of outputs through to systems which include forecasting models and optimisation routines.

- Some factors which help to ensure the sustainability of a decision support system include long-term funding and technical support and the active involvement of end users in the design. Systems need to be resilient to data loss and communications failures, particularly for emergency applications.
- Although a developing area, risk-based decision-making techniques are increasingly used for early warning applications and to support reservoir, water supply and agricultural operations. Probabilistic forecasts are often a key input, and some techniques for making use of this information include advanced visualisation techniques, probabilistic thresholds and methods from decision theory.

References

Addor N, Jaun S, Fundel F, Zappa M (2011) An operational hydrological ensemble prediction system for the city of Zurich (Switzerland): skill, case studies and scenarios. Hydrol Earth Syst Sci 15:2327–2347

Australian Government (2009) Manual 21 – Flood Warning. Australian Emergency Manuals series. Attorney General's Department, Canberra

Bartholmes JC, Thielen J, Ramos MH, Gentilini S (2009) The European Flood Alert System EFAS – Part 2: statistical skill assessment of probabilistic and deterministic operational forecasts. Hydrology and Earth System Sciences, 13: 141–153

Basher R (2006) Global early warning systems for natural hazards: systematic and people-centred. Philosophical Transactions of the Royal Society A, 364: 2167–2182

Baumgart LA, Bass EJ, Philips B, Kloesel K (2008) Emergency management decision making during severe weather. Weather Forecast 23:1268–1279

Coleman TA, Knupp KR, Spann J, Elliott JB, Peters BE (2011) The history (and future) of tornado warning dissemination in the United States. Bull Am Meteorol Soc., 92:567–582

Collier CG, Rihan F, Davies F, Robbins GL (2005) On the challenges arising from the use of high resolution NWP models to forecast heavy rain. ACTIF International Conference on Innovation Advances and Implementation of Flood Forecasting Technology, 17 to 19 October 2005, Tromsø, Norway

Dale M, Wicks J, Mylne K, Pappenberger F, Laeger S, Taylor S (2014) Probabilistic flood forecasting and decision-making: an innovative risk-based approach. Natural Hazards, 70(1): 159–172

Drabek TE (2000) The social factors that constrain human responses to flood warnings. In Floods. (Ed. Parker DJ) Routledge, London

Fenton N, Neil M (2007) Managing risk in the modern world: applications of Bayesian Networks. London Mathematical Society

Flikweert JJ, Coremans C, de Gooijer K, Wentholt L (2007) Automation of flood contingency plans: benefits and implementation experiences. In: Begum S et al (eds) Flood risk management in Europe. Springer, Dordrecht

Haimes YY (2009) Risk Modeling, Assessment, and Management (3rd Ed.). Wiley, Chichester

Harrison M, Troccoli A, Coughlan M, Williams J (2008) Seasonal forecasts in decision making. Chapter 2. In Seasonal Climate: Forecasting and Managing Risk. (Eds. Troccoli A, Harrison M, Anderson DLT, Mason SJ) NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht

IFRC (2012) Community early warning systems: guiding principles. International Federation of Red Cross and Red Crescent Societies, Geneva

Jensen FV (1996) Introduction to Bayesian Networks (1st ed.). Springer-Verlag, New York
Katz RW, Murphy AH (1997) Economic Value of Weather and Climate Forecasts. Cambridge University Press, Cambridge
Krzysztofowicz R (2001) The case for probabilistic forecasting in hydrology. Journal of Hydrology, 249: 2–9
Krzysztofowicz R, Kelly KS, Long D (1994) Reliability of flood warning systems. ASCE Journal of Water Resources Planning and Management, 120(6): 906–926
Langkamp EJ, Wentholt LR, Pengel BE, Gooijer C de, Flikweert JJ (2005) NOAH, the right information at the right time at the right place. In Floods, from Defence to Management. Taylor & Francis Group, London
Loucks DP (1996) Developing and implementing decision support systems: a critique and challenge. Journal of the American Water Resources Association, 31(4): 571–582
Lumbroso DM, Mens MJP, van der Vat MP (2009) A framework for Decision Support Systems for flood event management – application to the Thames and the Schelde Estuaries. In: Samuels P et al (eds) Flood risk management: research and practice. Taylor & Francis, London
MacFarlane R (2005). A Guide to GIS Applications in Integrated Emergency Management. Emergency Planning College, Cabinet Office, London
Martina MLV, Todini E (2009) Bayesian rainfall thresholds for flash flood guidance. In: Samuels P et al (eds) Flood risk management: research and practice. Taylor & Francis, London
Martini F, De Roo A (eds) (2007) EXCIFF guide: good practice for delivering flood related information to the general public. European Commission/Joint Research Centre report EUR22760EN
McCollor D, Stull R (2008) Hydrometeorological short-range ensemble forecasts in complex terrain. Part II: economic evaluation. Weather and Forecasting, 23(4): 557–574
Mileti DS (1995) Factors related to flood warning response. U.S.-Italy research workshop on the hydrometeorology, impacts, and management of extreme floods, Perugia, November 1995
Morss RE, Ralph FM (2007) Use of information by National Weather Service forecasters and emergency managers during CALJET and PACJET-2001. Weather Forecast 22:539–555
Morss RE, Lazo JK, Demuth JL (2010) Examining the use of weather forecasts in decision scenarios: results from a US survey with implications for uncertainty communication. Meteorol. Appl. 17: 149–162
Muluye GY (2011) Implications of medium-range numerical weather model output in hydrologic applications: Assessment of skill and economic value. Journal of Hydrology, 400(3–4): 448–464
NASA (2009) Water Management Glossary
NOAA (2010) Flash flood early warning system reference guide. University Corporation for Atmospheric Research, Colorado
NOAA/NWS (2014) Hydrologic Information on the Web: A Manual for Users. Version 1.3, US Department of Commerce
Pappenberger F, Cloke HL, Persson A, Demeritt D (2011) On forecast (in)consistency in a hydrometeorological chain: curse or blessing? Hydrol Earth Syst Sci 15:2391–2400
Pappenberger F, Stephens E, Thielen J, Salamon P, Demeritt D, van Andel SJ, Wetterhall F, Alfieri L (2013) Visualizing probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. Hydrological Processes, 27(1): 132–146
Parker DJ, Priest SJ (2012) The fallibility of flood warning chains: can Europe's flood warnings be effective? Water Resour Manage, 26(10):2927–2950
Parker DJ, Priest SJ, Tapsell SM (2009) Understanding and enhancing the public's behavioural response to flood warning information. Meteorol Appl 16:103–114
Persson A (2013) User guide to ECMWF forecast products, Version 1.1. ECMWF, Reading
Richardson D (2012) Economic value and skill. In: Jolliffe IT, Stephenson DB (eds) Forecast verification: a practitioners guide in atmospheric science, 2nd edn. Wiley, Chichester
Romang H, Zappa M, Hilker N, Gerber M, Dufour F, Frede V, Bérod D, Oplatka M, Hegg C, Rhyner J (2011) IFKIS-Hydro: an early warning and information system for floods and debris flows. Nat Hazards 56(2):509–527
Roulin R (2007) Skill and relative economic value of medium-range ensemble predictions. Hydrology and Earth System Sciences, 11: 725–737

Roulston MS, Smith L (2004) The boy who cried wolf revisited: the impact of false alarm intolerance on cost-loss scenarios. Weather Forecasting, 19(2): 391–397
Rubas DJ, Hill HSJ, Mjelde JW (2006) Economics and climate applications: exploring the frontier. Climate Research, 33: 43–54
Savage LJ (1972) The Foundations of Statistics. Dover, New York
Schilling W (ed) (1989) Real time control of urban drainage systems. The state of the art. IAWPRC Task Group on Real Time Control of Urban Drainage Systems, London
Schütze M, Campisano A, Colas H, Schilling W, Vanrolleghem PA (2004) Real time control of urban wastewater systems—where do we stand today? Journal of Hydrology, 299: 335–348
Sene (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht
Simonovic SP, Ahmad S (2005) Computer-based model for flood evacuation emergency planning. Natural Hazards, 34: 25–51
Sorensen JH (2000) Hazard warning systems: review of 20 years of progress. Nat Hazards Rev 1(2):119–125
Sorenson JH, Mileti DS (1987) Decision-making uncertainties in emergency warning system organisation. Int J Mass Emerg Disasters 5(1):33–61
Tretmans T, Wijbrans K, Chaudron M (2001) Software engineering with formal methods: the development of a storm surge barrier control system revisiting seven myths of formal methods. Formal Methods in System Design, 19(2): 195–215
Troccoli A, Harrison M, Anderson DLT, Mason SJ (2008) Seasonal Climate: Forecasting and Managing Risk. NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht
Tversky A, Kahneman D (1992) Advances in prospect theory. Journal of Risk and Uncertainty, 5(4): 297–323
UN/ISDR (2006) Developing early warning systems: a checklist. EWC III Third International Conference on Early Warning from Concept to Action, 27–29 March 2006, Bonn
UN/ISDR (2007) Drought risk reduction framework and practices: contributing to the implementation of the Hyogo Framework for action. United Nations Secretariat of the International Strategy for Disaster Reduction (UN/ISDR), Geneva, Switzerland, 98+vi pp
USACE (1996) Hydrologic aspects of flood warning-preparedness programs. US Army Corps of Engineers Report ETL 1110-2-540, Office of Chief of Engineers, Washington, DC
Van Oosterom P, Zlatanova S, Fendel EM (eds) (2005) Geo-information for disaster management. Springer, Berlin
Von Neumann J, Morgenstern O (1944) Theories of Games and Economics. Princeton University Press, Princeton, NJ
Werner K, Avery K, Owen G (2013) River Forecast Application for Water Management: Oil and Water? Wea. Climate Soc., 5: 244–253
WHO (2011) Guidelines for Drinking-Water Quality (4th Ed.). World Health Organisation, Geneva
WMO (2002) Guide on improving public understanding of and response to warnings. WMO/TD No. 1139, Geneva
WMO (2005) Guidelines on integrating severe weather warnings into disaster risk management. WMO-No. 1292, Geneva
WMO (2006a) Drought Monitoring and Early Warning: Concepts, Progress and Future Challenges. WMO-No. 1006, Geneva
WMO (2006b) Social aspects and stakeholder involvement in Integrated Flood Management. WMO No. 1008, Geneva
WMO (2006c) Preventing and Mitigating Natural Disasters. WMO No. 993, Geneva
WMO (2010) Guidelines on early warning systems and application of nowcasting and warning operations. WMO/TD No. 1559, Geneva
WMO (2011) Manual on flood forecasting and warning. WMO-No. 1072, Geneva
WMO (2012) Guide to Agricultural Meteorological Practices (GAMP) (2010 edition – updated in 2012). WMO-No.134, Geneva
Wolshon B, Urbina E, Wilmot C, Levitan M (2005) Review of policies and practices for hurricane evacuation. I: transportation planning, preparedness, and response. Natural Hazards Review, 6(3): 129–142

Part II
Selected Applications

Chapter 8
River Flooding

Abstract Flood forecasting models are a key component in many flood warning systems. Some typical forecasting techniques include rainfall-runoff, flow routing and hydrodynamic models and simpler empirical approaches such as level-to-level correlations. Models are usually operated within a forecasting system which gathers data, schedules model runs and post-processes model outputs into forecast products. Data assimilation and probabilistic techniques are also widely used to help to improve the accuracy of forecasts and estimate the uncertainty in outputs. This chapter provides an introduction to these topics and to approaches to forecasting snowmelt in colder regions and water levels in estuaries.

Keywords Flood warning • Thresholds • Rainfall-runoff • Flow routing • Hydrodynamic • Snowmelt • Estuary • Data assimilation • Forecast verification • Ensemble • Probabilistic • Uncertainty

8.1 Introduction

Floods can cause widespread disruption and damage with the potential for loss of life. The risks are particularly high if flood waters are deep, are fast flowing or have a high debris content and when flooding occurs at night or at low temperatures.

To help to reduce the impacts, most national hydrological services offer a flood warning service, sometimes in collaboration with other organisations such as river basin authorities and reservoir operators. Roles and responsibilities are usually defined in flood response (contingency) plans developed in collaboration with communities and civil protection authorities. If sufficient lead time is provided, property and valuables can be moved or protected and people and livestock evacuated from areas at risk. For example, USACE (1996) notes that some responses which may be required as a flood develops include:

- Providing search, rescue and evacuation services
- Scheduling closure of schools and transportation of students
- Curtailing electric and gas service to prevent fire and explosions
- Establishing traffic controls to facilitate evacuation and prevent inadvertent travel into hazardous areas

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- Dispersing fire and rescue services for continued protection
- Establishing emergency medical services and shelters
- Closing levee openings
- Moving public and private vehicles and equipment from areas subject to flooding
- Relocating or stacking contents of private structures
- Initiating flood-fighting efforts…
- Establishing security to prevent looting

Here flood-fighting is a term which describes activities to reduce the extent of flooding such as raising levee heights with sandbags or installing temporary (demountable) defences. In some cases, there may be scope to take actions at a larger scale; for example, by operating flow diversion channels or drawing down reservoir levels to increase flood storage.

A distinction is often made between the relatively slowly developing floods caused by large rivers and faster developing events. Although the boundaries are not clear-cut, flash floods are usually defined as those which occur when the time delay between heavy rainfall and the onset of flooding is several hours or less. In this case rainfall observations and forecasts generally assume more importance in a warning system, and there is a greater need for a community-based response before help arrives from further afield.

Chapter 9 discusses flash floods in more detail including the risks posed by ice jams, debris flows, flood defence breaches and dam breaks. In contrast, in this chapter the focus is on floods in large river basins which typically develop over periods of many hours or days. These types of flood are often called riverine, plains or fluvial floods, and Table 8.1 provides several examples of past events. Of course in a widespread storm riverine flooding is often preceded by flash floods on smaller tributaries in headwater regions of the basin and in urban areas.

Given the relatively slow response to rainfall in large river basins, in some flood warning systems alerts are based primarily on river gauge observations. Warnings are then issued when river levels exceed predefined threshold values at gauges near to the areas at risk and at locations further upstream. As discussed in Chap. 7, so-called 'remote' gauges potentially provide earlier indications of the risk of flooding but at the expense of more false alarms and a higher risk of missed alerts than with an 'at-site' gauge. Simple forecasting tools such as correlation models, rate-of-rise triggers and time-of-travel maps are often used as a supplement to these approaches (see Chap. 5).

Warnings are normally escalated as levels rise and in many cases the first stage of alert is a heavy rainfall warning, based on observed or forecast rainfall, as illustrated in Fig. 8.1. At each alert level, the actions to take are usually prescribed in operational procedures and contingency plans with flood maps to indicate the areas at risk; these are typically based on hydrodynamic modelling studies, statistical relationships and/or outlines from previous flood events (see Chaps. 5 and 9). For operational use maps are often annotated with information to assist with the emergency response such as flood warning zones, evacuation routes and the locations of critical infrastructure, vulnerable groups and temporary shelters. Here a zone is an area which can easily be related to threshold values and is meaningful at a community level; for example, a suburb in which most properties are likely to be affected when a certain river level is exceeded.

Table 8.1 Some examples of flooding incidents in large river basins

Location	Year	Description
USA	2011	Snowmelt and heavy rainfall led to some of the highest river levels on the Mississippi in recent decades and record-breaking values at some locations. River levels remained above flood stage values for 3–4 months at some sites although the peak of the flood occurred from about mid-April and into May. Flood relief channels (spillways) were operated to reduce the risk to New Orleans and Baton Rouge. More than 20,000 homes and businesses and 1.2 million acres of agricultural land were affected and the economic damages were almost three billion dollars. Approximately 1000 staff from the US Army Corps of Engineers were assigned to the flood-fighting effort (USACE 2012)
Central Europe	2013	Several days of heavy rainfall led to severe flooding along the Danube and Elbe rivers and to a lesser extent the Rhine, particularly affecting locations in Germany, Austria and the Czech Republic. River levels exceeded 1 in 100 year values at several locations and remained high in some places into June. The floods caused more than 25 fatalities and more than 12 billion Euros of damages (Grams et al. 2014)
Pakistan	2010, 2011	Extreme monsoon rainfall from July to September 2010 caused unprecedented flood peaks along the Swat, Kabul and Indus rivers affecting the length of the country. Approximately 29 million people were affected with about 2000 fatalities. The floodwaters covered an area of approximately 100,000 km^2. During 2011 as the recovery effort was still underway, shorter-duration intense rainfall caused floods which affected almost 10 million people with more than 500 fatalities (AfDB/World Bank 2012)
Mozambique	2013	Heavy rainfall in parts of Zimbabwe and South Africa led to severe flooding several days later on the floodplains of the lower Limpopo river in Mozambique, leading to several fatalities and requiring temporary evacuation of more than 150,000 people (UN 2013)

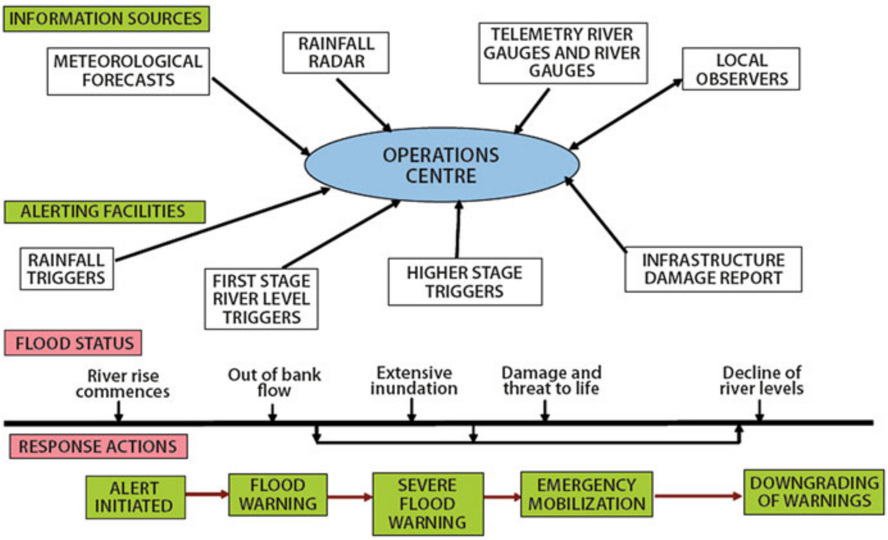

Fig. 8.1 Flood warnings and responses (WMO 2011a, courtesy of WMO)

Whilst much is possible using observations alone, this approach does have some limitations particularly when complications arise such as tidal influences, ungauged tributary inflows or spills onto the floodplain. Figure 8.2 illustrates a typical dilemma as river levels approach warning thresholds, and forecasting models can potentially help with decision-making in these types of situations.

The other key advantage of a forecast is of course the additional lead time provided, potentially allowing decisions to be taken earlier than would be possible when using observations alone. For example, it can take many hours or even days to evacuate large numbers of people from areas at risk and some other potentially time-consuming actions include the flood-fighting activities described earlier. Also, given enough advance warning, low-cost precautionary actions might be taken such as scheduling staff rosters around weekends, prepositioning emergency response equipment and briefing individual community leaders. These are sometimes called 'no-regrets' actions in the sense that they involve little cost or disruption or were planned anyway, but the potential benefits are large if flooding does occur (although of course all recipients need to understand the potential for false alarms). For example, in a UK context, Golding (2009) notes that for a large-scale flood event, where feasible the sequence of information actions might be:

- 3–5 days ahead: issue 'advisory' or 'period of heightened risk'; engage in awareness raising activities through the media, mobilize support organizations for the vulnerable; initiate 'participatory' information sharing by local flood response organizations.
- 1–2 days ahead: issue 'early warning' or 'watch'; activate mitigation measures for flood minimization and protection of critical infrastructure; provide active support to vulnerable groups; move to a 'consultative' engagement with those in the most vulnerable areas.
- Hours ahead: issue 'flood warning'; activate emergency response; evacuate most vulnerable groups if appropriate; provide 'prescriptive' advice to individuals.

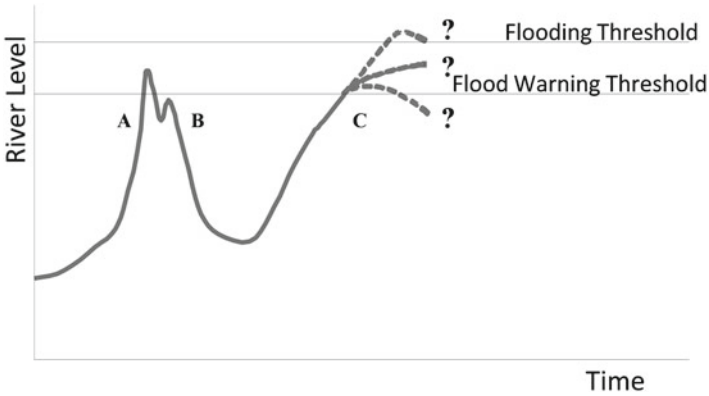

Fig. 8.2 Illustration of flood warning decisions when using observed levels alone for a telemetry site at or near a hypothetical location at risk from flooding. A first flood warning was issued at time *A*, but this was a false alarm since levels stopped rising before the flooding threshold was reached, whilst at time *B* levels dropped in time to avoid a second false alarm. At time *C*, the three scenarios shown by *dotted lines* have all occurred from this starting point in previous flood events in one case exceeding the flooding threshold and in another resulting in a 'near miss'

The way that forecasts are used operationally depends on a number of factors including organisational policy, confidence in the model outputs and the level of flood risk. For example, in some hydrological services, threshold values specific to flood forecasts are written into operational procedures, whilst in others the information provided is used in a less formal way primarily to raise situational awareness. Generally though due to the inherent uncertainties in outputs, most organisations require forecasts to be assessed and/or approved by duty officers before distribution, rather than issued automatically (or to include suitable caveats if values are published directly to a website). In particular, when evaluating model outputs against threshold values, there may be consistent bias, timing or other issues which need to be considered as part of the decision-making process. This in turn is part of the reason for the increasing use of probabilistic and risk-based decision-making techniques of the types discussed in Chaps. 1, 5 and 7.

The operation of a flood forecasting and warning system is normally a year-round activity and if not already operated around the clock is switched to a 24-h/7-day (24/7) status if a flood threat develops. As noted in WMO (2011a) operating and managing a service nowadays:

> …requires a full-time and structured organizational approach. It is no longer something that can be added on as a temporary contingency operation within an organization fulfilling other primary roles, for example public works or municipalities. Staff complement, pay and allowances, office facilities and equipment all have to be fully financed to reflect the importance of the services

Except for the simplest types, models are usually operated within an automated forecasting system which controls data gathering, the scheduling of model runs and the post-processing of model outputs. As noted in Chap. 1 there are potentially financial and operational advantages in developing forecasting models for a range of applications, although the focus in this chapter is on flooding applications. For example, in countries with a distinct flood season, this helps to maintain systems and staff skills year round and widens the user base for model outputs and products, potentially providing more opportunities for co-funding.

More generally it is important to note that for forecasts and warnings to be effective, these need to be embedded within a wider risk management process, as illustrated by Fig. 8.3 and discussed further in Chaps. 1 and 7. For example, regarding the dissemination of warnings, roles and responsibilities vary widely, but recipients typically include the emergency services, local authorities, utility operators and the public, and the techniques used vary from simple door knocking to automated phone dialling and multimedia systems. Indeed often part of the role of a forecaster is to establish good working relationships with key professional partners to build trust and understanding regarding the service provided.

The remainder of this chapter focusses on the technical aspects of flood forecasting and is divided into two main sections. Firstly Sect. 8.2 discusses some key technical issues which are relevant to riverine floods and provide useful background for Chap. 9, on flash floods. This includes a brief summary of modelling techniques although Chap. 5 provides a more detailed description. Section 8.3 then presents examples of modelling approaches for two applications typical of large river basins: namely, forecasting tidal and surge effects in estuaries and snowmelt and ice break-up forecasting in colder climates. In addition, Boxes 8.1 and 8.2 provide examples of operational systems, and Chap. 9 discusses community-based warning systems which are sometimes also used in locations at risk from riverine flooding.

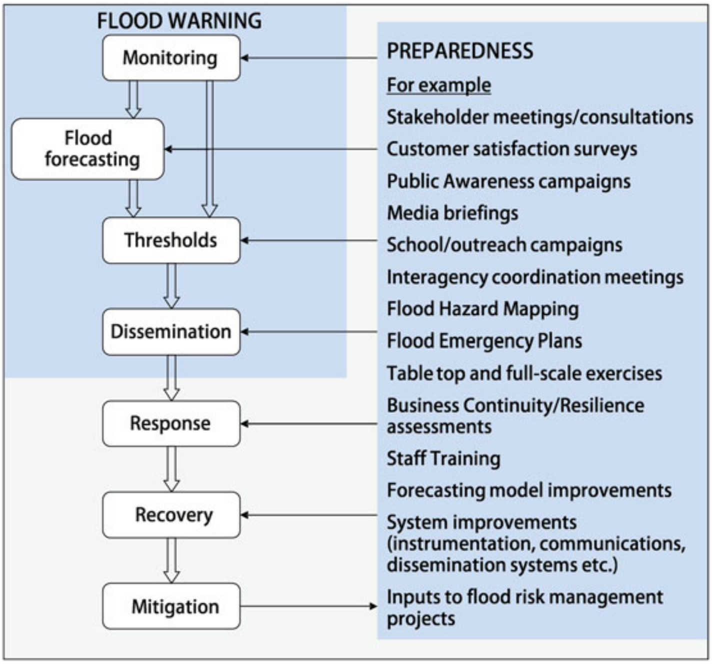

Fig. 8.3 Illustration of how a flood warning and forecasting system contributes to wider flood risk management objectives (Adapted from Sene 2008)

Box 8.1: Scottish Flood Forecasting Service

Scotland experiences a varied climate and the mean annual rainfall can exceed 3000 mm in parts of the western highlands. There is extensive snow cover in winter although the climate is moderated by the influence of the Gulf Stream. The total land area is about 78,000 km^2 and the coastline is estimated to exceed 10,000 km.

The varied climate and topography results in several types of flood risk as illustrated in Table 8.2. More than 100,000 properties are at risk representing approximately 1 in 22 homes and 1 in 13 businesses (SEPA 2013). River flooding issues include flash floods and slower-responding riverine and estuary floods and surface water flooding is a major issue in some towns and cities.

The responsibility for issuing flood warnings lies with the Scottish Environment Protection Agency (Cranston and Tavendale 2012) which aims to:

(continued)

Box 8.1 (continued)

- Reduce the impact of flooding through the provision of actively disseminated, reliable and timely flood warnings to registered users of a national flood warning service
- Provide an effective flood warning service and reduce the impact of flooding from all sources
- Work with communities to improve their response

Scotland's first river gauging station was established in 1913 by Captain WN McClean near to the village of Invergarry, and SEPA now operates more than 250 rainfall, river and coastal telemetered monitoring stations. Typically readings are received at 15-min intervals using a mixture of land line and cell phone-based telemetry, and values are published on the SEPA website. The Met Office also operates a network of four Doppler weather radars within Scotland which are in the process of being upgraded to dual polarisation capability; two radars in northeast England and Ireland provide some limited additional coverage within Scotland.

SEPA also collaborates with the Met Office through a joint initiative called the Scottish Flood Forecasting Service. This was established in 2011 to allow closer collaboration between meteorologists and hydrologists and to help to ensure that consistent information is provided to the public and emergency services. Table 8.3 summarises the main types of products and services offered. One of the main delivery mechanisms is an automated alerting service called Floodline which provides flooding information and advice around the

Table 8.2 Summary of the main types of flooding in Scotland (adapted from http://www.sepa.org.uk)

Type of flooding	Description
River	Occurs when a river cannot cope with the amount of water entering it. The level of the river rises until it eventually overflows onto surrounding land
Coastline	Occurs as weather and tidal conditions increase sea levels. Current predictions for climate change anticipate an increase in sea levels, storm surges and waves all around Scotland's coastline and it is predicted that the frequency and severity of this type of flooding will increase
Surface water	Happens when there is rainfall on ground that is already saturated or on paved areas where drainage is poor. The water has nowhere to go and so pools on the surface
Groundwater	Groundwater flooding can happen when rainfall causes the water that is naturally stored underground to rise to the surface. It can flood, or contribute to flooding, of low-lying areas in particular
Drain, sewer and broken water mains	Drain, sewer and broken water main flooding is not a natural type of flooding and is managed and assessed by Scottish Water, roads authorities or local authorities

(continued)

Box 8.1 (continued)

Table 8.3 Summary of river flood forecasting and warning outputs (Adapted from SEPA 2014)

Product/service	Maximum lead time	Scale (issued by)	Description
National Severe Weather Warning Service (NSWWS)	5 days ahead	Region-based (Met Office)	Includes Alerts and Warnings for the potential impact of rainfall. The impact will often be a flood risk or flood event
Flood Guidance Statements	5 days ahead	Area-based (Scottish Flood Forecasting Service)	Daily, national guidance statements which are issued to Category 1 and 2 responders, such as emergency responders, local authorities and other organisations with flooding management duties
Flood Alert	Up to 24 h ahead	Local authority or combined authority areas (SEPA)	A Flood Alert is an early indication of potential flooding from rivers, the sea and surface water. It is issued for larger geographical areas – usually the boundaries of local authorities
Flood Warning	Generally 3–6 h	More localised areas, based on detailed local forecasting models (SEPA)	Flood Warnings advise that flooding is imminent. Immediate action is required – take measures to protect yourself and your property

clock (24/7). This offers a wide range of options for receipt of warnings including web-based alerts and an automated telephone information service. Registered users can also receive flood messages to mobile phones or landline numbers and the system will automatically try up to 2 alternate numbers (if specified) if there is no reply. Forecast outputs are also available to key partners via a web-based portal.

Regarding river flooding, flood forecasts are generated for more than 200 forecasting points in approximately 70 catchments. Models are operated automatically around the clock on a flood forecasting system called FEWS Scotland (Werner et al. 2009). At most locations, forecasts are produced using integrated catchment models which combine conceptual rainfall-runoff models with hydrological flow routing and data assimilation components. Real-time hydrodynamic models are also widely used in higher-risk locations including a three-dimensional model for the Firth of Clyde, which includes the tidally influenced reaches of the River Clyde in Glasgow.

To provide an indication of flooding potential in ungauged catchments, a physical-conceptual distributed model is operated at a country-wide scale (Cole and Moore 2009; Cranston et al. 2012). This is operated on a 15-min time step with a grid scale of 1 km, and the main inputs include MOGREPS

(continued)

Box 8.1 (continued)
ensemble rainfall forecasts from the Met Office plus observed rainfall estimates based on weather radar and raingauge observations. As of 2015, a 12-member 2 km-grid ensemble was used for a maximum lead time of 36 h. A probabilistic heavy rainfall alert tool also provides alerts on an area basis.

Flood Guidance Statements are prepared based on discussions between SEPA hydrologists and Met Office weather forecasters using the forecasting model outputs as a guide. Typically each statement includes a description of current weather conditions and the flood risk, a summary of warnings and alerts in force and a map showing areas of concern (e.g. Fig. 8.4). More detailed information is included on the risk from surface water and river flooding. Decisions on the information to present are based on risk assessments which consider both the likelihood of flooding and the potential impacts, using risk matrices such as the example shown in the figure.

Guidance notes (SEPA 2014) state that area of concern maps 'will give further specific information on areas at risk, and how the risk colour has been chosen from the matrix. These are sometimes used even when the risk is very low (green) as there may still be minor impacts to be pointed out'. For example, a medium likelihood is defined as 'Flooding is likely. Forecast sug-

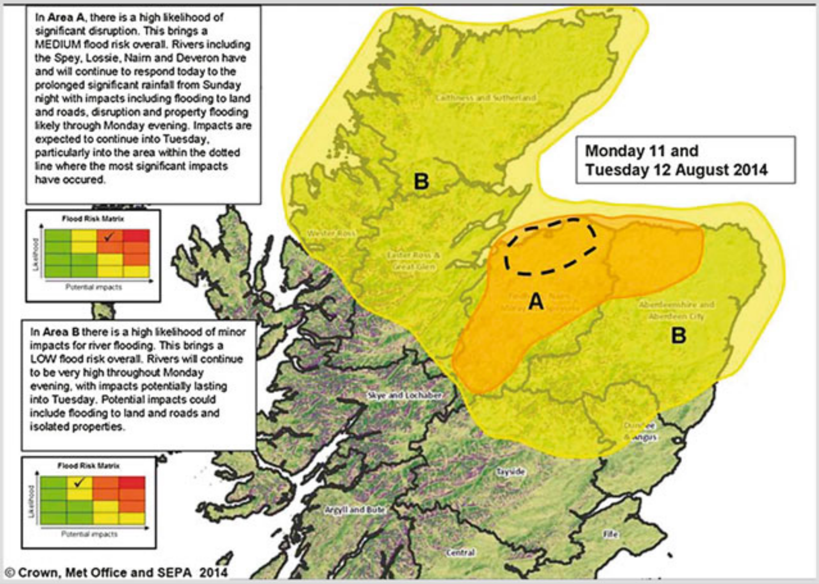

Fig. 8.4 Example of an area of concern map (Contains SEPA data © Scottish Environment Protection Agency and database right 2014 and the Met Office; SEPA 2014)

(continued)

Box 8.1 (continued)
gests between 40 and 60 % chance of occurrence' whilst an impact category of 'Severe disruption' has the following expected characteristics:

- Widespread flooding affecting whole communities
- Collapse of buildings/structures is possible
- Danger to life due to fast-flowing/deep water/wave-overtopping/wave inundation
- Widespread disruption or loss of infrastructure
- Large-scale evacuation of properties may be required

Here the probability estimates are derived from the ensemble model outputs and predefined threshold values. This general approach has also used as part of an experimental surface water flood warning service which is discussed in Chap. 9.

8.2 Forecasting Techniques

8.2.1 Modelling Approaches

Many modelling techniques are used in flood forecasting applications, and most of the methods discussed in Chap. 5 have probably been at least considered for operational use. This includes physically-based, conceptual and data-driven rainfall-runoff models – in distributed, semi-distributed or lumped forms – data-driven, hydrological and hydrodynamic flow routing models; and a variety of models for specific situations, such as for reservoir operations. Rainfall forecasts are increasingly used to extend forecast lead times, in both deterministic and ensemble forms (e.g. Boxes 8.1 and 8.2).

Regarding real-time inputs, some typical data sources include rainfall and river level or flow observations, plus other types as required, such as reservoir levels and gate settings. Air temperatures are usually also needed in regions where snowmelt is a potential issue. However, due to the measurement difficulties, as discussed in Chaps. 3 and 5, surrogate values are often used for soil moisture and evaporation inputs if these are required; for example, using seasonal profiles, Penman-type equations, simple water balance techniques or the internally generated values within the forecasting model.

For flood forecasting applications, distributed models are usually of the physical-conceptual type rather than purely physically-based, and Chap. 9 discusses this approach in more detail in the context of flash flood forecasting (see Box 8.1 also). In contrast, with a lumped approach the catchment is considered as a single unit and this type of model is widely used to represent the headwater and tributary inflows within semi-distributed models for large river basins. The runoff estimates are then routed through the river network using hydrological, data-driven or hydrodynamic approaches, together with some allowance for ungauged inflows; for example, using parameter transfer, regionalisation or scale-and-lag approaches (see Chap. 5).

Table 8.4 presents some examples of the types of rainfall-runoff models which are used – or have been considered for use – in flood forecasting applications. These are provided simply for illustration and this is by no means a complete list. For example,

Table 8.4 Some examples of operational and pre-operational applications of rainfall-runoff (hydrologic) forecasting models; note that many other types of model are used internationally

Category	Location	References
Distributed	Brazil	Collischonn et al. (2007)
	Europe-wide	Thielen et al. (2009)
	International	Alfieri et al. (2013)
	General	Butts et al. (2005)
	Texas	Vieux et al. (2005)
	UK	Cole and Moore (2009)
	USA	Koren et al. (2004), Seo et al. (2009)
Conceptual (lumped or semi-distributed)	China	Zhao (1992)
	France	Paquet and Garcon (2004)
	Netherlands	Lindström et al. (1997)
	Western Canada	Quick (1995)
	UK	Madsen (2000), Moore (2007)
	USA	Burnash (1995)
Data-driven	UK	Lees et al. (1994)
	UK	Yang and Han (2006)
	General	Dawson and Wilby (1999)

some citations for further examples include Singh (1995), Beven (2012), Moore (1999), Sene (2013), Todini (2007), and WMO (1992, 2009, 2011a). For the flow routing component, the choices are usually narrower and typically relate to the brand of hydrodynamic model to use or options such as whether to use a kinematic wave routing, transfer function or Muskingum-Cunge approach. As noted in Chap. 5 when using hydrodynamic models, there is the option to generate real-time inundation maps, although predefined maps are often preferred since these can be audited before use.

When choosing which approach to use, at a technical level some key deciding factors are often catchment response times, warning lead-time requirements, data availability and whether there are complicating factors to consider such as floodplain flows or backwater effects. For example, Fig. 8.5 illustrates some of the local issues which may need to be considered for an urban area on a river floodplain near to the coast; these include reservoir influences and the flood risk from sewer systems, tidal influences and overtopping of flood banks.

Table 8.5 provides a brief summary of these various issues together with a range of other factors which potentially need to be considered. Whilst organisational issues and budgets are often the overriding factor, the availability of calibration data is usually another key concern, sometimes requiring additional modelling assumptions, new instrumentation, additional survey data or even a change of approach.

In particular, as discussed in Chap. 5, due to the need for data assimilation, models are often configured around the locations of telemetry gauges and usually it is desirable to have at least one gauge at or near the location(s) at risk, rather than relying on extrapolating or interpolating model outputs. For example, NOAA/NWS (2010) suggests that some typical criteria for selection of a forecasting point include:

- The existence of a stream gage at the location
- A history of data collection at the location

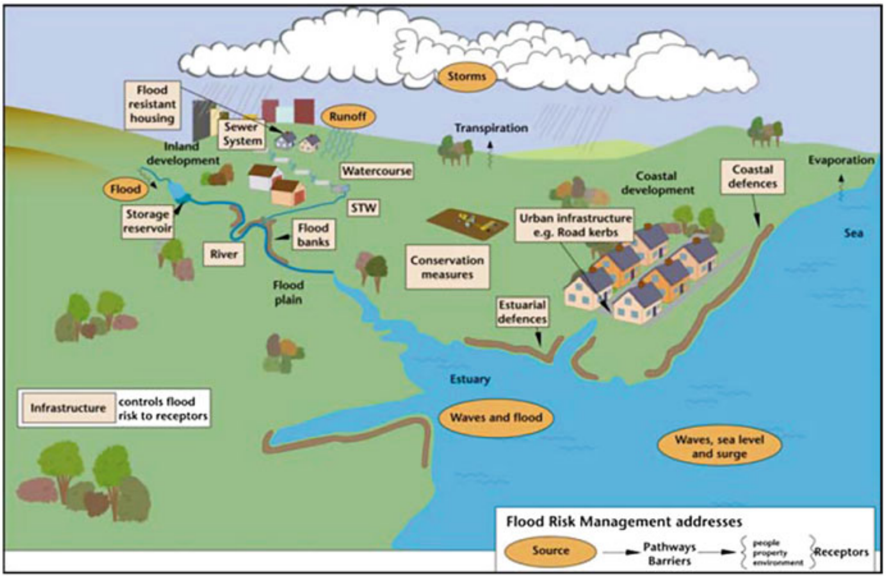

Fig. 8.5 A hydraulic perspective of the physical flooding system (Office of Science and Technology 2003)

- Rating Curves developed at many different river flows
- The river model calibrated for the river response during many different past precipitation events and seasons

Additional criteria noted include the size of the basin and the need for forecast information at a community level.

Another key factor listed in Table 8.5 is the level of flood risk. This is usually defined as the combination of the probability and consequences of flooding, often taking vulnerability into account (see Chaps. 1 and 7). For example, a more complicated modelling approach may be justified for a high-risk location such as a major city, compared to low-risk locations such as farmland or a few isolated properties. Indeed, in some cases, the financial benefits from implementing a warning system are estimated on the basis of the damages likely to be avoided, and various cost-benefit techniques have been developed specifically for flood warning applications (e.g. WMO 1973, USACE 1994, Carsell et al. 2004, Parker et al. 2005, Tilford et al. 2007).

Flood warning lead-time requirements are another important factor to consider. For example, for a forecasting point in the lower reaches of a large catchment, it may be possible to meet the requirements for lead times and accuracy using a flow routing model alone, based on inputs from a gauge further upstream. However, if longer lead times are required, then this could require the use of rainfall-runoff models with observed and possibly forecast rainfall values as inputs. Generally though there is a trade-off to consider between the shorter lead times but higher accuracy of flow routing approaches, compared to the longer lead times but greater uncertainty in rainfall-runoff model outputs, particularly when driven by rainfall forecasts.

Table 8.5 Some typical examples of factors which could influence the choice of modelling approach

Factor	Description
Artificial influences	The need to represent reservoirs, flow control structures and other factors which affect flooding
Catchment response	The nature and timing of the response to rainfall and any tidal, backwater, snowmelt or other influences which are relevant
Data availability	The information available in real time for input to models and for data assimilation, and off-line for model calibration, including the spatial coverage and resolution, quality and reliability and the availability of topographic survey data for hydrodynamic modelling (if relevant)
Flood risk	The level of risk to people and property including the vulnerability to flooding due to physical, social, health and other factors
Forecasting points	The locations in the catchment at which forecasts are required, such as areas at risk from flooding, telemetry gauges and flow control structures; the model calibration is often optimised for these locations
Forecasting system	The software, hardware and other constraints on the types of models available for real-time operation
Lead time	The minimum flood warning lead time ideally required by end users to give enough time for an effective emergency response
Organisational issues	Expertise in using the types of models envisaged, the availability of calibration and run-time software, organisational policy, budgets, etc.
Operational requirement	The types and frequency of issue of forecast products and other outputs required, such as flood inundation maps
Pre-operational testing	The requirement for model testing in a pre-operational setting; for example, in parallel with existing systems, with associated staff training, including deciding on the extent to which outputs will be used operationally (if at all)
What-if functionality	The requirements (if any) to be able to assess scenarios during a flood event; for example, 'what-if' model runs to explore the impacts if a gate fails or if an embankment is breached or if the rainfall from a previous major storm is repeated in the current event

However, it is worth noting that in practice the useful warning lead time is often less than expected from a consideration of model performance alone. For example, Fig. 8.6 shows an idealisation of the various time delays when using a single rainfall-runoff model to forecast flows at a single forecasting point. Here the sequence extends from the initial rainfall on the catchment through to the receipt of a flood warning by all recipients. Although the time delays are exaggerated in places, the diagram illustrates that the cumulative impact is to significantly reduce the time available for response, and these types of issues need to be factored into the model design. Similar examples are provided in Carsell et al. (2004), Nemec (1986) and USACE (1994) for other situations, and estimates for warning time delays can be obtained from approaches such as reviews of past flood events, emergency response drills and consultation exercises. In many cases though it may be possible to reduce some of these delays through measures such as:

- Streamlining the decision-making process; for example, by delegating authority for issuing warnings (with associated training and support)
- Improving the procedures used to issue flood warnings, such as by using automated phone dialling and multimedia systems and widening the choice of dissemination routes available

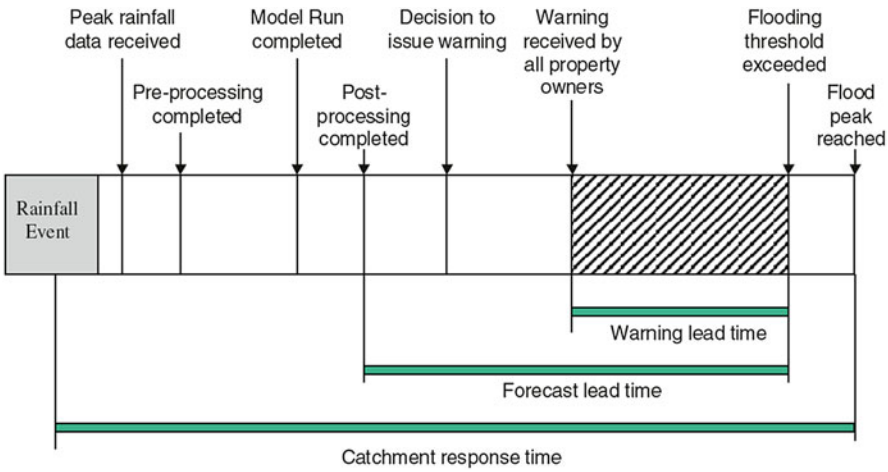

Fig. 8.6 Idealised illustration of the time delays in issuing a warning for a single rainfall-runoff model (Sene 2008)

- Installing instruments further upstream to potentially improve confidence in the model outputs at longer lead times

The polling interval for rainfall and river flow data also needs to be considered together with model run times and frequencies. For example, if river levels typically reach peak values in a few hours or less, then an hourly polling interval is unlikely to be sufficient to fully resolve the rising limb of the hydrograph, particularly around flood warning threshold values. If rainfall forecasts are used, then account needs to be taken of the time intervals at which forecasts are issued. This might be every 5–15 min for nowcasts through to every 6–12 h for medium- to long-range forecasts (see Chap. 4).

Regarding model run times, these are sometimes a significant factor for some types of model, such as hydrodynamic models, and when using probabilistic approaches. Operationally a typical requirement is that the model should be able to run reliably year round, perhaps 24–96 times per day, for lead times of days or more ahead for a large river basin. Section 8.2.4 discusses some options for reducing the run times with probabilistic forecasts, whilst, for hydrodynamic models, some possibilities include (e.g. Chen et al. 2005):

- Improving the model stability and convergence, thereby reducing the number of iterations required for each time step
- Improving the model operation under a wide variety of forcing conditions, such as unusually low and high flows and different permutations of gate settings
- Removing bottlenecks to data transfer both during preprocessing of input data and post-processing of model outputs
- Simplifying the model at locations away from the main forecasting points; for example, by removing unnecessary detail at structures and in river reaches

If funds are available for new hardware, then increases in computing power and parallel processing techniques provide additional options.

Box 8.2: Flood Forecasting System for the Rhine and Meuse Rivers (Netherlands)

The River Rhine originates in Switzerland and flows across Germany before reaching the coast in the Netherlands. The catchment includes parts of Austria, Belgium, France, Italy, Liechtenstein and Luxembourg and, with an area of 185,000 km^2, is the second largest in Europe (Fig. 8.7). The river enters the Netherlands at the village of Lobith where the mean discharge is approximately 2300 m^3s^{-1}. The average annual rainfall for the whole of the Rhine basin is approximately 910 mm/year and reaches more than 1400 mm in the Alps. There is a significant additional contribution to runoff in the spring from snowmelt although the highest flows at Lobith are typically observed in the winter months (Overeem 2005).

The main flood forecasting centres in the Rhine basin are in Switzerland, Germany (Baden-Württemberg and Rhineland-Palatinate) and the Netherlands. Within the Netherlands, forecasts are issued by the Division of Crisis Management and Information Supply in the Rijkswaterstaat Centre for Water Management and serve a range of purposes, including navigation, flood forecasting, drought forecasting and crisis management. Until 1999, forecasts were derived using a multiple regression approach which related levels at Lobith for up to 4 days ahead to levels and rainfall at approximately 20 gauging stations and raingauges further upstream in the catchment (Sprokkereef 2002). This approach has since been replaced by an integrated catchment model, with rainfall-runoff models linked to a hydrodynamic model of the river network, including the River Meuse (Beckers et al. 2008).

The main real-time inputs to the model consist of precipitation and air temperature for approximately 700 meteorological stations and water level observations at some 60 gauging stations. Weather forecast inputs include rainfall and air temperature forecasts from the German Weather Service (DWD), the Royal Netherlands Meteorological Institute (KNMI) and the European Centre for Medium-Range Weather Forecasts (ECMWF) in both deterministic and ensemble form. The extent and progression of rainfall events is also assessed from composite European weather radar images.

The forecasting system includes an extensive suite of data validation and automated data infilling routines. The modelling component includes approximately 150 conceptual rainfall-runoff models, which were developed using the HBV-96 model (Lindström et al. 1997). The models represent snow accumulation, snowmelt, evapotranspiration, soil moisture storage, groundwater and surface runoff. On the Rhine, the hydrodynamic model extends for 670 km from Maxau in Germany to the river-mouth. The model outputs are updated at key gauging stations using an ARMA error prediction algorithm and an ensemble Kalman Filtering approach (Weerts and El Sarafy 2006). Bayesian Model Averaging techniques have also been explored as a way to derive optimum flow estimates from model outputs based on a range of alternative meteorological forecast inputs (Beckers et al. 2008).

(continued)

Box 8.2 (continued)

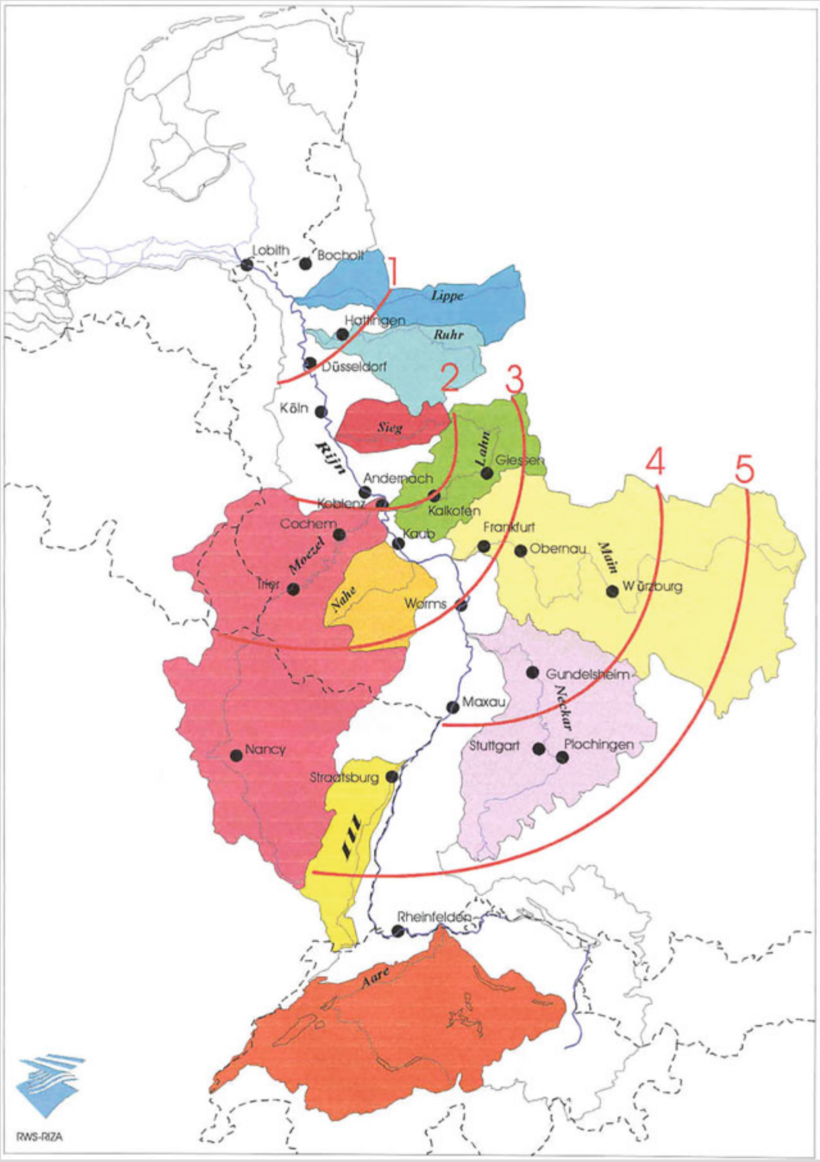

Fig. 8.7 The River Rhine basin with travel time isochrones (in days) (Parmet and Sprokkereef 1997)

The overall system is currently operated on an hourly time step and is considered to provide reliable forecasts at Lobith and downstream locations for lead times of up to 4 days. Ensemble forecasts are also used to provide flood

(continued)

Box 8.2 (continued)
warning pre-alerts at lead times of up to 14 days (e.g. Fig. 8.8). During floods, information bulletins on water levels are disseminated at least twice per day and more frequently in periods of extreme flows. Forecasts are also shared with other forecasting centres via the website for the International Commission for the Protection of the Rhine (ICPR). The forecasts for Lobith are used as inputs to a range of local forecasting models for branches of the Rhine within the Netherlands and to the ICPR Water Quality Alarm System, which is described in Chap. 12 and which provides early warnings of pollution incidents which might affect water supply, agriculture and recreation on the Rhine.

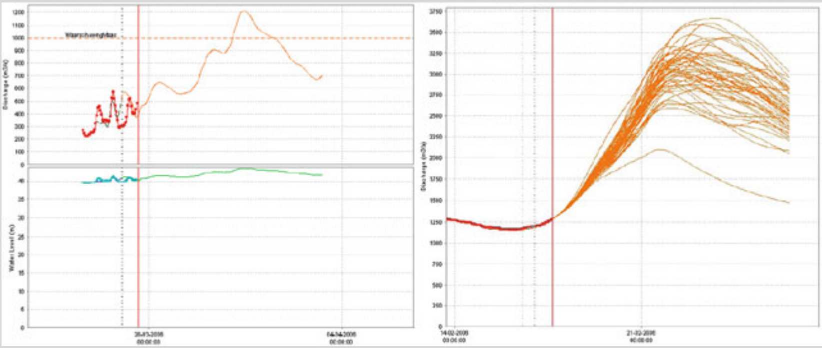

Fig. 8.8 Example of a deterministic forecast for Borgharen-Dorp on the Meuse and an ensemble forecast for Lobith on the Rhine (Beckers et al. 2008)

8.2.2 Forecasting Systems

As a flood develops the situation often changes rapidly with many sources of information to consider. In addition to model outputs, this can include rainfall observations and forecasts, river and reservoir observations and reports of flooding incidents. Given this complexity forecasting systems are widely used to help with routine operations and support decision-making. Increasingly a 'plug-and-play' open-architecture approach is provided allowing any model type which meets the specified standards to be integrated into the system, rather than being tied to specific 'brands' of model.

Chapter 5 discusses the functionality that is available in most modern systems and Table 8.6 provides a summary. Typically this includes preprocessing of input

Table 8.6 Some typical functionality in modern flood forecasting systems (Adapted from Sene 2008)

Item	Function	Description
Preprocessing	Data gathering	Polling of instruments directly or receiving data from a separate telemetry system (see data interfacing)
	Data interfacing	Interfacing to a range of real-time data feeds and forecast products from various sources (meteorological, river, coastal)
	Data validation	Real-time validation using a range of time-series, statistical and spatial techniques
	Data transformation	Transformation of input data into the values required by the modelling system (e.g. catchment rainfall estimates), including infilling missing values by interpolation and other approaches
Model runs	Model run control	Scheduling and control of model runs and error handling
	Data assimilation	Application of real-time updating/data assimilation algorithms
	Data hierarchy	Automatic fallback to alternative options in case of failure of one or more components (models, data inputs, etc.)
Post-processing	Model outputs	Processing of model outputs into reports, maps, graphs, web pages, etc.
	Inundation mapping	Intersection of inundation extents (if computed) with street and property maps to generate information on areas at risk
	Alarm handling	Raising alarms when thresholds are forecast to be exceeded, using map-based displays, email, text messaging, etc.
	Performance monitoring	Automated calculation and reporting of information on model performance and system availability
	Audit trail	Maintenance of a record of data inputs, model run control settings, model forecast outputs, operator identities, etc.
	Replay	The facility to replay model runs for post-event analysis, operator training and emergency response exercises
User interface	Model outputs	Map-based, graphical and other displays of input data, forecast outputs, alarms, etc., including overlays of aerial and satellite photography
	What-if functionality	For running scenarios defined during the design phase or in real time (e.g. for future rainfall scenarios, defence breaches, gate operations)
	System configuration	Interactive tools for off-line configuration of models, data inputs, output settings, alarms, etc.
	Model calibration	Off-line tools for calibration of models

data, model run control, data assimilation, post-processing of model outputs and storage of data and forecasts for future use. In many cases, it is possible to define different levels of user access to the system; for example, to simply display model outputs to some end users but to provide full access to the model configuration to technical specialists. Most systems also provide the option to keep track of river levels and raise alerts if threshold levels are exceeded, which is a useful facility since in some regional systems hundreds or even thousands of values are required to cover different combinations of flood risk zones, stages of alert and gauging stations.

Figure 8.9 provides an example of the information flow in this type of system. Here the polling and receipt of data is handled by a separate telemetry system, although another option is for the flood forecasting system to perform that function. In this example the system is operated on parallel servers in case one unit fails, and measures such as this to improve resilience are crucial for flood warning applications. Table 8.7 outlines some further possibilities.

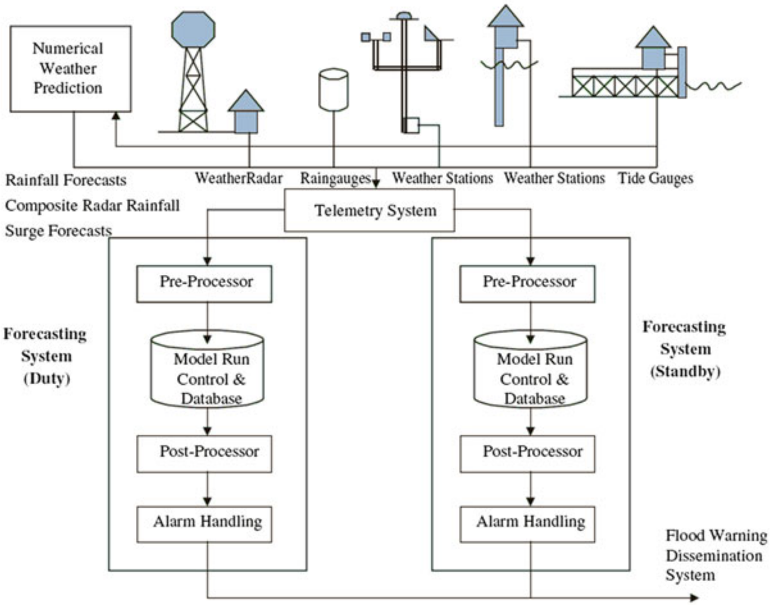

Fig. 8.9 Illustration of a possible configuration for a flood forecasting system (Adapted from Sene 2008)

Table 8.7 Some examples of approaches to improving the resilience of forecasting systems

Item	Description
Alternate models	Using simpler models, such as correlations, running in parallel with the main modelling system in case of failure of a model run (particularly for hydrodynamic models) and as a 'reality check' on the outputs from more complex models
Business continuity assessments	Systematic risk-based assessments of all aspects of the system including telemetry links and power supplies with alternates available where required such as hand-held radios and standby generators
Data hierarchies	Predefining fallback positions if a key instrument fails, such as designating alternative raingauges to use; alternate types of data, such as weather radar observations; and synthetic data, such as typical storm profiles
Geographic separation	In addition to operating parallel server systems, locating the backup system many kilometres from the main site to reduce the risks from widespread issues such as earthquakes, citywide power failures or region-wide floods
Manual forecasting procedures	Simpler graphical, chart-based or tabulated procedures for use in case of a major failure of the forecasting and telemetry system; for example, based on data relayed by observers using cell phones or hand-held radios for use with look-up tables
Telemetry resilience	Studies to assess the risk of raingauges or electrical equipment at gauging stations being flooded and then either relocating sites at risk or raising key equipment above likely flood levels; this is sometimes called flood hardening

8.2.3 Data Assimilation

Although there are many other complicating factors, compared to off-line simulation modelling one advantage in real-time forecasting is that there is the opportunity to revise model outputs based on recent observations. This process is called real-time updating or data assimilation and is widely used in flood forecasting applications. The aim is usually to achieve a closer match between observations and forecasts and in some cases to provide an estimate for the forecast uncertainty.

Chapter 5 provides an introduction to the main approaches and these are usually classified using the following terms: input updating, state updating, parameter updating and output updating (e.g. Refsgaard 1997). Some alternate names for output updating include error correction or error prediction and sometimes real-time adaptation, whilst the post-processing of meteorological forecasts (see Chap. 4) is sometimes regarded as a form of input updating or preprocessing for the hydrological component.

Output updating and state updating are probably the most widely used approaches in flood forecasting applications. For example, one technique is to fit an autoregressive moving average model to the time series of model errors and then in real-time to use that model to estimate how the sequence of errors might evolve over the forecasting horizon. In contrast, with state updating, the internal stores or states within the model are adjusted based on recent observations.

Chapter 5 discusses the basic principles of data assimilation but in brief for most approaches a general characteristic is that the effectiveness of any adjustments tends to decrease with increasing lead time as the information content of the input values decreases. In practice this means that data assimilation tends to only be effective over timescales comparable to catchment response times. However, it is worth noting that in large river basins, these sometimes extend to days or weeks ahead particularly if there is significant water storage such as in large lakes or seasonal snowpack.

Another consideration is that, at high flows, the measurement uncertainty increases, particularly for natural river sections where a stage-discharge relationship is required to estimate flows. In some cases there is therefore a risk that updating could degrade a forecast rather than improve it. In this situation, some possible options are to truncate the model output at levels beyond which there is little confidence in the outputs or to adopt a probabilistic approach which reflects these uncertainties (see Sect. 8.2.4). More generally, before approving a forecast, it is normally good practice to compare the model outputs with and without updating to check for any data or other issues; for example, some output updating approaches are sensitive to timing errors leading to rapid and unwanted changes in the sequence of model errors. Indeed in some countries, such as the USA, manually based updating techniques are routinely used in regional forecasting centres (e.g. Liu et al. 2012, Demargne et al. 2014).

Many approaches have been developed for data assimilation and Table 8.8 lists a small selection. Note that there is no entry for parameter updating since these

Table 8.8 Examples of data assimilation techniques which have been used operationally in flood forecasting applications

Type	Model type or parameter	Technique	References
Input updating	Observed rainfall and/or temperature	Model specific and manual techniques	Serban and Askew (1991)
	Quantitative precipitation and air temperature forecasts	Kalman filter, other approaches	See Chapter 4
	Soil moisture, snow cover, snow water equivalent	General	Alavi et al. (2009)
State updating	Distributed rainfall-runoff	Variational, Kalman filter, gain updating	Le Dimet et al. (2009), Seo et al. (2009)
	Conceptual rainfall-runoff	Gain updating, model specific (e.g. updating model store contents)	Moore (2007), Wöhling et al. (2006)
	Data-driven	Stochastic transfer function, gain updating	Young and Ratto (2009), Young et al. (2014)
	Conceptual rainfall-runoff, data-driven, hydrodynamic	Kalman filter (including extended and ensemble versions)	Beven (2009), Butts et al. (2005), and Weerts and El Sarafy (2006)
	Conceptual rainfall-runoff	Particle filter	Weerts and El Sarafy (2006)
	Snow water equivalent and snow cover	Model specific	Bell et al. (2000), Vehviläinen et al. (2005); see Chapter 13 also
Output updating	Can be used to post-process the outputs from most types of model	Autoregressive Moving Average (ARMA), adaptive gain, manual adjustments, several other approaches	Goswami et al. (2005), Moore (1999), Reed (1984), and Serban and Askew (1991)

techniques tend to be specific to the 'brand' of model, such as adjusting key coefficients in a hydrodynamic model or transfer function model. Indeed, the choice of approach to use is often restricted by the functionality provided by the modelling software or the forecasting system.

As noted in Chap. 5, there have been many studies of the strengths and limitations of data assimilation techniques, and further information can be found in the intercomparison studies reported by WMO (1992), Refsgaard (1997), Goswami et al. (2005) and in review articles such as those by Reed (1984), Serban and Askew (1991), Moore (1999), Beven (2009), WMO (2009) and Liu et al. (2012). It is also worth noting that some types of model are developed from the outset for use within a data assimilation framework, and some examples of this general approach include stochastic transfer function models (e.g. Young et al. 2014, Young 2002) and machine learning and artificial intelligence techniques (Shrestha and Solomatine 2008).

8.2.4 *Forecast Uncertainty*

Previous sections have discussed some of the operational impacts of forecast uncertainty. As a result, probabilistic flood forecasting techniques are increasingly used to help with decision-making and this is an active area for research.

Chapters 1 and 7 discuss some of the benefits of a probabilistic approach and the challenges in operational implementation. For example, Laeger et al. 2010 (in Sene et al. 2014) suggest that, for issing flood warnings and other operational decision-making during flood events, some of the principle benefits are:

- Providing a more structured and transparent approach for assessing uncertainties and their effects on flood forecasts regardless of the experience of individual forecasters. This should provide a clear audit trail of the information available and how it has (or has not) influenced operational decisions.
- Increasing lead times through using rainfall forecast ensembles, albeit with additional uncertainty at longer lead times (however, work still needs to be done to assess the readiness of duty officers and professional partners to utilise these forecasts).
- Allowing for calculated precautionary actions to be taken in high-risk locations in response to low-probability forecasts.
- Providing additional information to support marginal decisions.
- Targeting model, telemetry and data improvements to the areas where they matter most. Off-line assessments of model performance after flood events can play a major role in this.

In particular there is the potential to adopt more of a risk-based approach to decision-making. For example, a local authority might wish to receive low-probability warnings well in advance of any possible flooding even at the expense of more false alarms since this would allow precautionary actions to be taken of the types described earlier. Alternatively some users may require the model outputs directly for input to decision support systems such as those described in Chap. 7 for flood incident management and in Chap. 11 for tidal barriers and reservoir operations and Chap. 13 for water supply management.

The main sources of uncertainty typically arise from model structural issues and uncertainties in model parameters and initial and boundary conditions. Chapter 5 describes a range of techniques for helping to estimate the impacts of these factors, and in general terms (e.g. Beven 2009) these fall within the following categories:

- Forward uncertainty propagation – methods in which the uncertainty is propagated through the forecasting model or cascade in real time. Common approaches include 'what-if' and sensitivity studies and the use of ensemble meteorological forecasts.
- Probabilistic data assimilation – the use of techniques which not only constrain but provide estimates of uncertainty such as ensemble Kalman filtering and Particle filtering and some types of transfer function model.
- Probabilistic forecast calibration – the application of statistical models for the forecast uncertainty calibrated on the basis of past model performance; examples include quantile regression and Bayesian Uncertainty Processors.

Another option is to use multi-model techniques in which the outputs from several different models are combined to provide an indication of the uncertainties arising from model structural issues; for example, using Bayesian Model Averaging techniques.

Perhaps the first approach to be used operationally was the Ensemble Streamflow Prediction technique in the USA, which has been in use since the 1980s (e.g. Day 1985). As discussed in Chap. 5, the basis of the method is to draw samples of rainfall and air temperatures from the historical record for input to rainfall-runoff and/or snowmelt models, assuming current model states as a starting point. During the 1980s and 1990s, there were also rapid developments in the use of time series analysis techniques to provide estimates of forecast uncertainty (e.g. Lees et al. 1994; Young 2002), and there has been a resurgence of interest in these methods in recent years.

Another significant development was the introduction of ensemble techniques in meteorology during the 1990s, which quickly led to investigations into the use of these outputs in hydrological forecasting applications. A typical configuration is to consider between about 10 and 50 ensemble members and to feed these through the forecasting model or chain. Operational implementations of this approach are becoming increasingly widespread (e.g. Cloke and Pappenberger 2009, Thielen et al. 2009, Demargne et al. 2014 and Boxes 1.3, 8.1, 8.2 and 13.1). There is also increasing interest in quantifying the uncertainties arising from other sources such as weather radar inputs, raingauge-based estimates of catchment average rainfall, model parameters and stage-discharge relationships (see Chaps. 2, 3 and 5). However, as discussed in Chap. 5 an alternative approach is to use probabilistic data assimilation or forecast calibration techniques which provide estimates for the overall uncertainty in outputs rather than trying to disaggregate (or decompose) individual sources.

One key consideration when using all of these approaches is the information available for calibration. Whilst this is an issue for all types of model development work, it is a particular concern for uncertainty estimation techniques. For example, for flood applications ideally this requires many years of historical observations covering a wider range of flow conditions, including several significant flood events. Calibration datasets should also be based on measurement and/or modelling techniques representative of current operational systems.

However, due to gaps in data records and other issues, obtaining this information is sometimes a challenge even for river flow and raingauge data and the problem is more acute if using meteorological forecasts as model inputs. This is partly because archives of previous values often only extend back a few years and are not necessarily homogeneous due to changes in instrumentation and/or atmospheric models over the calibration period; for example, resulting from hardware upgrades or improvements to data assimilation techniques. As discussed in Chap. 4 reanalysis and reforecasting exercises are normally a considerable undertaking although with many potential benefits (e.g. Hamill et al. 2013). Similar techniques are increasingly used for other types of derived outputs, such as weather radar and satellite precipitation products (see Chap. 2).

Another consideration is the potential impact on model run times when using a probabilistic approach. For example, in automated flood forecasting systems, it is commonplace for forecasts to be generated at hourly or sub-hourly intervals, including any time required for pre- or post-processing of inputs and outputs. Perhaps the most demanding application is when using ensemble meteorological forecasts as inputs to a hydrodynamic model; however, at the other extreme some probabilistic data assimilation and statistical post-processing techniques take minimal additional time. Where run times are an issue, some potential options include improvements in the following areas:

- Computational efficiency – increased processor speeds, parallel processing, nested models, improved data transfer rates
- Model rationalisation – reconfiguration and simplification of models to make them run faster, particularly for hydrodynamic models (e.g. Chen et al. 2005)
- Statistical sampling – sampling or clustering a subset of ensemble members to represent the full ensemble (e.g. Cloke and Pappenberger 2009)

Simpler but faster running types of models such as transfer functions have also been proposed as a way to emulate the outputs of more complicated models (e.g. Young et al. 2009).

8.2.5 Forecast Verification

Another important consideration with operational forecasting systems is the need to have procedures and tools in place to evaluate model performance. Chapter 5 provides an introduction to this topic together with several key references.

For flood forecasting applications, performance measures are usually evaluated over a number of events both in simulation mode and when using data assimilation. Examples include the root mean square error, the timing and magnitude of peak values and the N-step ahead forecast, where N represents the number of time steps ahead of time now (e.g. 1, 2, 3….hours). In some cases values are normalised by factors linked to catchment characteristics such as the Mean Annual Flood to allow the performance to be compared between catchments.

Figure 8.10 illustrates the approach to estimating lead-time dependent measures and considers a river level (stage) forecast generated at hourly intervals over a 50-h period. The figure shows every tenth forecast together with the levels which were subsequently observed. In this example the effect of data assimilation was to cause the forecast values to match the observed values at the start of each forecast (the 'forecast origin' or 'time now') but to progressively overestimate the observations as the forecast lead time increased.

For illustration, the 3-h ahead forecasts are shown by a larger symbol and, if the full set of 50 forecasts was to be plotted, then these values could be joined to create a pseudo-hydrograph at a 3-h lead time. This allows performance measures to be estimated for different lead times and then to be plotted as a function of lead time to give an indication of the maximum value for which forecasts contain useful information or skill.

In this example, the forecast is truncated at a forecast horizon or length of 10 h; for example, this might be the maximum lead time at which the model is thought to provide useful results. This value could possibly be extended by using meteorological forecasts and – as discussed in the previous section – this would require access to the outputs from a reforecasting exercise to assist with verification. However,

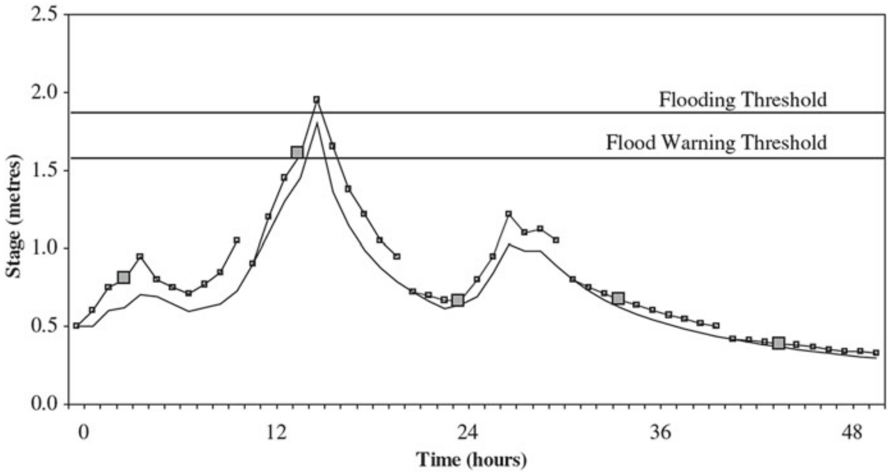

Fig. 8.10 Illustration of the construction of a fixed lead-time hydrograph; see text for description of symbols

comparisons are sometimes made less accurately using archived forecasts assuming that there have been no significant upgrades to affect performance over the period of interest.

The figure also shows some examples of flood warning and flooding thresholds, and, as discussed in Chap. 5, measures such as the Probability of Detection, False Alarm Ratio and timing errors provide a useful indication of model performance with respect to threshold values. For example, the second of the forecasts in the figure correctly predicted that the flood warning threshold would be exceeded, although approximately 1 h too early, but incorrectly predicted that the flooding threshold (at which properties might flood) would be exceeded. This would therefore have resulted in a false alarm if a warning had been issued based on the forecast alone.

The increasing use of ensemble and probabilistic forecasts has also raised the need to define appropriate performance measures when using this approach, and some examples of commonly used measures include the Brier Skill Score (including continuous versions), Ranked Probability Score, Relative Operating Characteristic, Reliability and Sharpness (e.g. Jolliffe and Stephenson 2011; Demargne et al. 2014). As discussed in Chap. 5, these assess issues such as the skill of the ensemble, compared to a suitable benchmark, and over the long term the closeness of probability density functions to observed values. There is, however, the difficulty that flood events tend to be rare, whilst some verification measures are tailored more towards applications where events occur more frequently. Some possible solutions include the pooling of results across many catchments and – again – the use of long-term hindcasts or reforecasts which include a number of extreme events.

However, it is important to note that these types of measures only consider the technical aspects of forecast performance, whereas a range of social and procedural issues affect the effectiveness of flood warnings. This topic is discussed further in Chap. 7, but the types of issues which can arise include warnings not being received in time (or at all), risk-taking behaviour and a lack of trust in the issuing authority. As noted in Chaps. 1 and 9, a community-based approach is widely advocated to raise public awareness and involvement and so help to make warnings more effective and Fig. 8.3 notes some typical activities in this area. In many flood warning services, there is also a requirement to produce post-event reports following major flood events, and acting upon the lessons learned is another major route to improving service effectiveness. In some cases this extends to routine social surveys of public satisfaction with the flood warning service and how people interpret and respond to warnings.

8.3 Selected Applications

8.3.1 Estuary Flooding

Many rivers flow into estuaries before meeting the coast. To reduce the flood risk, flood defence heights and building control regulations are often based on the highest levels likely to be reached due to the daily rise and fall of the tides plus a safety margin. Typically the highest tides occur around the time of the spring and autumn equinoxes when the combined gravitational pull of the sun and moon reaches a maximum. However, maximum levels can be higher for several reasons including:

- Backwater influences from locations further downstream, such as tidal barriers
- Wave action in strong winds
- Surge effects caused during ocean storms

The impacts vary depending on distance from the coast and, except near the estuary mouth, wave action presents perhaps the smallest risk. In contrast backwater and surge influences sometimes extend some way inland and are discussed further in this section.

Figure 8.5 shows the classical shape seen in many estuaries, narrowing from a wide open area at the coast towards the river channel inland. In heavily populated areas, a common sight around estuaries is a long line of earth embankments along both sides to protect properties and agricultural land from flooding. Where there are defences a common concern is that – if these are breached or overtopped – floodwaters are likely to extend for large distances and reach unusually high depths in comparison to fluvial flooding alone.

Tidal influences can extend a surprisingly long way inland, to distances of a 100 km or more in some rivers. Indeed when there is a high tidal range tidal bores sometimes arise such as that illustrated in Fig. 8.11. These are undular or breaking

Fig. 8.11 Surfers riding the Severn Bore near to Gloucester in the UK, approximately 15 km inland from the inner estuary; the Severn Estuary has one of the highest tidal ranges in the world, which sometimes exceeds 15 m between low and high tide

waves which travel upstream against the river flow and water levels and the flood risk often increase rapidly once the bore has passed, typically reaching a maximum 1–3 h later.

The tidal variations due to the moon and the sun are called the astronomical tides and there is roughly a 2:1 split in terms of their gravitational influences. In most places there is a roughly twice-daily tidal cycle resulting in peaks every 12 h or so. Based on harmonic analyses for the key orbital components, it is possible to estimate maximum and minimum tidal levels many years ahead, with some models assuming more than 100 components. The resulting water level predictions are generally more accurate and consistent than for most river flood forecasts, although as Hicks (2006) notes errors can arise from factors such as:

- The restrictive depths of the oceans not allowing the generated tidal wave to be in equilibrium with the rotation of the earth
- Irregular ocean depths over which the waves must travel
- Reflections and interactions of the waves from irregularly shaped continents
- Bottom friction
- Turbulence
- Viscosity of the water

In contrast, surge is a localised increase or decrease in sea levels due to atmospheric pressure and wind effects and typically occurs during tropical cyclones and mid-latitude storms. Due to resonance and other factors, this effect is often magnified in shallow coastal waters and values sometimes reach several metres in extreme events; for example, a surge of 7–9 m was observed in some locations in 2005 during Hurricane Katrina and contributed to the severe flooding in New Orleans during that event (Knabb et al. 2006). As might be expected another concern is when an extreme surge coincides with a high tide as happened in 1953 and 2013 along the east coast of England, for example (e.g. Fig. 8.12).

Typically the magnitude and timing of a surge is estimated using hydrodynamic models of the oceans and coastal waters, with the surface pressure and wind fields derived from numerical weather prediction models (e.g. Jelesnianski et al 1992, Flather 2000, Verlaan et al. 2005, Brassington et al. 2005, Massey et al. 2007, WMO 2011b, 2015). Chapter 5 shows an example of the map-based outputs from an operational surge forecasting system. Forecasts are usually produced by national meteorological services and ocean research centres and the resulting products are of interest to a wide range of users, such as shipping operators and port authorities, as well as for flood warning purposes. Increasingly an ensemble approach is used to help to assess the uncertainties in model outputs (Horsburgh 2014).

Surge predictions are usually derived for the open oceans and shorelines but, for estuaries, the situation is more complex, with influences from factors such as the reflections and currents resulting from the shape of the shoreline and from islands, headlands and channels. These factors also affect tidal predictions, and, for environmental and engineering design studies, 2D or 3D hydrodynamic models are widely used to estimate levels, flows and the transport of sediment and pollutants.

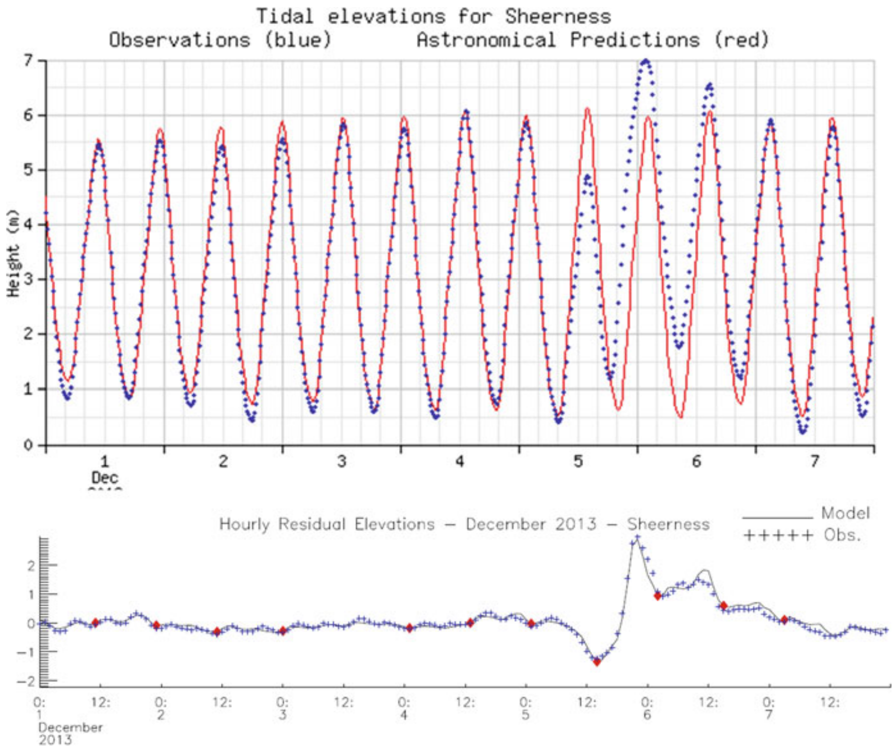

Fig. 8.12 Example of tidal observations, astronomical predictions and surge residual forecasts for Sheerness on the east coast of England from 1–7 December 2013; a major surge event occurred on 5–6 December (Reproduced with permission from the National Oceanography Centre; source: http://www.ntslf.org/; check website for latest estimates)

In the past it was often not practical to run these types of models in real-time for individual estuaries but, as noted in Chaps. 5 and 12 and Box 8.1, they are increasingly used in flood and water quality forecasting applications. However, more usually, models are run off-line to develop simpler look-up tables, nomograms, regression relationships or charts (or carpet plots) to assist with estimating levels as a high tide or surge develops. Typically these provide estimates at key points within the estuary for a range of possible levels within the river and at the coast (e.g. WMO 1998, 2011a). Whilst these types of tools are often derived on the basis of experience and observations alone, the use of a model allows a wider range of scenarios to be considered. When a forecasting system is available, the coefficients are often loaded to automate the generation of outputs.

Another possibility is to develop a simplified hydrodynamic model for the river and estuary, typically using a one-dimensional approach and focussing modelling effort on specific forecasting points. For real-time use, the downstream boundary would ideally be located at a tide gauge for which both water level observations and tidal predictions and surge forecasts are available. However, there are many uncertainties in all of these approaches, so as a precaution, when the risk is high, operational patrols are often deployed to monitor levels at high-risk locations and to check that tide gates and other structures operate correctly.

8.3.2 Snow and Ice

In some countries, particularly at higher latitudes and in mountainous areas, snowmelt presents a significant flood risk and needs to be represented in flood forecasting models. This typically arises from some or all of the following factors acting alone or in combination:

- Solar radiation
- Rising air temperatures
- Wind-driven turbulent heat exchange at the snow surface
- Rainfall falling on snow

The impacts are sometimes felt a long way downstream, in some cases extending into much drier regions at the foot of mountain ranges and further afield.

One simple empirical forecasting approach is to assume that the rate at which snow melts is proportional to the sum of air temperature values that exceed a threshold value. This is called a temperature-index or ‘degree-day’ approach and provides a measure of the energy input to the snowpack and is used as a component in some real-time models. Variations on this approach allow factors such as wind speed and radiation to be considered (e.g. Hock 2003). Linear or non-linear regression relationships provide another option and relate snowmelt to factors such as the air temperature, the water equivalent depth of the snow layer, the soil moisture, the rainfall and the depth of frozen soil (e.g. WMO 2009).

However, for operational forecasting conceptual and physical-conceptual models are perhaps the most widely used approaches (e.g. Bell et al. 2000; Vehviläinen et al. 2005; see Chap. 13 also). Typically the input precipitation is partitioned into rainfall or snowfall according to air temperature and/or elevation or lapse rate criteria, using a mass balance approach. Separate stores are usually included for components such as wet snow, melting snow and the soil layer(s), often using GIS analyses to distinguish between forests, open snow and other types of land cover. In more complex physically-based approaches, energy and advection terms are considered as well. Figure 8.13 shows an example of this approach which, in this case, represents factors such as the energy inputs from net radiation together with advection losses, evaporation losses, runoff to streams and rivers and recharge to sub-surface layers.

Many such models have been developed and in one major intercomparison experiment Essery et al. (2009), the outputs from 33 separate models were submitted from organisations in 11 countries, ranging from simple conceptual approaches to complex physically-based techniques.

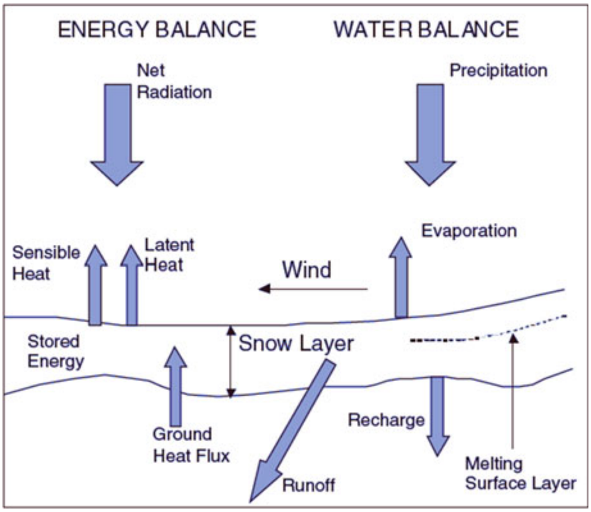

Fig. 8.13 Some key features in the energy and water balance for a melting snow layer; directions of fluxes may vary (Adapted from Sene 2008)

In real-time operation the main inputs to conceptual models are typically weather station observations and precipitation and air temperature forecasts, often in ensemble form. Estimates of snow cover and snow water equivalent depths are often based on satellite observations supplemented by in situ observations of the types described in Chap. 3, such as snow courses, ultrasonic gauges and snow pillows. However, for simpler types of models, each run is usually started using the states estimated during the previous run, with manual updates if the model states drift too far from observed values. As noted in Chap. 3 at least one river gauge is often installed downstream from areas prone to snowmelt as a backup in case the potential for flooding is missed either by the forecasting model or observations.

River ice also presents a flood risk in some locations and where this is an issue one key requirement is to estimate when the winter ice cover is likely to break up or melt. This is potentially of interest for a range of applications such as navigation, hydropower operations and assessing the ice jam risk. Ice jams often result mainly from increases in river flows and are discussed in Chap. 9, whilst – for forecasting the initial melting of river ice – both degree-day and correlation approaches are widely used, with air temperatures as the main input.

However, there has been much research into more physically-based approaches for forecasting ice break-up; for example, using hydrodynamic models for the flow component with an energy component to represent the formation and melting of ice (e.g. WMO 2009, Kubat et al. 2005). Some other areas for research include multivariate statistical methods, the use of ice break-up databases, artificial intelligence techniques and Kalman filtering (e.g. Daly 2003; White 2003; Morse and Hicks 2005; Mahabir et al. 2006).

8.4 Summary

- The types of floods which occur on the floodplains of large rivers are called riverine, fluvial or plains floods. Some typical characteristics include their slowly developing nature, sometimes lasting days or more, and the extensive areas which are covered, often affecting large numbers of people.
- For issuing flood warnings, much can be achieved by using observed river levels alone for gauges at or near the areas at risk and at locations further upstream. Simple forecasting tools such as correlation models, time-of-travel maps and rate-of-rise triggers are often used alongside this approach.
- Some key drivers towards using a more sophisticated approach include the need to interpret complexities in the flooding response and to extend the time available for the emergency response; for example, for evacuation and flood-fighting activities. Improvements to decision-making processes and warning dissemination provide other options for increasing the time available for the response
- For large river basins, a typical model configuration is to use a network of rainfall-runoff models whose outputs provide the inputs to flow routing models for the main river network. Real-time hydrodynamic models provide another option, particularly for high-risk locations and in estuary forecasting applications, and snowmelt components are required in some cases.
- Some factors to consider when selecting a modelling approach include the forecasting system on which the model(s) will run, catchment response times, warning lead-time requirements, the level of risk, the quality and availability of real-time data for data assimilation and how best to quantify the forecast uncertainty and convey that information to end users.
- Data assimilation in particular is one feature which distinguishes real-time models from their off-line counterparts and has the potential to significantly improve forecast accuracy. The most widespread approaches in flood forecasting applications are probably output and state updating techniques. Probabilistic techniques are also increasingly used to help with decision-making.
- For estuaries the main flood risks arise from high astronomical tides, surge and wave action, with the impacts depending on the location in the estuary. Forecasting techniques range from simple paper-based correlations and charts to real-time 2D or 3D models, often backed up by on-site patrols at high-risk locations.
- The main factors which cause snowmelt are rising air temperatures, high levels of solar radiation and wind and rain effects. Typically conceptual or physical-conceptual models are used for real-time forecasting and in some cases physically-based approaches incorporating energy and advection components. For forecasting river ice break-up, simple empirical techniques are usually relied upon, although there has been much research into more process based approaches.
- It is important to recognise that flood forecasts are just one aspect of a wider flood risk management process and that, for warnings to be effective, factors such as community engagement, public-awareness raising and routine performance monitoring need to be integrated into day-to-day activities.

References

AfDB/World Bank (2012) 2011 Pakistan Floods: Preliminary damage and needs assessment. Asian Development Bank and World Bank report.

Alavi N, Warland JS, Berg AA (2009) Assimilation of soil moisture and temperature data into land surface models: a survey. In Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications. Springer, Berlin-Heidelberg

Alfieri L, Burek P, Dutra E, Krzeminski B, Muraro D, Thielen J, Pappenberger F (2013) GloFAS – global ensemble streamflow forecasting and flood early warning. Hydrol Earth Syst Sci 17:1161–1175

Beckers J, Sprokkereef E, Roscoe K (2008) Use of Bayesian Model Averaging to determine uncertainties in river determine and water level forecasts. 4th International Symposium on Flood Defence, 6–8 May 2008, Toronto

Bell VA, Moore RJ, Brown V (2000) Snowmelt forecasting for flood warning in upland Britain. In Lees M, Walsh P (Eds.), Flood Forecasting: What does Current Research offer the Practitioner. BHS Occasional Paper 12, British Hydrological Society, London

Beven KJ (2009) Environmental Modeling: An Uncertain Future. Routledge, London

Beven KJ (2012) Rainfall-Runoff Modelling – the Primer, 2nd edn. Wiley-Blackwell, Chichester

Brassington GB, Warren G, Smith N, Schiller A, Oke PR (2005) BLUElink Progress on operational ocean prediction for Australia. Bull. Aust. Meteorol. Oceanogr. Soc. 18: 104–109

Burnash RJC (1995) The NWS river forecast system – catchment modeling. In Singh VP (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO

Butts MB, Falk AK, Hartnack J, Madsen H, Klinting A, van Kalken T, Cadman D, Price D (2005) Ensemble based methods for data assimilation and uncertainty estimation in the FLOODRELIEF project. ACTIF International conference on innovation advances and implementation of flood forecasting technology, 17–19 October 2005, Tromsø, Norway

Carsell KM, Pingel ND, Ford DT (2004) Quantifying the benefit of a flood warning system. Natural Hazards Review, ASCE, 5:131–140

Chen Y, Sene KJ, Hearn K (2005) Converting Section 105 or SFRM hydrodynamic river models for real time forecasting applications. 40th Defra Flood and Coastal Defence Conference, York, England

Cloke HL, Pappenberger F (2009) Ensemble flood forecasting: a review. Journal of Hydrology, 375: 613–626

Cole SJ, Moore RJ (2009) Distributed hydrological modelling using weather radar in gauged and ungauged basins. Advances in Water Resources, 32(7): 1107–1120

Collischonn W, Allasia DG, Silva BC, Tucci CEM (2007) The MGB-IPH model for large scale rainfall runoff modeling. Hydrological Sciences Journal, 52(5): 878–895

Cranston MD, Tavendale ACW (2012) Advances in operational flood forecasting in Scotland. Proceedings of the ICE - Water Management, Volume 165(2): 79–87

Cranston M, Maxey R, Tavendale A, Buchanan P, Motion A, Cole S, Robson A, Moore RJ, Minett A (2012) Countrywide flood forecasting in Scotland: challenges for hydrometeorological model uncertainty and prediction. Weather Radar and Hydrology (Eds. Moore RJ, Cole SJ, Illingworth AJ), IAHS Publication 351, Wallingford

Daly SF (2003) A state–space model for river ice forecasting. Cold Regions Research and Engineering Laboratory report ERDC/CRREL TR-03-9, New Hampshire

Dawson CW, Wilby RL (1999) A comparison of artificial neural networks used for flow forecasting. Hydrology and Earth System Sciences, 3: 529–540

Day GN (1985) Extended streamflow forecasting using NWSRFS. Journal of Water Resources Planning and Management, 111(2): 157–170

Demargne J, Wu L, Regonda SK, Brown JD, Lee H, He M, Seo D-J, Hartman R, Herr HD, Fresch M, Schaake J, Zhu Y (2014) The science of NOAA's operational Hydrologic Ensemble Forecast Service. Bulletin of the American Meteorological Society, 95: 79–98

Essery R, Rutter N, Pomeroy J, Baxter R, Stähli M, Gustafsson D, Barr A, Bartlett P, Elder K (2009) SnowMIP2: An Evaluation of Forest Snow Process Simulations. Bulletin of the American Meteorological Society, 90(8): 1120–1135

Flather R A (2000) Existing operational oceanography. Coast Eng 41: 13–40

Golding BW (2009) Long lead time warnings: reality of fantasy? Meteorol Appl 16:3–12

Goswami M, O'Connor KM, Bhattarai KP, Shamseldin AY (2005) Assessing the performance of eight real time updating models and procedures for the Brosna River. Hydrology and Earth System Sciences, 9(4), 394–411

Grams CM, Binder H, Pfahl S, Piaget N, Wernli H (2014) Atmospheric processes triggering the central European floods in June 2013. Nat. Hazards Earth Syst. Sci., 14, 1691–1702

Hamill TM, Bates GT, Whitaker JS, Murray DR, Fiorino M, Galarneau TJ Jr, Zhu Y, Lapenta W (2013) NOAA's second-generation global medium-range ensemble reforecast dataset. Bull Am Meteorol Soc 94:1553–1565

Hicks S D (2006) Understanding Tides. Centre for Operational Oceanographic Products and Services, NOAA

Hock R (2003) Temperature index melt modelling in mountain areas. Journal of Hydrology, 282(1–4): 104–115

Horsburgh K (2014) Real-Time Coastal Flood Forecasting. In: Beven K, Hall J (eds) Applied Uncertainty Analysis for Flood Risk Management. Imperial College Press, London

Jelesnianski CP, Chen J, Schaffer WA (1992) SLOSH: sea, lake and overland surges from hurricanes. NOAA Technical Report NWS 48, Silver Spring

Jolliffe IT, Stephenson DB (2011) Forecast verification. A practitioner's guide in atmospheric science, 2nd edn. Wiley, Chichester

Knabb R D, Rhome J R, Brown D P (2006) Tropical Cyclone Report: Hurricane Katrina 23–30 August 2005. National Hurricane Center, 20 December 2005 (updated 10 August 2006 for tropical wave history, storm surge, tornadoes, surface observations, fatalities, and damage cost estimates)

Koren V, Reed S, Smith M, Zhang Z, Seo DJ (2004) Hydrology Laboratory Research Modeling System (HL-RMS) of the National Weather Service. Journal of Hydrology, 291(3/4): 297–318

Kubat I, Sayed M, Savage S, Carrieres T (2005) Implementation and testing of a thickness redistribution model for operational ice forecasting. Proceedings 18th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'05, 2: 781–791, Potsdam, USA

Laeger S, Cross R, Sene K, Weerts A, Beven K, Leedal D, Moore RJ, Vaughan M, Harrison T, Whitlow C (2010) Risk-based probabilistic fluvial flood forecasts for integrated catchment models. In 'Role of Hydrology in Managing Consequences of a Changing Global Environment', Proceedings of British Hydrological Society Third International Symposium, Newcastle University, 19–23 July 2010

Le Dimet F-X, Castaings W, Ngnepieba P, Vieux B (2009) Data assimilation in hydrology: variational approach. In Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications. Springer, Berlin-Heidelberg

Lees M, Young P, Ferguson S, Beven KJ, Burns J (1994) An adaptive flood warning system for the river Nith at Dumfries. In (Eds. White WR, Watts J), 2nd International Conference on River Flood Hydraulics. Wiley, Chichester

Lindström G, Johannson B, Persson M, Gardelin M, Bergström S (1997) Development and test of the distributed HBV-96 hydrological model. Journal of Hydrology, 201: 272–288

Liu Y, Weerts AH, Clark M, Hendricks Franssen H-J, Kumar S, Moradkhani H, Seo D-J, Schwanenberg S, Smith P, van Dijk AIJM, van Velzen N, He M, Lee H, Noh SJ, Rakovec O, Restrepo P (2012) Advancing data assimilation in operational hydrologic forecasting: progress, challenges, and emerging opportunities. Hydrol. Earth Syst. Sci. Discuss., 9: 3415–3472

Madsen H (2000) Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. Journal of Hydrology, 235(3–4): 276–288

Mahabir C, Hicks FE, Robichaud C, Fayek AR (2006) Forecasting breakup water levels at Fort McMurray, Alberta, using multiple linear regression. Canadian Journal of Civil Engineering 33(9): 1227–1238

Massey W G, Gangai J W, Drei-Horgan E, Slover K J (2007) History of Coastal Inundation Models. Mar Technol Soc J 41(1): 7–17

Moore RJ (1999) Real-time flood forecasting systems: perspectives and prospects. In (Eds.R Casale and C Margottini), Floods and Landslides: Integrated Risk Assessment. Chapter 11, 147–189, Springer Verlag, Berlin and Heidelberg

Moore RJ (2007) The PDM rainfall runoff model. Hydrology and Earth System Sciences, 11(1): 483–499

Morse B, Hicks F (2005) Advances in river ice hydrology 1999–2003. Hydrological Processes, 19(1): 247–263

Nemec (1986) Hydrological Forecasting: Design and Operation of Hydrological Forecasting Systems. D. Reidel Publishing Company, Dordrecht

NOAA/NWS (2010) Factsheet: Understanding the River Forecast Process. Middle Atlantic River Forecast Centre, National Weather Service, State College, PA

Office of Science and Technology (2003) Foresight Flood and Coastal Defence Project. Phase 1 Technical Report Drivers, Scenarios and Work Plan, Office of Science and Technology, London, January 2003

Overeem A (2005) Description of the River Rhine basin. Royal Netherlands Meteorological Institute (KNMI) http://www.knmi.nl/

Paquet E, Garcon R (2004) Hydrometeorological forecast at EDF-DTG MORDOR hydrological model. 4th International MOPEX Workshop, July 2004, Paris

Parker D, Tunstall S, Wilson T (2005) Socio-economic benefits of flood forecasting and warning. ACTIF International conference on innovation advances and implementation of flood forecasting technology, 17–19 October 2005, Tromsø, Norway

Parmet, BWAH, Sprokkereef, E (1997) Hercalibratie Model Lobith: Onderzoek naar mogelijke verbeteringen van de voorspellingen met het meervoudig lineaire regressie Model Lobith na de hoogwaters van 1993 en 1995, RIZA, Lelystad

Quick M C (1995) The UBC watershed model. In Singh VP (ed.), Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, CO

Reed DW (1984) A review of British flood forecasting practice. Institute of Hydrology, Report No. 90, Wallingford

Refsgaard JC (1997) Validation and intercomparison of different updating procedures for real-time forecasting. Nordic Hydrology, 28(2): 65–84

Sene K (2008) Flood Warning, Forecasting and Emergency Response. Springer, Dordrecht

Sene K (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht

Sene K, Weerts AH, Beven K, Moore RJ, Whitlow C, Laeger S, Cross R (2014) Uncertainty estimation in fluvial flood forecasting applications. In: Beven K, Hall J (eds) Applied uncertainty analysis for flood risk management. Imperial College Press, London

Seo D-J, Cajina L, Corby R, Howieson T (2009) Automatic state updating for operational streamflow forecasting via variational data assimilation. Journal of Hydrology, 367(3–4): 255–275

SEPA (2013) Flood risk management in Scotland. Leaflet, Scottish Environment Protection Agency, Perth

SEPA (2014) Scottish Flood Forecasting Service: Your guide to using the Flood Guidance Statement. Third publication. Flood risk management in Scotland. Scottish Environment Protection Agency, Perth

Serban P, Askew AJ (1991) Hydrological forecasting and updating procedures. IAHS Publ. No. 201: 357–369

Shrestha DL, Solomatine DP (2008) Data-driven approaches for estimating uncertainty in rainfall-runoff modeling. Journal of River Basin Management, 6(2): 109–122

Singh VP (Ed.) (1995) Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO

Sprokkereef E (2002) Flood Forecasting for the River Rhine in the Netherlands. The Extremes of the Extremes: Extraordinary Floods. Proc. Symp. Reykjavik, Iceland, July 2000. IAHS Publ. 271

Thielen J, Bartholmes J, Ramos M-H, de Roo A (2009) The European Flood Alert System – Part 1: concept and development. Hydrology and Earth System Sciences, 13: 125–140

Tilford KA, Sene KJ, Khatibi R (2007) Flood Forecasting Model Selection: A Structured Approach. In (Eds. Begum S, Stive MJF, Hall JW), Flood Risk Management in Europe. Springer, Dordrecht

Todini E (2007) Hydrological catchment modeling: past, present and future. Hydrology and Earth System Sciences, 11(1): 468–482
UN (2013) Mozambique Floods 2013. Consolidated Early Recovery Strategy Humanitarian Country Team, Maputo, 25 April 2013
USACE (1994) Framework for estimating national economic development benefits and other beneficial effects of flood warning and preparedness systems. US Army Corps of Engineers, Institute for Water Resources Report IWR-94-3, Alexandria, Virginia
USACE (1996) Hydrologic aspects of flood warning-preparedness programs. US Army Corps of Engineers Report ETL 1110-2-540, Office of Chief of Engineers, Washington, DC
USACE (2012) Mississippi River and Tributaries System: 2011 Post Flood Report. US Army Corps of Engineers report, New Orleans
Vehviläinen B, Huttunen M, Huttunen I (2005) Hydrological Forecasting and Real Time Monitoring in Finland: the Watershed Simulation and Forecasting System (WSFS). ACTIF International conference on innovation advances and implementation of flood forecasting technology, 17–19 October 2005, Tromsø, Norway
Verlaan M, Zijderveld A, Vries H, Kroos J (2005) Operational storm surge forecasting in the Netherlands: developments in the last decade. Phil. Trans. R. Soc. Lond. 363(1831): 1441–1453
Vieux BE, Bedient PE, Mazroi E (2005) Real-time urban runoff simulation using radar rainfall and physics-based distributed modeling for site-specific forecasts. 10th International Conference on Urban Drainage, Copenhagen/Denmark, 21–26 August 2005
Weerts AH, El Sarafy G (2006) Particle filtering and ensemble Kalman Filtering state updating with hydrological conceptual rainfall-runoff models. Water Resources Research, 42: W09403, 1–17
Werner M, Cranston M, Harrison T, Whitfield D, Schellekens J (2009) Recent developments in operational flood forecasting in England, Wales and Scotland. Meteorological Applications, 16(1): 13–22
White KD (2003) Review of prediction methods for breakup ice jams. Canadian Journal of Civil Engineering, 30: 89–100
WMO (1973) Benefit and cost analysis of hydrological forecasts: a state of the art report. Operational Hydrology Report No. 3, WMO-No. 341, Geneva
WMO (1992) Simulated real time intercomparison of hydrological models. Operational Hydrology Report No. 38, Geneva
WMO (1998) Guide to Wave Analysis and Forecasting. 2nd edition. WMO-No. 702, Geneva
WMO (2009) Guide to Hydrological Practices, 6th edn. WMO-No. 168, Geneva
WMO (2011a) Manual on Flood Forecasting and Warning. WMO-No. 1072, Geneva
WMO (2011b) Guide to storm surge forecasting. WMO-No. 1076, Geneva
WMO (2015) Global Guide to Tropical Cyclone Forecasting (eds. Holland GJ et al). http://www.wmo.int/
Wöhling TH, Lennartz F, Zappa M (2006) Technical note: updating procedure for flood forecasting with conceptual HBV-type models. Hydrology and Earth System Sciences, 10:783–788
Yang Z, Han D (2006) Derivation of unit hydrograph using a transfer function approach. Water Resources Research, 42(1): 1–9
Young PC (2002) Advances in real-time flood forecasting, Phil. Trans. R. Soc. Lond. A, 360: 1434–1450
Young PC, Ratto M (2009) A unified approach to environmental systems modeling. Journal Stochastic Environmental Research and Risk Assessment, 23(7): 1037–1057
Young P, Leedal D, Beven K (2009) Reduced order emulation of distributed hydraulic simulation models. Paper WeB7.2. 15th IFAC Symposium on System Identification, July 6–8, 2009, Saint-Malo, France
Young PC, Romanowicz RJ, Beven K (2014) A Data-Based Mechanistic modelling approach to real-time flood forecasting. In: Beven K, Hall J (eds.) Applied Uncertainty Analysis for Flood Risk Management. Imperial College Press, London
Zhao RJ (1992) The Xin'anjiang model applied in China. Journal of Hydrology, 135: 371–381

Chapter 9
Flash Floods

Abstract Flash floods are one of the most destructive types of natural hazards. The main threat arises from the speed with which they develop and the depth and power of the resulting flows. Similar risks arise from related phenomena such as debris flows, ice jams, surface water (or pluvial) flooding, dam breaks and levee failures. Perhaps the most comprehensive way to provide warnings is to install gauges both at and upstream of areas at risk and to use the outputs from forecasting models to help to extend warning lead times. However, where this is not feasible, other options include heavy rainfall warnings, flash flood guidance techniques and region-wide distributed rainfall-runoff models. This chapter provides an introduction to these topics and to community-based approaches to flood warning.

Keywords Flash floods • Flood warning • Thresholds • Rainfall-runoff • Flash Flood Guidance • Distributed models • Heavy rainfall warnings • Forecast verification • Debris flows • Ice jams • Dam break • Levee breach • Surface water flooding

9.1 Introduction

The classical image of a flash flood is of a wall of water or mud arriving suddenly in a dry river bed. Floods of this type do sometimes occur, particularly in desert regions, and some impressive video footage can be found from an Internet search.

More usually though flash floods are characterised by a rapid increase in water levels, perhaps from already high values, and often have considerable debris content. Typically the main risks to people and property arise from the sudden onset and speed and depth of the flow. For example, Montz and Gruntfest (2002) suggest that flash floods have the following characteristics:

- They occur suddenly, with little lead time for warning
- They are fast-moving and generally violent, resulting in a high threat to life and severe damage to property and infrastructure
- They are generally small in scale with regard to area of impact

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- They are frequently associated with other events, such as riverine floods on larger streams and mudslides
- They are rare (Gruntfest and Handmer 2001)

Flash floods are sometimes called ‘short-fuse’ events along with other types of rapid-onset events such as tornadoes and thunderstorms. In addition to floods in rivers, some other types include:

- Debris flows – flows of mud, rocks and other debris either along existing watercourses or directly overland, sometimes related to hillside erosion, vegetation clearance or recent wildfires.
- Ice jams – floods resulting from river ice which has accumulated at bridges and other obstructions, with a flood risk arising both upstream due to backwater influences and downstream if the ice jam subsequently breaks up suddenly.
- Surface water floods – flooding in urban areas when surface runoff exceeds the capacity of the drainage network and natural watercourses; alternative names include pluvial or stormwater flooding.
- Dam and flood defence failures – floods arising from overtopping or failure of dam walls and flood defences (levees or dikes) and from the collapse of ice or moraine dams at the outlets of glacial lakes, which are often called Glacial Lake Outburst Floods.

Table 9.1 provides some examples in each category for which, in addition to heavy rainfall, some other causal factors included ice-related issues and the failure of hydraulic structures. Debris issues sometimes also play a role in river flooding; for example, when blockages occur at bridges and culverts or over the longer term due to reductions in channel-carrying capacities, which is a serious issue in some countries due to catchment degradation.

Table 9.1 Some examples of major flash flood events

Type	Location	Year	Description
River flooding	Gard region, southern France	2002	An extensive slow-moving mesoscale convective system deposited more than 600 mm of rainfall in 24 h resulting in 23 deaths and economic damages valued at about 1.5 billion dollars (Delrieu et al. 2005; Anquetin et al. 2009)
	Big Thompson Canyon, USA	1976	Approximately 300–350 mm of rainfall fell in 4–5 h due to a near-stationary thunderstorm. About 144 people died and 418 homes and businesses were damaged, and many mobile homes, vehicles and bridges (Gruntfest 1996; USGS 2006)
	Colorado Front Range, USA	2013	Sustained heavy rainfall over several days, exceeding 400 mm in places, led to severe flooding and localised flash flooding, landslides and debris flows resulting in several fatalities and damages exceeding two billion dollars (Gochis et al. 2014)

(continued)

Table 9.1 (continued)

Type	Location	Year	Description
Debris flow	Northern Venezuela	1999	Fourteen days of heavy rainfall were followed by 900 mm of rainfall in 3 days. Thousands of people were killed in the resulting debris flows and many towns devastated along a 50 km section of the coastal zone (Lopez and Courtel 2008)
	Southern Taiwan	2009	A slow-moving typhoon (Morakot) with daily rainfall reaching 1200 mm in some places, and some 4-day totals exceeding 3000 mm, caused widespread flash flooding and debris flows resulting in more than 700 fatalities and losses of about $500 million (Chien and Kuo 2011)
Ice Jam	Montpelier, USA	1992	An ice jam formed at a bridge causing river levels upstream to increase rapidly leading to extensive flooding in the city within 1 h. Hundreds of residents were evacuated and 120 businesses were disrupted in the subsequent flood (Abair et al. 1992)
Surface water flooding	Texas, Louisiana, USA	2001	Flash flooding from heavy rainfall and thunderstorms associated with Tropical Storm Allison, with rainfall exceeding 250 mm in a few hours in the Houston area, resulted in 22 fatalities and flooding of more than 45,000 homes and businesses and 70,000 vehicles in Harris County with further impacts elsewhere (U.S. Department of Commerce 2001)
	Hull, UK	2007	Heavy sustained rainfall of about 110 mm in about 10 h following weeks of wet weather caused flooding of approximately 8600 homes and 1300 businesses due primarily to the drainage system being overwhelmed (Coulthard et al. 2007)
Dam and levee failures	Johnstown, USA	1889	An unusually heavy storm crossed the region and continued into the following day, with the 24-h rainfall for the previous day estimated at 150–250 mm. Some 2209 people perished and 27,000 were left homeless in the town of Johnstown when a dam failed (e.g. Frank 1988)
	New Orleans, USA	2005	During Hurricane Katrina, which resulted in more than 1000 fatalities, a significant proportion of the flood damages resulted from the failure of concrete floodwalls or overtopping and erosion of levees in more than 50 locations (ASCE 2007)
	Huaraz, Peru	1941	The moraine dam containing Lake Palca collapsed due to an icefall into the lake. There were more than 6000 fatalities in the city of Huaraz located 22–23 km downstream (Lliboutry et al. 1977)

Adapted from Sene (2013)

Several types of flash flood can occur during a single widespread rainfall event such as a mid-latitude storm or landfall of a tropical cyclone. For example, one particular risk is if debris dams form in rivers and then break with little or no warning. This is one of the greatest causes of fatalities during flash floods along with the risks to vehicle drivers; in the latter case accounting for more than half of all victims in the USA (e.g. Jonkman and Kelman 2005; Ashley and Ashley 2008). Indeed the National Weather Service operates an awareness-raising campaign aimed specifically at road users called 'Turn Around Don't Drown!', and this includes educational material, road signage at critical locations and highlighting the risks in warning messages (http://tadd.weather.gov/).

One common approach to defining flash floods is in terms of the catchment response time at the location at risk and values of 4–6 hours are often quoted. The following description (WMO 2009) provides an example of this approach:

> Flash floods are rapidly rising flood waters that are the result of excessive rainfall or dam break events. Rain-induced flash floods are excessive water flow events that develop within a few hours – typically less than six hours – of the causative rainfall event, usually in mountainous areas or in areas with extensive impervious surfaces such as urban areas. Although most of the flash floods observed are rain induced, breaks of natural or human-made dams can also cause the release of excessive volumes of stored water in a short period of time with catastrophic consequences downstream. Examples are the break of ice jams or temporary debris dams

An alternative approach (ACTIF 2004) is to compare catchment response times with emergency response capabilities at the location at risk as follows:

> A flash flood can be defined as a flood that threatens damage at a critical location in the catchment, where the time for the development of the flood from the upstream catchment is less than the time needed to activate warning, flood defence or mitigation measures downstream of the critical location. Thus with current technology even when the event is forecast, the achievable lead-time is not sufficient to implement preventative measures (e.g. evacuation, erecting of flood barriers)

This definition therefore considers both technological capability and the ability to respond, which is affected by a range of social and institutional factors. Over time, views on what is regarded as a flash flood may therefore change due to improvements in both of these areas, allowing a better service to be offered to existing users and new locations to be considered which previously would not have been considered to be feasible. Indeed many hydrological services develop capabilities in this way, starting with offering a service for riverine floods then at a later date extending this to different types of floods, such as flash floods. Another useful type of definition – particularly when developing flood forecasting models – is to consider factors such as the typical spatial scale and duration of rainfall in relation to catchment areas and response times (e.g. Kelsch 2001, Kobiyama and Goerl 2007).

In this chapter, the definition is left open and instead the focus is on forecasting and warning techniques for which – compared to riverine floods (see Chap. 8) – there are often the following additional challenges:

- Emergency response – the rapidity with which events develop, sometimes in remote locations, usually places greater emphasis on a community-based response in the initial stages, before help arrives from further afield; risks are particularly high at night and/or in cold weather.

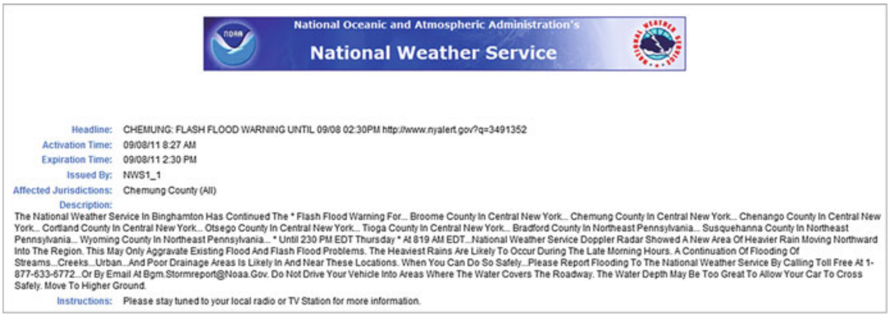
- Flood forecasting – for some types of flash floods, technical understanding of runoff and flooding mechanisms is generally less advanced than for riverine floods so there is greater uncertainty in model outputs, particularly for events caused by mechanical failures such as ice jam break-ups, dam breaks, levee failures and outburst floods.
- Flood risk assessments – an initial screening may show many locations potentially at risk in a region, including some with little recent history of flooding, making it more difficult to prioritise improvements to early warning systems than when considering just a single large river basin.
- Flood warning dissemination – although flash floods often occur in remote areas, the numbers of people affected can still be large, sometimes making it a challenge to issue warnings to all of the people likely to be affected in time to take effective action.
- Meteorological observations – flash floods are often caused by localised events which are difficult to detect without very dense raingauge networks, which are usually not available; in addition in mountain areas there are orographic influences on rainfall to consider and coverage issues with weather radar observations.

Given these uncertainties, local observers have a valuable role to play in feeding back information on flooding impacts, in particular regarding event-specific issues such as debris blockages. In addition to information relayed by cell phone or hand-held radio, this increasingly includes images taken by smartphones or messages on social media. For example, in the USA about 300,000 volunteers provide information on severe weather impacts to the National Weather Service (http://www.skywarn.org/) including reporting on flash floods, hail, hurricanes, lightning, thunderstorms and tornadoes. Similarly in Switzerland a national web-based decision support tool allows this type of on-the-ground information to be viewed alongside observations and forecasts for a wide range of hazards including flash floods (e.g. Heil et al. 2010, Romang et al. 2011). Remotely-controlled camera systems are also useful for monitoring how conditions develop in urban areas.

Despite these various challenges, many national hydrological services offer at least a basic warning service for some types of flash floods. For example, initial alerts are typically issued for general areas such as at county or district level, and Fig. 9.1 shows an example for which the core part of the message reads:

> Doppler radar showed a new area of heavier rain moving northward into the region. This may only aggravate existing flash and flash flood problems. The heaviest rains are likely to occur during the late morning hours. A continuation of flooding of streams … creeks … urban and poor drainage areas is likely in and near these locations.

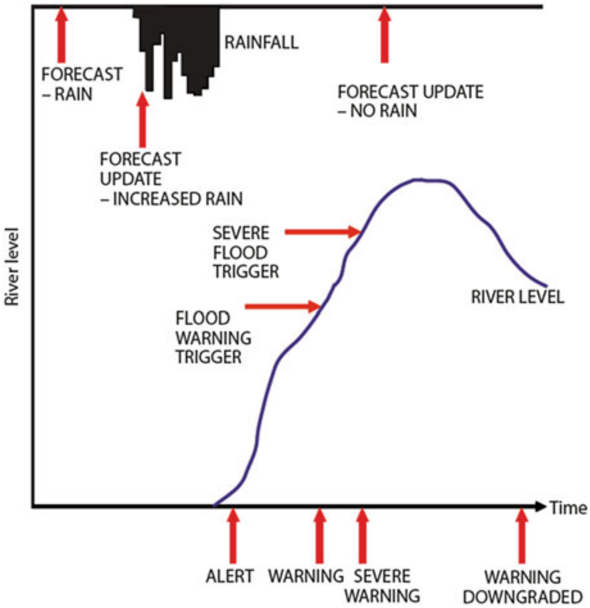
However sometimes it is possible to offer a more targeted service and, as for riverine floods, a staged approach is normally used to issuing warnings as illustrated in Fig. 9.2. Although the terminology differs widely between organisations, the first stage of alert is often based on rainfall forecasts or observations. However, given the uncertainties in the likely flooding impacts, as above this usually only specifies the general area likely to be affected. Some typical activities at this stage could include


National Oceanic and Atmospheric Administration's
National Weather Service

Headline: CHEMUNG: FLASH FLOOD WARNING UNTIL 09/08 02:30PM http://www.nyalert.gov/?q=3491352
Activation Time: 09/08/11 8:27 AM
Expiration Time: 09/08/11 2:30 PM
Issued By: NWS1_1
Affected Jurisdictions: Chemung County (All)
Description:
The National Weather Service In Binghamton Has Continued The * Flash Flood Warning For... Broome County In Central New York... Chemung County In Central New York... Chenango County In Central New York... Cortland County In Central New York... Otsego County In Central New York... Tioga County In Central New York... Bradford County In Northeast Pennsylvania... Susquehanna County In Northeast Pennsylvania... Wyoming County In Northeast Pennsylvania... * Until 230 PM EDT Thursday * At 819 AM EDT...National Weather Service Doppler Radar Showed A New Area Of Heavier Rain Moving Northward Into The Region. This May Only Aggravate Existing Flood And Flash Flood Problems. The Heaviest Rains Are Likely To Occur During The Late Morning Hours. A Continuation Of Flooding Of Streams...Creeks...Urban...And Poor Drainage Areas Is Likely In And Near These Locations. When You Can Do So Safely...Please Report Flooding To The National Weather Service By Calling Toll Free At 1-877-633-6772...Or By Email At Bgm.Stormreport@Noaa.Gov. Do Not Drive Your Vehicle Into Areas Where The Water Covers The Roadway. The Water Depth May Be Too Great To Allow Your Car To Cross Safely. Move To Higher Ground.
Instructions: Please stay tuned to your local radio or TV Station for more information.

Fig. 9.1 Example of a flash flood warning issued for Chemung County by the NOAA/National Weather Service in September 2011 during Tropical Storm Lee. This copy of the message was displayed on the New York State All-Hazards Alert and Notification web-based portal, which can also provide alerts by cell phone, email, Twitter ® and other technologies http://www.nyalert.gov/

Fig. 9.2 Flood forecasting and warning schematic (WMO 2011a, courtesy of WMO)



preparatory actions such as activating response plans, discussing the situation with emergency responders and starting more frequent monitoring of river levels. More location-specific warnings are then issued if predefined threshold values are reached, with a warning downgrade message issued once the threat has passed.

In some cases the responsibility for issuing warnings is shared between national authorities and the communities likely to be affected, and community-based schemes often play an important role as discussed in Box 9.1. However, the organisational requirements are similar to those discussed in Chaps. 1 and 8 for riverine floods and include the need to develop response plans, identify vulnerable groups, raise public awareness of the risks and perform regular drills or simulation exercises. In particular, the legal status and mandates for issuing warnings and responding to flood emergencies need to be defined together with funding arrangements.

Box 9.1: Community-Based Flood Warning Systems
Due to the speed with which flash floods develop, there is often a greater need for self-reliance at a community level than during riverine floods. Community-based flood warning systems therefore have an important role to play as a complement to a regional or national flood warning service, and some typical abbreviations include:

- CBFFWS – Community-Based Flood Forecasting and Warning System (WMO 2008b)
- LFWS – Local Flood Warning System (NOAA 2010)

National meteorological and hydrological services often provide technical support in establishing these types of schemes and usually there is a two-way flow of information during a flood event, benefitting all parties. For example, following the Colorado floods of 2013 (see Table 9.1), one conclusion regarding local observation networks (Gochis et al. 2014) was that:

> It cannot be overemphasized how much more dangerous this event would likely have been to the population without the information from these instrument networks feeding into local forecast offices, emergency response agencies, the media and the public alike, particularly in remote mountain locations.

Perhaps the most widespread use of this approach is in the USA (USACE 1996; FEMA 2006, 2014; NOAA/NWS 2012a). Although not always established specifically for flash floods, that is often a focus, and some essential elements can include (Hall 1981):

- Volunteer rainfall and stream gauge observers
- A reliable and rapid local communication system with emergency backup
- A flash flood warning coordinator and alternative
- Forecast procedures
- A warning dissemination plan
- An adequate preparedness plan (including public education)

In the early days, observations were typically made manually and relayed to a local operations centre by phone or radio. Whilst that approach is still sometimes used, the latest systems typically include locally operated networks of automated gauges which in many cases make use of the ALERT and

(continued)

Box 9.1 (continued)
IFLOWS telemetry protocols that are described in Chaps. 2 and 3. When there is a flood threat, notification is typically provided to state departments, city mayors, community leaders and local radio and television stations, amongst others. In particular the needs of groups such as tourists, hikers, and campers need to be taken into account. Simple forecasting techniques are also widely used, such as rainfall depth-duration thresholds and correlation models; for example, in the form of paper-based charts or look-up tables.

Schemes are typically managed at city or county level with additional funding from local communities and businesses, who can also qualify for reduced insurance premiums under the Community Rating System (CRS) within the National Flood Insurance Program (FEMA 2006, 2014). Here the qualifying elements fall into the general categories of public information activities, mapping and regulations, flood damage reduction activities, and warning and response. Accreditation to the NOAA 'StormReady' programme is another option for which the requirements include developing a response plan and establishing methods to gather data and disseminate warnings and a range of community-level preparedness activities, such as emergency response drills; this includes establishing a 24-h warning point and – for larger communities – an emergency operations centre (http://www.stormready.noaa.gov).

Whilst the insurance aspects are perhaps unique to the USA, this general approach has long been used in some other countries, such as Australia. Indeed there are an increasing number of applications worldwide (e.g. IFRC 2012, WMO 2012) such as well-established programmes in the Philippines and Mozambique. Typically these types of scheme are established in partnership with non-governmental organisations as well as the national authorities. Monitoring techniques are normally adapted to local budgets and cultures, ranging from manually based approaches to cell- or radio-based telemetry systems.

For disaster risk managers, cell phones and hand-held radios are probably the most common approaches to voice communications during emergencies, although with the caveat that networks sometimes become overloaded during flood events due to the high volume of calls and cell towers may be affected by storm or flood damage. In particular flash flood prone areas are often in mountain valleys with possible cell phone and radio coverage issues. At village level, some typical approaches to issuing warnings include megaphones, sirens, cell phones, community-based radio stations and more traditional techniques such as church bells and messengers. Local disaster risk management committees usually play a central role in operating these types of systems in collaboration with national agencies and non-governmental organisations. In many cases duties extend to search and rescue and helping with evacuation of properties, and post-flood surveys, running emergency response exercises, and reporting on system performance.

Fig. 9.3 Temporary barriers on display at an exhibition in the UK (*left*) and a flood closure gate in a levee system in the USA (*right*) (Adapted from Sene 2013)

When a warning is received, in principle many of the actions outlined in Chap. 8 could be taken, such as flood-fighting and evacuation of areas at risk. However, for flash floods what is realistic is constrained by the shorter time available. For example, closing a flood gate might be easily achievable but installing a demountable barrier less feasible (e.g. Fig. 9.3). However, in practice what is possible depends on a wide range of factors including the effectiveness of monitoring, forecasting and warning procedures and the level of preparedness in the communities likely to be affected. Also in some cases it may be possible to extend warning lead times simply through streamlining operational procedures, as discussed in Chap. 8. The social aspects of response also need to be considered such as the extent to which individuals and organisations understand, trust and act upon warnings (e.g. Drabek 2000, Parker et al. 2009; Morss et al. 2015).

Chapters 1, 7 and 8 provide some further information on these wider aspects of disaster risk management, and it is also important to consider the physical setting when assessing lead-time requirements. For example, in a steep-sided river valley, people may be able to reach safer ground much more quickly than if the main risk is on flatter terrain, such as at the foot of a mountain range or a line of coastal hills.

The remainder of this chapter focusses on the technical aspects relating to forecasting flash floods. The discussion begins (Sect. 9.2) with a general introduction to forecasting techniques, and Sect. 9.3 then provides more detail for surface water floods, debris flows, ice jams and dam and levee failures. Further information can be found in guidelines such as those summarised in Table 9.2, and these typically consider both the technical and societal aspects of warning systems.

Table 9.2 Examples of guidelines on early warning systems for flash floods and related phenomena

Type	Country	Originator (reference)
General	International	World Meteorological Organisation (WMO 2011a)
		WMO/GWP Associated Programme on Flood Management Technical Document No. 16 (WMO 2012)
		University Corporation for Atmospheric Research, Denver (NOAA 2010)
	USA	Federal Emergency Management Agency (FEMA 2006, 2014)
Debris flows	Australia	Australian Emergency Manuals Series, Attorney General's Department (Australian Government 2001)
	Japan	Ministry of Land, Infrastructure, Transport and Tourism (MLIT 2007)
	International	World Meteorological Organisation (WMO 2011b)
Surface Water flooding	International	WMO/GWP Associated Programme on Flood Management, Technical Document No. 11 (WMO 2008a)
	International	UNESCO-IHP urban water series (UNESCO 2007)
Dam break	Australia	Australian Emergency Manuals Series, Attorney General's Department (Australian Government 2009)
	USA	Federal Emergency Management Agency (FEMA 2004, updated in 2013)

9.2 Forecasting Techniques

9.2.1 Flash Flood Risk

Flood hazard mapping is an important aspect of flood risk management, and applications include developing maps to include in emergency response plans, defining flood warning zones, generating lists of subscribers for use with automated warning systems and assessing the flood risk for proposed new developments.

For high-risk areas alongside large rivers, a typical approach is to use one-dimensional (1D) hydrodynamic models or combined 1D/2D models for the river channel and floodplain of the types described in Chap. 5. When combined with hydrological models, this allows peak flows to be assessed in probabilistic terms such as for a range of return periods or annual exceedance probabilities. Where budgets allow, high-resolution laser (LiDAR) survey data – based on overflights by aircraft or helicopter – is generally the preferred way to represent the topography of the floodplain, and sub-models for stormwater drainage networks are sometimes included where relevant. Models are normally validated using a combination of feedback from local experts and evidence of flood depths and extent from previous flood events.

If there is a known flood risk and sufficient budget available, this approach is also used for flash flood-prone locations, provided that the hydrological aspects are understood. However, a common situation is that there are many locations potentially at risk, each with a significant risk of loss of life but in many cases with no recent history of flash flooding. To help to prioritise improvements, the need then arises for simpler approaches which can be applied on a wider scale. As for riverine floods some possible approaches include:

- Anecdotal evidence – discussions with local residents, hydrometric staff, local authorities and others with experience of dealing with flooding issues in a region
- Flood reports – literature searches for scientific papers, newspaper reports, post event reports and other sources which provide information on previous flood events, such as satellite imagery and aerial photographs (if available)
- Site visits – walkover visits by flood experts to assess possible flooding mechanisms and look for evidence of past flooding, such as high-water marks on buildings or flood markers inscribed on bridges

Of course, when considering evidence from previous floods, account needs to be taken of any subsequent changes which might have occurred both locally – such as building flood defences – or at a catchment scale, such as dam construction.

Another option is to search for linkages between the extent of flooding and factors which are thought to increase the flood risk (e.g. Collier 2007; NOAA 2010). Table 9.3 shows some examples of potential indicators, depending on the application. The degree of influence is usually expressed using user-defined indices, such as values on a scale from 0 to 1. These are then combined using weighting factors to

Table 9.3 Some examples of potential indicators for use in flash flood risk assessments, in addition to the catchment area

Category	Description
Catchment response times	Estimates for the typical time delay between the heaviest rainfall and peak flows based on historical data and/or unit hydrograph techniques
Channel characteristics	Factors expressing the influences of sedimentation on channel-carrying capacity, which is a serious issue in many countries due to catchment degradation, plus other issues such as seasonal vegetation growth (if relevant)
Hydraulic structures	Factors indicating the potential for bridges, culverts, weirs and other features of the built environment to impede the passage of high flows and/or trap debris
Infiltration	Estimates or indices for the likely infiltration rates in river channels following dry periods and indicators linked to infiltration capacity; for example, for soils that are compacted or dried to a crust and have little capacity to absorb heavy rainfall. These factors are particularly important in arid and semiarid regions
Land use	Percentage values based on spatial coverages of land-use types including farmland, forests, grasslands and urban areas
Slope	A key factor affecting velocities and catchment response times and the erosive potential of flows
Soil types	Spatial coverages of indices for soil types such as clays, sands, loam and other categories, which all have different runoff responses to rainfall
Snowmelt	Factors expressing the risks of sudden increases in river depths and flows from snowmelt following a sudden rise in air temperature and/or heavy rainfall falling on snowpack

Adapted from Sene (2013)

derive an overall index or by using multiple regression relationships. If possible the resulting maps should then be improved using feedback from local experts.

In the USA some regional forecasting centres derive maps of flash flood risk using this approach, based on factors such as slope, soil type, forest cover and land use (e.g. NOAA 2010). The resulting Flash Flood Potential Index values are mapped on a gridded or sub-basin scale. Similarly for debris flows the US Geological Survey routinely produces hazard maps of debris flow risk following major wildfires. These are typically based on factors such as the burned area extent, soil properties and basin gradient for a range of possible rainfall depth-duration values (Cannon et al. 2010).

9.2.2 Site-Specific Warnings

On large rivers, flood warnings are normally issued once critical values are exceeded at river gauges at or near locations at risk and at sites further upstream. Flow routing models are often used to estimate how the flood is likely to propagate between gauges, in some cases combined with rainfall-runoff models to further extend forecast lead times. Chapters 5 and 8 describe several examples of this approach.

This site-specific or local flood warning approach is also an option for flash flood-prone catchments if there is a known flood risk and the skills and budgets are available to implement and operate the system. Warnings can be issued on the basis of observations alone, as in many community-based systems, or with additional information from a forecasting model. However, if a model is to be developed, then given the smaller catchment sizes, there is usually a greater emphasis on rainfall-runoff modelling techniques than in larger catchments; indeed in some cases this might consist of just a single river gauge at or near the site of interest and a lumped catchment model to forecast flows at that location, as illustrated in Fig. 9.4.

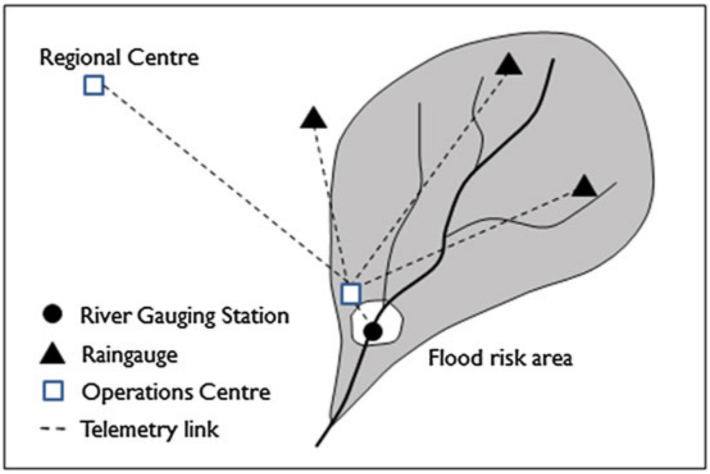


Fig. 9.4 Simple example of a flash flood warning system telemetry network

With this approach the rainfall inputs are typically based on raingauge observations and/or weather radar data, often combined with ensemble rainfall forecast inputs to further extend forecast lead times. Satellite precipitation estimates, in comparison, are usually at too coarse a spatial and temporal resolution to be suitable. When raingauge inputs are used, ideally the gauges would be within the catchment area although nearby gauges are potentially useful if they experience a similar rainfall regime, particularly if located at high elevations, comparable to those in the headwaters of the catchment.

At forecasting point(s) data assimilation is particularly important given the many uncertainties in the runoff response, if possible combined with probabilistic techniques. Given the speed of response, river gauges may need to be polled at more frequent intervals than on larger rivers, such as every 5 or 15 min. If snowmelt is an issue, then air temperature observations and forecasts are normally required.

Chapters 5 and 8 discuss this general approach in more detail and system resilience is again an important factor to consider such as designating alternate gauges to use if the primary gauge(s) fail and providing simpler paper-based forecasting procedures at a backup. To make best use of observations and forecasts, well-rehearsed, documented procedures need to be in place to issue and respond to warnings, including community response and other contingency plans (e.g. WMO 2011a). Rapid warning dissemination techniques provide another way to potentially give more time for the response, such as multimedia systems, traffic alert messages on car radios, automated dialling systems and remotely activated sirens.

Automatically triggered alerting systems provide another possibility for low-risk applications if there are suitable backup procedures in place in case they fail; examples include warning lights, electronic signs and barriers and these are sometimes placed at road low-water crossings (fords) and at the start of hiking trails in canyons and along riverside footpaths and parks. There are also various options available for end users to receive automated alerts from telemetry networks when critical levels are exceeded, either via direct transmission from the gauge modem or via a centrally operated web server; however, as discussed in Chaps. 3 and 7, this is normally for information only and users must decide how to interpret the information provided. More generally there may be scope to reduce some of the time delays in the warning process simply through procedural changes, and some examples discussed in Chap. 8 include reducing the times taken to receive data, run models and evaluate the flood threat.

In addition to cost and the level of risk, some key factors in deciding whether to implement a site-specific system include catchment response times, warning lead-time requirements and data availability. Chapter 5 discusses these issues in more detail together with the need for routine performance monitoring once a system is in place. However, as noted in Box 9.1, if budgets are an issue, simpler approaches based on manually observed gauges and simple forecasting techniques provide another option if this would provide the required performance.

9.2.3 *Heavy Rainfall Warnings*

Warnings of heavy rainfall are widely used to provide an initial alert or 'heads up' of flooding potential and as a first stage of alert in site-specific warning systems. Alerts are typically based on raingauge or weather radar observations and – in some cases – rainfall forecasts and/or satellite precipitation estimates. Since there is usually considerable uncertainty in the likely timing and locations of runoff, the main use is normally to trigger initial discussions and preparatory actions of the types described earlier. However, warnings are sometimes issued in situations where catchment antecedent conditions play less of a role such as in some semiarid or arid regions and debris flow and surface water flooding applications (see later).

The basis of the method is to estimate the depths of rainfall likely to cause flooding for a range of durations, such as the 1-, 2-, 3-, 6- and 12-h values. Normally these threshold values are based on a combination of past experience and analyses of historical rainfall and river flow data. Bayesian techniques also provide a way to consider additional factors such as stakeholder risk profiles (Martina et al. 2006). Values are normally site specific, and if sufficient observations are available for calibration then thresholds can be set so as to achieve a suitable balance between 'hit rates', lead times and the number of false alarms. Thresholds are sometimes linked to the likely severity of flooding, as shown by the example in Fig. 9.5 which, for illustration, assumes three levels of alert. Seasonally varying values are appropriate in some locations.

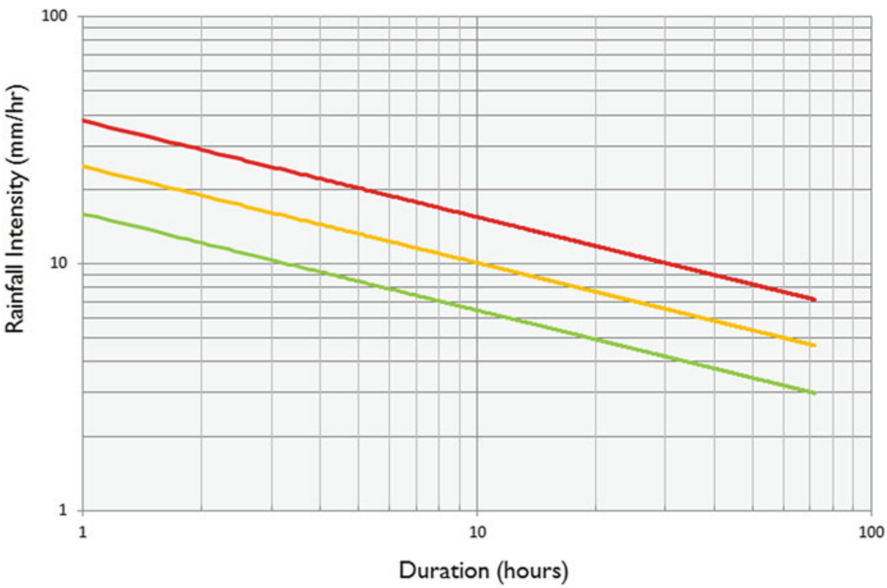


Fig. 9.5 Illustration of rainfall threshold values using three levels of alert; values are site specific and not applicable to other locations (Adapted from Sene 2013)

Operationally the crossing of threshold values is normally detected automatically within a telemetry or flood forecasting system or manually by referring to look-up tables or charts. An important point is that values should be calibrated using inputs from the same systems that will be used operationally so as to account for any bias and other uncertainties. This is usually straightforward for raingauge and weather radar observations if suitable archives are available but less so for rainfall forecasts; the main complicating factor being that an archive of reforecasts would be required from the current operational forecasting system (see Chap. 4).

However, the advantage of using rainfall forecasts is that this potentially provides more advance notice of a potential flood threat although at the expense of greater uncertainty, particularly at longer lead times. The use of ensemble forecasts and probabilistic thresholds therefore provides one way to help to take account of this uncertainty and to adopt more of a risk-based approach, combining probability and consequence (e.g. Koskinen et al. 2011). For example, in the UK the severe weather warnings issued by the Met Office are colour coded according to the combined likelihood and impact of an event. The level of alert is estimated using a weather impact matrix, as shown by the example in Fig. 9.6. In addition, warnings are qualified by the type of hazard for which the categories are rain, snow, wind, fog or ice or some combination of these variables.

More generally though it is worth noting that meteorological forecasters usually have access to a much wider range of information than just rainfall observations and forecasts, and Chap. 4 describes some examples. Regarding indicators of potential rainfall, these include observations of lightning activity and diagnostic outputs from numerical weather prediction models, radiosonde ascents and satellite observations such as the integrated precipitable water, lifted index, Convective Available Potential Energy (CAPE) and measures of wind shear and convergence.

In addition, the current catchment state needs to be considered as well, except possibly in some situations, such as arid regions. Some typical indicators of soil moisture conditions include the Soil Moisture Deficit, cumulative antecedent rainfall, Catchment Wetness Index, Baseflow Index or Antecedent Precipitation Index (e.g. USACE 1996, WMO 2009). This then leads to the use of threshold values based on a combination of rainfall amounts and indicators of catchment conditions.

In some cases these can be defined from observations alone; however, more usually off-line modelling studies are used to explore the combinations of rainfall, initial flows and soil states likely to lead to flooding. This type of approach is often used for ungauged catchments, and bank-full flows or flooding thresholds are normally assumed to occur for flows of a given return period, as estimated from long-term simulations using the model. For example, geomorphological studies of river processes typically suggest that out of bank flows occur for return periods of up to a few years (e.g. Leopold et al. 1995, Schneider et al. 2011), with values of 1–2 years typical. As for heavy rainfall warnings, other factors such as stakeholder perceptions and risk profiles have been considered in some studies (Martina and Todini 2009). This general approach also forms the basis of Flash Flood Guidance techniques, as discussed in Box 9.2.

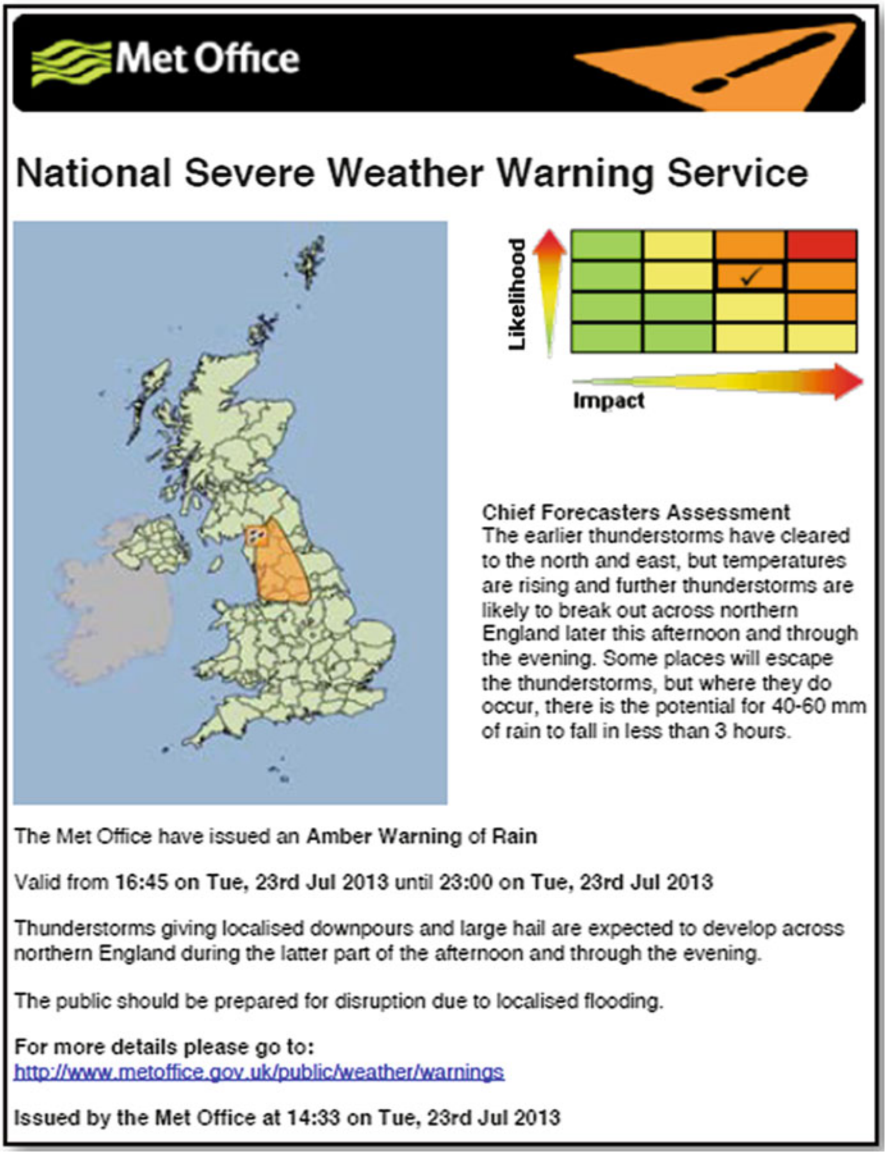


Fig. 9.6 Example of a severe weather warning in email format for emergency responders (Met Office 2015; Contains public sector information licensed under the Open Government Licence v1.0)

Box 9.2: Flash Flood Guidance

Flash flood guidance methods provide another option for taking account of both rainfall and catchment conditions when issuing alerts. The technique is generally used to provide a basic warning service for locations along smaller streams and rivers without a site-specific service. It was first developed in the USA in the 1970s and has since been applied in several countries (e.g. Norbiato et al. 2009); in particular as part of the WMO Global Flash Flood Guidance Project for which there have been several regional implementations (e.g. NOAA 2010; De Coning and Poolman 2011).

Flash Flood Guidance is defined as '…the average rain needed over an area during a specified period of time to initiate flooding on small streams in an area' (Sweeney 1992), and Table 9.4 summarises the main components in the approach. The guidance of a given duration is then the estimated amount of rainfall required under current catchment conditions for the runoff to reach threshold values, which are typically based on return period values such as the 1-in-2-year flood.

Operationally, observed and forecast rainfall values of different durations are compared with the corresponding guidance values to assess the flood threat. A Flash Flood Threat is also calculated which is the amount of rainfall above the guidance values and so gives an indication of the potential for flows that exceed bank-full values. Figure 9.7 shows an example of some of the types of outputs available.

Various permutations of this basic approach have been developed by different forecasting offices depending on factors such as local flooding

Table 9.4 Some key components in the Flash Flood Guidance approach

Item	Description
Input rainfall	Observed values from weather radar, satellite or multisensor precipitation estimates and/or rainfall forecasts
Soil moisture estimates	Values estimated from a regional or basin-wide operational forecasting model; for example, the Sacramento Soil Moisture Accounting (SAC-SMA) conceptual rainfall-runoff model is widely used in the USA (Burnash 1995) and distributed rainfall-runoff models are increasingly used (e.g. Schmidt et al. 2007, Koren et al. 2004)
Threshold runoff values	Estimates for the runoff that would cause a small stream at the catchment outlet to slightly exceed bank-full levels for a given starting soil moisture state
Rainfall-runoff curves	Curves showing the amount of rainfall needed to cause threshold runoff values to be exceeded for a range of durations, such as 1, 3, 6, 12 and 24 h, based on recent estimates for the catchment conditions and updated on a regular basis
Decision-support tools	A suite of post-processing tools to assist forecasters with interpreting the outputs, including map-based displays at sub-basin scale

Adapted from Sene (2013)

(continued)

Box 9.2 (continued)

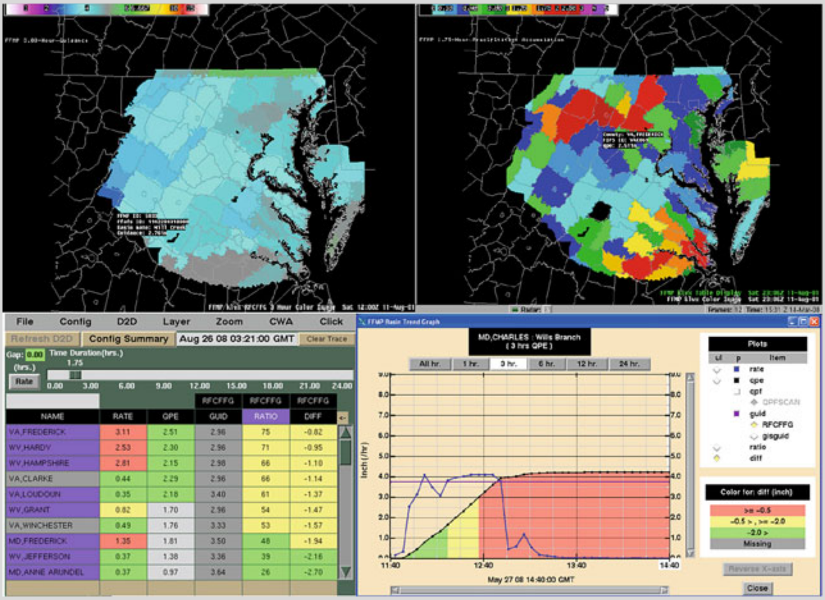


Fig. 9.7 Examples of some of the outputs available in the NOAA/National Weather Service Flash Flood Monitoring and Prediction system (for various locations, durations and time periods): Flash Flood Guidance map, Precipitation Accumulation map, Basin Trend graph, Basin Table output (NOAA/NWS 2008, check NOAA websites for the latest formats and products)

mechanisms, the operational models in use and data availability, including grid-based approaches (e.g. NOAA/NWS 2003; Georgakakos 2006; Hong and Gourley 2014). The outputs are sometimes viewed in conjunction with Flash Flood Potential Index maps of the types discussed earlier. One active area for research is into techniques for verification of outputs (e.g. Gourley et al. 2013), and this topic is discussed further in the following section within the context of distributed rainfall-runoff models, which offer a number of potential advantages (e.g. Cosgrove and Clark 2012).

9.2.4 Distributed Rainfall-Runoff Models

Techniques such as heavy rainfall alarms have the advantage that they are easily applied, using manual procedures if necessary. As discussed, an additional refinement is to use thresholds which take account of the catchment state, and a logical next step – budgets permitting – is to use a distributed rainfall-runoff model to bring in more details of the catchment response, particularly for ungauged catchments. Models are often – although not always – grid based, and as discussed in Chap. 5 the two main approaches at the grid or sub-basin scale are:

- Physically-based approaches – which attempt to represent key catchment processes, using differential equations with some conceptual aspects where that is not feasible
- Physical-conceptual models – which use networks of interconnected stores to represent surface runoff and other aspects of the hydrological cycle

Physically-based models are often too complex to use in real time although are valuable tools for research into catchment processes. Physical-conceptual models on the other hand are increasingly used to provide an indication of flooding potential at a regional scale, and two typical applications are:

- Medium- to long-range forecasts in large river basins, using ensemble rainfall forecasts as inputs for lead times of up to 3–15 days
- Short- to medium-range indications of flash flood potential based on rainfall observations and deterministic and/or ensemble rainfall forecasts

The first application is most relevant to slower-responding riverine flooding of the type described in Chap. 8, but the basic rainfall-runoff modelling approaches are similar in both cases. However, one key difference is often that the runoff between grid squares or sub-basins needs to be included when considering large river basins, whilst in some flash flood applications, it is sometimes useful to consider locally generated runoff; for example regarding localized rainfall and small streams and creeks (e.g. Cosgrove and Clark 2012). The latest modelling systems often include this choice as a modelling option together with a range of optional additional components to represent features such as reservoirs, lakes and wetlands.

The key inputs are typically spatially averaged raingauge data, or weather radar observations or raingauge-adjusted radar outputs. Some examples specific to flash floods include those described by Javelle et al. (2010, 2012), Cosgrove and Clark (2012) and Younis et al. (2008); these are from France, the USA and at a Europe-wide scale, respectively. Chapters 5 and 8 discuss further examples where the focus is at a larger scale and/or longer lead times. Some models are also developed for specific types of hydrological response such as in arid and semiarid regions (e.g. Yatheendradas et al. 2008) and for surface water flooding issues (see Box 9.3). Another novel application has been use of a distributed model to help with providing an early warning service for a regional road network (Versini et al. 2010; Naulin et al. 2013). Here, locations potentially at risk are identified using a digital terrain model with the distributed rainfall-runoff model operated at a grid scale of 1 km^2 every 15 min.

As discussed in Chap. 5, at the level of individual grids, the approaches used for runoff production are usually based on – or derived from – techniques developed for conceptual rainfall-runoff models. This provides continuous accounting for components such as the soil moisture storage and infiltration, evapotranspiration, recharge and runoff rates. If a routing component is included, this is often of the kinematic wave type. The outputs are typically displayed on maps at river reach or sub-basin scale, using colour coding to indicate the level of alert and accompanied by a range of tabulated and other outputs. As with other forecasting techniques, decisions need to be taken on how the forecast outputs will be integrated into operational procedures and the information conveyed to civil protection agencies and the public. The limitations in the results also need to be made clear if – as is often the case – forecast products are published automatically to a website.

To define threshold values, threshold-frequency approaches are widely used based on the outputs from model runs over a long calibration period (the so-called 'model climatology'). This has the advantage of accounting to some extent for any bias in the model results at ungauged sites (e.g. Reed et al. 2007). For reasons discussed earlier, flooding is usually assumed to occur for events with a return period of a few years such as the 1-in-2-year estimates. Normally it is possible to refine these values later based on experience with using the model and to take account of any catchment changes which occur, such as construction of reservoirs or flood defences. If using ensemble rainfall forecasts, then exceedance probabilities need to be defined, such as the 10 or 20 % values (see Chaps. 5 and 8). Some potential advantages that a distributed approach provides include (Cosgrove and Clark 2012):

- Quantitative estimates for the likely severity of flooding (not just binary occurrences)
- More flexibility in the grid scales used, with the option for flow routing between grid cells
- The option to include a snowmelt model, where appropriate
- The potential for more frequent updating of outputs

However, one of the challenges with all approaches is to verify the outputs since there is often little or no river flow data available in locations affected by flooding (e.g. Javelle et al. 2014). In the USA, for example, this has led to programmes being established to routinely collect and archive information on hail, wind, flash flood and tornado impacts both during and soon after events, for combination with information from US Geological Survey river gauges and National Weather Service Storm Reports (Gourley et al. 2012, 2013). In some cases this includes phoning residents in areas which have experienced heavy rainfall, as shown by weather radar data, or for which flood warnings have been issued. The types of questions asked relate to the lead time and accuracy of any warnings received and the depth and extent of flooding. Crowdsourcing techniques are also increasingly used; for example via smartphone applications and web interfaces.

More generally, performance is typically evaluated in terms of statistics such as the Probability of Detection and False Alarm Ratio. These measures consider whether a flood was predicted (or a warning wrongly issued) but not the timing or magnitude of the event. As discussed in Chaps. 4 and 5, for events with a small spatial scale such as flash floods, the focus is usually on whether an event occurred in the general area predicted, rather than its precise location. These types of results are useful both for routine reporting on system performance and to help with refining models and threshold values.

9.3 Selected Applications

9.3.1 Surface Water Flooding

When heavy rainfall occurs in an urban area, surface water normally drains into natural watercourses and stormwater drainage systems. However, floods often occur when drainage or pumping capacities are exceeded and other issues may arise such as impoundment of water behind flood defences. There is also the risk of event-specific factors such as blockages at culverts and in watercourses and reverse flows due to surcharging of drainage networks (e.g. Fig. 9.8).

This type of flooding is often called surface water or pluvial flooding and, in the latter case, this sometimes relates specifically to runoff before it enters the drainage network or watercourses. The onset is often rapid due to the small catchment areas and large expanses of impervious surfaces typical of urban areas. Large numbers of people can be affected as shown by the examples presented in Table 9.1 and there is sometimes a significant risk to life, particularly for vehicle drivers and in vulnerable locations such as underpasses, underground malls and building basements. In some cases snowmelt or river flooding exacerbate the impacts.

As for other types of flash floods, approaches to issuing warnings range from a largely community-based approach, relying on observations by local authorities and volunteers (e.g. FEMA 2005), to more centralised systems based around telemetry observations and rainfall forecasts. However, this is a developing area and the extent to which a warning service is offered varies widely between agencies, with river flooding often being a higher priority.

To provide an indication of flooding potential, rainfall alerts are widely used although due to the inherent uncertainties these are usually not specific regarding the locations likely to be affected. Depth-duration thresholds are normally either defined at a regional level or, if records are available, from analyses of past flood events in specific urban areas. Other criteria are sometimes included such as the cumulative rainfall in preceding days, thereby providing some allowance for the current capacity in the drainage network.

If ensemble rainfall forecasts are used then there is the option to define thresholds in probabilistic terms. For example for an experimental service in England and Wales which operated from 2009 to 2011 (Met Office/Environment Agency 2010; Hurford et al. 2011; Ochoa-Rodriguez et al. 2015) alerts were issued '…..when

Fig. 9.8 Illustration of culvert inlet with trash screens to trap debris (Sene 2013) and outflows at a manhole cover (Defra 2010 © Crown Copyright 2010) (Adapted from Sene 2013)

there is a 20 % or greater probability of the following thresholds being exceeded: 30 mm per hour, 40 mm in three hours or 50 mm in six hours'. The benefits of this service, which has since been developed further to take account of soil moisture, impacts and other factors, were foreseen to include:

- Impacts on road network, local transport and associated services minimised
- Local authorities and utility companies better informed to manage their response to surface water flooding
- Staff and resources deployed and managed more effectively
- Equipment, such as sandbags, mobilised and deployed in advance
- Communication teams better informed and prepared to handle media and public response

Box 9.3 decribes another option for use of ensemble rainfall forecasts, namely as inputs to a distributed rainfall-runoff model. For high-risk locations, if budgets allow there is the option to install additional instrumentation to assist with issuing warnings, and Table 9.5 provides examples of the types of sensors used in urban areas.

A typical scenario would be for observations to be relayed by telemetry to a centralised location, perhaps as frequently as every 1–2 min due to the speed at which events develop. Alerts and warnings are then issued based on threshold values or other criteria defined for each sensor. Due to the many uncertainties, decisions on the actions to take are normally taken by operational staff; however, automated alerts are sometimes used where the risks of a missed warning or a false alarm are not serious or as a 'last resort' backup in case all other warning mechanisms fail.

As indicated earlier, options include triggering warning signs and flashing lights along roads and footpaths and closing road barriers. Also many modern instrument systems have the capability to send alerts directly to mobile phones, although clear procedures need to be in place for making use of this information. Both of these approaches potentially provide a useful time saving when responding to fast developing situations; for example, if text messages are sent to operational staff working nearby, then some examples of actions which could be taken include clearing debris from drains and watercourses and closing access to areas at risk such as roads and car parks.

Table 9.5 Examples of types of instrumentation for real-time detection of factors which could lead to surface water flooding

Instrument	Description
Cameras	CCTV, webcam or other digital imaging equipment at locations prone to localised flooding or blockages such as at culverts, grills and trash screens
Differential pressure sensors	Pairs of sensors to monitor water levels or pressures upstream and downstream of structures prone to blockages by debris during high flows
Pressure transducers	Sensors installed in drainage channels and watercourses to detect water levels and sometimes in roadside drains
Raingauges	Tipping bucket, weighing, impact, hot plate or other types of gauge for rainfall observations
Ultrasonic sensors	Devices placed inside pipes and channels within the drainage network to record flow rates and velocities, plus downward-looking ultrasonic or radar devices to measure water levels in watercourses and channels

Regarding raingauges, due to the complexities of the runoff response, network densities generally need to be significantly higher than in more rural areas, which may not be financially or technically feasible. Weather radar therefore potentially plays a useful role if beam blockage is not an issue. For example, in Tokyo several X-band radars have been installed in and around the city to supplement the C-band radars in the national network to assist with providing warnings of surface water flooding, landslides and other natural hazards (Maki et al. 2010). A similar approach is used in Denmark (Pedersen et al. 2010) and is actively under consideration in some other countries (e.g. http://www.raingain.eu/; see Box 4.2 also). As discussed in Chap. 2 networks of phased array weather radars using agile sensing have the potential to revolutionise rainfall detection in urban areas in the future.

For operational use, it is useful to have maps or lists of properties, roads and critical infrastructure at risk. Some simple options include developing maps based on reports of flooding extent in previous events or spatial analyses in which an assumed volume of runoff is distributed over the ground surface, perhaps applying a factor to allow for sub-surface drainage. Hydrodynamic models provide another option and normally include considerable detail for both surface features and the sub-surface drainage network (e.g. Hunter et al. 2008, Maksimovi§ et al. 2009, Saul et al. 2011); for example, even apparently minor factors such as roadside kerbs sometimes influence flow paths. Usually the underlying digital elevation model is based on LiDAR survey information (e.g. Fig. 9.9), and resolutions of the order of 1 m horizontally and 0.1 m vertically are now achievable. Typically one- or two-dimensional models are used for the surface water component and integrated with detailed models for the drainage network incorporating pipes, valves and other key components. The

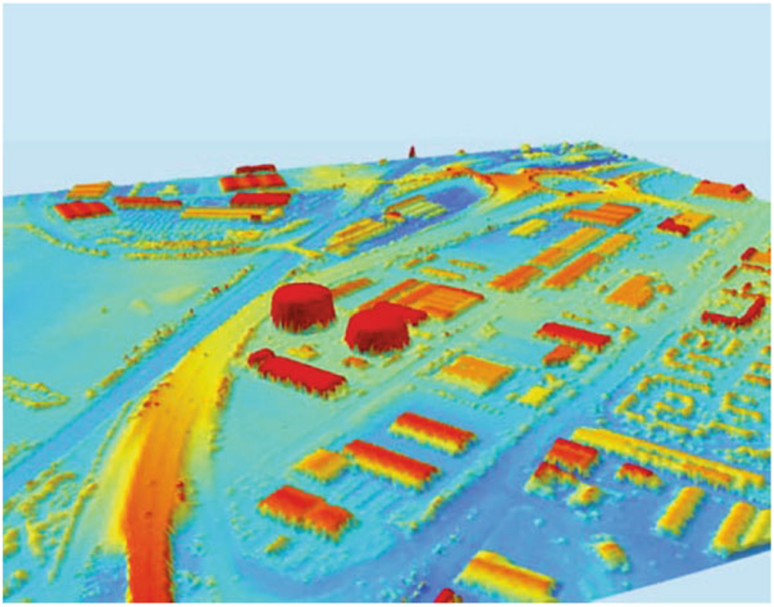


Fig. 9.9 A 3D view of an urban area based on LiDAR remote-sensing observations (Defra 2010 © Crown Copyright 2010)

surface and sub-surface interactions are then either represented dynamically by linking the models together or by using simplified representations such as assumptions regarding the fraction of surface flows which enters the drainage network.

For the future, models of this type provide a possible basis for real-time forecasting of runoff, and this is an active area for research, in combination with probabilistic techniques (e.g. Achleitner et al. 2008, Falconer et al. 2009, Schellart et al. 2011, Liguori et al. 2012). Much research is also underway into tools and techniques to help operate drainage systems in a more dynamic way to make better use of the capacity available as discussed further in Chap. 11.

Box 9.3: Surface Water Flood Forecasting in Scotland

In Scotland approximately one-third of the risk from flooding arises from surface water issues in towns and cities. To assist SEPA to develop its forecasting capability for surface water flooding, a pilot study was performed during the Commonwealth Games which were held in Glasgow in 2014. This drew on elements of the existing service (Cranston and Tavendale 2012; see Box 8.1 also) and was performed in collaboration with the Met Office, CEH Wallingford, Deltares and the James Hutton Institute.

The basis of the approach was to use ensemble rainfall forecasts as inputs to a distributed rainfall-runoff model (Cole and Moore 2009; Speight et al. 2015). The model was already in use for providing 5-day outlooks on flood risk (SEPA 2014) and for this pilot study was set up for a domain of 10 × 10 km using land cover, slope and other settings appropriate to an urban area. The grid scale used was 1 km and the rainfall forecasts provided by the Met Office consisted of a blended product combining ensemble nowcasts and numerical weather prediction model outputs. These consisted of 24-member 15-min rainfall accumulations at a 2 km grid scale for lead times of up to 32 h.

Figure 9.10 illustrates the risk-based process used for deciding whether to issue flood alerts. One novel feature was that to assess the flood risk, predefined pluvial flood maps and impact assessments were automatically selected from an archive based on the estimated runoff values. This approach avoided the need to use a real-time inundation mapping approach which is still a developing area for urban drainage networks. The map selection criterion used was to equate the surface runoff forecasts from the model with the 3-hourly effective rainfall inputs used in the mapping studies.

During the Games, surface water flood forecasts were issued on a daily basis to key responders. Bulletins were modelled on the Flood Guidance Statements issued as part of the wider flood warning service and included additional colour-coded maps showing the anticipated risks to people and property, roads and railways (e.g. Fig. 9.11). The pilot studies showed the potential for this approach together with some of the operational and technical issues to consider, and the methodology is now being considered for wider application in urban areas in Scotland.

(continued)

Box 9.3 (continued)

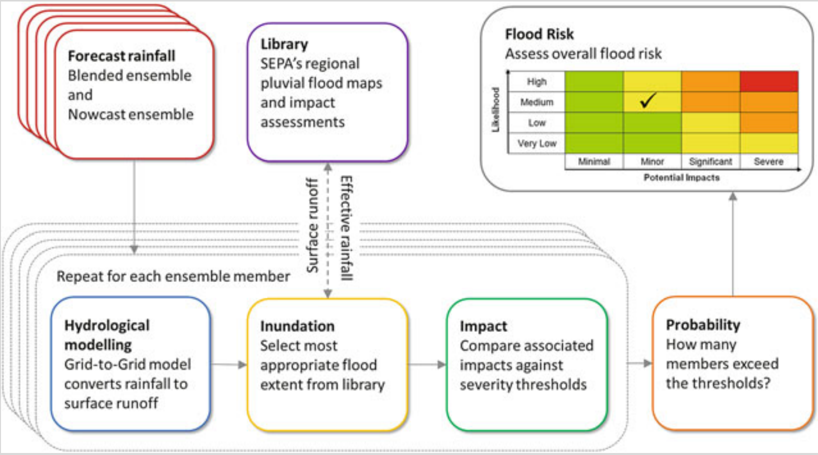


Fig. 9.10 Surface water forecasting methodology used in the pilot model (Speight et al. 2015) (contains SEPA data © Scottish Environment Protection Agency and database right 2014; SEPA 2014)

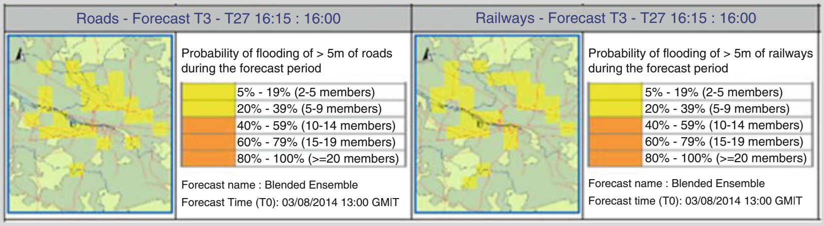


Fig. 9.11 Example of the map-based presentations in the guidance statements, showing just the roads and railways sections (Moore et al. 2015) (contains SEPA data © Scottish Environment Protection Agency and database right 2014; SEPA 2014)

9.3.2 *Debris Flows*

When soil and other material becomes mobilised by water, the resulting flow is usually called a debris flow. This type of flow has the potential to cause considerable damage to property and transport routes with a risk of loss of life; for example, flow velocities can exceed 10 ms^{-1} and flows carry boulders 10 m in diameter (Iverson 1997). Although flash floods in rivers usually contain debris, concentrations in debris flows tend to be higher, and there is often a distinct frontal wave or wall to the flow. Once the flow reaches a flatter area, it spreads out laterally and due to the reduction in velocity progressively deposits its contents. The resulting debris fans are characteristic features in the foothills of many mountain regions.

Some risk factors for the generation of debris flows include steep slopes, saturated soils and areas of fractured rock, plus issues such as deforestation, vegetation clearance and wild fire damage. Lahars, caused when volcanic deposits become mobilised by rainfall, are a closely related phenomenon. Debris flows are usually initiated by heavy rainfall although snowmelt is sometimes a factor and typically begin as shallow landslides or due to soil or bed erosion by overland or stream flows. Iverson (1997), Hungr et al. (2001) and Jakob (2010) amongst others provide a more detailed description of the mechanics of debris flows and the impacts that they cause.

Flash floods and debris flows often occur together in the same region and rainfall thresholds are perhaps the most widely used approach for deciding whether to issue warnings, and are normally based on raingauge, weather radar or, possibly, satellite observations. As for flash floods in rivers, threshold values are typically defined for a range of durations. Power-law relationships are widely used (e.g. Caine 1980, Wieczorek and Glade 2005, Guzzetti et al. 2008, WMO 2011b) and sometimes include auxiliary variables such as soil moisture, cumulative rainfall or snow water equivalent depth. In Japan, for example, grid-based values are used based on rainfall forecasts and soil moisture values estimated using a conceptual rainfall-runoff model (Osanai et al. 2010). In operational use, colour-coded maps are then produced for lead times of several hours ahead in increments of one hour, where the colours relate to four levels of alert.

Where there is a known risk then setting up a site-specific warning system may be justified. This potentially allows more precise warnings to be issued compared to rainfall alarms, although of course with less lead time for people to respond. As for flash flood warning systems, the various time delays in decision-making and issuing warnings need to be considered although, as noted earlier, even a few minutes of advance warning is useful in some situations, such as in steep-sided valleys. Some possible ways of rapidly disseminating warnings include remotely activated sirens, voice-broadcasting systems, barriers and flashing warning lights.

Table 9.6 shows some examples of the types of instrumentation which are used in this type of system (e.g. Fig. 9.12). Instruments are normally installed well above likely flow paths or beneath the ground surface due to the destructive nature of the flows. Addition of a data logger and modem then allows values to be recorded and transmitted to a central location.

Some examples of countries in which operational debris flow warning systems are installed include Canada (Jakob et al. 2011), Japan (Osanai et al. 2010), Switzerland (Badoux et al. 2009), Taiwan (Wu 2010) and the USA (Baum and Godt 2010).

If budgets are available a typical configuration is to place raingauges, soil moisture and pore-pressure sensors in potential flow initiation areas and cameras, geophones, pendulums, trip wires and downward-looking sensors along preferred flow pathways (e.g. Wieczorek and Glade 2005). Threshold values need to be defined individually for each observation system where appropriate, in some cases filtering out signals from causes other than debris flows, such as earth tremors or rock falls. Observations by staff and volunteer observers are usually another important factor

Table 9.6 Examples of the types of instrumentation which could be used for real-time detection of debris flows (e.g. La Husen 2005, Arattano and Marchi 2008)

Instrument	Description
Cameras	CCTV, webcam or other digital imaging equipment to view the passage of a debris flow
Geophones	Acoustic sensors placed in the bed of potential flow pathways to detect the vibrations caused by passage of a debris flow
Pendulums	Suspended wires with a weight on one end which move when hit by a debris flow and are connected to electronic sensors
Pore-pressure sensors	Transducers installed underground in potential flow initiation areas and/or along flow pathways
Soil moisture sensors	Capacitance, heat and other types of sensor installed in potential flow initiation areas
Trip wires or beams and sensors	Metal wires placed across possible flow paths carrying an electrical current which are broken as the flow passes or infrared or laser beams which are interrupted if a flow develops
Ultrasonic sensors	Downward-looking sensors placed on bridges or purpose-made frames above typical flow paths to detect passage of the flow from interruptions to the reflected signal, plus microwave (radar) or laser devices

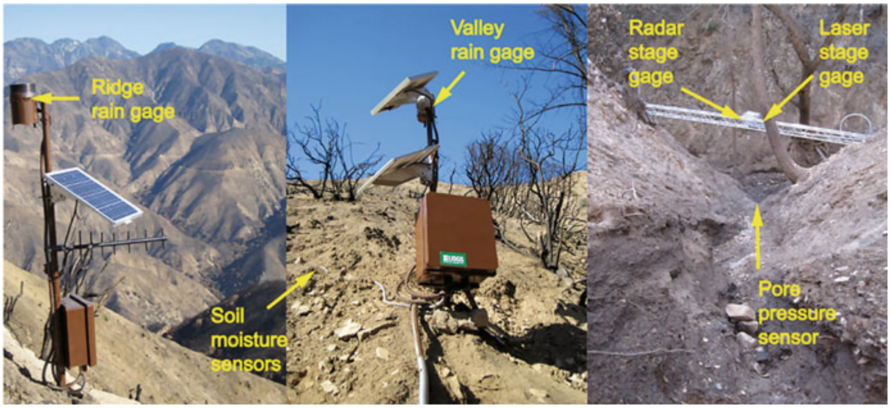


Fig. 9.12 Illustration of instruments installed by the US Geological Survey for monitoring flash floods and debris flows in a small basin in the Arroyo Seco canyon in California, which was one of many canyons affected in the 647 km^2 Station Fire of August and September 2009. Values are reported at 0.1–2 s intervals during rainfall (except for soil moisture readings) and at 1-min intervals otherwise for display on a publicly accessible website, using radio telemetry to the ridge raingauge location and then a cell phone modem (courtesy of the US Geological Survey; http://landslides.usgs.gov/)

particularly given the risk of debris blockages at bridges and other obstacles. However, compared to flash floods for rivers, flow forecasting techniques are less well advanced so are normally not used, except perhaps for simple regression approaches.

Hazard maps are normally prepared based on local expertise, geomorphological evidence and post-event survey data. Indeed in some countries, such as Switzerland, national services maintain databases of previous events and their impacts (e.g. Hilker et al. 2009). However, as for river flooding, hazard mapping models are increasingly used albeit with greater uncertainty in the results. The usual approach is to develop regression relationships between factors such as the mean slope, the deposition area, the debris volume and/or the runout distance, which is usually defined as the distance from the point of initiation of the flow to the centroid of the debris fan. Flow routing and hydrodynamic approaches are increasingly used for higher-risk locations, in some cases supported by high-resolution (LiDAR) topographic survey data (e.g. Dai et al. 2002, Coe et al. 2004, Rickenmann 2005, Hürlimann et al. 2008, Lopez and Courtel 2008).

9.3.3 Ice Jams

In some countries, river ice is a common occurrence during colder times of the year. The main cause of ice break-up is usually an increase in river flows although other factors such as increasing air and water temperatures and solar radiation effects sometimes play a role (e.g. Snorrason et al. 2000; Beltaos 1995, 2008). In some cases, a distinct moving front appears between the unbroken ice in front and the broken ice behind, much as with a debris flow. The resulting ice floes present a flood risk if they accumulate at bridges, river channel constrictions and other obstacles, and the two main causes of flooding are:

- Backwater influences from the ice jam causing river levels to rise at locations further upstream
- Rapid increases in river levels and flows at locations downstream if the ice jam clears or breaks up suddenly

If floods occur then the onset tends to be rapid, such as the event which occurred in Montpelier in the USA described in Table 9.1 (Fig. 9.13). Ice jam-related floods are therefore often considered as a type of flash flooding although it is worth noting that the ice jams themselves sometimes persist for days to weeks.

Along some rivers ice jams tend to occur at the same locations in most winters so allowing more detailed contingency plans to be put in place; for example, describing steps to evacuate areas at risk if an ice jam forms and steps to avoid one forming in the first place, such as blasting river ice so that it breaks up in a more controlled way. Other options which are sometimes available are to divert warmer discharged water from power station or industrial cooling water systems and/or to regulate reservoir outflows in a way which helps to prevent the build-up of ice.

To help predict where ice jams form, databases of previous occurrences are maintained by some organisations such as in the USA and Canada (e.g. White 2003) and simple statistical models are sometimes used (e.g. WMO 2009). If time permits then hydrodynamic modelling studies can help to better assess the risk and similar

Fig. 9.13 Ice jam in Montpelier, Vermont, 1992 (USACE 2009)

Table 9.7 Examples of some types of instrumentation for real-time detection of river ice and ice jams

Instrument	Description
Cameras	CCTV, webcam or other digital imaging equipment at locations prone to ice jam formation and for river ice further upstream
Ice-motion sensors	Temporary sensors such as wires installed in river ice and connected to an electrical supply which generate a signal if the ice moves
River gauges	Gauges placed upstream of locations at risk to detect sudden increases in river levels and further downstream in case an ice jam breaks up
Temperature sensors	Thermocouples installed to detect sudden increases in air or water temperatures

approaches are used to those discussed in Chaps. 5 and 8. However, additional modelling components are required to represent the flow constrictions caused by the ice jam and river ice (e.g. Morse and Hicks 2005, Tang and Beltaos 2008). Modelling ice jam break-ups though remains an area for research due to the combination of mechanical, thermal and hydraulic processes involved (e.g. Carson et al. 2011).

Table 9.7 summarises some of the monitoring techniques which are used to help with providing warnings for the flood risk from ice jams. If suitable threshold values are defined, this allows alerts to be provided to the emergency services and others (e.g. Williams and White 2003). In some systems flow forecasting model outputs and rainfall and air temperature forecasts are used to help decide whether to issue an initial alert regarding the potential for river ice break up. Satellite observations and feedback from local observers play an increasingly important role, in some cases combined with reports from aircraft flights such as in the RiverWatch programme in Alaska (NOAA/NWS 2012b).

9.3.4 Dam Breaks and Levee Failures

Although fortunately it is a rare occurrence, when a dam fails the resulting floodwaters have the potential to reach great depths and inundate large areas further downstream. Similar issues arise if a flood defence is breached. Due to the speed with which flows develop, floods of this type are often classified as flash floods.

For dams, some typical causes of failure include external factors such as earthquakes and more local issues such as settlement, defects in the foundations or structure, and problems where the dam wall joins surrounding rock. The precise mechanisms depend on the construction materials used and these include masonry, rock fill and concrete, plus earth embankments for smaller structures such as farm dams. Signs of potential problems can become apparent during routine inspections or develop more suddenly, in some cases with little or no warning.

Some well-known dam breaks include the failure of the Malpasset Dam in France which resulted from defects at one of the dam wall abutments (Delatte 2009) and the Johnstown flood of 1889 (Fig. 9.14; Table 9.1) which resulted from an accumulation of maintenance issues. There is also the risk from landslides or debris flows into the reservoir causing a sudden flood wave which overtops the dam wall, such as

Fig. 9.14 Artists' impression of the South Fork Dam as it appeared when newly constructed and during the breach of 1889 (*left*); peak flood levels marked on a corner of the city hall in Johnstown; the highest mark (at 21 ft) was from the 1889 flood, whilst the lower marks relate to river floods (*right*) (Art by L. Kenneth Townsend, http://www.shadedrelief.com/, Patterson 2005) (Adapted from Sene 2013)

occurred at Vaiont Dam in Italy in 1963 causing catastrophic losses further downstream (Graham 2000). In the case of the Johnstown flood, the peak outflows were estimated to be about 12,000 m^3s^{-1} (Ward 2011), whilst the Malpasset and Vaiont Dam events led to flood depths of tens of metres further downstream.

In mountain areas such as the Himalaya and Andes, temporary dams resulting from landslides, glacier recession and volcanic activity sometimes present a risk as illustrated by the example from Peru shown in Table 9.1. The resulting floods if these barriers fail are called Glacial Lake Outburst Floods (or GLOFs) or – in Iceland – Jökulhlaups, which are linked to geothermal and volcanic activity (e.g. Costa and Schuster 1988; Snorrason et al. 2000; Ives et al. 2010). In the Himalaya, for example, it is estimated that flows of 30,000 m^3s^{-1} have occurred in the past affecting areas 200 km or more downstream (Richardson and Reynolds 2000).

Regarding flood defences, these are a common feature in urban areas and often protect large numbers of properties from flooding. Some alternative names include levees or dikes. Typically defences are designed so that the crest height corresponds to a given estimated annual exceedance probability or return period of flooding, plus a safety margin, often called the freeboard. Similar construction materials are used as for dam walls, with concrete and masonry structures common in towns and cities and earth embankments in rural areas to protect agricultural land. There are many potential failure mechanisms including erosion following overtopping, impact damage from flood debris and issues relating to the initial design or subsequent maintenance. For example, some common issues with earth embankments include damage due to vegetation growth and erosion of bank tops due to uncontrolled access by vehicles and pedestrians.

For dams and – to a lesser extent – flood defences, there is often a legal requirement to develop emergency response plans in case of failure including inundation and evacuation maps. Typically hydrodynamic models are used to help assess the risk, based on satellite-derived ground elevations or LiDAR data. For dams, statistical and probabilistic techniques are often used to assess the potential loss of life (e.g. Needham 2010), and bathymetric survey is sometimes commissioned as part of risk assessments to check if the reservoir capacity has been affected by sedimentation since the dam was built.

However, providing a warning service for dam breaks or defence breaches is normally a challenge due to a combination of both technical and social issues. For example, failure may arise from a complex combination of hydraulic, hydrological, structural and geotechnical factors, whilst some social challenges include the need to convince people of the risk and to maintain public awareness over the long term. Nevertheless, many flood warning services have procedures for dealing with the threat of breaches and in some cases offer a site-specific service for high-risk locations, particularly when construction works are in progress.

Perhaps the simplest approach of all is to offer just a responsive service; for example, if operational staff report potential problems. Additional staff can then be deployed on site, civil protection agencies informed, response plans activated and monitoring intensified. Inundation and evacuation maps may already be available for the site, but, if time allows, hydrodynamic modelling studies are often performed to better assess the risk. Some examples of features which are typically shown on maps include areas of safe ground, shelters, bridges and roads at risk, evacuation routes and the locations of vulnerable groups who require particular assistance.

If flooding seems likely then in addition to warning the public some typical types of response include closing roads and railway lines, controlled shutdown of equipment (e.g. at power stations or factories) and evacuating areas at risk. In some cases it is possible to reduce the risk of flooding; for example, by emergency drawdown of reservoir levels or reinforcing weak points in an embankment. However, there are sometimes difficult decisions to take such as balancing the need to reduce reservoir levels with the increased flood risk that the flow releases might cause to areas further downstream. For moraine dams, other options include controlled breaches to reduce water levels and measures to stabilise the ice core.

Table 9.8 illustrates some of the technical options for more detailed monitoring either manually on site or – in some cases – via automated equipment and a telemetry link. Typically warning criteria or thresholds are defined either individually or in combination for a range of sensors. For example, in addition to rainfall and river and reservoir level thresholds, this can include triggers for issues such as earthquake occurrence, seepage flow, seepage turbidity, deformation and cracking, controls malfunction (flood gates and valves), controlled failures (fuse plugs) and hillside instability (Australian Government 2009).

Sirens are a common approach to issuing warnings for dam or defence failures in combination with a range of other techniques, of the types discussed in Chap. 7. Due to the short time available, if a breach occurs, operational procedures may

Table 9.8 Examples of some types of instrumentation for real-time detection of the risks of flooding due to dam and flood defence failures

Item	Description
Embankments and dam walls	Instrumentation to record movement, deformation and – for earth embankments – soil moisture and pore pressures, including accelerometers, crack monitors, extensometers, inclinometers, piezometers, pressure cells, pressure transducers, pendulums, seismometers, strain gauges, tensiometers, thermistors, tiltmeters and time-domain reflectometry equipment. One newer approach is to use fibre optic cables for monitoring movement and infiltration in structures over many hundreds of metres or more
Survey and remote sensing	Remote sensing by satellite or aircraft, particularly for Glacial Lake Outburst Flood risks; ground-based observations by camera, video and thermal imaging; and survey of crest levels and other areas using continuous GPS, marker lights placed along the crest and laser or ultrasonic ranging. Some of the techniques discussed in Sect. 9.3.2 provide additional options if landslides or debris flows are a consideration
River and reservoir levels	Monitoring using float in stilling well, pressure transducer, bubbler, ultrasonic or radar gauges (see Chap. 3), float switches and sump, drain and borehole level monitoring. For example, for a reservoir, some typical locations for installing level gauges are close to the spillway crest, on tributary inflows and in the area immediately downstream of the dam

Adapted from Sene (2013)

allow dam operators and local civil protection staff to issue warnings directly to local populations.

Flood forecasting outputs would also be useful to help to extend the warning lead times available due to a structural failure, but this is a developing area, although river forecasting models can provide indications of the risk of river levels overtopping defences, perhaps with the addition of a more detailed reservoir model when considering dam-related risks. In some cases predefined breach scenarios are prepared in case of failure for use in 'what-if' model runs.

For a more tailored approach then details of the actual or estimated size and shape of the breach would need to be available in near real time. For off-line planning typically a simple weir equation is used based on the assumed depth, width and shape of the breach; however, development of more dynamic approaches – for example, forecasting how an initial structural weakness might evolve over time – remains an active area for research (e.g. Morris et al. 2008; de Wrachien and Mambretti 2009).

9.4 Summary

- Flash floods are usually defined in terms of catchment response times alone, storm and catchment scales, or in comparison with the time needed for an effective emergency response. Some key characteristics normally include the rapid onset and the risk to life, particularly to vehicle drivers.
- Flash floods are normally caused by heavy rainfall and may be exacerbated by factors such as snowmelt and blockages to watercourses by debris. Debris flows, ice jam floods, surface water flooding and the floods caused by dam and flood defence failures are often also viewed as types of flash flood.
- Depending on flooding mechanisms and the information available, some techniques for assessing areas at risk include reviews of historical evidence of flooding, site visits by expert staff, hydrodynamic modelling and statistical techniques; for example, relating flood risk to factors such as catchment area, land use, soil types and slope. However compared to riverine flooding applications there are usually much greater uncertainties in the results.
- Due to the rapid onset of events, it can be technically challenging to issue warnings in time for people to respond. However, many flood warning services offer at least a basic service. Community-based warning systems are of particular importance and volunteer observers or spotters have a valuable role to play in providing on-the-ground information to assist with decision-making at both local and national level.
- For river floods, debris flows and surface water flooding, rainfall depth-duration thresholds are perhaps the most widespread approach to providing alerts. Normally these are based on rainfall observations, but rainfall forecasts offer the potential to extend lead times and ensemble forecasts allow thresholds to be expressed in probabilistic terms, allowing more of a risk-based approach to decision-making.

- Rainfall-based approaches have the advantage of providing longer lead times than is possible than if waiting for flows to develop but with the disadvantage that alerts can usually only be issued in general terms for a wide area. They are therefore mainly used for an initial alarm with more site-specific warning systems established if justified by the risk and available budgets. A typical configuration for a site-specific warning service is to install instrumentation in headwater areas, the area at risk and along anticipated flow pathways.
- For flash floods in rivers, similar monitoring and forecasting techniques are used to those for slower-responding riverine floods, including the use of data assimilation and probabilistic techniques. The main difference is that there tends to be a greater reliance on rainfall-runoff models in both lumped and distributed form. Simpler approaches such as flash flood guidance techniques are also widely used.
- For surface water flooding, the main technical challenges to monitoring and forecasting are the interactions between the surface and sub-surface drainage networks and the complexity of the runoff response. For flood risk modelling hydrodynamic models are increasingly used incorporating a high level of detail and these have the potential for real-time application; another option is to link maps generated off-line with the outputs from distributed rainfall-runoff models. In addition to raingauges and weather radar, monitoring options in urban areas include differential pressure sensors, water level sensors and ultrasonic flow sensors in pipes and culverts.
- For debris flows in addition to raingauges, monitoring options include geophones, pore-pressure sensors, trip wires and ultrasonic sensors. Warnings tend to be issued mainly on the basis of observations although the development of forecasting techniques is an active area for research. Hydrodynamic models are also increasingly used to help to assess the risk from debris flows.
- For ice jams if these develop in similar locations most years, or build up over a period of time, then there may be scope for hydrodynamic modelling of possible flood extents to help to assess areas at risk. More generally though modelling and forecasting techniques are less widely used and most warnings are issued on the basis of observations of parameters such as river levels and water temperatures and the outputs from equipment such as ice-motion sensors. Satellite and aerial observations also play a valuable role in assessing the extent of river ice and hence the potential to form ice jams.
- For dam breaks and flood defence failures, having identified a potential problem, the main challenge is usually to predict when failures might occur and how severe they will be. Typically decisions are made on the basis of on-site inspections and expert knowledge of the hydraulic, hydrological, structural and geotechnical risks. However, warning systems are sometimes installed at high-risk locations, particularly whilst construction is in progress. There is a wide range of monitoring techniques available using intrusive, external and remote-sensing techniques, and hydrodynamic models are widely used to assess the flood risk to areas further downstream.
- In addition to the purely technical aspects, the institutional and social aspects of a warning service are key factors to consider, with a community-based approach

widely advocated. Typically this includes activities such as developing contingency plans and operational procedures, running simulation exercises, performance monitoring and public-awareness-raising activities. Given the lack of time available for emergency response, there is often a particular focus on reducing time delays in the monitoring, forecasting, warning and response chain. Improvements can be both institutional, such as streamlining decision-making processes, and technical, such as more automated approaches to issuing warnings

References

Abair J, Carnahan P, Grigsby A, Kowalkowski R, Racz I, Savage J, Slayton T, Wild R (1992) Ice & Water: the flood of 1992 –Montpelier, Vermont. Ice and Water Committee, Vermont

Achleitner S, Fach S, Einfalt T, Rauch W (2008) Nowcasting of rainfall and of combined sewage flow in urban drainage systems. 11th International Conference on Urban Drainage, Edinburgh

ACTIF (2004) Some research needs for river flood forecasting in FP6. Achieving Technological Innovation in Flood Forecasting. European Commission Project EVK1-CT-2002-80014

Anquetin S, Ducrocq V, Braud I, Creutin J-D (2009) Hydrometeorological modelling for flash flood areas: the case of the 2002 Gard event in France. J. Flood Risk Manage, 2:101–110

Arattano M, Marchi L (2008) Systems and sensors for debris flow monitoring and warning. Sensors 8:2436–2452

Ashley ST, Ashley WS (2008) Flood fatalities in the United States. J Appl Meteorol Clim 47:805–818

ASCE (2007) The New Orleans hurricane protection system: what went wrong and why. Report by the American Society of Civil Engineers Hurricane Katrina External Review Panel

Australian Government (2001) Manual 24 – reducing the community impact of landslides. Australian Emergency Manuals Series, Attorney General's Department, Canberra

Australian Government (2009) Emergency Management Planning for Floods affected by Dams. Australian Emergency Manuals Series. Attorney General's Department, Canberra

Badoux A, Graf C, Rhyner J, Kuntner R, McArdell BW (2009) A debris flow alarm system for the Alpine Illgraben catchment: design and performance. Nat Hazards 49(3):517–539

Baum RL, Godt JW (2010) Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7:259–272

Beltaos S (ed) (1995) River Ice Jams. Water Resources Publications, Highlands Ranch

Beltaos S (2008) Progress in the study and management of river ice jams. Cold Reg Sci Technol 51(1):2–19

Burnash RJC (1995) The NWS River Forecast System-catchment modeling. In: Singh VP (ed) Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch

Caine N (1980) The rainfall intensity: duration control of shallow landslides and debris flows. Geogr Annaler Ser A, Phys Geogr 62(1/2):23–27

Cannon SH, Gartner JE, Rupert MG, Michael JA, Rea AH, Parrett C (2010) Predicting the probability and volume of post wild fire debris flows in the intermountain western United States. Geol Soc Am Bull 122(1/2):127–144

Carson R, Beltaos S, Groeneveld J, Healy D, She Y, Malenchak J, Morris M, Saucet J-P, Kolerski T, Shen HT (2011) Comparative testing of numerical models of river ice jams. Can J Civ Eng 38(6):669–678

Chien F-C, Kuo H-C (2011) On the extreme rainfall of Typhoon Morakot (2009). J Geophys Res 116:D05104

Coe JA, Godt JW, Baum RL, Bucknam RC, Michael JA (2004) Landslide susceptibility from topography in Guatemala. In: Lacerda WA, Ehrlich M, Fontura SAB, Sayão ASF (eds) Landslides: Evaluation and Stabilization. Taylor & Francis, London

Cole SJ, Moore RJ (2009) Distributed hydrological modelling using weather radar in gauged and ungauged basins. Advances in Water Resources, 32(7): 1107–1120
Collier CG (2007) Flash flood forecasting: what are the limits of predictability. Quarterly Journal of the Royal Meteorological Society, 133: 3–23
Cosgrove BA, Clark E (2012) Overview and initial evaluation of the Distributed Hydrologic Model Threshold Frequency (DHM-TF) flash flood forecasting system. NOAA Tech. Report, U.S. Department of Commerce, Silver Spring
Costa JE, Schuster RL (1988) The formation and failure of natural dams. Geol Soc Am Bull 100(7):1054–1068
Coulthard T, Frostick L, Hardcastle H, Jones K, Rogers D, Scott M, Bankoff G (2007) The June 2007 floods in Hull. Final Report by the Independent Review Body, 21st November 2007
Cranston MD, Tavendale ACW (2012) Advances in operational flood forecasting in Scotland. Proceedings of the ICE - Water Management, Volume 165(2): 79–87
Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: an overview. Eng Geol 102:152–163
De Coning E, Poolman E (2011) South African Weather Service operational satellite based precipitation estimation technique: applications and improvements. Hydrol Earth Syst Sci 15:1131–1145
Defra (2010) Surface Water Management Plan technical guidance and annexes. Flood Management Division, Department for Environment, Food and Rural Affairs, London
Delatte NJ (2009) Beyond Failure: Forensic Case Studies for Civil Engineers. ASCE Press, Reston
Delrieu G, Ducrocq V, Gaume E, Nicol J, Payrastre O, Yates E, Kirstetter P-E, Andrieu H, Ayral P-A, Bouvier C, Creutin J-D, Livet M, Anquetin S, Lang M, Neppel L, Obled C, Parent-Du-Châtelet J, Saulnier G-M, Walpersdorf A, Wobrock W (2005) The catastrophic flash-flood event of 8–9 September 2002 in the Gard Region, France: a first case study for the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory. J Hydrometeorol 6:34–52
de Wrachien D, Mambretti S (2009) Dam-break problems, solutions and case studies. WIT Press, Southampton
Drabek TE (2000) The social factors that constrain human responses to flood warnings. In: Parker DJ (ed) Floods. Routledge, London
Falconer RH, Cobby D, Smyth P, Astle G, Dent J, Golding B (2009) Pluvial flooding: new approaches in flood warning, mapping and risk management. J Flood Risk Manag 2:198–208
FEMA (2004) Federal guidelines for dam safety: emergency action planning for dam owners. Federal Emergency Management Agency, Washington, DC
FEMA (2005) Reducing damage from localized flooding: a guide for communities. Federal Emergency Management Agency, FEMA 511/June 2005, Washington, DC
FEMA (2006) National Flood Insurance Program Community Rating System CRS credit for flood warning programs 2006. Federal Emergency Management Agency, Department of Homeland Security, Washington, DC (plus 2013 update)
FEMA (2014) National Flood Insurance Program community rating system coordinator's manual. Report FIA-15/2013, Federal Emergency Management Agency, Department of Homeland Security, Washington, DC
Frank W (1988) The cause of the Johnstown flood. Civ Eng 58:63–66
Georgakakos KP (2006) Analytical results for operational Flash Flood Guidance. Journal of Hydrology, 317: 81–103
Gochis D and 25 co-authors (2014) Great Colorado Flood of September 2013. Bulletin of the American Meteorological Society. e-View doi: http://dx.doi.org/10.1175/BAMS-D-13-00241.1
Gourley JJ, Erlingis JM, Hong Y, Wells EB (2012) Evaluation of tools used for monitoring and forecasting flash floods in the United States. Wea. Forecasting, 27: 158–173
Gourley JJ, Hong Y, Flamig ZL, Arthur A, Clark R, Calianno M, Ruin I, Ortel T, Wieczorek ME, Kirstetter PE, Clark E, Krajewski WF (2013) A Unified Flash Flood Database across the United States. Bulletin of the American Meteorological Society, 94(6): 799–805
Graham WJ (2000) Floods caused by dam failure. In: Parker DJ (ed) Floods. Routledge, London

Gruntfest E (1996) What we have learned since the Big Thompson Flood. Proceedings of a meeting 'Big Thompson Flood, Twenty Years Later', Fort Collins, CO, 13–15 July 1996

Gruntfest E, Handmer J (2001) Dealing with flash floods: contemporary issues and future possibilities. In: Gruntfest E, Handmer J (eds) Coping with flash floods. Kluwer, Dordrecht

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5(1):3–17

Hall AJ (1981) Flash flood forecasting. WMO Operational Hydrology Report No. 18, Geneva

Heil B, Petzold I, Romang H, Hess J (2010) The Common Information Platform for natural hazards in Switzerland. Nat Hazards. doi: 10.1007/s11069-010-9606-6

Hilker N, Badoux A, Hegg C (2009) The Swiss flood and landslide damage database 1972–2007. Nat Hazards Earth Syst Sci 9:913–925

Hong Y, Gourley J (2014) Radar hydrology: principles, models, and applications. CRC Press, Boca Raton/London/New York

Hungr O, Evans SG, Bovis MJ, Hutchinson JN (2001) A review of the classification of landslides of the flow type. Environ Eng Geosci VII(3):221–238

Hunter NM, Bates PD, Neelz S, Pender G, Villanueva I, Wright NG, Liang D, Falconer RA, Lin B, Waller S, Crossley AJ, Mason DC (2008) Benchmarking 2D hydraulic models for urban flooding. Proc ICE – Water Manag 161(1):13–30

Hurford AP, Priest SJ, Parker DJ, Lumbroso DM (2011) The effectiveness of extreme rainfall alerts in predicting surface water flooding in England and Wales. Int J Climatol. doi: 10.1002/joc.2391

Hürlimann M, Rickenmann D, Medina C, Bateman A (2008) Evaluation of approaches to calculate debris-flow parameters for hazard assessment. Eng Geol 102:152–163

IFRC (2012) Community early warning systems: guiding principles. International Federation of Red Cross and Red Crescent Societies, Geneva

Iverson RM (1997) The physics of debris flows. Rev Geophys 35(3):245–296

Ives JD, Shrestha RB, Mool PK (2010) Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu

Jakob M (2010) State of the art in debris flow research: the role of dendrochronology. In: Stoffel M, Bollschweiler M, Butler DR, Luckman BH (eds) Tree rings and natural hazards: a state-of-the-art. Springer, Dordrecht

Jakob M, Owen T, Simpson T (2011) A regional real-time debris-flow warning system for the District of North Vancouver, Canada. Landslides. doi: 10.1007/s10346-011-0282-8

Javelle P, Fouchier C, Arnaud P, Lavabre J (2010) Flash flood warning at ungauged locations using radar rainfall and antecedent soil moisture estimations. J Hydrol 394(1–2):267–274

Javelle P, Pansu J, Arnaud P, Bidet Y, Janet B (2012) The AIGA method: an operational method using radar rainfall for flood warning in the South of France. Weather Radar and Hydrology (Eds. Moore RJ, Cole SJ, Illingworth AJ), IAHS Publication 351, Wallingford

Javelle P, Demargne J, Defrance D, Pansu J, Arnaud, P (2014) Evaluating flash-flood warnings at ungauged locations using post-event surveys: a case study with the AIGA warning system. Hydrological Sciences Journal, 59 (7): 1390–1402

Jonkman SN, Kelman I (2005) An analysis of the causes and circumstances of flood disaster deaths. Disasters 29(1):75–97

Kelsch M (2001) Hydrometeorological characteristics of flash floods. In: Gruntfest E, Handmer J (eds) Coping with flash floods. Kluwer, Dordrecht

Kobiyama M, Goerl RF (2007) Quantitative method to distinguish flood and flash flood as disasters. SUISUI Hydrol Res Lett 1:11–14

Koren V, Reed S, Smith M, Zhang Z, Seo DJ (2004) Hydrology Laboratory research modeling system (HL-RMS) of the National Weather Service. Journal of Hydrology, 291(3/4): 297–318

Koskinen JT, Poutiainen J, Schultz DM, Joffre S, Koistinen J, Saltikoff E, Gregow E, Turtiainen E, Dabberdt WF, Damski J, Eresmaa N, Göke S, Hyvärinen O, Järvi L, Karppinen A, Kotro J, Kuitunen T, Kukkonen J, Kulmala M, Moisseev D, Nurmi P, Pohjola H, Pylkkö P, Vesala T,

Viisanen Y (2011) The Helsinki Testbed: a mesoscale measurement, research, and service platform. Bull Am Meteorol Soc 92(3):325–342
La Husen R (2005) Debris- flow instrumentation. In: Jakob M, Hungr O (eds) Debris-flow hazards and related phenomena. Springer, Berlin
Leopold LB, Wolman MG, Miller JP (1995) Fluvial processes in geomorphology. Dover, New York
Liguori S, Rico-Ramirez MA, Schellart ANA, Saul AJ (2012) Using probabilistic radar rainfall nowcasts and NWP forecasts for flow prediction in urban catchments. Atmos Res 103:80–95
Lliboutry L, Arnao BM, Pautre A, Schneider B (1977) Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention. J Glaciol 18(79):239–354
Lopez JL, Courtel F (2008) An integrated approach for debris-flow risk mitigation in the north coastal range of Venezuela. 13th IWRA World Water Congress, 1–4 September, Montpellier
Maki M, Maesaka T, Kato A, Shimizu S, Kim D-S, Iwanami K, Tsuchiya S, Kato T, Kikumori T, Kieda K (2010) X-band polarimetric radar networks in urban areas. ERAD 2010 – 6th European Conference on Radar in Meteorology and Hydrology, 6–10 September 2010, Sibiu
Maksimović C, Prodanović D, Boonya-Aroonnet S, Leitão JP, Djordjević S, Allitt R (2009) Overland flow and pathway analysis for modelling of urban pluvial flooding. J Hydraul Res 47(4):512–523
Martina MLV, Todini E, Libralon A (2006) A Bayesian decision approach to rainfall thresholds based flood warning. Hydrology and Earth System Sciences, 10: 413–426
Martina MLV, Todini E (2009) Bayesian rainfall thresholds for flash flood guidance. In: Samuels P et al (eds) Flood Risk Management: research and practice. Taylor & Francis, London
Met Office/Environment Agency (2010) Extreme Rainfall Alert user guide. Flood Forecasting Centre, Exeter
Met Office (2015) Together: make a difference with a coordinated response to emergency management: England. Met Office, Exeter
MLIT (2007) Sediment-related disaster warning and evacuation guidelines. April 2007. Sabo (Erosion and Sediment Control) Department, Ministry of Land, Infrastructure, Transport and Tourism, Japan
Montz BE, Gruntfest E (2002) Flash flood mitigation: recommendations for research and applications. Environ Hazards 4:15–22
Moore RJ, Cole SJ, Dunn S, Ghimire S, Golding BW, Pierce CE, Roberts NM, Speight L (2015) Surface water flood forecasting for urban communities, CREW report CRW2012_03. Available online at www.crew.ac.uk/publications
Morris M, Hanson G, Hassan M (2008) Improving the accuracy of breach modelling: why are we not progressing faster? J Flood Risk Manag 1(3):150–161
Morse B, Hicks F (2005) Advances in river ice hydrology 1999–2003. Hydrol Process 19(1):247–26
Morss RE, Demuth JL, Bostrom A, Lazo JK, Lazrus H (2015) Flash flood risks and warning decisions: a mental models study of forecasters, public officials, and media broadcasters in Boulder, Colorado. Risk Anal. doi: 10.1111/risa.12403
Naulin J-P, Payrastre O, Gaume E (2013) Spatially distributed flood forecasting in flash flood prone areas: Application to road network supervision in Southern France. Journal of Hydrology, 486: 88–99
Needham JT (2010) Estimating loss of life from dam failure with HEC-FIA. 2nd Joint Federal Interagency conference, Las Vegas, 27 June–1 July 2010
NOAA/NWS (2003) Flash Flood Guidance improvement team. National Weather Service Final Report: February 6, 2003, Washington, DC, USA
NOAA/NWS (2008) FFMPA Flash Flood Monitor and Prediction: Advanced graphical user interface guide for users. Version OB9, 2 October 2008
NOAA (2010) Flash Flood Early Warning System Reference Guide. University Corporation for Atmospheric Research, Denver
NOAA/NWS (2012a) Flood warning systems manual. National Weather Service, US Department of Commerce, Washington DC

NOAA/NWS (2012b) River Watch program. National Weather Service, one page flyer and website
Norbiato D, Borga M, Dinale R (2009) Flash flood warning in ungauged basins by use of the flash flood guidance and model-based runoff thresholds. Meteorological Applications, 16(1): 65–75
Ochoa-Rodríguez S, Wang L-P, Thraves L, Johnston A, Onof C (2015) Surface water flood warnings in England: overview, assessment and recommendations based on survey responses and workshops. Journal of Flood Risk Management. doi: 10.1111/jfr3.12195
Osanai N, Shimizu T, Kuramoto K, Kojima S, Noro T (2010) Japanese early-warning for debris flows and slope failures using rainfall indices with Radial Basis Function Network. Landslides 7:325–338
Parker DJ, Priest SJ, Tapsell SM (2009) Understanding and enhancing the public's behavioural response to flood warning information. Meteorol Appl 16:103–114
Patterson T (2005) Looking closer: a guide to making bird's-eye views of National Park Service cultural and historical sites. Cartogr Perspect 52:59–75
Pedersen L, Jensen NE, Madsen H (2010) Calibration of local area weather radar-identifying significant factors affecting the calibration. Atmos Res 97(1–2):129–143
Reed S, Schaake J, Zhang Z (2007) A distributed hydrologic model and threshold frequency- based method for flash flood forecasting at ungauged locations. J. Hydrology, 337(3–4): 402–420
Rickenmann D (2005) Runout prediction methods. In: Jakob M, Hungr O (eds) Debris-flow hazards and related phenomena. Springer, Berlin
Richardson SD, Reynolds JM (2000) An overview of glacial hazards in the Himalayas. Quat Int 65–66:31–47
Romang H, Zappa M, Hilker N, Gerber M, Dufour F, Frede V, Bérod D, Oplatka M, Hegg C, Rhyner J (2011) IFKIS-Hydro: an early warning and information system for floods and debris flows. Nat Hazards 56(2):509–527
Saul AJ, Djordjević S, Maksimović C, Blanksby J (2011) Integrated urban flood modelling. In: Pender G, Faulkner H (eds) Flood Risk Science and Management, 1st edn. Blackwell Publishing Ltd., Chichester
Schellart A, Ochoa S, Simões N, Wang L-P, Rico-Ramirez M, Liguori S, Duncan A, Chen AS, Keedwell E, Djordjević S, Savić DA, Saul A, Maksimović C (2011) Urban pluvial flood modelling with real time rainfall information–UK case studies. 12th international conference on urban drainage, Porto Alegre, 10–15 Sept 2011
Schmidt JA, Anderson AJ, Paul JH (2007) Spatially-variable, physically-derived Flash Flood Guidance. Preprints 21st conference on hydrology, American Meteorological Society, San Antonio, 15–18 January 2007
Schneider C, Flörke M, Eisner S, Voss F (2011) Large scale modelling of bankful flow: An example from Europe. J Hydrol 408:235–245
Sene K (2013) Flash Floods: Forecasting and Warning. Springer, Dordrecht
SEPA (2014) Scottish Flood Forecasting Service: Your guide to using the Flood Guidance Statement Third publication. Flood risk management in Scotland. Scottish Environment Protection Agency, Perth
Snorrason Á, Björnsson H, Jóhannesson H (2000) Causes, characteristics and predictability of floods in regions with cold climates. In: Parker DJ (ed) Floods. Routledge, London
Speight L, Cole SJ, Moore RJ, Pierce C, Wright B, Golding B, Cranston M, Tavendale A, Ghimire S, Dhondia J (2015) Developing surface water flood forecasting capabilities in Scotland: an operational pilot for the 2014 Commonwealth Games in Glasgow. Journal of Flood Risk Management (in press)
Sweeney TL (1992) Modernized Areal Flash Flood Guidance. NOAA technical report NWS HYDRO 44, Hydrology Laboratory, National Weather Service, NOAA, Silver Spring, MD
Tang P, Beltaos S (2008) Modeling of river ice jams for flood forecasting in New Brunswick. 65th Eastern Snow Conference, 28–30 May 2008, Fairlee, Vermont
UNESCO (2007) Data requirements for integrated urban water management. In: Fletcher TD, Deletić A (eds) UNESCO-IHP urban water series. United Nations Educational, Scientific and Cultural Organization/Taylor & Francis, Paris/The Netherlands

U.S. Department of Commerce (2001) Service assessment Tropical Storm Allison heavy rains and floods Texas and Louisiana. June 2001
USACE (1996) Hydrologic aspects of flood warning preparedness programs. Report ETL 1110-2-540, U.S. Army Corps of Engineers, Washington DC
USACE (2009) Ice Jam Database. US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory
USGS (2006) 1976 Big Thomson Flood, Colorado-thirty years later. U.S. Department of the Interior, U.S. Geological Survey, Fact Sheet 2006–3095, July 2006
Versini PA, Gaume E, Andrieu H (2010) Assessment of the susceptibility of roads to flooding based on geographical information – test in a flash flood prone area (the Gard region, France). Nat Hazards Earth Syst Sci 10:793–803
Ward SN (2011) The 1889 Johnstown, Pennsylvania flood: a physics-based simulation. In 'The Tsunami Threat – Research and Technology' (Ed. Nils-Axel Mörner) http://www.intechopen.com/
White KD (2003) Review of prediction methods for breakup ice jams. Can J Civ Eng 30:89–100
Wieczorek GF, Glade T (2005) Climatic factors influencing occurrence of debris flows. In: Jakob M, Hungr O (eds) Debris-flow hazards and related phenomena. Springer, Berlin
Williams C, White K (2003) Early Warning Flood Stage Equipment. Ice Engineering, US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, ERDC/CRREL Technical Note 03–2, Hanover, New Hampshire
WMO (2008a) Urban Flood Risk Management: a tool for integrated flood risk management. WMO/GWP Associated Programme on Flood Management, APFM Technical Document No. 11, Flood Management Tools Series, Geneva
WMO (2008b) General guidelines for setting-up a Community-Based Flood Forecasting and Warning System (CBFFWS). Hernando HT (ed) WMO/TD-No. 1472, Geneva
WMO (2009) Guide to Hydrological Practices, 6th edn. WMO-No. 168, Geneva
WMO (2011a) Manual on Flood Forecasting and Warning. WMO-No. 1072, Geneva
WMO (2011b) Management of sediment-related risks. WMO/GWP Associated Programme on Flood Management, Technical Document No 16, Flood Management Tools series, Geneva
WMO (2012) Management of Flash Floods. WMO/GWP Associated Programme on Flood Management, Integrated Flood Management Tools Series No.16
Wu H-L (2010) Non-structural strategy of debris flow mitigation in mountainous areas after the Chichi Earthquake. INTERPRAEVENT 2010, 26–30 April 2010, Taipei
Yatheendradas S, Wagener T, Gupta H, Unkrich C, Goodrich D, Schaffner M, Stewart A (2008) Understanding uncertainty in distributed flash flood forecasting for semiarid regions. Water Resour Res 44:W05S19
Younis J, Anquetin S, Thielen J (2008) The benefit of high-resolution operational weather forecasts for flash flood warning. Hydrol. Earth Syst. Sci., 12: 1039–1051

Chapter 10
Droughts

Abstract Droughts are often classified in terms of their meteorological, hydrological, groundwater, agricultural or socioeconomic impacts. Some forecasting challenges include the slow onset and wide spatial variability of events and the choice of criteria for issuing alerts. Modelling approaches range from simple empirical techniques through to integrated catchment models driven by rainfall observations and forecasts. At longer timescales, statistical and probabilistic techniques are widely used together with drought indices. This chapter presents an introduction to these techniques together with examples of warning systems for streamflow and agricultural droughts.

Keywords Drought • Forecasting • Early warning • Meteorological drought • Hydrological drought • Groundwater drought • Agricultural drought • Drought indices • Low flows • Streamflow drought • Famine early warning

10.1 Introduction

Despite their slow onset, droughts are one of the most devastating of natural hazards. Estimates suggest that, in the period 1900–2004, more than ten million people died and almost two billion were affected (Below et al. 2007). In more recent years (1970–2012), it is estimated that droughts accounted for about 35 % of all fatalities and 8 % of the economic losses caused by weather, climate and water-related extremes (WMO 2014). The impacts can spread across entire regions and continents as illustrated in Table 10.1; for example, the changes in rainfall associated with the 1982/1983 and 1997/1998 El Niño events affected parts of the USA, Africa, Asia and South America (e.g. Hoerling and Kumar 2003; Smith 2012).

Droughts can occur in almost any climatic region and vary widely in duration, severity and spatial extent. The initial causes are usually a cumulative shortfall or deficit in rainfall or snowfall and a broad definition (UN/ISDR 2009) is that:

> drought is a deficiency of precipitation over an extended period of time, usually a season or more, which results in a water shortage for some activity, group, or environmental sectors

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Table 10.1 Some examples of significant drought events in recent decades

Region/country	Years	Examples of impacts
Australia	1982–1983	Spatially extensive drought with major economic losses; other drought events include 1895–1902, 1937–1945, 1965–1968, 1991–1995
Europe	1975–1976	Widespread water rationing and economic impacts
	2003	Forest fires, reductions in agricultural production, power cuts due to lack of cooling water, and low river levels affecting navigation
India	1979, 1987, 2002	Millions of people affected in each event
Sahel Region, Africa	1968–mid-1980s	Widespread famine, with several hundred thousand deaths in the Sahel Region in 1974–1975 and in Ethiopia and Sudan in 1984–1985. Earlier examples include 1910–1914 and 1940–1944
Southern Africa	1982–1983, 1991–1992	Widespread harvest failures, reductions in hydropower production
USA	1930s	The 1930s were known as the Dust Bowl years with a series of drought episodes across about two-thirds of the country with severe impacts on crop yields, water supply and the economy and prompting widespread migration between states
	1988, 2002	Severe impacts on hydropower generation, river navigation and crop yields
	2012	More than half of all counties in the USA (in 32 states) were listed as natural disaster areas by the US Department of Agriculture; the following year also marked the start of an extended drought in California

Tallaksen and Van Lanen (2004), Guha-Sapir et al. (2004), Wilhite (2005), WMO (2006), Smith (2012), Peterson et al. (2013), Masih et al. (2014)

However, there are numerous other definitions, and one literature review found more than 150 examples (Wilhite and Glantz 1985). As noted by Wilhite (2005), 'drought means something different for a water manager, an agriculturalist, a hydro-electric power plant operator, and a wildlife biologist'.

For drought forecasting, it is often convenient to consider the impacts on the main components in the hydrological cycle. A typical sequence is for a shortfall in rainfall to lead initially to drier soils followed by impacts on river flows and then groundwater levels, leading to the following types of drought (e.g. Tallaksen and Van Lanen 2004; Fig. 10.1):

- Meteorological Drought – a lack of precipitation over a large area and for an extensive period of time
- Soil Moisture Drought – a reduction in soil moisture due to a shortfall in precipitation, perhaps combined with high evaporation/evapotranspiration rates

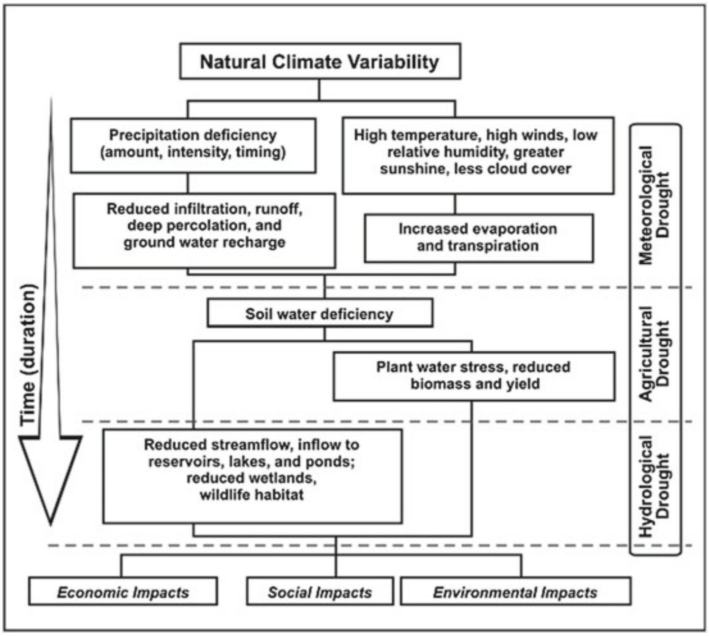

Fig. 10.1 Sequence of drought occurrence and impacts for commonly accepted drought types (National Drought Mitigation Center, University of Nebraska–Lincoln, USA; http://drought.unl.edu/)

- Hydrological Drought – a reduction in streamflow, reservoir and lake levels and groundwater levels and recharge

A hydrological drought can be further divided into a streamflow drought and – if the rainfall deficit persists – a slower-onset groundwater drought. The recovery following significant rainfall typically occurs in the same sequence with soil moisture being replenished first and stream flows recovering next, before finally, possibly months or even years later, groundwater levels return to normal.

In terms of impacts, a soil moisture drought typically leads to reductions in crop yields and a so-called agricultural drought. Similarly, unless alternative sources are available, a hydrological drought may lead to water shortages for public water supply, irrigation, and hydropower generation and cause a range of environmental impacts (see Chap. 12). A drought which causes major social, economic or political disruption is often called a socioeconomic drought.

Over longer timescales, feedback influences between the land surface and atmosphere are increasingly seen as a mechanism for exacerbating droughts and causing desertification in areas such as the Sahel. For example, changes in vegetation cover may affect both evapotranspiration and albedo values affecting the water and radiation balance at the land surface and future growth in those areas. Representing these types of impacts is one of the key aims in earth system models of the types described in Chap. 13.

As with many other types of early warning system, in drought alert systems, the model outputs are usually just one aspect of a wider decision-making process; for example, other key sources of information normally include rainfall and river observations and feedback on impacts from government agencies, the public and the media. As discussed in Chap. 1, contingency planning is a key aspect in disaster risk reduction, and drought response plans normally consider a wide range of social, economic and environmental factors and in particular the needs of vulnerable groups (e.g. Wilhite 2000; UN/ISDR 2009; WMO 2011). Some possible types of drought response include (USACE 1994):

- *Strategic measures* – long-term physical and institutional responses such as water supply structures, water law and plumbing codes
- *Tactical measures – such as* water rationing, are developed in advance to respond to expected short-term water deficits
- *Emergency measures* – are implemented as an ad hoc response to conditions that are too specific or rare to warrant the development of standing plans

Thus, if water shortages seem likely, voluntary or compulsory restrictions on water use are often imposed such as for irrigation and non-essential domestic use. Additional sources of water might be obtained such as bringing in supplies from other regions using water tankers, laying temporary pipelines, installing temporary dams in streams and rivers and drilling additional boreholes. In a severe drought, drastic measures may be needed; for example, making drinking water available only at certain times of day or limiting supplies to communal standpipes.

Risk-based techniques are increasingly used when deciding on the approaches to take, considering both the probability of an event occurring and the economic or other consequences. For example, Wilhite and Knutson (2008) note that the principles of drought risk management can be promoted by:

- Encouraging the improvement and application of seasonal and shorter-term forecasts
- Developing integrated monitoring and early warning systems and associated information delivery systems
- Developing preparedness plans at various levels of government
- Adopting mitigation actions and programs
- Creating a safety net of emergency response programs that ensure timely and targeted relief
- Providing an organizational structure that enhances coordination within and between levels of government and with stakeholders

Regarding early warning systems, Table 10.2 shows some examples of operational systems at a regional or national scale.

Typically, a multi-agency approach is required to cover all sectors; for example, in Australia in addition to a drought monitoring service, the Bureau of Meteorology offers a seasonal flow forecasting service (see Chapter 13) and the Department of Agriculture provides information relevant to agricultural production (see Sect. 10.3). In contrast, in the USA the National Integrated Drought Information System

Table 10.2 Some examples of drought early warning systems

Name/organisation	Location	Main objectives	Reference
Bureau of Meteorology	Australia	To provide a consistent starting point for national drought alerts and drought-related products	http://www.bom.gov.au/
China Meteorological Administration (CMA)	China	Monitoring of drought development including providing a range of bulletins and web-based products	http://www.cma.gov.cn/
IGAD Climate Prediction and Applications Centre, Nairobi (ICPAC)	East Africa	Climate outlooks and early warnings to national meteorological and hydrological services	http://www.icpac.net
Crop Weather Watch Group	India	Alerts regarding the agricultural impacts of drought	Samra (2004) http://www.agricoop.nic.in
National Integrated Drought Information System (NIDIS)	USA	Drought monitoring, forecasting and early warning	Wilhite (2005), NIDIS (2007), NDMC (2014) http://www.drought.gov/

(NIDIS 2007) provides a focus for drought monitoring, forecasting and early warning and includes a web-based portal (http://www.drought.gov) which is part of an interactive system to:

- Provide early warning about emerging and anticipated droughts
- Assimilate and quality control data about droughts and models
- Provide information about risk and impact of droughts to different agencies and stakeholders
- Provide information about past droughts for comparison and to understand current conditions
- Explain how to plan for and manage the impacts of droughts
- Provide a forum for different stakeholders to discuss drought-related issues

Although long-established for post flood reporting, service assessments related to droughts are another recent development (NOAA 2015).

In addition to producing regional forecast products, the IGAD centre listed in Table 10.2 hosts the meetings of the Regional Climate Outlook Forum for the Greater Horn of Africa (e.g. Mwangi et al. 2014). These are held before the start of each rainfall season, and – with WMO support – similar meetings are held at more than ten centres worldwide. These include locations in South and Central America, Africa, Europe, Asia, the Caribbean and the Pacific region. Typically, the aim of these meetings is to evaluate current seasonal climate outlooks and assess the potential impacts on different sectors to agree a 'consensus' forecast for use in the region. They are normally attended by national and international experts in meteorology, health, disaster risk management, agriculture and food security and water resources (WMO 2009a). WMO also coordinates the Integrated Drought Management

Programme in collaboration with the Global Water Partnership, and this is centred around the following four principles (WMO 2011):

- To shift the focus from reactive to proactive measures through drought mitigation, vulnerability reduction and preparedness
- To integrate the vertical planning and decision-making processes at all levels into a multi-stakeholder approach including key sectors, especially agriculture and energy
- To promote the evolution of the drought knowledge base and to establish a mechanism for sharing knowledge and providing services to stakeholders across sectors at all levels
- To build capacity of various stakeholders at different levels

Chapter 1 provides further information on approaches to disaster risk reduction including references to a number of guidelines on this topic (see WMO/GWP 2014 also). In this chapter the focus is on drought monitoring and forecasting techniques, and Sect. 10.2 describes a range of approaches, whilst Sect. 10.3 discusses streamflow and agricultural droughts in more detail. Later chapters consider a number of issues relevant to drought forecasting such as reservoir operation models (Chap. 11), environmental impacts at low flows (Chap. 12) and seasonal forecasting techniques (Chap. 13).

10.2 Forecasting Techniques

Hydrological and meteorological services use a range of techniques for forecasting the onset and progression of droughts.

Typically, water availability is estimated from observations of rainfall, river flows and reservoir and groundwater levels. Satellite monitoring of vegetation cover is also widely used together with ground-based monitoring of soil moisture conditions and major water abstractions. Other less quantitative sources may provide useful information such as an increase in enquiries from the public and the media regarding water supply and related issues, such as damage to environmentally sensitive sites.

Rainfall and air temperature forecasts also provide the potential to extend the lead times offered in early warning systems. As discussed in Chap. 4, at longer ranges these are usually based on a combination of statistical techniques and the outputs from Numerical Weather Prediction (NWP) models. Much of the predictability at these timescales arises from the influences of large-scale features in the atmosphere and oceans, and Table 10.3 provides some examples of possible linkages. These so-called teleconnections are discussed further in Chaps. 1, 4 and 13. In some river basins, there may also be sufficient water storage to provide forecasting skill at these timescales based mainly on hydrological considerations; for example, in basins with large lakes and reservoirs or extensive snow cover during the winter months (see Chap. 13).

Flow forecasting techniques for droughts and low flows range from simple regression approaches to time series analysis methods, supply demand models and

Table 10.3 Examples of links between droughts and features of the atmospheric and ocean circulation

Feature	Examples of locations affected	Typical timescale	Drought mechanism(s)
Inter Tropical Convergence Zone (ITCZ)	Equatorial regions worldwide; typically up to ±10° N/S, but as much as 45° N in Southeast Asia	Once or twice yearly depending on latitude	Reductions in rainfall extent and intensity related to variations in the northwards or southwards progression of the zone and its impacts on regional air masses
El Niño Southern Oscillation (ENSO)	Australia, Southeast Asia, Northeastern Brazil, Southern Africa, Caribbean, Central America	Typically every 2–7 years for a few months or more	Changes in sea surface temperatures in the Pacific Ocean resulting in widespread regional changes in rainfall; a similar phenomenon occurs in the Indian Ocean (the Indian Ocean Dipole)
North Atlantic Oscillation (NAO)	Europe, North Africa	Up to several years	Diversion of storm tracks to higher or lower latitudes, with tentative links to dry conditions in Southern Europe and blocking anticyclones

E.g. Chiew and McMahon (2002), Manatsa et al. (2011), Palmer and Hagedorn (2006), Ropelewski and Folland (2000), Saji et al. (1999), Troccoli et al. (2008)

integrated catchment models. Generally the approaches used are similar to those in other hydrological applications and are discussed in Chaps. 5, 11 and 13; however, Sect. 10.3 describes some examples of their application to drought forecasting.

As in many other aspects of early warning, predefined threshold values are a key tool in helping to decide whether to issue or escalate alerts. These are sometimes called drought triggers and can be based on observed or forecast values, such as for river flows or reservoir levels or using drought indices (Table 10.4). Often a key challenge is to decide on the threshold values to set including the durations to consider. In some cases, proposed values are available from the original papers describing development of the methodology; however, typically these are based on studies for specific river basins or regions, and locally derived values may be more appropriate.

The choice of parameters or indices to consider usually depends on factors such as the lead times required, catchment response characteristics and the spatial scales of interest. For example, in arid or semiarid areas, reservoir and groundwater levels are likely to provide more information about the drought situation than river flows (e.g. Gustard et al. 2004).

However, it is often recommended that multiple threshold values are used to provide more resilience and potentially allow earlier detection of possible issues. For example, WMO (2006) notes that 'An effective monitoring, early warning and delivery system continuously tracks key drought and water supply indicators and climate-based indices and delivers this information to decision makers. This allows for the early detection of drought conditions and timely triggering of mitigation and emergency response measures, the main ingredients of a drought preparedness plan'. In operational use, the performance of the values chosen should also be

Table 10.4 Examples of drought-monitoring indicators and indices

Category	Name	Basis of approach
Meteorological	Rainfall percentiles/deciles	Percentile values for cumulative rainfall for different durations (e.g. 3 or 6 months), sometimes expressed on a scale of 1–10 (i.e. deciles)
	Standardised Precipitation Index (SPI)	Cumulative rainfall for a range of durations (e.g. from 3 to 48 months) compared with values from normalised rainfall probability distributions based on long-term records, expressed in terms of anomalies relative to long-term values
	Palmer Drought Severity Index (and Palmer Hydrological Drought Severity Index)	A conceptual water-balance approach which compares the available water to the climatological normal, considering rainfall, evapotranspiration, soil recharge and runoff, and which is widely used in the USA, for example
	Water Requirement Satisfaction Index	The ratio of actual to potential cumulative crop evapotranspiration, usually at a seasonal time scale
Soil moisture	Crop Moisture Index	A component of the Palmer Drought Severity Index calculation focusing on short-term changes in soil moisture
Hydrological	Low flow statistics	Flow duration values (e.g. Q95), cumulative deficit (run-sum) values and other statistical measures of flows or volumes for various durations (e.g. 1-day, 10-day); see Chap. 5
	Surface Water Supply Index	Weighted sum of snowpack, streamflow, precipitation and reservoir storage values normalised by non-exceedance frequencies
Agricultural	Aridity Index	Various definitions typically linked to the normalized differences between precipitation, actual and/or potential evaporation (or humidity and/or air temperature)
General	Normalised Difference Vegetation Index (NDVI)	Normalised difference between near-infrared and infrared reflectance values, giving a measure of vegetative cover

Hayes (2015), Knutson et al. (2005), McKee et al. (1995), Palmer (1965, 1968), Senay and Verdin (2003), Shafer and Dezman (1982), Svoboda et al. (2002), Wilhite (2005), WMO (2000, 2006, 2009b, 2012a)

assessed on a regular basis using a range of verification measures, such as hit rates and false alarm ratios (see Chap. 5). In some cases a combined approach using index values and long-range ensemble forecasts may outperform existing techniques (e.g. Mwangi et al. 2014).

Generally when defining values, it is desirable to select analysis periods which are long enough to include a number of previous significant droughts for the location(s) of interest. This is particularly the case for arid and semiarid regions where rainfall may remain consistently above or below average for years at a time.

Typically this requires record lengths of at least 20–30 years and preferably more (e.g. Hayes 2015; WMO 2012a). However, values should be consistent over time, and considerable effort may be required to identify and account for factors such as changes in instrumentation and artificial influences over the analysis period.

Ideally threshold values should be defined in collaboration with key stakeholders, particularly where an alert could lead to major socioeconomic impacts such as restrictions on abstractions for irrigation or industrial use. The slow onset of droughts also means that it can be difficult to recognise if a dry spell of some days and weeks will become an intense prolonged drought (Glantz 2004), raising the prospect of false alarms and reduced credibility for future forecasts. In the USA, for example, some key research needs that were identified as part of a regional review included (Western Governors' Association 2004):

- Improving capabilities to monitor, understand and forecast droughts
- Developing methodologies to integrate data on climate, hydrology, water available in storage and socioeconomic and ecosystem conditions, in order to better understand and quantify the linkages between the physical characteristics of drought, the impacts that result from droughts and the triggers used by decision-makers who respond to drought
- Identifying regional differences in drought impacts and related information needs and delivery systems and developing regionally specific drought monitoring and forecasts
- Developing new decision support tools, such as drought 'scenarios' (e.g. 'if, then'), that would give decision-makers (such as agricultural producers) a better range of risks and options to consider
- Improving the scientific basis for understanding ground water and surface water relationships and developing triggers and thresholds for critical surface water flows and ground water levels

More generally, some of the main challenges internationally with developing drought monitoring and early warning systems include (WMO 2006):

- Meteorological and hydrological data networks are often inadequate in terms of the density of stations for all major climate and water supply parameters. Data quality is also a problem because of missing data or an inadequate length of record
- Data sharing is inadequate between government agencies and research institutions, and the high cost of data limits their application in drought monitoring, preparedness, mitigation and response
- Information delivered through early warning systems is often too technical and detailed, limiting its use by decision-makers
- Forecasts are often unreliable on the seasonal timescale and lack specificity, reducing their usefulness for agriculture and other sectors
- Drought indices are sometimes inadequate for detecting the early onset and end of drought

- Drought monitoring systems should be integrated, coupling multiple climate, water and soil parameters and socio-economic indicators to fully characterize drought magnitude, spatial extent and potential impact
- Impact assessment methodologies, a critical part of drought monitoring and early warning systems, are not standardized or widely available, hindering impact estimates and the creation of regionally appropriate mitigation and response programmes
- Delivery systems for disseminating data to users in a timely manner are not well developed, limiting their usefulness for decision support

10.3 Selected Applications

10.3.1 Streamflow Droughts

A streamflow drought typically occurs when river flows are consistently below their usual values, defined in terms of the long-term response at the locations of interest.

The impacts can include deteriorations in water quality, damage to ecosystems and a shortage of water for water supply, irrigation, navigation and other applications. However, the rate at which a drought develops is strongly influenced by the amount of storage available at the onset; for example, in groundwater-dominated systems and catchments with large reservoirs or lakes, river flows may only be sensitive to rainfall deficits over a period of weeks or months.

Figure 10.2 illustrates some low flow forecasting techniques. Some of the first to be applied – and which still remain widely used nowadays – were empirical approaches such as multiple regression relationships and recession techniques. For example, in recession forecasting, it is assumed that river flows will continue to decrease following an assumed relationship, which is usually exponential in form. The parameters of the expression are normally estimated from a number of previous recession periods (e.g. WMO 2012b). Time series analysis techniques provide a more sophisticated option, such as transfer functions and autoregressive moving average (ARMA) or Markov chain models (e.g. WMO 2009b).

For longer-term forecasting, supply demand models are widely used of the types described in Chap. 13. These represent the key water sources, water transfers, abstractions and discharges in a water supply system and maintain a water balance, although normally do not account for effects such as flow attenuation and backwater influences. Optimisation routines are often included to provide guidance on how to operate systems to meet multiple objectives, such as in conjunctive use water supply systems. For reservoir applications, simulations are typically started from current reservoir levels but using synthetic or stochastic flow sequences based on analyses of long-term flow records.

Integrated catchment models provide another option to assist with operations, of the types used in flood and water resources applications. Indeed as noted in Chap. 1, using

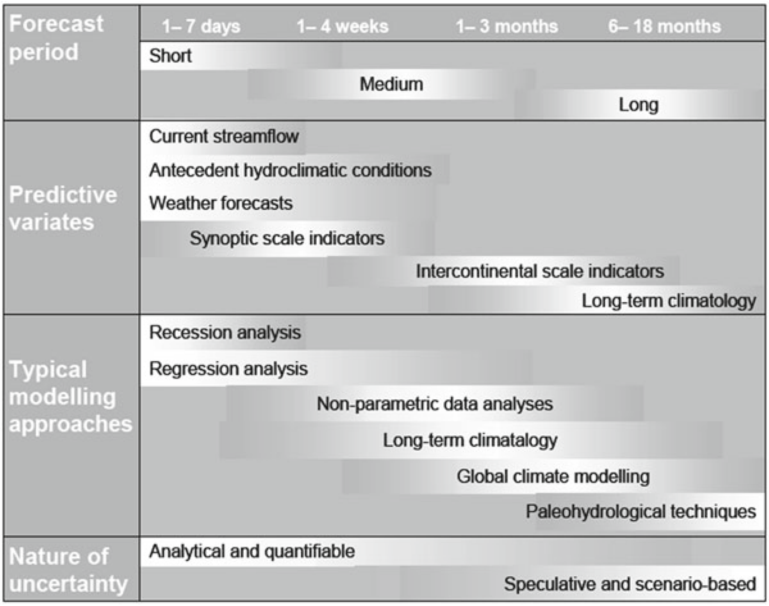

Fig. 10.2 Notional range of application of different aspects of forecast methodology (WMO 2008, courtesy of WMO)

the same forecasting approach year round for a range of applications can bring financial, operational and other advantages although typically requires more effort during the initial model development phase. In this approach (see Chaps. 5 and 13), estimates for catchment runoff are generated from a semi-distributed network of rainfall-runoff models, and the resulting flows are then routed through the river network using flow routing or hydrodynamic models. Some drought-related examples include systems from South Africa (Fair et al. 2003) and the UK (Huband and Sene 2005; Moore et al. 1989).

Real-time inputs to these types of models usually include raingauge or weather radar observations of rainfall plus rainfall forecasts, in deterministic or ensemble form, and observations of river and reservoir levels. As for supply demand models, for drought forecasting applications, some aspects which usually require particular attention include the linkages between surface water flows and groundwater abstractions and the influences of abstractions and return flows on river flows.

Distributed models of the types described in Chaps. 5 and 9 provide another option. For example, in the Netherlands a national drought forecasting system provides estimates of surface, groundwater and soil conditions to support decisions on allocation of water to different users (agriculture, navigation, industry, etc.). The system is driven by observed precipitation and evaporation and deterministic and ensemble meteorological forecasts and incorporates surface water and water distribution models coupled with a groundwater model of the saturated-unsaturated zone for the whole country (Weerts et al. 2009).

The choice of forecasting approach usually depends on a range of factors, including the lead times required, the level of risk, flow response times, budgets, staff skills and the forecasting system (if any) available for model operation. Chaps. 5, 7 and 8 discuss these issues in more detail together with topics such as probabilistic forecasting, data assimilation, forecast verification and risk-based decision-making techniques.

10.3.2 Agricultural Drought

Agricultural droughts typically arise when the soil moisture available to crops decreases due to a lack of sufficient rainfall or irrigation water. Dry weather conditions also have the potential to affect evapotranspiration rates with consequences for the amount of water required (see Chap. 6). Some potential influences on crop yields include soil water holding capacity, crop condition (e.g. diseases and pests), the drought resistance of individual crops and the impacts of any water restrictions that are imposed. Crop planting schedules also need to be considered; for example, WMO (2006) notes that 'the effects of drought on crop yield may vary considerably for maize, wheat, soybeans and sorghum because they are planted at different times during the growing season and do not have the same water requirements and sensitivities to water and temperature stress at various growth stages'.

Depending on when water shortages become apparent in the growing season, some possible responses could include:

- Obtaining supplementary sources of irrigation water
- Changing application rates of fungicides and pesticides
- Greater use of crop protection and soil water conservation measures such as weeding and mulching
- Deciding to plant more drought-resistant crops
- Changing sowing/planting and harvest dates and the mixture/spacing of crops

At a regional or national scale, other possible measures include rationing, stockpiling and importing of food supplies (e.g. UN/ISDR 2009). The lead times required for some of these decisions typically vary from days to weeks ahead for crop management issues through to longer-term financial and strategic decisions such as on the types of crop to plant and import arrangements (e.g. Laughlin and Clark 2000; Meinke and Stone 2005; Sivakumar 2006; WMO 2012b).

To help to assess the impacts of drought, one approach is to use trend or multiple regression relationships to relate crop yields to anticipated climate conditions (e.g. Boken et al. 2005; Funk and Brown 2006). Typically, these approaches make use of recent survey information on factors such as current soil moisture conditions and crop growth, leaf area index and rooting depths. River flow and supply-demand forecasts, of the types described in the previous section, can also provide information on the amount of water potentially available for irrigation.

Crop simulation models of the types described in Chap. 6 are a more sophisticated approach. Models can be operated at a range of scales, from field scale through to catchment, regional or national level, with different types of inputs appropriate at each scale (e.g. Stone and Meinke 2005; Hansen et al. 2006). Decision support services which make use of these types of model are increasingly offered by agrometeorological services, research organisations and the private sector for a range of weather-related hazards. As in other areas of drought early warning, risk-based approaches are increasingly used; for example, based on forecasts it might make sense to increase production in average to good years and take precautionary measures in drier years. However, this is only possible if forecasts are credible and appropriate methods are in place for the dissemination of appropriate information to potential users (Vogel and O'Brien 2006).

These types of approaches are also used by some national meteorological services and international agencies to offer regional or continental scale services. Typically, satellite observations are a key source of information, considering factors such as crop development, soil moisture, evapotranspiration and irrigated or flooded areas. Some typical indices used in monitoring crop areas and condition include the Normalised Difference Vegetation Index (NDVI) (see Table 10.4) and Leaf Area Index (LAI).

In Europe, for example, the MARS (Monitoring Agricultural ResourceS) programme of the Joint Research Centre provides crop yield forecasts at a European scale and internationally. Regular bulletins are issued throughout the year including a meteorological assessment (temperature, evapotranspiration, rainfall and water balance), map-based summaries (e.g. Fig. 10.3) and anticipated crop yields and more detailed analyses at a country or regional level. Special bulletins are sometimes issued, together with interim climatic updates, based on observations and meteorological forecasts. Crop development is estimated using an approach called the Crop Growth Monitoring System, which uses meteorological, soil and crop parameters as inputs to a range of statistical and generic crop simulation models, with statistical post-processing of model outputs.

Some other examples of operational agrometeorological forecasting systems at a national or international scale include:

- *The Crop Watch System* from China which reports on items such as crop growing condition, crop production, and crop structure using a combination of ground-based observations and remote sensing (Bingfang 2007). A range of drought indices is used, based on vegetation-condition and temperature indices and soil moisture conditions. Bulletins and newsletters are published providing information on crop conditions throughout China and a number of other countries (http://www.cropwatch.com.cn/).
- *The National Agricultural Monitoring System (The Monitor)* which provides information on historical, current and emerging climatic and agricultural conditions across Australia (http://www.daff.gov.au). More than 100 types of map, graph and other types of output are available, including historical and current rainfall and temperature data, predicted wheat and sorghum yields and simulated pasture growth and various economic indicators.

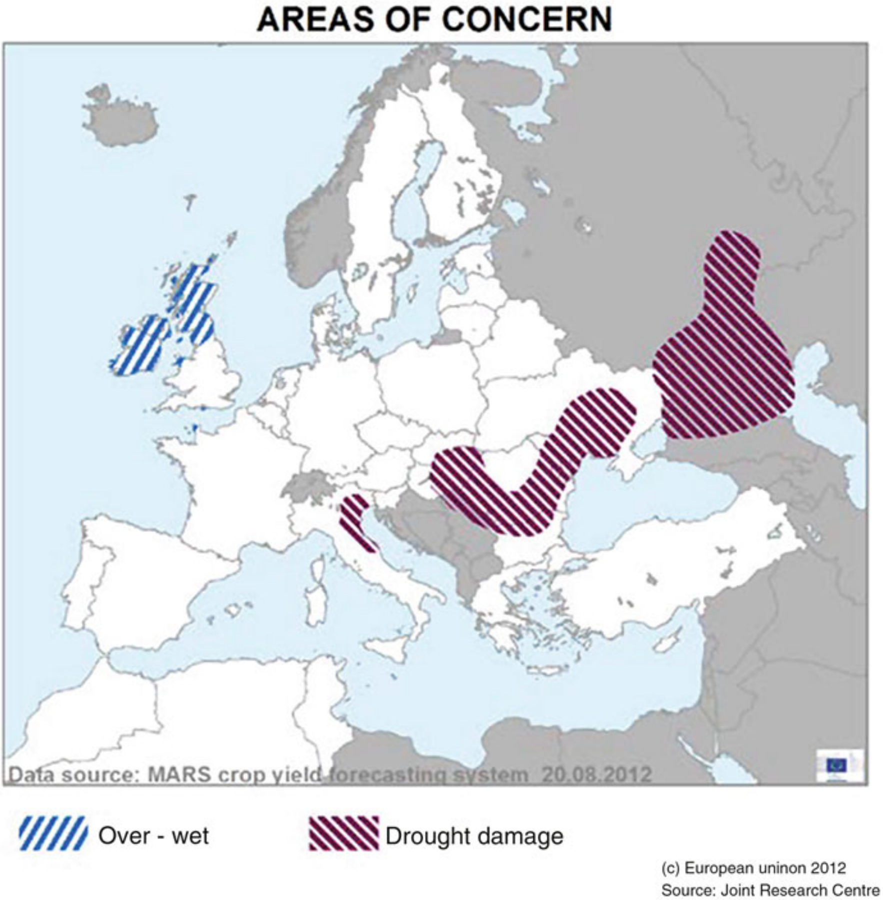

Fig. 10.3 Example of Areas of Concern Map from the MARS Crop Monitoring in Europe Bulletin issued on 27 August 2012 (JRC/IES MARS 2012, © European Union, 2012)

Another application of drought forecasting techniques is in famine early warning systems. Often the focus is on meteorological drought since many subsistence economies rely mainly on rainfed agriculture for both crops and livestock production. Systems of this type typically make use of satellite precipitation estimates and remote sensing of vegetation cover and reports from local staff and other agencies on the current situation. Some examples of indicators of potential stress include crop yields, food and livestock prices, the incidence of health-related and nutritional problems and other risk indicators such as border closures due to civil unrest (e.g. UN/ISDR 2009; Brown 2008). Crop simulation and water supply demand models are sometimes used to better assess the likely impacts at a more local scale.

Some notable examples include FEWS NET, which is described in Box 10.1, and the Global Information and Early Warning System (GIEWS) on food and agriculture which is operated by the United Nations Food and Agriculture Organization. In the case of GIEWS, this provides local and regional situation reports and bulletins on crop prospects and the food situation worldwide based on satellite observations of land cover, vegetation and land use and locally collected information on food supply and demand, livestock and markets (http://www.fao.org/giews). Computer software is available to participating countries and organisations for viewing satellite and other outputs in near real time alongside database entries for items such as on crop types and demographic information (FAO 2015).

Box 10.1: FEWS NET Famine Early Warning System

The Famine Early Warning System (http://www.fews.net) was established in 1985, partly in response to devastating famines in East and West Africa. The system is implemented as an inter-agency partnership between the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the United States Geological Survey (USGS) and the United States Department of Agriculture (USDA). Overall coordination and funding is provided by the United States Agency for International Development (USAID), with support from a range of regional and national organisations. The focus of FEWS NET is primarily on Africa but also extends to parts of Central America, the Caribbean and Central Asia. Forecasts and early warnings are issued from a network of regional and national field offices and some typical duties for field personnel (Brown 2008) include:

- Hazard monitoring, early warning and hazard impact assessment: Field personnel identifies and monitor both natural (e.g. droughts, extreme weather events, frost) and socio economic hazards (e.g. food price increases, proposed changes in food-related policies, conflict, border closures, infrastructure failures, etc.) with an objective of delivering early warning of an imminent threat to food security. If the hazard actually occurs, field personnel will assess the impacts it has on household food-related livelihood conditions and market systems
- Food security and vulnerability monitoring and assessment: At least once every month, FEWS NET field personnel will assess and report on food access, food availability and food utilisation conditions, as well as the risks and hazards that affect them, in conjunction with other partners

(continued)

Box 10.1 (continued)

Some key products from FEWS NET include regular Food Security Outlooks and Updates, and shorter Alert statements which use an internationally accepted 5-stage alerting system applied at household and area scale (IPC Global Partners 2012). Web-based products are also available, such as maps showing food security (current status and outlook), weather hazards, and satellite imagery. More in-depth studies are made on topics such as livelihoods and markets to provide additional information to support the analyses as well as programme and policy development. Users of the information can range from farmers and cooperative members in remote locations through to regional and government organisations, donor agencies and voluntary organisations.

The hydrometeorological inputs to the system are primarily from remotely sensed data, with an emphasis on deriving indicators that are as close to measuring the actual problem as possible. For example, rather than providing rainfall anomalies, models are used to show the impact of these anomalies on maize, millet and other crop yields at each stage of their productive cycle (Brown 2008). Impact assessments are performed in terms of livelihood zones (Table 10.5), which consist of geographic areas with relatively homogeneous ecological and economic characteristics, such as the approaches that households use to access food and income, which allows meaningful results to be presented over large geographical areas.

Table 10.5 Description of a few main rural livelihoods

Rural livelihoods	Description
Agriculture	Commercial agriculture
	Subsistence grain farming (highland, midland, lowland)
	Mixed cash-crop/grain farming
	Agri-horticulture
Livestock Production	Commercial ranching (dairy/meat farming)
	Pastoralism
Agro-Pastoralism	Mixed agriculture-livestock production
Fishing	Off-shore (ocean-based)
	In-shore (lake/river based)
	Mixed agro-fishing
Labor-Based	Plantation/ranch/commercial farm worker
	Migratory labor
	Mining labor
Hunter-Gatherer	Forest-based subsistence economy

Adapted from FEWS NET livelihood profiles (Brown 2008)

(continued)

Box 10.1 (continued)

Regarding hydrometeorological information, some key contributions from FEWS NET partners (http://www.fews.net) include:

- NOAA's Climate Prediction Center provides regular weather forecasts and longer-term seasonal outlooks, highlighting trends, hazards and anomalies.
- NASA's Applied Sciences Program conducts interdisciplinary research and develops land-surface models on vegetation and water availability.
- USGS's Earth Resources Observation and Science Center analyzes remote sensing and geospatial data on vegetation, rainfall, and water use to produce country and region specific depictions related to the growing season.

For example, rainfall estimates are used as inputs to a soil water balance model which considers crop water requirements and soil types. Outputs include estimates for the Water Requirement Satisfaction Index (WRSI), which is an indicator of crop performance based on the availability of water to the crop during a growing season, and a Moisture Index, which relates rainfall to current soil water content (Senay and Verdin 2003; Verdin and Klaver 2002; Verdin et al. 2005).

10.4 Summary

- Droughts typically arise from a shortfall in precipitation, usually in terms of rainfall but sometimes a lack of snow in headwater regions. Droughts are usually classified in terms of their impacts on the hydrological cycle, and a typical sequence is to progress from a meteorological drought to soil moisture and hydrological droughts, which may be further subdivided into streamflow and groundwater droughts. Some potential consequences include agricultural and socioeconomic droughts.
- Some key challenges in forecasting the onset and progression of a drought typically include the slow rate of onset and the wide spatial extent of the impacts. Information therefore needs to be combined from many sources and is often interpreted using risk-based techniques. There is an increasing trend to move from simply responding to droughts to a more proactive multi-agency approach to risk reduction.
- Some key inputs to drought monitoring and warning systems usually include satellite-based, river, rainfall and catchment observations and meteorological forecasts. Decisions to issue alerts or warnings or escalate the response are typically made on the basis of threshold values, defined in terms of rainfall, reservoir, groundwater and river flow observations and drought indices. The key decision criteria need to be developed in consultation with key stakeholders and the performance regularly assessed.
- For streamflow forecasting, modelling techniques range from simple empirical approaches such as recession techniques to supply demand, distributed and integrated catchment models. However, the choice of modelling approach is sometimes limited by the quality and availability of data, both for real-time use and model calibration.

- Statistical and crop simulation models are an integral part of most agricultural monitoring systems at a regional scale with an emphasis on satellite-based model inputs. Information is typically made available via websites and bulletins. Similar techniques are used in famine early warning systems although supplemented to a greater extent by 'on-the-ground' information on the current situation.
- Some research needs in drought forecasting include improvements to seasonal forecasting techniques, probabilistic and risk-based decision-making techniques and the methods used to post-process meteorological forecasts to hydrological scales of interest. In many countries there are potentially major gains from improvements to monitoring and warning dissemination systems and through training and capacity building in these areas.

References

Below R, Grover-Kopec E, Dilley M (2007) Documenting drought-related disasters. A global reassessment. The Journal of Environment & Development, 16(3): 328–344

Bingfang W (2007) Introduction of China CropWatch system with remote sensing. ISPRS Archives XXXVI-8/W48 Workshop proceedings: Remote Sensing Support to Crop Yield Forecast and Area Estimates, Stresa, Italy (Eds. Baruth B, Royer A, Genovese G), 30 November–1 December 2006

Boken VK, Cracknell AP, Heathcote RL (2005) Monitoring and Predicting Agricultural Drought: A Global Study, Oxford University Press, Oxford

Brown ME (2008) Famine Early Warning Systems and Remote Sensing Data. Springer-Verlag, Berlin, Heidelberg

Chiew FHS, McMahon TA (2002) Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. Hydrological Sciences Journal, 47: 505–522

Fair KA, McKenzie RS, Craig AR (2003) Using real time data and a flow prediction model to assist in the operation of the Orange River. In Early Warning Systems for Natural Disaster Reduction (Eds. Zschau J, Kueppers AN), Springer, Berlin

FAO (2015) GIEWS: The Global Information and Early Warning System on food and agriculture. Information Booklet, Food and Agriculture Organization of the United Nations, Geneva

Funk CC, Brown M (2006) Intra-seasonal NDVI change projections in semi-arid Africa. Remote Sensing of Environment, 101(2): 249–256

Glantz MH (convener) (2004) Usable Science 8: Early Warning Systems: Do's and Don'ts Report of Workshop, Shanghai, 20 – 23 October 2003

Guha-Sapir D, Hargitt D, Hoyois P (2004) Thirty years of natural disasters 1974–2003: the numbers. Centre for Research on the Epidemiology of Disasters (CRED) Report. UCL Presse Universitaires de Louvain, Brussels

Gustard A, van Lanen HAJ, Tallaksen LM (2004) Outlook. Chapter 12 in Hydrological drought: processes and estimation methods for streamflow and groundwater. Developments in Water Science 48 (Eds. Tallaksen L M, Van Lanen HAJ), Elsevier, Amsterdam

Hansen JW, Challinor A, Ines A, Wheeler T, Moron V (2006) Translating climate forecasts into agricultural terms: advances and challenges. Climate Research, 33: 27–41

Hayes MJ (2015) Drought Indices. The National Drought Mitigation Center, Lincoln, Nebraska. http://www.drought.unl.edu/

Hoerling M, Kumar A (2003) The perfect ocean for drought. Science, 299(5607): 691–694

Huband M, Sene KJ (2005) Integrated catchment modelling issues for flow forecasting applications. Scottish Hydraulics Study Group, Catchment Modelling for Flood Risk Management, 18 March 2005

IPC Global Partners (2012) Integrated food security phase classification technical manual Version 2.0. Evidence and standards for better food security decisions. FAO, Rome

JRC/IES MARS (2012) Crop monitoring in Europe. MARS Bull 20(8). AGRI4CAST (JRC/IES MARS Unit), Publications Office of the European Union

Knutson CL, Svoboda MD, Kluck DR (2005) A pilot program for a low flow impacts database at the National Weather Service. AMS Forum: Living with a Limited Water Supply, San Diego, 9–13 March 2005

Laughlin G, Clark A (2000) Drought science and drought policy in Australia: a risk management perspective. Expert Group Meeting on Early Warning Systems for Drought Preparedness and Drought Management, Lisbon, Portugal, 5–7 September 2000

Manatsa, D., Matarira, C.H., Mukwada, G. (2011) Relative impacts of ENSO and Indian Ocean dipole/zonal mode on east SADC rainfall. International Journal of Climatology, 31(4): 558–577

Masih I, Maskey S, Mussá FE F, Trambauer P (2014) A review of droughts on the African continent: a geospatial and long-term perspective, Hydrol. Earth Syst. Sci., 18: 3635–3649

McKee TB, Doesken NJ, Kleist J (1995) Drought monitoring with multiple time scales. Ninth Conference on Applied Climatology. American Meteorological Society, Boston

Meinke H, Stone RC (2005) Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. Climatic Change, 70: 221–253

Moore RJ, Jones DA, Black KB (1989) Risk assessment and drought management in the Thames basin. Hydrological Sciences Journal, 34(6): 705–717

Mwangi E, Wetterhall F, Dutra E, Di Giuseppe F, Pappenberger F (2014) Forecasting droughts in East Africa, Hydrol. Earth Syst. Sci., 18: 611–620

NIDIS (2007) The National Integrated Drought Information System Implementation Plan. A Pathway for National Resilience. http://www.drought.gov/

NDMC (2014) What is the US Drought Monitor? National Drought Mitigation Centre, Lincoln, Nebraska

NOAA (2015) California drought: 2014 service assessment. US Department of Commerce, National Oceanic and Atmospheric Administration

Palmer WC (1965) Meteorological drought. Research Paper No. 45, US Weather Bureau, Washington, USA

Palmer WC (1968) Keeping track of crop moisture conditions, nationwide: the new crop moisture index. Weatherwise, 21(4): 156–161

Palmer T, Hagedorn R (Eds.) (2006) Predictability of Weather and Climate. Cambridge University Press, Cambridge

Peterson TC, Hoerling MP, Stott PA, Herring SC (2013) Explaining extreme events of 2012 from a climate perspective. Bulletin of the American Meteorological Society, 94(9): S1–S74

Ropelewski CF, Folland CF (2000) Prospects for the prediction of meteorological drought. In Drought: A Global Assessment (Ed. Wilhite DA). Natural Hazards and Disasters Series, Routledge, London, New York

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401: 360–363

Samra JS (2004) Review and Analysis of Drought Monitoring, Declaration, and Management in India. Working Paper 84, International Water Management Institute

Senay GB, Verdin J (2003) Characterisation of yield reduction in Ethiopia using a GIS-based crop water balance model. The Canadian Journal of Remote Sensing, 29(6): 687–692

Shafer BA, Dezman LE (1982) Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In Proceedings of the Western Snow Conference, Colorado State University, Fort Collins, Colorado

Sivakumar MVK (2006) Climate prediction and agriculture: current status and future challenges. Climate Research, 33: 3–17

Smith K (2012) Environmental Hazards: Assessing Risk and Reducing Disaster. (6th Ed.). Routledge, London and New York

Stone RC, Meinke H (2005) Operational seasonal forecasting of crop performance. Philosophical Transactions of the Royal Society B: Biological Sciences, 360(1463): 2109–2124
Svoboda M, Lecomte G, Hayes M, Heim R, Gleason K, Angel J, Rippey B, Tinker R, Palecki M, Stooksbury D, Miskus D, Stephens S (2002) The Drought Monitor. Bulletin of the American Meteorological Society, 83(8): 1181–1190
Tallaksen LM, Van Lanen HAJ (2004) Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science 48, Elsevier, Amsterdam
Troccoli A, Harrison M, Anderson DLT, Mason SJ (2008) Seasonal Climate: Forecasting and Managing Risk. NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht
UN/ISDR (2009) Drought risk reduction framework and practices: Contributing to the implementation of the Hyogo Framework for Action. United Nations Secretariat of the International Strategy for Disaster Reduction (UN/ISDR), Geneva
USACE (1994) Managing water for drought. National Study of Water Management during Drought. IWR REPORT 94-NDS-8
Verdin J, Klaver R (2002) Grid cell based crop water accounting for the Famine Early Warning System. Hydrological Processes, 16: 1617–1630
Verdin J, Funk C, Senay G, Choularton R (2005) Climate science and famine early warning. Philosophical Transactions of the Royal Society B, 360: 2155–2168
Vogel C, O'Brien K (2006) Who can eat information? Examining the effectiveness of seasonal climate forecasts and regional climate-risk management strategies. Climate Research, 33: 111–122
Weerts AH, Berendrecht WL, Veldhuizen A, Goorden N, Vernimmen R, Lourens A, Prinsen G, Mulder M, Kroon T, Stam J (2009) Drought Forecasting System of the Netherlands. Geophysical Research Abstracts, Vol. 11, EGU2009-1765-2, EGU General Assembly 2009
Western Governors' Association (2004) The National Integrated Drought Information System: Creating a Drought Early Warning System for the 21st Century
Wilhite DA, Glantz MH (1985) Understanding the drought phenomenon: the role of definitions. Water International, 10: 111–120
Wilhite DA (Ed.) (2000) Drought: A Global Assessment. Natural Hazards and Disasters Series, Routledge, London, New York
Wilhite DA (Ed.) (2005) Drought and Water Crises: Science, Technology, and Management Issues. CRC Press, Boca Raton, FL
Wilhite DA, Knutson CL (2008) Drought management planning: conditions for success. Options Mediterraneennes Series A, 80: 141–148
WMO (2000) Proceedings of an Expert Group Meeting (Eds. Wilhite DA, Sivakumar MV K, Wood DA), Lisbon, Portugal, September 5–7, 2000. WMO/TD No. 1037, Geneva
WMO (2006) Drought Monitoring and Early Warning: Concepts, Progress and Future Challenges. WMO-No. 1006, Geneva
WMO (2008) Manual on low-flow estimation and prediction. Operational Hydrology Report No. 50, WMO-No. 1029, Geneva
WMO (2009a) Regional climate outlook forums. Flyer 1.4, Geneva
WMO (2009b) Guide to hydrological practices, 6th edn. WMO-No. 168, Geneva
WMO (2011) Integrated Drought Management Programme: Building Drought Resilience to Reduce Poverty. Concept Note plus flyer (2014), World Meteorological Organisation/Global Water Partnership, Geneva
WMO (2012a) Standardised Precipitation Index: User Guide. WMO-No. 1090, Geneva
WMO (2012b) Guide to Agricultural Meteorological Practices (GAMP) (2010 edition – updated in 2012). WMO-No.134, Geneva
WMO (2014) Atlas of mortality and economic losses from weather, climate and water extremes (1970–2012). WMO-No. 1123
WMO/GWP (2014) National Drought Management Policy Guidelines: A Template for Action (Wilhite DA). Integrated Drought Management Programme (IDMP) Tools and Guidelines Series 1. World Meteorological Organisation, Geneva, Global Water Partnership, Stockholm

Chapter 11
Flow Control

Abstract Hydraulic structures such as dams, weirs and barrages are widely used to manage flows and control river levels. This chapter provides an introduction to techniques for forecasting the impacts of structure operations ranging from real-time applications to long-term planning studies. This includes a discussion of the role of ensemble techniques and decision support systems. Two specific applications are also discussed in more detail, namely the operation of tidal barrages and real-time control systems for urban drainage networks.

Keywords Hydraulic structure • River • Reservoir • Dam • Tidal barrier • Urban drainage • Decision support system • Flow control • Real-time control

11.1 Introduction

Many river catchments contain hydraulic structures which influence river levels and flows. Figure 11.1 shows some examples and Table 11.1 summarises some typical applications. One key distinction between types of structure is the extent to which they can be actively controlled. For example, most weirs and reservoir spillways have no mechanism with which to regulate flows, whereas tidal barriers and hydropower schemes often have sophisticated monitoring and control systems. Manually operated structures are also commonplace, particularly for canal systems and in irrigation schemes. For some larger schemes, such as major dams, there may be staff permanently on site for routine operations and maintenance and in case problems occur. Another option is for gate settings to be triggered remotely via a telemetry system.

Chapter 6 provides more background on the operation of irrigation and hydropower schemes, and Chap. 3 discusses river gauging structures in more detail. The upstream and downstream influences vary widely depending on the type of structure, and Table 11.2 provides some examples although – as noted for weirs – there may be significant differences in flow regime under flood conditions. For example, culverts sometimes become surcharged or backwater influences arise from locations further downstream, such as bridge decks and pipeline crossings if they become submerged.

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Fig. 11.1 Illustration of some types of hydraulic structures; clockwise from *top left*: (**a**) sluice gates at an off-line flood detention area, (**b**) culvert in urban area, (**c**) river tide gates, (**d**) irrigation-scheme barrage

Table 11.1 Some examples of applications of hydraulic structures

Application	Typical examples	Description
Coastal flood risk	Tidal barriers, flap gates, tide gates	Barrages which are raised (or lowered) to help protect inland areas during high tides and possibly surge events, plus simpler structures such as flap gates and automatically controlled tide gates
Flood control	Dams, off-line reservoirs, flow diversion channels	Reservoirs with flood storage capacity and washlands and other flood detention areas to store flood flows temporarily to reduce impacts further downstream; also diversion channels to divert flows to lower-risk areas
Hydropower	Dams, barrages, flow diversions	Run-of-river schemes and dams to regulate and, in some cases, store flows for hydropower generation and flow diversion weirs for micro-hydropower schemes
Irrigation	Barrages, weirs, gates, dams	Weirs and barrages to raise water levels for supply to irrigation canals, gates to regulate the rate of abstraction, reservoirs to store water for later use
Navigation/shipping	Locks, gates, barrages	Gates and other structures to maintain river levels for navigation, and lock gates in canals
River gauging	Weirs, flumes	Purpose-made structures for monitoring river flows such as Crump weirs and thin-notch weirs
Water supply	Dams, pumped river offtakes	Reservoirs to store water and pumped or gravity-fed abstraction points in river systems

Table 11.2 Examples of some typical impacts of river control structures on river conditions when in operation; exceptions may occur

Structure	Upstream influences	Downstream influences
Barrage	Increases in river levels and reductions in flows, acting as a small -scale 'reservoir'	Dependent on the type and purpose of the barrage, but for some irrigation schemes, the bulk of the river flow is withdrawn in dry periods (subject to environmental flow requirements)
Dams	In some cases, backwater influences into tributaries at high reservoir levels	Again dependent on the type and purpose of the dam; Sect. 11.2 discusses this topic in more detail
Pumped or gravity-fed abstractions	Usually only minor local influences	Variations in levels and flows linked to abstractions for irrigation and water supply, in some cases leading to the appearance of quasi-sinusoidal variations in levels if water is abstracted at a similar time each day
Sluice	Raised levels upstream and reduced flow velocities locally	Reduced levels downstream and increased flow velocities locally
Tidal barrier, tide gate, flap gate	Increased levels when the structure is closed, in some cases with a flood risk	Not applicable except in narrow estuaries where there might be some increase in levels when the structure is closed
Weir	Raised levels upstream; some minor storage	Lowered levels downstream although in flood conditions some weirs 'drown' such that flows become non-modular (see Chap. 3)

Regarding tidal influences, these are discussed in more detail in Chaps. 5 and 8, but, in brief, at most coastal locations, there is a twice-daily tidal cycle, and gates are typically closed for up to a few hours either side of high tide, either year round or during exceptionally high tides. In the case of tidal flap gates, these are simple devices which close automatically when tide levels are high but open again at low tide due to the influence of river flows.

In a forecasting system, the extent to which structures are represented depends on the application and a range of other factors, such as the level of risk, budgets and the modelling software available (see Chap. 5). In some cases, a simple water balance or flow routing approach is adequate to model the impacts, but – where more detailed information is required on river flows and depths – often a hydrodynamic model is required, such as in the following applications:

- Ecologically sensitive sites – locations where slight changes in water depths and flow velocities could potentially have significant adverse impacts on habitat
- Impounding structures – situations where a structure, such as a barrage, has the potential to impound significant volumes of water in the river channel immediately upstream, presenting a flood risk

- Real-time control systems – structures at which frequent adjustments are made to settings on the basis of real-time observations of levels, flows and other variables and possibly forecast values
- Water level management – situations where levels need to be managed to within narrow bands for navigation, environmental, recreational or other purposes

In some cases, water quality impacts need to be considered such as influences on water temperatures, sediment transport or saline intrusion. For example, some typical considerations with reservoir operations include the impacts of variations in water temperatures on fisheries further downstream and of reductions in sediment load on fish spawning grounds and river geomorphology.

For controllable structures, traditional techniques such as charts and look-up tables are still widely used, particularly where the risks of failure are low or budgets limited. Typically, the actions to take – such as closing a gate or issuing a flood warning – are taken on the basis of observed levels, threshold values, operational needs and possibly other factors such as recent rainfall. Time-based rules are used in some situations, for example, linked to the daily tidal cycle.

For higher value or risk applications, decision support systems of the types discussed in Chap. 7 provide another option. However, due to the various uncertainties in observations and forecasts, this is normally to guide decision-making rather than for direct control of a structure, although there are exceptions such as when there are potential financial or safety benefits from a more dynamic approach. For example, during floods reservoir operators often face difficult decisions regarding the actions to take, with a need to balance the risks to the dam structure against the impacts that emergency flow releases could have on communities further downstream. In addition, there may be opportunity costs or losses if due to an incorrect decision water is released unnecessarily which could potentially have been used at a later date for water supply, irrigation or hydropower generation.

In some cases, a hydrodynamic modelling component is included, and typically this is programmed with logical rules to represent structure operations. For example, these might state that a sluice gate should be raised by 0.2 m or a radial gate rotated by 10° if river levels exceed a certain value. Rules can be surprisingly complicated for some structures, and when there are multiple structures in a river reach, feedback effects may need to be considered. However, some more general challenges in model development can include:

- Departures from operating rules – Operators often use different rules to those originally envisaged for a range of operational, economic or political reasons.
- Lack of documentation – The original design documents may no longer be available, particularly for older structures, and/or current procedures may not be fully documented.
- Operational issues – Full flow control may not be possible whilst parts of the structure are undergoing routine maintenance or due to longer-term issues such as the need for repairs due to flood damage or a lack of funds for maintenance.

Due to these types of issues, it sometimes requires a considerable amount of investigative work and exploratory modelling to determine how in practice a structure is operated. In addition, when there are multiple objectives, the decisions taken may vary significantly between events; for example, during development of a flood warning system for a river basin in Austria with several reservoirs, it was noted (Blöschl 2008) that:

> Future operation is decided by the operator on a case by case basis. The main factors that control future release are the technical characteristics of the reservoir system, legal constraints such as pre-releases, maximum operating levels and maximum release discharges under certain inflow conditions, anticipated inflow into the reservoirs, and other pieces of information that cannot be easily quantified, such as 15 min fluctuations of the market price of electricity, tourist activities and, in case of flooding, political considerations...(*continued*)...Because of this, the philosophy of developing the reservoir simulation routine was to mimic the decisions of the operator of the scheme in terms of released discharges for different situations rather than to minimise a cost function.

This chapter discusses these various modelling and forecasting issues for several types of hydraulic structure, with a particular focus on reservoir operations. The discussion begins (Sect. 11.2) with an introduction to forecasting techniques for a range of lead times, and Sect. 11.3 then describes two applications in which real-time decision support and control systems are widely used, namely for tidal barriers and urban drainage control systems. Further information is provided in the many textbooks and guidelines on these topics including publications by Chanson (2004), Novak et al. (2006) and WMO (2011). Chapters 3 and 9 also discuss a range of monitoring techniques relevant to hydraulic structures.

11.2 Forecasting Techniques

11.2.1 Reservoirs

Reservoirs are a common feature of many river basins. For example, a register maintained by the International Commission on Large Dams (ICOLD 2015) suggests that for single-purpose dams, irrigation is the main use followed by hydropower and then water supply. For multi-purpose dams, the key uses include irrigation, hydropower, water supply and flood control in roughly equal measure, followed by recreation, navigation and fish farming. Single-purpose dams represent about half of all dams. Here the basic requirement for inclusion in the register is ‘a structural dam height above foundation not less than 15 metres’.

Figure 11.2 shows some examples of types of dams. These are all of the in-stream type in which a reservoir is formed when a structure is placed across a river or at a lake outlet; alternative names include on-stream or in-line reservoirs. These types of dam usually have a spillway to avoid the risk of overtopping of the dam wall during floods and usually this is located at the dam, but sometimes at an offtake within the reservoir. Self-priming siphons are also used at some reservoirs and

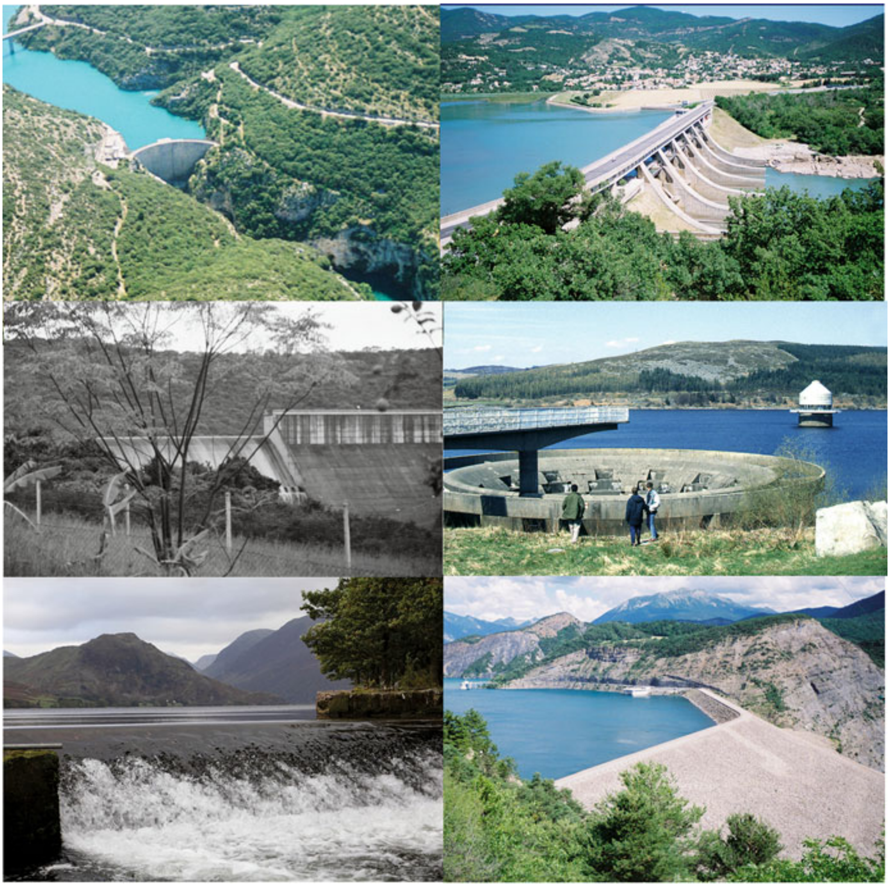

Fig. 11.2 Some examples of types of dams and spillways; from *top left clockwise*: (**a**) arch dam, (**b**) run-of-river hydropower scheme, (**c**) bellmouth spillway, (**d**) earth-fill dam with side tunnel outlets for hydropower generation and flood relief, (**e**) weir at lake outlet, (**f**) gravity dam with overflow spillway

activate automatically if critical levels are exceeded so as to rapidly draw down water levels.

In contrast, off-stream reservoirs are normally created by constructing earth embankments to enclose an area of land alongside a river. These are typically used for flood mitigation for areas further downstream, and some alternative names include off-line reservoirs, washlands or retarding basins. These should be distinguished from polders which have a similar appearance but for which the main purpose is to provide flood protection to the land enclosed by the embankments.

For larger off-stream reservoirs, there are often internal compartments to control which areas are flooded. River inflows are typically controlled by gates or sluices (e.g. as shown in Fig. 11.1) or an engineered spillway is provided with the crest below river bank heights to allow flows to enter before flood defence levels are reached.

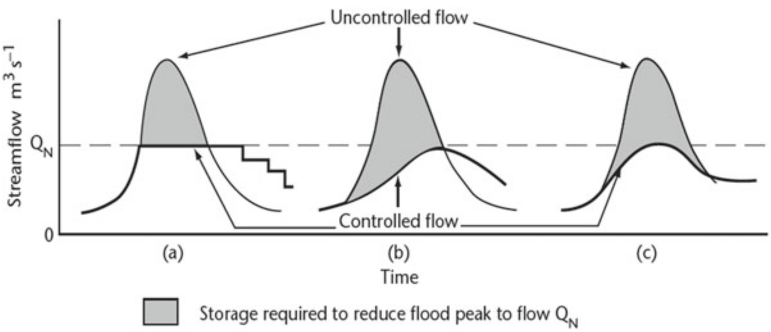

Fig. 11.3 Effects of reservoirs on floods: (**a**) regulated storage, (**b**) unregulated on-stream storage and (**c**) unregulated off-stream storage (WMO 2009, courtesy of WMO)

Some schemes include sacrificial embankment sections which are breached when required. Rather than leave the land within the reservoir unused, often it is made available for farming or recreation, or even some limited settlement if there are robust flood warning procedures in place. Usually there are agreements with local stakeholders regarding the conditions under which water will be stored and released; for example, at certain times of year or only during flood conditions.

For both in-stream and off-line reservoirs, flow releases are normally controlled using gates, sluices or valves. However, when reservoir levels are high, control may be lost to some extent due to spillway flows or – in the case of off-stream reservoirs – because river levels are too high to allow water to be released. Figure 11.3 illustrates some typical impacts on flows further downstream during flood conditions; in all cases, the effect is to reduce the magnitude of flows further downstream and in one case to delay the timing of the peak value.

The magnitude of these effects partly depends on the initial storage available in the reservoir at the start of the flood event. For example, some operators provide, or are required to maintain, spare capacity for flood storage at certain times of the year, and this is often called a flood buffer. Operating procedures sometimes include provision for a rapid emergency drawdown of levels if a major inflow is anticipated. In some cases, these are linked to economic incentives; for example, some flood regulation authorities rent buffer space from dam operators during the flood season, or have a compensation scheme in place so that local farmers receive payments if off-stream reservoirs are used.

The requirements for flood buffers, water supply, environmental flow releases and other objectives are usually encapsulated in a set of control rules, which are sometimes called rule curves or steering rules. Typically, these take the form of monthly or seasonally varying values which define how a reservoir should be operated depending on current levels or storage; for example, indicating whether levels are high enough to allow water to be supplied as required or if restrictions need to be imposed. In addition, the levels corresponding to spillway flows and dead or inactive storage are usually indicated.

In many cases, there is a need to keep a balance between the short-term (tactical) response, such as releasing water to meet immediate demands, and the longer-term strategic objectives of maintaining sufficient water to meet water supply and other requirements. The longer-term operating plan then provides overall constraints on short- to medium-term operations, such as minimum allowed reservoir levels at a given time of the year. For large reservoirs or multiple reservoir systems, strategic objectives may extend over periods of years, rather than months. This is particularly the case in arid and semiarid regions where a large reservoir capacity is needed to compensate for high inter-annual variations in rainfall and inflows and the large evaporation losses.

Control rules are normally derived on the basis of reservoir simulations using long-term inflow records or stochastically generated records. These are then refined as experience is gained with reservoir operations and can be complex, particularly for large multi-purpose reservoirs and multi-reservoir systems. Linear, non-linear and dynamic programming techniques are widely used in rule derivation (e.g. Loucks 1989; Wurbs 1992; McMahon and Adeloye 2005). However, it has long been recognised that a more dynamic approach to reservoir operations could help to maximise benefits (e.g. Yeh 1985), and this topic is discussed further in Sect. 11.2.2.

For flood control operations, in addition to the timing and magnitude of the current threat, a key question of interest is often whether this will be followed by further events, such as when a succession of storms is passing over a region. For example, it can take many hours to free up sufficient storage capacity in advance of the next event. Similar levels of complexity arise in many other applications, such as in hydropower scheduling where fluctuations in electricity demands and spot-price markets need to be considered at a range of timescales (see Chap. 6).

Real-time forecasting models therefore have a valuable role to play in assessing the likely impacts on reservoir levels and outflows, and Table 11.3 provides some examples of the types of information required for model development and operation. Regarding the reservoir model in some cases a simple water balance or flow routing approach is sufficient of the types discussed in Chaps. 5 and 13. However, if more precise information is required on reservoir levels, then a real-time hydrodynamic model is usually required, perhaps including water quality and ecological components, as discussed further in Chaps. 5 and 12.

However, in practice a key challenge in calibrating a model is that in many cases the only records available are for reservoir levels and possibly for gate releases and/or flows at a gauging station further downstream. Where this is the case, this typically requires some exploratory modelling to determine if developing a model is feasible; for example, whether it is possible to relate operating rules in a plausible way to known quantities such as reservoir levels. Some typical techniques used in this type of analysis include:

- Net inflows – analyses of observed reservoir levels and outflows to infer the net inflows from a reservoir water balance equation
- Spillway flows – estimation of spillway flows from reservoir levels using a weir-type formulae or from hydraulic modelling studies
- Tributary inflows – estimation of ungauged inflows using parameter transfer, scaling or regionalisation techniques as discussed in Chap. 5

Table 11.3 Some examples of the types of information ideally required for a reservoir or lake forecasting model

Item	Description
Inflows	In addition to the main river flow, in some cases there may be significant inflows from tributaries around the shoreline, particularly for large lakes or reservoirs (see Chap. 5 for estimation techniques). In multi-reservoir systems, inflows may consist of regulated flows from reservoirs further upstream plus natural runoff from incremental catchment areas
Meteorological conditions	Precipitation monitoring options include raingauges and weather radar and possibly satellite precipitation estimates for large catchment areas (see Chap. 2). Rainfall forecasting options include the outputs from nowcasting and numerical weather prediction models and possibly statistical techniques at seasonal timescales (see Chap. 4). Air temperature information is required if snowmelt is an issue, and direct rainfall and evaporation at the water surface is sometimes a significant component in the water balance
Demands / releases	Forecasts for the likely release schedule either in terms of aggregated demands or as component parts; for example, for hydropower, irrigation or water supply (see Chap. 6) and interbasin/reservoir transfers
Level-storage-area relationship	Initial estimates are often available from the original design studies before the reservoir was filled although the accuracy of the survey should be evaluated, particularly if based on satellite observations or orthophoto estimates. The reservoir capacity may have been affected by sedimentation since it was commissioned, and in some cases, this requires a bathymetric survey to define the current level-storage-area relationship more precisely, combined with ground-based or LiDAR survey for surrounding areas below the maximum envisaged water level
Outflows	For regulated storage, outflows are typically controlled at gates, sluices or valves. For in-stream reservoirs, uncontrolled spillway and possibly siphon flows are another factor to consider once reservoir levels rise above the crest level of the spillway(s). Seepage at the dam wall or within the reservoir sometimes needs to be considered

For high-risk locations, it is often desirable to extend the monitoring network so that all key inflow, outflow and gate setting terms are recorded to assist both with real-time operations and future modelling studies. The main types of forecasting techniques include:

- Integrated catchment models – rainfall-runoff, flow routing and possibly hydrodynamic models to represent river flows at a catchment scale, with a more detailed model for the reservoir(s) (see Chap. 5)
- Supply demand models – water balance techniques to represent abstractions, discharges and other gains and losses to the system, in some cases with inflows derived using rainfall-runoff models (see Chap. 13)

Due to the inherent uncertainties in observations and meteorological forecasts, probabilistic techniques are widely used, particularly at longer lead times. For example, Fig. 11.4 shows a research-oriented product for the Great Lakes which provides probabilistic forecasts for water levels based on ensemble meteorological inputs to lake models. For comparison observed levels are shown from 1860 plus the 3-month ahead forecasts for the previous year.

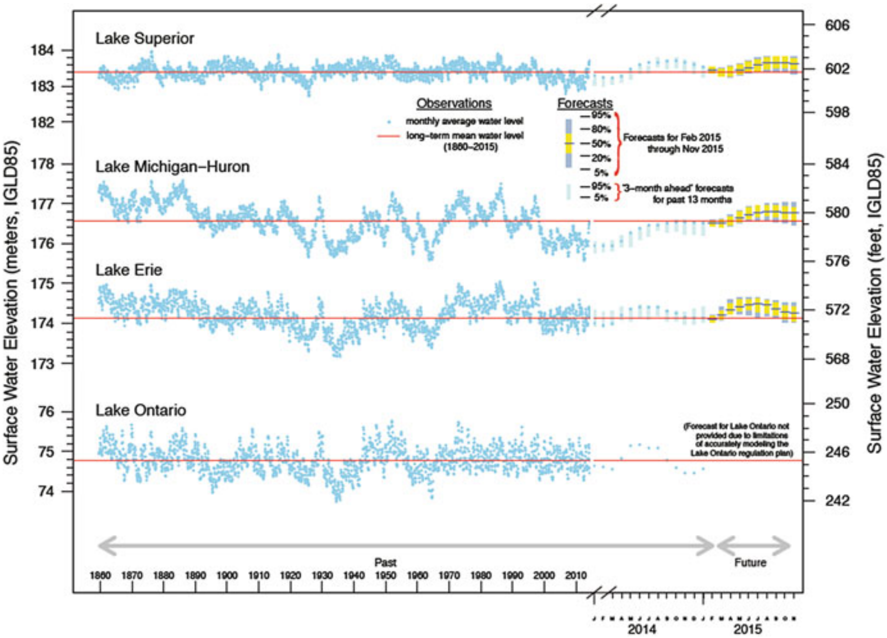

Fig. 11.4 A research-oriented forecast generated by NOAA-GLERL's Great Lakes Advanced Hydrologic Prediction System (AHPS) on 5 February 2015 based on observed weather patterns and Great Lakes water levels from 1948 to present, along with NOAA Climate Prediction Center's regional forecasts (NOAA/GLERL 2015; image courtesy of NOAA, Great Lakes Environmental Research Laboratory)

Perhaps, the longest-established probabilistic approach is that of Ensemble Streamflow Prediction which is described in Chap. 5 and is based on sampling from long-term historical records for rainfall and air temperatures. The resulting values are then used as inputs to the rainfall-runoff component of the forecasting model to derive probabilistic estimates for the reservoir inflows, using current catchment states as a starting point. Other options include the direct use of ensemble rainfall and air temperature forecasts and of statistical seasonal forecasting techniques, and these approaches are discussed further in Chaps. 8 and 13, including some reservoir-related examples. 'What-if' scenarios also provide a simpler qualitative approach in which model runs are repeated using different scenarios such as for future precipitation values or gate settings.

11.2.2 Multi-purpose Operations

In real-time operation, software tools are increasingly used to help to guide operators on the most appropriate actions to take, particularly in high-risk applications. Whilst in some cases operating rules reduce to binary decisions such as to close

Table 11.4 Some examples of operational objectives for a reservoir system

Objective	Description
Environmental	To regulate outflows so as to maintain levels, flows and water temperatures within a suitable range for protected species and fisheries
Flood control	To minimise flood damages further downstream and also minimise opportunity losses due to unnecessary flow releases or penalty payments
Hydropower	To meet electricity demands, maximise revenue and avoid penalties or reputational damage due to failures to meet demand, including under peak load conditions
Irrigation	To meet irrigation demands throughout the crop growing season(s), ideally using gravity-fed rather than more expensive pumped supplies where possible
Navigation	To provide sufficient flow depth for boats and ships in rivers downstream from reservoirs and regulated lakes
Recreation	To maintain water levels high to allow access from piers and for visual amenity
Water supply	To supply water to a given reliability and quality year-round including short-term spikes in demand and allowing for any pollution/turbidity issues

gate X if Y occurs, often the decision-making process is considerably more complex than this and includes multiple, competing objectives. For example, Table 11.4 summarises some typical objectives for reservoir operations.

Although originally developed for reservoir design, the linear, non-linear and dynamic optimisation techniques mentioned in the previous section are sometimes used in near real time; for example, to update reservoir release plans on a regular basis (e.g. Loucks 1989; Yeh 1985; Wurbs 1992; McMahon and Adeloye 2005; Nandalal and Bogardi 2007). These techniques typically explore the range of reservoir levels (states) which can be achieved for a range of potential inflow and release scenarios, starting from current or assumed conditions, and using simplified representations of the overall system. Optimum reservoir release strategies are then derived based on prescribed optimisation criteria and subject to the physical constraints of the system, such as limitations on maximum flows and volumes. In multi-reservoir systems, the fill and drawdown sequence needs to be considered across the entire system (e.g. Labadie 2004).

Optimisation criteria are often expressed either in financial terms or as utility or penalty functions (see Chap. 7). Models are typically operated on a daily, weekly or monthly basis, depending on the time horizon of interest, in some cases with models of differing complexity nested at different timescales with differing objectives. For longer timescales, typically a simple water balance approach is used to estimate reservoir storage, and hence levels, for a given set of control rules. This initial estimate is then sometimes fine-tuned using a more detailed simulation model.

For real-time forecasting, ensemble approaches are increasingly supplementing or replacing stochastic techniques (e.g. Addor et al. 2011; Liu et al. 2012; Pyke and

Porter 2012; Georgakakos et al. 2012; Box 11.1). The following types of modelling components are typically included:

- Meteorological forecasts – ensemble rainfall forecasts post-processed to reduce bias and other issues, plus air temperatures if required for input to snowmelt forecasting models; also reforecasts for model calibration (see Chap. 4)
- Inflow forecasts – ensemble flow forecasts derived from rainfall-runoff models and using data assimilation techniques such as error prediction, Kalman filter or variational approaches (see Chaps. 5 and 8)
- Decision support tools – for risk-based evaluation of scenarios based on control rules and current operational requirements; for example, relating to release schedules, multi-reservoir operations, outages for maintenance/repairs and event-specific factors such as flood releases and water quality issues

Box 11.1: Folsom Dam and Reservoir (USA)
Folsom Lake is situated on the American River approximately 40 km to the northeast of Sacramento in Northern California. The 427 m long Folsom Dam was commissioned in 1955 with the multiple objectives of hydropower generation, flood control, water supply and recreation. The dam is operated by the US Bureau of Reclamation (USBR), and forms part of the Central Valley Project, which provides irrigation and water to several million people in California. The reservoir has an active storage of approximately of 1200 Mm^3, of which about half is available for flood control, and the hydropower plant has a 200 MW generating capacity. The spillway design capacity is about 3200 m^3s^{-1}, although this is currently being increased as part of a dam upgrade project which is scheduled for completion in 2017.

The reservoir catchment rises in the Sierra Nevada mountains, and the area to the spillway is approximately 4,800 km^2 (Fig. 11.5). Snowmelt forms a significant input to the reservoir during the winter and spring months, although

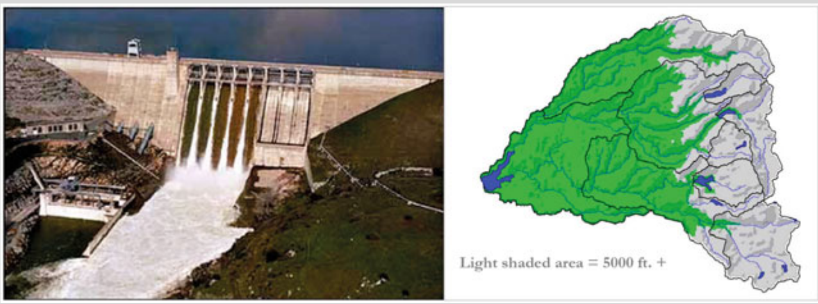

Fig. 11.5 Folsom Dam and sub-catchments used in the inflow forecasting model (Fickenscher 2005)

(continued)

Box 11.1 (continued)

the largest flows come from heavy rainfall events with moderately high snow levels. Inflow forecasts for the next 5 days are provided to USBR at least twice per day by the California-Nevada River Forecasting Center (CNRFC) of NOAA's National Weather Service, in collaboration with the California Department of Water Resources. The forecast system leverages a fairly well-developed real-time data collection network (20+ rain gauges, 20+ air temperature sensors, 10+ snow pillows, 10+ reservoir level sensors and 20+ stream gauges). Quantitative Precipitation Forecasts (QPF), snow level forecasts and forecast air temperatures are provided by the CNRFC HAS (Hydrometeorological Analysis and Support) Unit with guidance/support from National Centers for Environmental Protection (NCEP) and the local National Weather Service Office (WFO) in Sacramento.

In the forecasting model, the reservoir catchment is represented by fifteen sub-basins with runoff estimated using the Sacramento Soil Moisture Accounting SAC-SMA model (Burnash 1995) and the SNOW-17 snowmelt model (Anderson 1968). The model states are updated using observed river stage data. Approximately 75 % of the upstream reservoir storage in the catchment is represented, together with an allowance for ungauged flow diversions, and the main inter-basin transfers (Fickenscher 2005; Fig. 11.6). Long-term (365-day ahead) ensemble forecasts are also produced daily by leveraging the

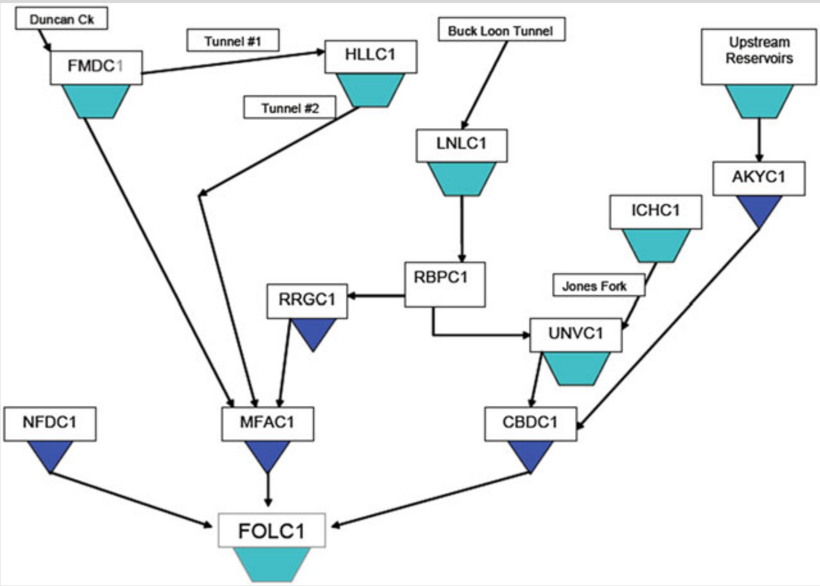

Fig. 11.6 Schematic of the "simplified" watershed model (Fickenscher 2005)

(continued)

Box 11.1 (continued)
spatial and temporal coherence of historical rainfall and air temperature records using an Ensemble Streamflow Prediction approach (Day 1985). This process has been improved in recent years to include the information provided through short- and medium-range numerical weather prediction models as well as climate models.

Reservoir releases are controlled by the Central Valley Operations Office of USBR. Reservoir release rates, downstream river levels and reservoir refill are estimated from the 5-day inflow forecasts and other real-time information (e.g. upstream reservoir levels), and application of the flood control and emergency spillway release rules.

A Decision Support System is also available which serves a range of purposes, including developing and testing operating rule changes, operator training, emergency management table-top exercises and assisting downstream emergency managers in developing protocols for using release forecasts to improve emergency planning (Bowles et al. 2004). What-if runs can also be used to explore alternative operating strategies, including maximum surcharge and maximum release scenarios. This includes an uncertainty mode to provide probabilistic estimates based on multiple inflow scenarios generated using a Monte-Carlo approach based on the model error statistics for historical events. Some potential uses of this feature include off-line studies of alternative operating rules, and some of the various trade-offs in operation; for example, use of the full floodway capacity versus the risk of overtopping levees due to forecast inaccuracies, impacts on water supply following pre-releases for flood control, and the net economic benefits of different operating strategies.

A number of research studies have been performed into improved forecasting techniques for Folsom Lake, and the American River Basin was one of the first experimental catchments to be considered within the NOAA Hydrometeorology Testbed (HMT) project, which is evaluating the use of advanced observational and modelling tools for Quantitative Precipitation Estimation (QPE) and Quantitative Precipitation Forecasts (QPF) for operational flow forecasting applications (http://hmt.noaa.gov/). Some examples of other developments include studies into the use of ensemble forecasts from Numerical Weather Prediction models, and adaptive and dynamic probabilistic decision-making methodologies (e.g. Yao and Georgakakos 2001; Carpenter et al. 2003; Georgakakos et al. 2012), and the development of seasonal release rules to regulate downstream temperatures for fishery habitats (Field and Lund 2006).

Table 11.5 Examples of real-time decision support systems for reservoir control

Location	Reservoir uses	Forcing inputs	Some key considerations	Reference
Austria	Hydropower, recreation, flood control	Ensemble	Flood control, hydropower	Blöschl (2008)
China	Reservoir flood forecasting and control system	Deterministic	Flood control	Guo et al. (2004)
Ebro river basin, Spain	Multi-reservoir systems	Deterministic	Flood control, water management	Garcia et al. (2005)
Fetsui Reservoir, Taiwan	Water supply, hydropower	Deterministic	Flood control during typhoons	Nandalal and Bogardi (2007)
Folsom Dam, California	Flood protection, hydropower, water supply, recreation	Deterministic, ensemble	Flood control, multi-objective	Fickenscher (2005); see Box 11.1
Lake Como, Italy	Irrigation, hydropower	Stochastic	Flood control	Todini (2005)
Netherlands	Polder systems	Artificial intelligence techniques	Optimisation of water level management	Lobbrecht et al. (2005)
New York	Multi-purpose, multiple reservoir system	Ensemble, stochastic	Water supply, hydropower, environmental, other	Pyke and Porter (2012)
Northern California	Multi-purpose multiple reservoir systems	Ensemble, statistical	Dynamic reservoir regulation, multi-objective trade-offs	Georgakakos et al. (2012)
Brazil	Hydropower, flood control	Deterministic	Hydropower, flood control	Collischonn et al. (2007), Fan et al. (2014)
Powell and Lois rivers, Canada	Hydropower	Ensemble, statistical	Hydropower generation	Howard (2007)
Zurich, Switzerland	Real-time forecasting for Zurich city	Ensemble	Flood control, hydropower generation	Addor et al. (2011)

Adapted from Sene (2008)

Given the complexities even for a single reservoir, but particularly for multi-reservoir and hydropower systems, these techniques are often incorporated into a real-time decision support system. Table 11.5 presents some examples of research and operational applications of systems of this type, whilst Sect. 6.4 discusses some further examples for hydropower operation. Chapter 7 also discusses some more general operational considerations when using decision support systems such as the need to ensure that backup procedures are in place in case of system failure and for long-term programmes of training and support.

11.3 Selected Applications

11.3.1 Tidal Barriers

The aim of a tidal barrier is usually to provide protection from tidal flooding to inland areas within estuaries. Some other applications include hydropower generation and amenity use; for example, maintaining levels upstream within a defined range to permit harbour-side developments.

These can be major structures, in some cases rivalling large dams in terms of the scale and cost of the construction effort. As part of the design, detailed hydrodynamic modelling studies are usually performed, and laboratory tests are sometimes justified, based on small-scale models of the channel and structure. Box 11.2 describes three well-known examples, whilst others include the tidal barrier scheme at Venice in Italy (Caporin and Fontini 2014) and the 25-km-long St Petersburg Flood Protection Barrier in Russia which was opened in 2011 (Hunter 2011). Horn (2015) discusses these and additional examples.

Box 11.2: Some Examples of Tidal Barriers
Three examples of tidal barriers are discussed here: the Maeslant Barrier in the Netherlands, the Thames Barrier in England and the Cardiff Bay Barrage in Wales.

The Maeslant Barrier was constructed between 1991 and 1997 in a 360-m-wide section of the New Waterway ship canal to Rotterdam Harbour (Fig. 11.7). Together with the smaller Hartel Barrier, the barrier provides flood protection to the Rotterdam and Dordrecht areas and consists of two pivoting, hollow, curved gates. These are normally stored in dry docks on the river banks and are moved into the river when required. In the closed position, the gates are filled with water and sink to the river bed; this water is then pumped out again before the gates are moved back to the open position.

The gates are controlled automatically based on forecasts for water levels at Rotterdam and Dordrecht, coastal forecasts for the Hook of Holland and other locations and operation of a hydrodynamic model for the Rhine and Meuse estuaries (Bol 2005). The computer control system was designed to achieve a high standard of reliability using a formal software engineering approach which is discussed briefly in Chap. 7 (Tretmans et al. 2001).

The Thames Barrier was constructed between 1974 and 1982 to protect London from coastal flooding and has a span of 520 m. Control is provided by six rising sector gates and four simple radial gates (Fig. 11.8), and the rising sector gates lie in sills flat against the river bed when not in use (Horner 1985).

(continued)

Box 11.2 (continued)

Fig. 11.7 Aerial view of the Maeslant Barrier (Rijkswaterstaat, part of the Ministry of Infrastructure and Environment http://www.keringhuis.nl/)

Fig. 11.8 The Thames Barrier (Environment Agency 2015, © Crown Copyright 2015. Contains public sector information licensed under the Open Government Licence v3.0)

(continued)

Box 11.2 (continued)
The gates are typically closed 4–6 h before high tide on the basis of observed river levels upstream of London and coastal forecasts for tidal levels and surge in the Thames Estuary. These rules are based on detailed hydraulic modelling performed at the time that the barrier was being designed, combined with experience gained since completion of the barrier. Operations are supported by a detailed real-time hydrodynamic model for the river and estuary (e.g. see Sene 2008).

The Cardiff Bay Barrage was constructed between 1994 and 1999 and is situated at the lower end of the Rivers Taff and Ely in South Wales (Hunter and Gander 2002). The barrage was built to create a freshwater lake as a focus for urban renewal and for flood control and is approximately 1.1 km long. Key hydraulic structures include five vertical-lifting sluice gates, a fish pass and three navigation locks for boats. Water levels in the bay upstream of the barrage are controlled to remain with a narrow range, which can be exceeded (up to a limit) during times of high river flows. The operating rules for the barrage were derived from physical (scale) model tests and extensive hydrodynamic modelling. The modelling studies considered a range of tidal and flow scenarios and free flow and drowned flow gate operating modes, depending on upstream and downstream water levels (Faganello and Dunthorne 2005). The resulting rules were refined to achieve an acceptable number of gate operations and time of gate operation and are programmed into an automated control system which uses information from an extensive network of sensors on the upstream and downstream sides of the barrage.

In operational use, one particular challenge is that both coastal and river conditions need to be considered (Table 11.6). Decision-making tends to be based around the twice-daily tidal cycle and – for barriers which normally allow ships to pass – some key considerations associated with each closure typically include:

- Gate closure times – How long does it takes to close gates fully once the decision has been made to operate the barrier?
- Operating costs – Normally, there is a cost associated with each closure due to staff time, power usage, interruptions to shipping and impacts on asset life.
- River flows – Levels normally rise upstream of a barrier whilst it is closed, raising the risk of flooding if flows are already high.

In the latter case, the risks of riverine flooding have to be balanced against those from tidally influenced flooding if the barrage is not closed in time.

Table 11.6 Some typical considerations during tidal barrier operations

Item	Component	Description
Coastal conditions	Astronomical tide predictions	Predictions for tidal levels over the next few tidal cycles (see Chap. 8)
	Tide gauge observations	Observed water levels at or near to the barrage and at coastal sites
	Surge forecasts	Current surge forecasts for forecasting points near to the barrier and along the coast (see Chaps. 5 and 8)
	Wave forecasts	In some cases, current wave height forecasts for the coastal reach
River conditions	River gauge observations	Observed river levels and/or flows immediately upstream of the barrage and further upstream in the catchment
	River flow forecasts	Forecasts for river flows for lead times spanning at least the next few tidal cycles
Threshold levels	Coastal and river conditions	The levels at which flood contingency plans need to be activated, warnings issued, and at which flooding is likely
Operational constraints	Operations and maintenance	The current operational status of each gate in the structure and – if out of use – how long backup procedures will take to implement
	Shipping	Estimated times of arrival and departure to/from inland ports upstream of the structure

Perhaps, the greatest risks occur when a high tide coincides with a storm surge and river flows are high; for example, during a prolonged period of stormy weather with high wind speeds and heavy rainfall further inland. Due to the various uncertainties involved, ensemble forecasts are increasingly used as part of the decision-making process, for both the river flow and surge components. For example, if a barrier is normally operated several times a year or more, then this frequent operation and the well-defined nature of the costs and losses potentially lends itself to the use of risk-based decision-making techniques of the types described in Chap. 7 (e.g. Dale et al. 2014).

11.3.2 Real-Time Urban Drainage Control Systems

Urban drainage systems typically consist of a surface network of culverts, heavily modified watercourses and open drains and a subsurface network of pipes and tunnels. Other typical components include flood detention areas, control structures such as diversion weirs and control equipment such as gates, pumps and pressure relief valves. The subsurface network is usually designed to be able to convey runoff from

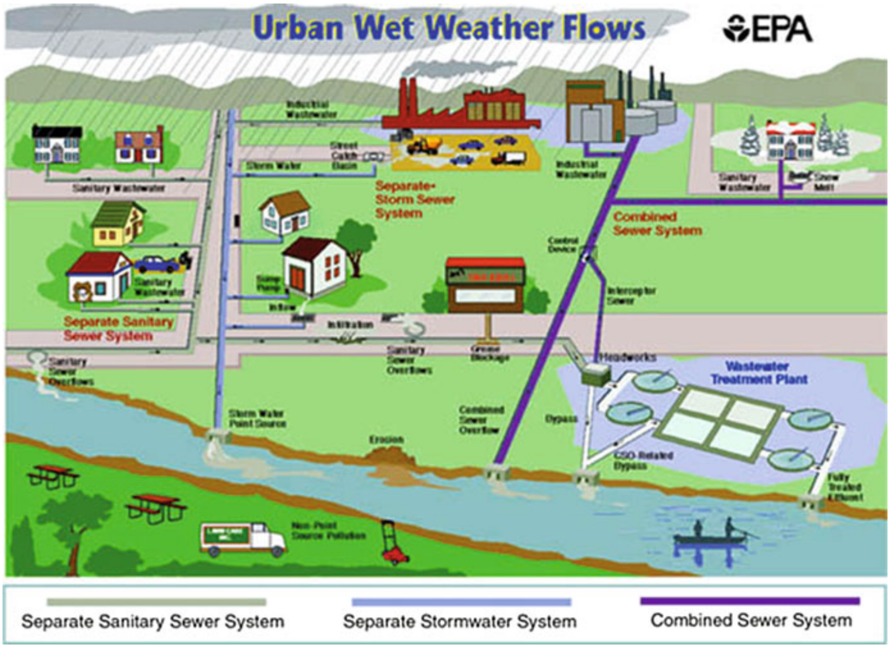

Fig. 11.9 An illustration of the three types of systems that are used for sewage and stormwater disposal (US Environmental Protection Agency; http://www.epa.gov)

heavy rainfall events up to a certain return period or annual exceedance probability. For more severe events, or if there are blockages or other issues, surface water flows have the potential to collect in low-lying areas causing localised flooding.

Figure 11.9 illustrates some typical approaches to conveying surface water or wet weather flows. In older designs, the surface runoff is normally carried away along the same routes as the sewerage. These are called combined sewer systems, and during heavy rainfall, flows which exceed the capacity of treatment works are typically discharged into rivers or the sea. This is usually through structures called Combined Sewer Overflows (CSOs), and the discharges are sometimes a major source of pollution. However, due to stricter legislation in recent years, many water suppliers now have major capital works programmes in place to address these issues. Newer systems also tend to use separate routes for the waste and storm runoff components thereby avoiding this problem except in the most extreme events.

The most common approach to providing alerts of the potential for surface water flooding is to use rainfall depth-duration alarms, although in recent years distributed rainfall-runoff models and hydrodynamic models have started to be used operationally. Chapter 9 discusses some examples of these techniques. There is also renewed interest in the use of real-time control systems for urban drainage networks although this approach has been used in some cities for many years. Indeed the first research studies were performed in the 1960s with an early example being a system to control CSO discharges in Seattle. This was initially implemented in 1971, and a rainfall-runoff modelling component was added in 1992 (EPA 2004). Another early implementation of this approach was in Quebec, beginning with a demonstration study for the western part of the city's sewer network (Field et al. 2000; Pleau et al. 2001). The operational system uses data from flow and weather station sites, radar rainfall images and rainfall forecasts (Schütze et al. 2004; Pleau et al. 2010). The optimisation criteria which were used whilst developing the system included:

- To minimise the volumes discharged at CSOs, the number of CSO incidents and the surcharge flows from private connections
- To maximise the treatment plant utilisation, subject to tidal variations in the St Lawrence River, and the use of existing in-line storage capacity

By 2006, more than 20 cities in the USA, Canada, Europe and Japan were operating this type of system. Some examples of operational goals include (EPA 2006):

- Reducing or eliminating sewer backups and street flooding
- Reducing or eliminating sanitary sewer overflows (SSOs)
- Reducing or eliminating CSOs
- Managing/reducing energy consumption
- Avoiding excessive sediment deposition in the sewers
- Managing flows during a planned (anticipated) system disturbance (e.g. major construction)
- Managing flows during an un-planned (not anticipated) system disturbance, such as major equipment failure or security-related incidents
- Managing the rate of flow arriving at the wastewater treatment plant

Another objective is often to make better use of existing capacity so as to defer the need for capital expenditure on additional flood storage options.

A typical approach is to use remotely or automatically controlled devices to divert flows in the drainage network away from areas which are operating at full capacity and/or to off-line facilities such as flood retention ponds (e.g. Schilling 1989; Colas et al. 2004; Schütze et al. 2004). The types of devices used include pumps, valves, sluice gates and inflatable dams. Control rules are typically derived off-line using detailed hydraulic models of the urban drainage network, of the types often developed for water supply network design. The rules can then be implemented in a specialised decision support system for use in real time, in some cases including an optimisation component; for example, using expert system, artificial intelligence or linear or dynamic programming techniques. Increasingly, real-time hydrodynamic models are included as part of the overall control system.

Normally, the control objectives vary between dry and flood conditions. For example, during dry weather conditions, some typical aims might be to reduce pumping and treatment costs, whilst in wet weather, the focus would be on avoiding surface water flooding and CSO incidents. As with any software-based approach, the system needs to be resilient to failure of any component, and one design criterion which is sometimes used is that if the system fails, it should degrade to a situation equivalent to or better than that before the introduction of a real-time control component (Schütze et al. 2004).

Several recent developments in forecasting and observation techniques have spurred renewed research interest in this area. These include the increasing use of short-range X-band radar devices in urban areas (see Chap. 2), step changes in the resolution of numerical weather prediction models (see Chaps. 4 and 9) and computational advances which have made running urban drainage models in real time a more practical proposition than it was in the past (see Chaps. 5 and 9). These developments together with others such as phased-array weather radar (see Chap. 2) may lead to significant improvements in urban drainage forecasting in the next few years.

11.4 Summary

- River levels and flows are often influenced by hydraulic structures, particularly in urban areas, whilst dams are a common feature in upland areas. Some typical applications include water supply, hydropower generation and irrigation and regulating river levels or flows for recreation or navigation.
- The extent to which a river structure needs to be represented in a forecasting model depends on a range of factors, including the application and the level of risk. The approaches used range from simple water balance and flow routing approaches to real-time hydrodynamic models. Water quality, sediment and ecological factors sometimes need to be considered.
- For controllable structures, the operating rules usually need to be represented in a forecasting model. However, sometimes considerable investigation is required to determine the actual rules used in practice. In hydrodynamic models, these are usually represented as logical rules dependent on river or reservoir conditions and current gate settings.
- Reservoirs are typically operated using predefined control rules which define the releases permitted at different times of year according to current reservoir levels or storage. Multiple objectives often need to be considered including water supply, irrigation, navigation and hydropower generation. Particularly for large dams, control rules are often derived using sophisticated linear, non-linear or dynamic programming techniques.
- A reservoir forecasting model typically includes some representation of inflows, outflows and gate operations and possibly other terms such as direct rainfall and evaporation at the water surface. Modelling techniques range from simple water balance approaches to flow routing and hydrodynamic models. Probabilistic techniques are increasingly used, particularly for long-term forecasts and high-risk applications.
- There is increasing interest in more dynamic approaches to reservoir operations rather than relying on predetermined control rules both to increase operating efficiencies and to help to deal with event-specific issues. This is particularly the case for multi-objective and multi-reservoir systems, and probabilistic approaches have a valuable role to play.

- Decision support systems are increasingly used to guide operators on operating strategies although normally not to automatically activate control gates and other structures directly due to the uncertainties in observations and forecasts. Suitable backup procedures also need to be in place in case of system failure.
- For tidal barriers, both river and coastal conditions need to be considered when deciding whether to close a barrier to reduce the risk from coastal flooding. This typically requires consideration of observed river and tidal conditions plus river flow and surge forecasts and astronomical tide predictions. Ensemble forecasts show potential to help guide the decision-making process.
- In urban areas, real-time control systems potentially offer a number of benefits for the operation of drainage networks. These include lower operating and capital costs and reducing pollution issues due to Combined Sewer Overflow incidents. Systems of this type are increasingly used, and recent developments in weather radar systems and weather forecasting techniques offer the potential for wider use of this approach in future.

References

Addor N, Jaun S, Fundel F, Zappa M (2011) An operational hydrological ensemble prediction system for the city of Zurich (Switzerland): skill, case studies and scenarios. Hydrol Earth Syst Sci 15:2327–2347

Anderson E (1968) Development and testing of snow pack energy balance equations. Water Resources Research 4(1):19–37

Blöschl G (2008) Flood warning-on the value of local information. Int J River Basin Manag 6(1):41–50

Bol R (2005) Operation of the 'Maeslant Barrier': storm surge barrier in the Rotterdam New Waterway. Chapter 38 in Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge (Eds. Fletcher C, Spencer T), Cambridge University Press, Cambridge

Bowles D S, Mathias J D, Chauhan SS, Countryman J D (2004) Reservoir Release Forecast Model for Flood Operation of the Folsom Project including pre-releases. Proceedings of the 2004 USSD Annual Lecture, St. Louis, MO, March 2004

Burnash RJC (1995) The NWS River Forecast System - Catchment modeling. In Singh VP (ed.), Computer Models of Watershed Hydrology, Water Resources Publications

Caporin M, Fontini F (2014) The value of protecting Venice from the Acqua Alta phenomenon under different local sea level rises, http://www.mosevenezia.eu/

Carpenter TM, Georgakakos KP, Graham NE, Georgakakos AP, Yao H (2003) Incorporating hydroclimatic variability in reservoir management at Folsom Lake. Paper 7.10, American Meteorological Society 83rd Annual Meeting, Long Beach, CA, 9–13 February 2003

Chanson H (2004) Hydraulics of Open Channel Flow, an Introduction (2nd ed.). Butterworth-Heinemann, Oxford

Colas H, Pleau M, Lamarre J, Pelletier G, Lavallée P (2004) Practical perspective on real-time control. Water Quality Research Journal of Canada, 39(4): 466–478

Collischonn W, Tucci CEM, Clarke RT, Chou SC, Guilhon LG, Cataldi M, Allasia D (2007) Medium-range reservoir inflow predictions based on quantitative precipitation forecasts. Journal of Hydrology, 344: 112–122

Dale M, Wicks J, Mylne K, Pappenberger F, Laeger S, Taylor S (2014) Probabilistic flood forecasting and decision-making: an innovative risk-based approach. Natural Hazards, 70(1): 159–172

Day G N (1985) Extended Streamflow Forecasting using NWSRFS. J. Water Resources Planning and Management, 111(2): 157–170
EPA (2004) Report to Congress: Impacts and control of CSOs and SSOs. US Environmental Protection Agency Report EPA 833-R-04-001
EPA (2006) Real time control of urban drainage networks. Report EPA/600/R-06/120
Faganello E, Dunthorne S (2005) The modeling of Cardiff Barrage Bay control system. Chapter 37 in Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge (Eds. Fletcher C, Spencer D T), Cambridge University Press, Cambridge
Fan FM, Collischonn W, Meller A, Botelho L (2014) Ensemble streamflow forecasting experiments in a tropical basin: The São Francisco river case study. Journal of Hydrology, 519 (Part D): 2906–2919
Fickenscher P (2005) Hydrologic forecasting on the American River. California-Nevada River Forecast Center. Proceedings of the California Extreme Precipitation Symposium, Sacramento, CA. Precipitation and Flood Forecasting in the American River Basin. American River Watershed Institute
Field R, Villeneuve E, Stinson M, Jolicoeur N, Pleau M, Lavallée P (2000) Get real! Implementing real-time control schemes offers combined sewer overflow control for complex urban collection systems. Water Environment Federation, 64–67
Field R, Lund J R (2006) Multi-Objective Optimization of Folsom Reservoir Operation. Operating Reservoirs in Changing Conditions: Proceedings of the Operations Management 2006 Conference (Eds. Zimbelma D, Lohlein W), Sacramento, California, USA, 14–16 August 2006
Garcia RR, Sáez AL, Salete EG, García LL (2005) Reservoir management in real-time flood forecasting and decision support in the Ebro river basin. ACTIF International conference on innovation advances and implementation of flood forecasting technology, 17–19 October 2005, Tromsø, Norway
Georgakakos AP, Yao H, Kistenmacher M, Georgakakos KP, Graham NE, Cheng F-Y, Spencer C, Shamir E (2012) Value of adaptive water resources management in Northern California under climatic variability and change: reservoir management. Journal of Hydrology, 412–413: 34–46
Guo S, Zhang H, Chen H, Peng D, Liu P, Pang B (2004) A reservoir flood forecasting and control system for China. Hydrological Sciences Journal, 49(6): 959–972
Horn DP (2015) Storm Surge Warning, Mitigation, and Adaptation. Coastal and Marine Hazards, Risks, and Disasters, Chapter 6, 153–180
Horner RW (1985) Dugald Clerk lecture: The Thames Barrier. Proceedings of the Institution of Civil Engineers, Part 1, 78: 15–25
Howard, CDD (2007) Hydroelectric operations – ensemble optimisation procedures. Workshop on the Hydrological Ensemble Prediction Experiment (HEPEX), Stresa, Italy, 27–29 June 2007
Hunter P D, Gander H C W (2002) Cardiff Bay Barrage: Planning and design. Proceedings of ICE, 154(2): 117–128
Hunter P (2011) The St Petersburg Flood Protection Barrier: design and construction. CETMEF PIANC Paris 2012
ICOLD (2015) World Register of Large Dams. International Commission on Large Dams http://www.icold-cigb.org/
Labadie JW (2004) Optimal operation of multi-reservoir systems: state-of-the-art review. J Water Resour Plann Manag 130(2): 93–111
Liu Y, Weerts AH, Clark M, Hendricks Franssen H-J, Kumar S, Moradkhani H, Seo D-J, Schwanenberg S, Smith P, van Dijk AIJM, van Velzen N, He M, Lee H, Noh SJ, Rakovec O, Restrepo P (2012) Advancing data assimilation in operational hydrologic forecasting: progress, challenges, and emerging opportunities. Hydrol. Earth Syst. Sci. Discuss., 9: 3415–3472
Lobbrecht AH, Dibike YB, Solomatine DP (2005) Networks and fuzzy systems in model based control of the Overwaard Polder. Journal Water Resources Planning and Management, 131(2): 135–145
Loucks DP (Ed.) (1989) Systems Analysis for Water Resources Management, Closing the Gap Between Theory and Practice. IAHS Publication No. 180, Wallingford

McMahon TA, Adeloye AJ (2005) Water Resources Yield. Water Resources Publications LLC, Colorado

Nandalal KDW, Bogardi JJ (2007) Dynamic Programming Based Operation of Reservoirs Applicability and Limits. Cambridge University Press, Cambridge

NOAA/GLERL (2015) Water Levels of the Great Lakes. Bulletin: February 2015. Great Lakes Environmental Research Laboratory, Ann Arbor, MI

Novak P, Moffat AIB, Nalluri C, Narayanan R (2006) Hydraulic Structures (4th ed.). Taylor and Francis, London

Pleau M, Pelletier G, Colas H, Bonin R (2001) Global predictive real-time control of Quebec urban community's westerly sewer network. Water Science and Technology 43(7): 123–130

Pleau M, Fradet O, Colas H, Marcoux C (2010) Giving the rivers back to the public. Ten years of Real Time Control in Quebec City. Novatech 2010, Lyon, 27 June-1 July 2010

Pyke G, Porter J (2012) Forecast-based Operations Support Tool for the New York City Water Supply System. AGU Fall Meeting, San Francisco, 3–7 December 2012

Schilling W (Ed.) (1989) Real time control of urban drainage systems. The state of the art. IAWPRC Task Group on Real Time Control of Urban Drainage Systems, London

Schütze M, Campisano A, Colas H, Schilling W, Vanrolleghem PA (2004) Real time control of urban wastewater systems—where do we stand today? Journal of Hydrology, 299: 335–348

Sene K (2008) Flood Warning, Forecasting and Emergency Response. Springer, Dordrecht

Todini E (2005) Holistic flood management and decision support systems. In River Basin Modelling for Flood Risk Mitigation (Eds. Knight D W, Shamseldin A Y), Taylor and Francis, London

Tretmans T, Wijbrans K, Chaudron M (2001) Software engineering with formal methods: The development of a storm surge barrier control system: revisiting seven myths of formal methods. Formal Methods in System Design, 19(2): 195–215

WMO (2009) Guide to hydrological practices, 6th edn. WMO No-168, Geneva

WMO (2011) Reservoir operations and managed flows. Integrated Flood Management Tools Series No.5, Geneva

Wurbs R A (1992) Reservoir-system simulation and optimization models. Journal of Water Resources Planning and Management, 119(4): 455–472

Yao H, Georgakakos A (2001) Assessment of Folsom Lake response to historical and potential future climate scenarios. J. Hydrology, 249: 176–196

Yeh WWG (1985) Reservoir management and operations models: a state-of-the-art review. Water Resour Res 21(12):1797–1818

Chapter 12
Environmental Impacts

Abstract Water quality forecasting models are increasingly used to help with issuing pollution alerts and developing longer-term management strategies for rivers, lakes and reservoirs. Typically the functionality in flow forecasting models is extended to represent the transport of chemical or biological constituents as required. Sediment and thermal pollution issues sometimes need to be considered and ecological forecasting techniques are actively under development. This chapter provides an introduction to these topics including examples of approaches to forecasting bathing water quality issues and the spread of harmful algal blooms.

Keywords Water quality • Pollution incidents • Ecological forecasting • Ecosystem forecasting • Harmful algal blooms • Bathing water quality

12.1 Introduction

Water quality problems in rivers, lakes and reservoirs can present a risk to drinking water supplies, ecosystems and recreational water users. Perhaps the first operational warning systems related to public water supply and real-time forecasting models are widely used to predict the spread of pollutants should a spill occur. Some options for mitigating actions on receipt of a warning include placing temporary restrictions on water use and diluting or replacing contaminated waters with other supplies.

The impacts of poor water quality on wildlife and beaches have also become an increasing concern in recent decades. In many countries this has led to tighter controls on pollution and a requirement to provide water users with better information about the risks. For example, in Europe some objectives of the Water Framework Directive include 'preventing and reducing pollution, promoting sustainable water usage, protecting the environment, improving the state of aquatic ecosystems and reducing the effects of floods and droughts'. This sets specific deadlines for member states to implement measures over the period 2009–2027, based on a river basin management approach (European Commission 2008; http://ec.europa.eu/).

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Whilst pollution incidents sometimes arise from a single 'point' source, the cumulative effects at a catchment scale are often an issue. This is called diffuse or non-point pollution and Table 12.1 shows some typical examples of the impacts.

Some key sources include runoff from farmland, industrial sites and urban areas. For example, the US Environmental Protection Agency (http://water.epa.gov/) notes that sources of non-point pollution include:

- Excess fertilizers, herbicides and insecticides from agricultural lands and residential areas
- Oil, grease and toxic chemicals from urban runoff and energy production
- Sediment from improperly managed construction sites, crop and forest lands and eroding streambanks
- Salt from irrigation practices and acid drainage from abandoned mines
- Bacteria and nutrients from livestock, pet wastes and faulty septic systems
- Atmospheric deposition and hydromodification

So-called 'acid rain' is probably the most common type of atmospheric deposition and in water bodies leads to acidification, affecting some fish and plant species.

The complexity of forecasting techniques varies with the application. For rivers, simple routing or water balance techniques sometimes suffice, although

Table 12.1 Some examples of the impacts of poor water quality on water supplies and ecosystems

Impacts	Description
Eutrophication/hypoxia	Depletion of dissolved oxygen (hypoxia) due primarily to the decomposition of algae and plants, in many cases following an explosion in algal growth due to nutrient pollution (eutrophication)
Fish spawning grounds	Damage caused by deposition of sediment onto areas of gravel and other substrates favoured for spawning by some species of fish, such as salmon and trout
Food webs	Changes in the distribution of plant and fish species in lakes and rivers due to changes in water chemistry and temperature and consequent impacts, in some cases favouring the spread of so-called invasive or non-native fish and plant species
Harmful algal blooms	Increasing numbers of *Cyanobacteria*, which sometimes clump together to form unsightly and, at times, toxic floating rafts or blooms on the water surface
Hydropower generation	Sediment erosion of turbine blades and loss of capacity in reservoirs and forebays and blockages from increases in aquatic vegetation
Potable water supplies	Changes in water colour, turbidity and odour affecting drinking water supplies and potentially blocking filtration units
Sedimentation	Reduction of river channel-carrying capacities, affecting navigation and sometimes leading to a significant increase in flood risk and loss of reservoir storage capacities, in some cases leading to reservoirs being decommissioned

hydrodynamic models are usually required for more complex problems involving local impacts. For diffuse pollution, methods range from simple regression approaches to physically-based distributed models. As discussed in Box 12.1, additional modelling components are often required to consider ecological impacts and – at long timescales – global-scale issues may require consideration such as the overall carbon and nitrogen balance (see Chap. 13).

Table 12.2 lists some examples of the types of constituents which may need to be considered. For short-term forecasts, real-time observations are usually required to support model operation, and Chaps. 2 and 3 discuss a range of monitoring techniques. In particular one significant development in recent years has been the increasing use of automated sensors for continuous recording of water quality variables. Although there are exceptions, electronic sensors are now available for most of the common types of contaminants, providing information suitable for recording on a data logger and transmission using a telemetry system.

As in other forecasting applications, decisions on the actions to take are often made by comparing forecast values with predefined thresholds. Chapter 7 discusses this topic in more detail, but, for water quality applications, threshold values are often prescribed by environmental or health authorities; for example, the World Health Organisation (WHO 2011) defines so-called operational or critical limits covering a wide range of chemical, organic, microbial and pesticide compounds.

Table 12.2 Some examples of sources and types of constituents

Type	Examples	Point sources	Diffuse or non-point sources
Fuels/hydrocarbons	Oil, petrol, gasoline	Transport (road/rail) accidents, incidents at refineries	Roads, airports, urban and industrial areas
Heated water		Power station cooling systems	
Heavy metals	Cadmium, mercury, lead	Industry, mine tailings	Open-cast mining, former industrial sites
Nutrients	Nitrogen, phosphorus	Sewage/wastewater treatment works	Arable/livestock farming, horticulture
Pathogens	Bacteria, protozoa, viruses	Wastewater treatment works, Combined Sewer Overflows (CSOs); see Chap. 11	Arable/livestock farming, leaking sewerage systems, septic tanks
Pesticides		Accidental spills	Arable farming, horticulture
Solvents		Paper, food, textile industries	Industrial areas
Suspended solids, sediment		Industry, construction sites	Farming, forestry, road construction

Risk-based and probabilistic techniques are also used to help in decision-making, and it is worth noting that some of the earliest practical uses were in water quality applications (e.g. Loucks and Lynn 1966; Beck and van Straten 1983). More recently Luo et al. (2011) note that one characteristic feature of ecological forecasting is that it provides a 'probabilistic statement on future states of an ecological system after data are assimilated into a model'. Here data assimilation is the use of real-time data to improve forecasts (e.g. Luo et al. 2011; Robson 2014) and is widely used in flow forecasting systems (see Chaps. 5, 8 and 13).

This chapter provides a general introduction to these various modelling and forecast interpretation issues. The discussion begins (Sect. 12.2) with a description of forecasting techniques for rivers, lakes and reservoirs and at a catchment scale. Section 12.3 then provides examples of two short-term forecasting applications, namely providing alerts for harmful algal blooms and bathing water quality problems. Further information can be found in the many textbooks, review articles and guidelines on these topics including Chapra (2008), Chin (2006), Huber (1993), Ji (2008), Robson (2014) and WMO (2013). Chapter 5 also discusses some wider model selection issues common to all forecasting applications; for example, relating to the level of risk, the budget available, data availability and the forecast lead times required.

Box 12.1: Ecosystem Forecasting

The aim of ecological forecasting or ecosystem forecasting is to forecast the impacts of environmental change on ecosystems. For example, in relation to ocean, coastal and Great Lakes ecosystems, NOAA (2014) notes that:

> Ecological forecasts are used to predict likely changes in ecosystems and ecosystem components in response to environmental drivers (e.g. climate variability, extreme events and hazards, and land and resource use) and resulting impacts on people, economies and communities that depend on ecosystem services. Ecological forecasts provide early warnings of the possible effects of ecosystem changes on coastal systems, and on human health and local and regional economies with sufficient lead time to allow mitigation strategies to be developed and corrective actions to be taken.

Some priorities in the USA include developing forecasting capability 'for harmful algal blooms, hypoxia, pathogens and habitat, in regions of the country where these are issues of major concern'.

One such area is the Great Lakes system which lies in the border region between the USA and Canada and holds approximately 18 % of the world's total freshwater (http://www.glerl.noaa.gov/). Table 12.3 summarises some key areas of concern, and NOAA/GLERL (2012) notes that for the Great Lakes ecosystem, forecasting is a term that is 'used to cover a broad set of activities that includes modeling and prediction of the physical environment (e.g. hydrology, currents, waves, weather, and climate), modeling and prediction of ecological characteristics (e.g. food webs), and especially modeling

(continued)

Box 12.1 (continued)

Table 12.3 Great Lakes Environmental Research Laboratory (GLERL) science issue areas and major forecasts of concern for the Great Lakes and marine coastal environments (NOAA 2006); see NOAA/GLERL (2012) for priorities

Issue Area	Forecasts
Physical Environment	Offshore Wave Heights
	Coastal Erosion
	Rip Currents
	Nearshore Wave Heights and Condition
	Ice Thickness and Extent
	Spill/Search and Rescue
	Storm Surge
	Offshore Currents
	Water Temperature
Water Quantity	Water Levels
	Tributary Flows
Water Quality	Turbidity/Clarity
	Taste and Odor
	Bacteria Concentration
Human Health	Beach Closings (Bacteria/Pathogens)
	Fish Contamination
	Harmful Algal Blooms
Fish Recruitment and Productivity	Numbers of Fish by Species
	Size of Fish
	Fish Condition
	Fish Distribution
Invasive Species	New Non-Native Species Introductions
	Spread of Introduced Species
	Impact on Ecosystem

and prediction linking the physical and ecological realms' and also that it involves 'the coupling of:

- Meteorological models for dynamical downscaling of climate
- Hydrodynamic and ice models for thermal structure and circulation forecasting
- Hydrologic models for forecasting water levels and tributary loading
- Ecological models for understanding impacts to food webs and populations of fish and zooplankton'

Other aspects include assessing forecast skill and uncertainty assessments of model outputs.

(continued)

Box 12.1 (continued)
Some priority science questions include (NOAA/GLERL 2012):

- Which models are needed to reliably predict water quality and coastal hazards (e.g. algal blooms, beach water quality) on short-term and small spatial scales?
- What combination of models can be used to reliably forecast large-scale water quantity and quality parameters (e.g. water levels, ice, turbidity, stratification) on a seasonal basis (one month to one year)?
- Can an integrated ecological modeling system be developed to predict the regional impacts of climate and invasive species on physical and ecological conditions on a multi-decadal scale?
- What are the appropriate measures of accuracy and skill for integrated models?

12.2 Forecasting Techniques

12.2.1 Rivers, Lakes and Reservoirs

For river forecasting applications, the aim is usually to predict the changes in concentration over time as a contaminant travels downstream. Some typical locations for forecasting points include water quality monitoring sites and offtakes for water supply.

Chapter 5 discusses a range of flow routing and hydrodynamic modelling techniques for use in flow forecasting. The additional water quality-related issues which need to be represented vary between applications, but in general terms an increase in river flow (WMO 2009) leads to the following developments:

- Enhanced dilution of pollutants entering with wastewaters
- An increase in suspended solids derived from surface runoff and disturbance of bottom sediments
- The release of materials adsorbed by, or precipitated in, sediments such as phosphates and heavy metals
- Higher demand for biochemical oxygen caused by stirring up reducing substances from the riverbed
- Decreased ratio of groundwater to surface runoff in the river flow, generally resulting in a lower pH
- The washing out, and subsequent reduction of benthic organisms and in residence times
- Attenuated effects of sudden inputs of pollutants
- The reduced absorption of solar radiation and a related decline in water temperature and photosynthetic activity
- Greater turbulence and better aeration leading to higher levels of dissolved oxygen in conjunction with lower temperatures

For river pollution applications, hydrological flow routing models are widely used, together with sub-models for the specific contaminants of interest. However, if more detail is required at specific locations, then a hydrodynamic modelling approach may be required; for example, to assess the impacts on river habitat in a river reach or to consider issues such as saline intrusion in estuaries. Where diffuse pollution is an issue, pollutant loadings are often estimated from a watershed or catchment model of the types described later, in some cases with direct coupling between the watershed and river components.

Perhaps the widest use of forecasting models is to support decision-making following accidental pollutant spills (e.g. Box 12.2). Some key information required for model initialisation typically includes the time and location of occurrence, the type – or types – of contaminant and the indicative total volume(s). Figure 12.1 shows conceptually how the concentration might vary downstream from the incident location.

For the water quality component, the rate of change in concentrations is usually parameterised by a diffusion or dispersion coefficient for use within an advection-dispersion model (e.g. Chapra 2008; Huber 1993; Ji 2008). This type of model – sometimes called an advection-diffusion model – is derived from a consideration of conservation of mass for each contaminant and is typically solved using a finite difference approximation. Additional components are sometimes included to represent other processes such as the reaction or decay of contaminants. Due to their site-specific nature, estimates for the model coefficients are preferably derived from field observations, typically using tracer experiments or longer-term monitoring of background pollution.

In locations where more complex factors need to be considered, this normally requires a hydrodynamic modelling approach. Some typical examples include river reaches with low rates of mixing (‘dead zones’) or tidal influences. For point sources of pollution, another factor which is sometimes considered is the near-field mixing

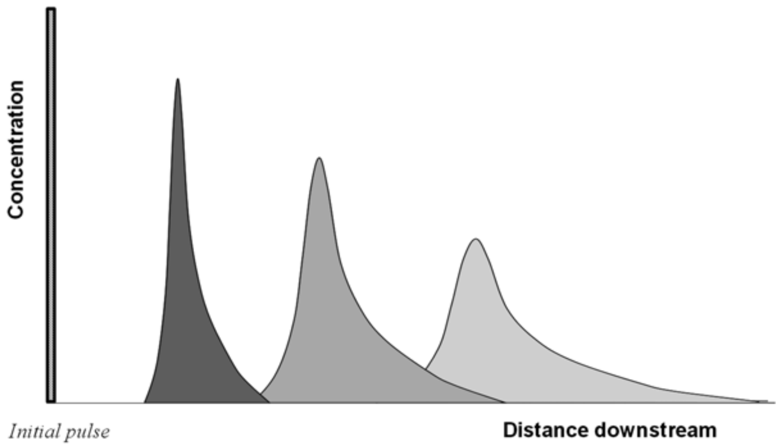

Fig. 12.1 Idealised example of the transport of a pulse of pollution down a river channel

around the point of discharge since this can have a strong influence both locally and on concentration profiles further downstream. For example, one application – at least for off-line studies – is in modelling the spread of thermal plumes at the outfalls from power station cooling water systems.

With both flow routing and hydrodynamic approaches, the river system is normally divided into a number of discrete reaches within which conditions are assumed to be constant. This also allows additional inflow and outflow terms to be included if required, such as those due to tributary inflows and water abstractions. Where the reaction and decay (or conversion) of contaminants are represented, a typical approach is to use reaction or rate coefficients. A first-order approximation is to assume that the rate of decay or production is proportional to the concentration of the constituent. However, solution schemes can be considerably more complex than this and sometimes represent the interactions between constituents, such as dependencies on temperature and dissolved oxygen content and factors such as photosynthesis in ecological applications. Sub-models for sediment transport are often required, considering the transport, settling and resuspension of particles and the impacts on turbidity

Whilst these are perhaps the most widely used approaches, simpler multiple regression relationships also have a role; for example, to estimate travel times and volumes from catchment characteristics (e.g. Wilson et al. 1997). For some applications water balance techniques are sufficient, and supply demand modelling systems of the types described in Chap. 13 sometimes include a water quality modelling component. As noted earlier data assimilation techniques are also used to help to improve forecasts based on real-time observations; for example, Kim et al. (2014a) describe a river pollution model in which a maximum-likelihood ensemble filter is used to update the initial states for several constituents, such as dissolved oxygen, nitrate, phosphate and chlorophyll a. Stochastic transfer functions provide another option and combine the data assimilation and input-output aspects in a single model (e.g. Young 1998).

For lakes and reservoirs, an additional complication is that currents are often driven mainly by wind and temperature effects. This ideally requires use of a two- or three-dimensional hydrodynamic model to represent the overall circulation. In addition to the various processes noted above, some other factors which may need to be represented include mixing due to tributary inflows and the effects of wave action. Chapter 5 provides more background on this general approach, and for water quality applications some potential real-time uses include forecasting the spread of harmful algal blooms (see Sect. 5.3) and estimating water temperature and turbidity profiles to support drinking water supply operations (e.g. Pyke and Porter 2012). However, as for river applications, in some cases a simple mass-balance approach may suffice if all that is required is to track overall pollution loads at a broad scale.

Box 12.2: RIZA AQUALARM system
The Netherlands lies at the lower end of the River Rhine and, since 1957, water has been abstracted for public water supply at the Nieuwegein treatment works (Stoks 1994) and is also used for agriculture and recreation. The Rhine provides about two-thirds of the freshwater inflows to the Netherlands, and water quality is an important consideration since the river passes through a number of heavily populated and industrialised regions in Germany and several other countries and is used extensively for shipping. Pollution incidents occur several times each year although most are detected in time to take effective action and rarely result in significant environmental or health hazards.

The main organisation which is responsible for river water quality in the Netherlands is the Rijkswaterstaat, which is part of the Ministry of Infrastructure and Environment. Since 1974, the Rijkswaterstaat Centre of Water Management Netherlands has operated a system called AQUALARM to monitor water quality at border stations on the Rhine and the other main transboundary river in the Netherlands, the Meuse. Due to the short travel times from the German and Belgian borders, monitoring is initially performed at the point of measurement from floating laboratories (Fig. 12.2) before more detailed analyses are performed elsewhere. The measuring station at Lobith (RIZA 2009) is part of a Dutch-German International measuring station at Bimmen/Lobith and is jointly operated with the German LANUV (Das Landesamt für Natur, Umwelt und Verbraucherschutz, NRW).

A wide range of physical and chemical parameters is monitored, including dissolved oxygen, temperature, conductivity, turbidity, pH, chloride, fluoride, cyanide, radioactivity, organic pollutants and, in the Meuse only, heavy metals such as cadmium, copper, lead and zinc. Continuous biological monitoring of algae and daphnids also acts as an early warning of the presence of unknown toxic pollutants, such as herbicides. If predefined thresholds are crossed, warnings are provided to the appropriate authorities, particularly the water

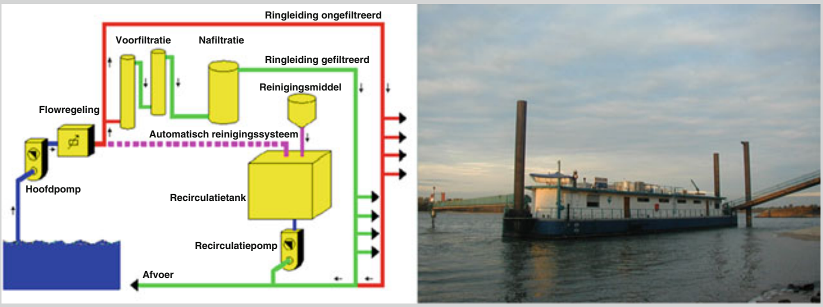

Fig. 12.2 Illustration of the sampling system and monitoring station at Lobith on the River Rhine (Rijkswaterstaat – Centre of Water Management Netherlands; http://www.aqualarm.nl/)

(continued)

Box 12.2 (continued)

intake station ir. Cornelis Biemond at Nieuwegein which is run by water company Waternet. Some options for dealing with pollution incidents include dilution with water from other sources to bring contaminant levels back within limits or temporary interruptions to supplies.

The Netherlands also participates in the International Warning and Alarm Plan 'Rhine' which is coordinated by the International Commission for the Protection of the Rhine (ICPR). The main components include a network of monitoring stations at Basel, Strasbourg, Moselle Metz, Luxembourg, Koblenz, Mannheim, Düsseldorf and Arnhem and operation of a pollutant forecasting model called the Rhine Alarm Model (Broer 1991; van Mazijk et al. 1999; Diehl et al. 2005). River flow forecasts are available from a network of rainfall-runoff and hydrodynamic models, as described in Chap. 8.

The Rhine Alarm Model has been operational since 1989 and extends from Lake Constance in the Alps to the Dutch coastline and includes the main tributaries of the Rhine. The model represents the river network by reaches, typically each a few kilometres in length, in which the advection velocity for pollutants can be considered relatively constant, for a given river level. Typical level-flow time curves are derived from off-line hydrodynamic modelling studies. A one-dimensional advection diffusion equation is used to model the transport of pollutants in each reach and allows for stagnant zones, floating pollutants (e.g. oil) and linear decay of pollutants.

Pollutant inputs can consist of either instantaneous (pulse) inputs or time-varying contributions. Estimates for mean transport velocities and longitudinal dispersion coefficients were obtained over the course of a series of tracer experiments between 1988 and 1992 which covered about 1500 km of the Rhine and its tributaries (Leibundgut et al. 1993). The model is optimised for relatively constant low to medium flows, rather than rapidly changing flows. The key inputs include the location, time and duration of the discharge and the amount and biodegradation percentage for harmful substances. Information is also required on whether pollutants are likely to float on the water surface (e.g. oil) or mix with the river water. The types of outputs include forecasts of changes in concentration over time at given locations or concentrations at a given time along a river reach, and map-based displays showing forecast concentrations colour-coded by ranges (e.g. Fig. 12.3).

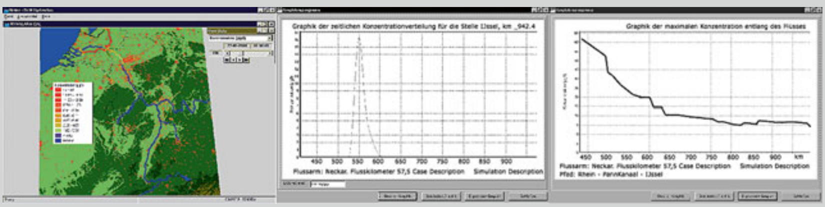

Fig. 12.3 Examples of outputs from the Rhine Alarm Model for a fictitious discharge of harmful substances, showing a colour-coded map display and concentrations at a given time and along a river reach (International Commission for the Hydrology of the Rhine Basin http://www.chr-khr.org/)

12.2.2 Catchment-Scale Models

Within a river catchment, there are often many different sources of pollutants. Typically rates of production vary according to factors such as topography, land use, soil types and the nature of the drainage network. Table 12.4 summarises some of the processes which may need to be represented in a forecasting system; for example, to estimate pollutant loads and sedimentation rates in rivers, lakes and reservoirs.

The extent to which these are represented depends on the application. In particular, impacts on water quality can appear throughout the hydrological cycle and at a range of timescales and are often influenced by land management practices and policy. For example, Figure 12.4 shows a conceptual framework for considering these types of issues for a catchment in the northwest of England.

The techniques for modelling diffuse pollution range from statistical and empirical approaches to more complex conceptual and physically-based (or mechanistic) models. For example, multiple regression techniques and simple conceptual models are widely used to estimate total pollutant loads on a daily or longer basis, typically based on factors such as runoff volumes, topography, slope length and steepness and land-use types. Often these types of analyses are performed within a Geographical Information System (GIS) modelling framework to allow the spatial variations to be considered in detail.

More complex semi-distributed or distributed models have also been used since at least the 1970s for off-line (simulation) studies (e.g. Borah and Bera 2003; Merritt et al. 2003; WMO 2003; Yang and Wang 2010), although their use in real-time applications is a more recent development (e.g. Table 12.5). These are usually called catchment or watershed models and typically make use of either sub-catchment, land use zone or grid-based formulations (e.g. Lindström et al. 2010). Additional regression, conceptual or process-based components are normally required to represent the rate of production of contaminants in each modelling unit and the subsequent transport to the points of interest. Other factors such as decay, dilution and reaction processes may be represented.

Table 12.4 Some typical examples of factors which influence diffuse (non-point source) pollution

Item	Examples
Catchment characteristics	Drainage network, topography, sub-catchment divisions, vegetation/crop types, urban areas, soil types, geology, water bodies, land management practices, hydraulic structures
Forcing variables	Precipitation (rainfall, snow, etc.), air temperature, evapotranspiration, solar radiation, wind speed, humidity
Initial conditions	River flows, soil moisture, contaminant concentrations, groundwater levels, lake levels, vegetation/crop growth stage
In-stream processes	Hydraulic, deposition, resuspension, oxidation, biodegradation processes
Land-surface processes	Rainfall-runoff, percolation, sub-surface flow, erosion and sedimentation processes, vegetation/crop growth, point source inputs, contaminant production, atmospheric deposition

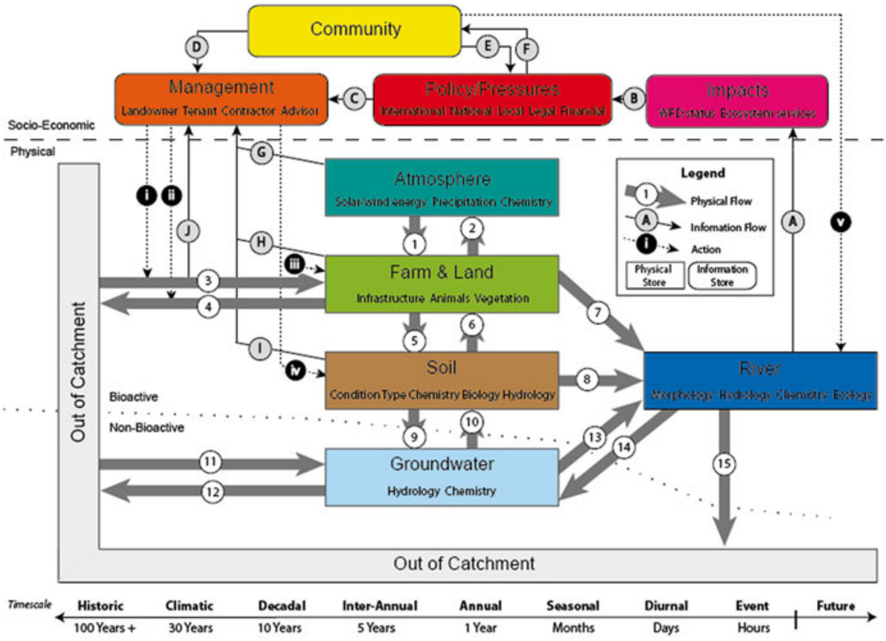

Fig. 12.4 The Eden Demonstration Test Catchment conceptual model; on the website users can select individual components and pathways for further background information on key water quality and policy issues (Lancaster Environment Centre; http://www.edendtc.org.uk/)

A key modelling challenge is often how to scale up understanding of physical processes at the field scale to larger scales and there have been many experimental studies to consider this issue. For example, for some contaminants such as phosphates, heavy rainfall often generates the bulk of the loading (see Chap. 3 for example), whereas for others the main pathway may be via sub-surface flows. Data availability is sometimes also an issue requiring additional gauges to be installed as part of the model development process to record the catchment response for at least a few flood and low flow events.

In ecological applications, another developing area is the use of Bayesian Belief Networks or Bayesian Networks for short (Aguilera et al. 2011). The earliest practical uses were in the 1980s in areas such as medicine and software fault diagnosis, and these techniques have since been used in a wide range of technological and environmental applications (e.g. Fenton and Neil 2007), for example in the developing area of ecosystem services (e.g. Haines-Young 2011; Landuyt et al. 2013). One particular advantage is that the Bayesian formulation allows observations to be combined with less precise, more subjective information, such as the views of key stakeholders.

Table 12.5 Some examples of systems for forecasting pollutant loads due to diffuse pollution

Country	Description
Finland	Application of a real-time nutrient and sediment load simulation model at a national scale. Approximately 6200 river basins and 58000 lakes are represented, and forecasts are displayed on a website as graphs, maps and tables including values for phosphorus, nitrogen and sediment loads and total organic carbon. At a field scale, each location is represented in terms of slope profile, crop and soil types and sub-models to take account of factors such as farming practices, fertiliser application rates, crop growth, leaching and soil erosion. The outputs are then routed through the river and lake network using a flow routing and mass balance approach, including representation of sedimentation and de-nitrification in rivers and lakes (Vehviläinen et al. 2005; Huttunen et al. 2008, 2013)
Korea	Development of an integrated forecasting system, combining a watershed model with hydrodynamic models for key reservoirs to help with managing issues with algal blooms. Ensemble meteorological forecasts and point source discharge measurements are used as inputs and the outputs include forecasts for phosphate and chlorophyll a concentrations. The system includes use of an ensemble Kalman filter approach to help to assess the uncertainties arising from the catchment model for a range of constituents (Kim et al. 2014b)
USA	Use of a process-based pollutant fate and transport model to forecast fecal indicator bacteria loads in the Great Lakes. The model estimates the likely inputs from wildlife and leaking septic tanks in the watershed, accounting for the lifespan of bacteria in different conditions. The outputs are used as inputs to hydrodynamic models for selected locations which simulate the movement of bacteria due to currents and water temperature and water level variations. Model outputs are routinely verified based on nearshore bacterial water quality monitoring (adapted from NOAA/GLERL 2015a)

Typically the relationships between inputs and outputs (or cause and effect) are represented graphically as a network of nodes and links (or arcs). Each node has an associated probability table, typically representing the probability distribution in discrete form or a simple true/false condition (Jensen 1996). The links then represent causal or influential relationships; for example, the variable represented by Node A may cause a change in, or influence the state of, the variable represented by Node B. Each probability table expresses the conditional probability of each possible outcome at a node given the probability of outcomes at the nodes to which it is attached.

Given a set of new observations (or evidence), the prior assumptions (distributions) are then revised using Bayes' Theorem to obtain the posterior distributions (or revised beliefs) for variables at any point in the network. Bayesian Networks therefore provide a framework for successively updating beliefs as new information becomes available with associated estimates of the uncertainty in the results. Some areas for research include the use of continuous, rather than discrete, probability distributions, statistical learning for parameters and network verification techniques (e.g. Fenton and Neil 2007).

12.3 Selected Applications

12.3.1 Harmful Algal Blooms

Harmful algal blooms are formed from *Cyanobacteria*, which are more usually called blue-green algae. These are a type of bacteria although often appear similar to some types of algae. They are a natural feature of many rivers, lakes and reservoirs but cause problems when numbers are excessive (e.g. Fig. 12.5). Typically this occurs as a result of nutrient pollution combined with other conditions which promote their development such as warm weather and light winds.

Cyanobacteria are one of the oldest living species and are able to survive extremes of heat, cold and salinity. Strains are found in the oceans, estuaries and freshwater and range from single-cell organisms to colonies and filaments of cells. In rivers and lakes, blooms form when large numbers rise to the surface towards the end of their lifecycle, sometimes forming unsightly 'mats'. These are usually blue green in colour although sometimes appear in shades of green brown or red brown, in some cases with a strong odour and/or with the appearance of foam or paint. Whilst many species are harmless, some release toxins with potential impacts on people including vomiting, diarrhoea, rashes and respiratory problems, with a risk of death to animals and fish. Other risks include blockages in water abstraction intakes and filtration systems and impacts on dissolved oxygen content and drinking water quality.

Fig. 12.5 Harmful Algae Bloom at Bolles Harbor, Monroe, MI, Lake Erie, 22 July 2011 (image courtesy of NOAA, Great Lakes Environmental Research Laboratory, NOAA/GLERL 2015b)

The long-term aim of much research is to develop models capable of predicting the full life cycle of harmful algal blooms, including their occurrence, toxicity, transport and the fate of toxins (e.g. Lopez et al. 2008). One widespread approach to forecasting the risk of algal blooms forming is to use regression techniques. Some typical predictors include total phosphate and nitrate loads and sometimes turbidity and water temperatures. Bayesian hierarchical techniques also provide a useful statistical framework (Obenour et al. 2014), and fuzzy logic approaches have been evaluated (Blauw et al. 2006). For forecasting the motion of blooms once formed, hydrodynamic models are increasingly the preferred option if budgets allow.

Typically when reports or forecasts of algal blooms are received, the authorities place warning signs at locations where people may be affected, such as at lakeside beaches and popular places for fishing and boating. Web-based and email bulletin services are increasingly offered as well. For reservoirs there is the option to release flows to 'flush' blooms out of the system provided that this would still allow water supply and other objectives to be met.

Operational forecasting services are provided in several countries both for *Cyanobacteria* and certain marine organisms which also form blooms (e.g. Anderson et al. 2015). For example, in the USA, forecasts are routinely issued for the coastlines of Florida and Texas for the so-called 'red tides' caused by the organism *Karenia brevis* and are based on expert assessment of meteorological and coastal forecasts, field assessments and satellite, buoy and autonomous underwater vehicle observations (NOAA 2010). As in many other applications, probabilistic techniques are increasingly used; for example, Fig. 12.6 shows extracts from an experimental product for harmful algal bloom projections in Lake Erie in the USA. The values are based on a bloom severity model and estimated phosphorus loads from the Maumee River since the start of the loading season (1 March).

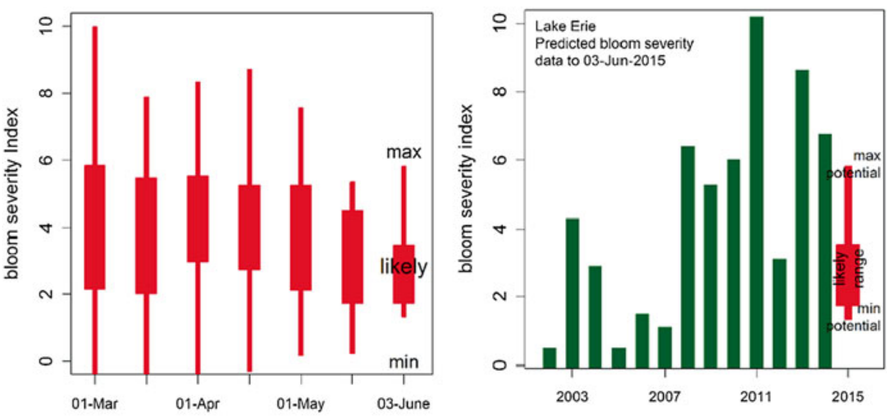

Fig. 12.6 Loading season projections for 2015 starting March 1st, where a bloom severity of 10 indicates the record-breaking bloom of 2011 (*left*). Projected bloom compared to previous years; the wide bar is the likely range of severity based on data from the last 15 years; the narrow bar is the potential range of severity (*right*) (NOAA/GLERL 2015c; images courtesy of NOAA, Great Lakes Environmental Research Laboratory)

Similarly in some years blue-green algae are a significant problem in Finland and are monitored by satellite and ships and at several hundred permanent monitoring locations at lakes and in the Baltic Sea. Algal bloom forecasts are issued weekly during the high-risk season based on monitoring, ocean modelling and expert opinion, also making use of the nutrient loads estimated using the model described in the previous section.

12.3.2 Bathing Water Quality

Pollution at lakeside and coastal locations can sometimes cause a range of health problems to water users. Typically, the main issue is from bacterial infections arising from diffuse pollution from farmland and urban areas. Point source pollution from urban drainage systems, particularly Combined Sewer Overflows, is another typical concern (see Chap. 11).

In addition to public pressure, some key drivers for improvements include accreditation schemes for bathing waters such as the popular Blue Flag certification scheme and legislation such as the European Bathing Water Quality Directive (e.g. Box 12.3). The choice of pathogen(s) to consider depends on a number of factors, including legislative requirements, the feasibility of monitoring and the likely risk to health at the specific location. However, tests for the concentrations of *Escherichia Coli* (*E. coli*) and intestinal enterococci are perhaps the most common. More generally, across a range of contaminants, there have been considerable advances in the speed and reliability of monitoring techniques in recent years, with the time required for analysis reducing from a day or more to hours or less with some types of equipment (e.g. Noble and Weisberg 2005).

In many cases, the trigger for a pollution incident is heavy rainfall, resulting in increased surface runoff and river flows and an increase in pollution from the land surface. Several studies (e.g. EPA 1999) have shown that rainfall depth-duration thresholds provide a good indicator of the potential for problems, and these are used in local warning systems in several countries. Typically rainfall estimates are based on raingauge observations, although weather radar and rainfall forecasts provide other possibilities.

Multiple regression techniques provide another widely used approach, and, in addition to rainfall, some examples of possible predictors include wind speeds and directions, tidal conditions (for coastal sites), wave heights, the season, water temperatures and the number of dry days since rainfall last occurred. Where there are many factors to consider, decision support tools such as decision trees are sometimes used as part of the decision-making process (e.g. Stidson et al. 2012).

If the sources of pollution are well understood, there is the potential to develop a more process-based approach; for example, using an advection-dispersion model for river transport and a distributed catchment model to estimate pollutant loads, combined with hydrodynamic models for lakes, reservoirs or coastal reaches.

For example, for Copenhagen Harbour in Denmark, a three-dimensional hydrodynamic model is operated to estimate *E. coli* concentrations at several beach locations (e.g. Mark and Erichson 2007). If critical thresholds are exceeded, then warnings are issued via a website, text messages and smartphone applications. Figure 12.7 illustrates another example, in this case for the Great Lakes in the USA. Here, as noted earlier, the forecasting system combines process-based pollutant fate and transport models for catchment areas with hydrodynamic models for selected locations around lake shorelines. The models are used to simulate the motion of faecal indicator bacteria such as *E. coli* and *Enterococcus* due to currents and water temperature and water level fluctuations (NOAA/GLERL 2015a).

Hydrodynamic models can also be used off-line to derive look-up tables or graphs for real-time use. For example, EPA (1999) describes an approach which was developed for the New York-New Jersey-Connecticut metropolitan area in which multiple scenarios were run using a three-dimensional model for 29 discharge locations and 53 beaches/shellfish areas. The model outputs were then used to develop a quick reference tool to allow total coliform concentrations to be estimated as a result of a spill at any one of the discharge locations. In operational use, the following parameters were required as input: discharge location, receptor site location, water temperature, volume of discharges, discharge concentration and bacteria type to analyse (total coliform was the default). After several years of operation, the initial version was improved to include multiple discharge sites for a wider geographical area and to consider enterococci bacteria and conservative tracers such as metals (Dujardin et al. 2008).

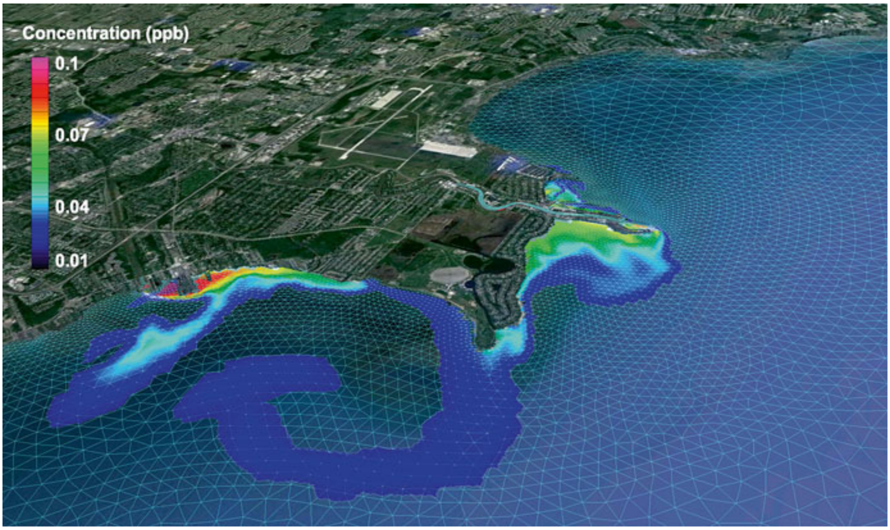

Fig. 12.7 Output from the GLERL-developed Huron to Erie Connecting Waterways Forecasting System with Google overlay. The model predicts real-time water levels and currents to simulate where bacteria and other possible contaminants will travel in the lake (NOAA/GLERL 2015a; image courtesy of NOAA, Great Lakes Environmental Research Laboratory)

Box 12.3: SEPA Bathing Water Signage

Within Europe, minimum standards for bathing water quality are prescribed by the European Commission's 2006 Bathing Water Quality Directive. From 2012, the directive has required that bathers should be provided with information regarding potential risks to their health.

In Scotland, the Scottish Environment Protection Agency (SEPA) monitors water quality at more than 80 identified bathing water sites and provides daily predictions at 23 of these sites. Information is displayed in real time on electronic variable message signs (e.g. Fig. 12.8) and can also be obtained from the SEPA website (http://www.sepa.org), a mobile website and a phone line service (Beachline).

To help raise awareness of the issues, bathing water profiles are available for each site (SEPA 2015) and these provide:

- A description, map and photograph of the bathing water
- Information on potential pollution sources and risks to water quality
- Descriptions of measures being taken to improve water quality
- Information on reporting and responding to any pollution incidents
- Local contact details for sources of further information

Within the directive, Excellent, Good, Sufficient and Poor water quality classifications are specified based on bacterial sampling over a period of 3–4 years, and SEPA uses the following messages to describe the risk of known predicted periods of short-term poor quality by posting either:

- No predicted water quality issues today
- Poor = Bathing not advised today. Risk of poor water quality

Although water quality is generally of a high standard, experience shows that quality sometimes deteriorates during or following wet weather (e.g. Crowther

Fig. 12.8 Electronic bathing water quality sign at Prestwick (McPhail 2007)

(continued)

Box 12.3 (continued)
et al. 2001). The main risks are of elevated levels of microbiological pollution from Combined Sewer Outfalls and from animal waste and other contaminants from roads, urban areas and farmland which runoff into rivers and streams which discharge to the sea at or near bathing waters. For example, regarding the Prestwick site shown in the figure, the profile notes that the main risks are:

> The principal risks and source of wet weather driven short term pollution at this bathing water arise from surface water run-off from urban drainage, overflows from the sewerage system and agricultural run-off. These events are expected to last 1–2 days depending on the duration of the rainfall. Our regulatory and scientific assessment indicates that there are no significant pollution inputs to this bathing water under normal situations. Bathing is not advisable during or following (one or two days after) rainfall. Bathing or swimming after storms, floods or heavy rainfall should be avoided as the risk of illness following short term water pollution is increased.

To provide the overall annual water classification and during the season help identify any potential problems, water quality is sampled every two weeks throughout the main bathing season from early June to mid-September. The main checks are for *Escherichia coli* and Intestinal enterococci, and checks are also made for a range of other potential issues such as *cyanobacteria*, marine phytoplankton and excess seaweed. More frequent monitoring is performed during periods when water quality has deteriorated, whilst some sites are eligible for reduced sampling due to sustained improvements in water quality.

Predictions of water quality are based on historical correlations between bacterial concentrations and rainfall measured by an extensive network of SEPA raingauges. Rainfall depth-duration thresholds for issuing warnings are defined in terms of rainfall for the previous 24, 48 and 72 h, together with rainfall forecasts for the current day to midday (e.g. Stidson et al. 2012). For some sites, river flow information is also included in the regression relationships. Using this approach, between 2004 and 2007 the Probability of Detection of poor water quality was about 80 %, although with a significant number of false alarms (Dale and Stidson 2007). Some factors which can affect the accuracy of the method include variations in catchment antecedent conditions, tidal conditions and the current storage in the sewer network.

The use of radar rainfall data has also been investigated as an alternative or complement to raingauge data and has the potential to improve detection of rainfall during localised convective rainfall events (SNIFFER 2007; Dale and Stidson 2007). Radar-based rainfall forecasts (nowcasts) might also be used to extend forecast lead times. Other areas being investigated include the use of hourly and catchment average rainfall values in the regression relationships – and tide, solar radiation and wind speed/direction information – together with a wider implementation of a decision tree approach to help decide whether to issue alerts and make water quality predictions at the tighter standards required by the 2006 directive classifications (e.g. Stidson et al. 2012).

12.4 Summary

- Diffuse and point source pollution can present a risk to people and wildlife and result in adverse effects such as the formation of harmful algal blooms. Over longer timescales, increased sedimentation due to catchment degradation is another potential concern and the acidification of lakes due to atmospheric deposition.
- For rivers, the main forecasting techniques include statistical and advection-dispersion models and in some cases one-dimensional hydrodynamic models. Model operation is typically supported by real-time observations for a range of constituents. For lakes and reservoirs, real-time two- or three-dimensional hydrodynamic models are increasingly used when factors such as thermal stratification, currents, and wave action need to be considered.
- Models for diffuse pollution loads range from simple regression techniques through to complex GIS-based catchment or watershed modelling approaches representing a wide range of processes in a fine level of detail. The model performance is usually constrained by the data available for calibration and the challenges in relating information available from small-scale studies to a catchment scale.
- Harmful algal blooms are a major concern in many water bodies, and their formation is often linked to high levels of nutrient runoff from the land surface. Some forms present a risk to people and animals and operational forecasting and warning systems are increasingly being implemented, with associated web- and smartphone-based alerting procedures. Forecasts are usually based on regression relationships or catchment models, sometimes supplemented by hydrodynamic models to predict the motion of blooms on the water surface.
- Many organisations offer alert systems for poor bathing water quality. Multiple regression and decision-tree approaches are widely used to relate conditions at the coast or lakeshore to those inland in the contributing catchment area. Bayesian and fuzzy logic techniques also show potential and hydrodynamic models are increasingly used to estimate the spread of pollutants.
- There is much research underway into real-time forecasting techniques for water quality and ecological applications, including the development of coupled watershed, meteorological and hydrodynamic models. In particular this includes the increasing use of data assimilation techniques and extending the scope of ecosystem (or ecological) forecasting models. Bayesian Belief Networks also show potential for exploring the complex linkages between water quantity, water quality and ecosystems at long timescales.

References

Aguilera PA, Fernández A, Fernández R, Rumí R, Salmerón A (2011) Bayesian networks in environmental modelling. Environmental Modelling & Software, 26(12): 1376–1388

Anderson CR, Moore SK, Tomlinson MC, Silke J, Cusack CK (2015) Living with Harmful Algal Blooms in a changing world: strategies for modeling and mitigating their effects in coastal marine ecosystems. Chapter 17 in Coastal and Marine Hazards, Risks, and Disasters (Eds. Ellis JT, Sherman DJ), pages 495–561

Beck MB, van Straten G (Eds.) (1983) Uncertainty and Forecasting of Water Quality, Springer Verlag, Berlin

Blauw AN, Anderson P, Estrada M, Johansen M, Laanemets J, Peperzak L, Purdie D, Raine R, Vahtera E (2006) The use of fuzzy logic for data analysis and modelling of European Harmful Algal Blooms: Results of the HABES project. African Journal of Marine Science, 28 (2): 365–369

Borah DK, Bera M (2003) Watershed-scale hydrologic and nonpoint-source pollution models: Review of mathematical bases. Transactions of the ASAE, 46(6): 1553–1566

Broer G J A A (1991) Alarm system for accidental pollution on the River Rhine. Hydrology for the Water Management of Large River Basins. Proceedings of the Vienna Symposium, August 1991, IAHS Publ. No. 201

Chapra SC (2008) Surface Water-Quality Modeling, McGraw-Hill, New York

Chin (2006) Water-Quality Engineering in Natural Systems. Wiley, Chichester

Crowther J, Kay D, Wyer M D (2001) Relationships between microbial water quality and environmental conditions in coastal recreational waters: the Fylde coast, UK. Water Research, 35(17): 4029–4038

Dale M, Stidson R (2007) Weather radar for predicting beach bathing water quality. WaPUG conference, Blackpool, November 2007

Diehl P, Gerke T, Jeuken A, Lowis J, Steen R, van Steenwijk J, Stoks P, Willemsen H G (2005) Early warning strategies and practices along the River Rhine. In Volume 5 of The Handbook of Environmental Chemistry (Ed. Knepper T P), Springer Berlin Heidelberg

Dujardin C, Sattler P, Kumaraswamy A (2008) Development of a regional model to predict the impact of bacterial and conservative discharges. Third Passaic River Symposium, New Jersey, 16 October 2008

EPA (1999) Review of potential modeling tools and approaches to support the BEACH Program. United States Environmental Protection Agency, Office of Science and Technology, Report 823-R-99-002

European Commission (2008) Water Note 2: Cleaning up Europe's Waters: Identifying and assessing surface water bodies at risk. DG Environment, European Commission, Brussels

Fenton N, Neil M (2007) Managing risk in the modern world: applications of Bayesian Networks. London Mathematical Society

Haines-Young R (2011) Exploring ecosystem service issues across diverse knowledge domains using Bayesian Belief Networks. Progress in Physical Geography, 35(5): 681–699

Huber WC (1993) Contaminant Transport in Surface Water. Chapter 14 in Handbook of Hydrology (Ed. Maidment DR), McGraw Hill, New York

Huttunen I, Huttunen M, Tattari S, Vehviläinen B (2008) Large scale phosphorus load modelling in Finland. Proceedings of the XXV Nordic Hydrological Conference 2008, ISBN 978-9979-68-238-7

Huttunen M, Huttunen I, Korppoo M, Seppänen V, Vehviläinen B (2013) The national-level nutrient loading estimation tool for Finland: WSFS-Vemala. Geophysical Research Abstracts, 15: EGU2013-4119-2

Jensen FV (1996) Introduction to Bayesian Networks (1st ed.). Springer-Verlag, New York

Ji Z (2008) Hydrodynamics and Water Quality: Modelling Rivers, Lakes and Estuaries, Wiley, Chichester

Kim S, Seo D-J, Riazi H, Shin C (2014a) Improving water quality forecasting via data assimilation – Application of Maximum Likelihood Ensemble Filter to HSPF. Journal of Hydrology, 519(D): 2797–2809

Kim K, Park M, Min J-H, Ryu I, Kang M-R, Park LJ (2014b) Simulation of algal bloom dynamics in a river with the ensemble Kalman filter. Journal of Hydrology, 519(D): 2810–2821

Landuyt D, Broekx S, D'hondta R, Engelen G, Aertsens J, Goethals PM (2013) A review of Bayesian belief networks in ecosystem service modelling. Environmental Modelling & Software, 46: 1–11

Leibundgut Ch, Speidel U, Wiesner H (1993) Transport processes in rivers investigated by tracer experiments. Tracers in Hydrology (Proceedings of the Yokohama Symposium, July 1993), IAHS Publ. No. 215

Lindström G, Pers C, Rosberg J, Strömqvist J, Arheimer B (2010) Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. Hydrol Res 41(3-4): 295–319

Lopez CB, Jewett EB, Dortch Q, Walton BT, Hudnell HK (2008) Scientific assessment of freshwater Harmful Algal Blooms. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC

Loucks DP, Lynn WR (1966) Probabilistic models for predicting stream quality. Water Res. Research, 2(3): 593–605

Luo Y, Ogle K, Tucker C, Fei S, Gao C, Ladeau S, Clark JS, Schimel DS (2011) Ecological forecasting and data assimilation in a data-rich era. Ecological Applications, 21(5): 1429–1442

Mark O, Erichson A (2007) Towards implementation of the new EU Bathing Water Directive – Case studies: Copenhagen & Århus, Denmark. Novatech 2007, 6th International Conference on Sustainable Techniques and Strategies in Urban Water Management, Lyon, 25–28 June 2007

Mazijk A van, Leibundgut Ch, Neff H.-P (1999) Rhein-Alarm-Modell Version 2.1 Erweiterung um die Kalibrierung von Aare und Mosel. Kalibrierungsergebnisse von Aare und Mosel aufgrund der Markierversuche 05/92, 11/92 und 03/94, Report no. II-14 of the International Commission for the Hydrology of the Rhine Basin

McPhail C (2007) Bathing Water Signage and Predictive Models in Scotland. Beaches World Tour 2007, Toronto, 9–11 October 2007

Merritt WS, Letcher RA, Jakeman AJ (2003) A review of erosion and sediment transport models. Environmental Modelling & Software, 18(8–9): 761–799

NOAA (2006) Great Lakes Environmental Research Laboratory Science Strategy 2007–2011. Great Lakes Environmental Research Laboratory, Ann Arbor, MI

NOAA (2010) HAB Bulletin Guide – An Overview. US Department of Commerce, National Oceanic and Atmospheric Administration, Washington

NOAA (2014) A Strategic Vision for NOAA's Ecological Forecasting Roadmap 2015–2019, National Oceanic and Atmospheric Administration, Washington

NOAA/GLERL (2012) NOAA Great Lakes Environmental Research Laboratory Innovative Research for the Freshwater Seas: Strategic Plan 2012. US Department of Commerce, National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Washington

NOAA/GLERL (2015a) Great Lakes beach, tributary, & nearshore bacterial water quality: Hydrologic and Hydrodynamic Data and Model Assimilation Project. Information sheet, Great Lakes Environmental Research Laboratory, Ann Arbor, MI

NOAA/GLERL (2015b) Great Lakes Restoration Initiative. Information sheet, Great Lakes Environmental Research Laboratory, Ann Arbor, MI

NOAA/GLERL (2015c) Lake Erie Harmful Algal Bloom Early Season Projection. National Centers for Coastal Ocean Science and the National Center for Water Quality Research. Bulletin, 3 June 2015, Projection 03, Great Lakes Environmental Research Laboratory, Ann Arbor, MI

Noble RT, Weisberg SB (2005) A review of technologies for rapid detection of bacteria in recreational waters. J.Water Health, 3: 381–92

Obenour DR, Gronewold AD, Stow CA, Scavia D (2014) Using a Bayesian hierarchical model to improve Lake Erie cyanobacteria bloom forecasts, Water Resour. Res., 50: 7847–7860

Pyke G, Porter J (2012) Forecast-based Operations Support Tool for the New York City Water Supply System. AGU Fall Meeting, San Francisco, 3–7 December 2012

RIZA (2009) Transboundary water quality monitoring of the Rhine (in Dutch and German). Brochure

Robson BJ (2014) When do aquatic systems models provide useful predictions, what is changing, and what is next? Environmental Modelling & Software, 61: 287–296

SEPA (2015) Scottish Bathing Waters: 2014–2015. Scottish Environment Protection Agency, Perth

SNIFFER (2007) Methods for estimating impacts of rainfall on bathing water quality. Scotland & Northern Ireland Forum for Environmental Research, Project UKQL07

Stidson R, Gray CA, McPhail CD (2012) Development and use of modelling techniques for real-time bathing water quality predictions. Water and Environment Journal, 26(1): 7–18

Stoks P G M (1994) Water quality control in the production of drinking water from river water. Proceedings of the 1st Monitoring Tailor Made Conference, the Netherlands

Vehviläinen B, Huttunen M, Huttunen I (2005) Hydrological forecasting and real time monitoring in Finland: The Watershed Simulation and Forecasting System (WSFS). ACTIF International conference on innovation advances and implementation of flood forecasting technology, 17 to 19 October 2005, Tromsø, Norway

WHO (2011) Guidelines for drinking-water quality, 4th edn. World Health Organisation, Geneva

Wilson DA, Butcher DP, Labadz JC (1997) Prediction of travel times and dispersion of pollutant spillages in non-tidal rivers. British Hydrological Society 6th National Hydrology Symposium, Salford, 15–18 September 1997

WMO (2009) Guide to hydrological practices, volume II: Management of water resources and application of hydrological practices, WMO-No. 168, 6th edn. WMO, Geneva

WMO (2003) Manual on sediment management and measurement. Operational Hydrology Report No. 47, WMO-No. 948, Geneva

WMO (2013) Planning of water quality monitoring systems. WMO-No. 1113, Geneva

Yang YS, Wang L (2010) A review of modelling tools for implementation of the EU Water Framework Directive in handling diffuse water pollution. Water Resources Management, 24(9): 1819–1843

Young PC (1998) Data-based mechanistic modelling of environmental, ecological, economic and engineering systems. Environmental Modelling and Software, 13(2): 105–122

Chapter 13
Water Resources

Abstract To forecast the availability of water in a catchment or region, many factors may need to be considered such as reservoir operations and water demands from a range of users. Water balance techniques are typically used to assess supply and demand together with integrated catchment models for operational forecasting. Distributed models are also increasingly used at a regional scale, particularly for climate change projections. Forecast outputs are often probabilistic, particularly for seasonal and longer timescales. This chapter presents an introduction to these techniques including the topics of seasonal flow forecasting and integrated water resources management.

Keywords Water resources planning • River basin management • Integrated Water Resources Management • Supply demand • Forecasting • Data assimilation • Probabilistic • River flow • Seasonal forecasting • Climate change

13.1 Introduction

Estimates of water availability can be required at a range of timescales ranging from short-term operational applications through to strategic studies considering planning horizons from years to decades ahead. Some typical applications include:

- Hours to days – hydropower scheduling and water supply operations
- Seasonal – reservoir management and crop planting strategies
- Years to decades – river basin management and water resources management plans

Similar forecasting techniques are used to those discussed in previous chapters; however, compared to flood forecasting, for example, there is usually a greater emphasis on maintaining an overall water balance. Indeed, as noted in Chap. 1, there can be advantages in operating models year round for a range of applications since, although this initially requires some additional model development work, there are often technical, data sharing and other benefits from an integrated approach.

The main types of modelling techniques include distributed rainfall-runoff models, integrated catchment models and water balance models, which are often called supply demand or water allocation models in water resources applications. As discussed in Chap. 5, in practice the choice of approach usually depends on a

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range of factors such as the lead times ideally required by end users, data availability, budgets and the level of risk.

Generally it is important to consider any abstractions, discharges and losses that affect river flows and water availability, and Table 13.1 provides some examples of the types of factors which may need to be considered. As part of model calibration, it is often necessary to adjust recorded flows to remove the influence of the most significant factors and this process is called flow naturalisation (e.g. WMO 2009). These terms then need to be accounted for in the model in operational use. Similar considerations apply to drought forecasting applications (see Chap. 10).

One additional consideration is the need to leave sufficient water in river systems downstream of any abstraction or impoundment, and some examples of environmental flow requirements include:

- Rivers – minimum flow values that must be maintained or exceeded and which are sometimes called prescribed or hands-off flows
- Reservoirs – the releases which are required to maintain flows downstream of a dam, which are sometimes called compensation flows

Values are typically defined in agreement with key stakeholders on the basis of river surveys, national guidelines and/or modelling studies. Water quality issues also need to be considered as discussed in Chap. 12.

Table 13.1 Some typical examples of low flow related factors in water resources applications (see Chap. 6 for more details)

Item	Description
Boreholes	The potential influences of groundwater abstractions on aquifer levels and river flows and possibly emergency pumping to augment river flows
Canals	Flow abstractions to provide replacement water lost during lock operations plus evaporation and other losses in canal systems
Hydropower	Flow diversions and return flows for micro-hydropower or pumped storage schemes and representation of the influence of reservoir operations
Industry	Abstractions for a wide range of possible applications, including in the chemical, paper, petroleum and waste industries, possibly with return flows of raw or treated water
Interbasin transfers	Transfers of water between river basins such as via pipelines, aqueducts and canals and consideration of aquifers which extend beyond basin boundaries
Irrigation	Pumped or gravity-fed abstractions for surface irrigation, spray irrigation and other uses and return flows via gravity or pumped drainage
Mining	Abstractions for cooling, washing, conveyance and other purposes, possibly with return flows of treated or contaminated water
Reservoirs	Downstream flow releases during low flow periods and possibly emergency releases to augment river flows
Thermoelectric power stations	Abstractions for cooling water and return flows in some types of cooling water system
Wastewater treatment works	Discharges of treated effluent, taking into account river water quality objectives
Water supply (potable consumption)	Pumped or gravity-fed abstractions to water treatment works and storage reservoirs

For real-time applications, information would ideally be available on all significant abstractions and discharges. However, in practice, values are often only available from major users and not necessarily in a timely manner due to data-sharing issues or a lack of suitable telecommunications links (e.g. WMO 2012a). This typically requires some approximations to be made such as aggregating smaller contributions and assuming typical seasonal profiles or pump operating rules. In countries with well-developed licence or permit systems, the agreed amounts may provide a guide although some common issues include:

- Over-abstraction – some users taking more water than allowed, either continuously or at certain times of the day, month or year
- Under-utilisation – situations where the full licenced amount is rarely required or the licence itself is no longer needed but this information is not yet reflected in management information systems

As discussed in Chap. 6, in some applications there are sometimes hundreds or even thousands of permits to consider, requiring considerable effort to understand the current situation if low flow forecasts are required at that level of detail.

At longer timescales the resilience to climate variations is another important consideration including the potential impacts of climate change. Catchment degradation may also be a concern with – as discussed in Chap. 12 – potential impacts on reservoir storage, hydropower operations, navigation and flood risk. Often multiple competing objectives need to be considered as in the following examples:

- Water Resources Management Plans – which typically consider how best to operate and develop water supply networks in an integrated way to meet demands for a range of uses and for which some key issues include the level of service required, environmental impacts and the likely capital and operating costs
- Integrated Water Resources Management studies – investigations into approaches to managing a catchment or river basin in a holistic way considering a range of socioeconomic and environmental objectives, typically leading to an agreed strategy for managing resources at a basin scale, in some cases with an international (transboundary) dimension

This chapter provides an introduction to these various topics and begins (Sect. 13.2) with a discussion of forecasting techniques. Section 13.3 then provides some examples of applications in the areas of seasonal flow forecasting and water resources planning.

13.2 Forecasting Techniques

13.2.1 Supply Demand Models

Supply demand models are widely used for assessing the availability and reliability of water resources in a catchment or region. Typically, models are operated on a daily or longer time step, sometimes including typical time delays for water transit along pipes, rivers and canals but usually ignoring more dynamical effects.

Some alternative names include integrated simulation or optimisation models, basin simulation models and water allocation models.

Whilst approaches such as spreadsheets may be suitable for simpler problems, modelling packages are widely available that provide much greater functionality. For example, some typical options include water quality and rainfall-runoff modelling components, plus a range of data management tools. Most modern systems provide a map-based (GIS) user interface to assist with network configuration using a node and link representation of the system (e.g. Fig. 13.1).

Most systems also include dialog boxes to allow the flow characteristics and operating rules for each component to be entered together with any operating constraints such as maximum capacities or permit conditions. Often there is the option to place a priority order on sources and demand centres such as in the following examples:

- Sources – specifying that gravity-fed supplies should be used in preference to more expensive pumped supplies or that higher quality water sources should be chosen first to reduce water treatment costs
- Demand – giving a higher priority to drinking water supplies than irrigation or top priority to regional or interbasin water supply routes and some of the reservoir operation criteria discussed in Chap. 11

Where water quality models are included, there may be options to represent factors such as the decay of contaminants and the influence of water temperatures.

These types of models are widely used in long-term planning studies and increasingly in operational forecasting, and can be applied at a scheme, basin or regional scale. For example, as a drought develops models might be operated every day using the most recent saved states and current reservoir levels to initialise model runs. If a rainfall-runoff modelling component is available, rainfall observations or forecasts would also be required as inputs or values derived from an ensemble streamflow prediction approach (see Chap. 5). 'What-if' scenarios might also be considered, such as no future rainfall or rainfall reverting to long-term climatological means. Following each model run, the reliability of supplies can then be estimated and possible points of failure or water stress investigated further.

Whilst much can be achieved using trial-and-error approaches, optimization techniques are widely used as a guide to potential improvements to operating strategies and control rules, particularly for multi-reservoir systems (e.g. Loucks et al. 1981, Yeh 1985, Loucks 1996, Wurbs and Wurbs 1995, McKinney et al. 1999, Millington et al. 2006). As discussed in Chap. 11, solution techniques include linear, non-linear and dynamic programming approaches and genetic algorithm and other artificial intelligence techniques. The optimisation criteria depend on the application but are often formulated in terms of the required reliability of supplies or the overall system yield. Some other possibilities include the overall operating costs, water treatment costs or maximum carbon emissions, plus multi-objective criteria.

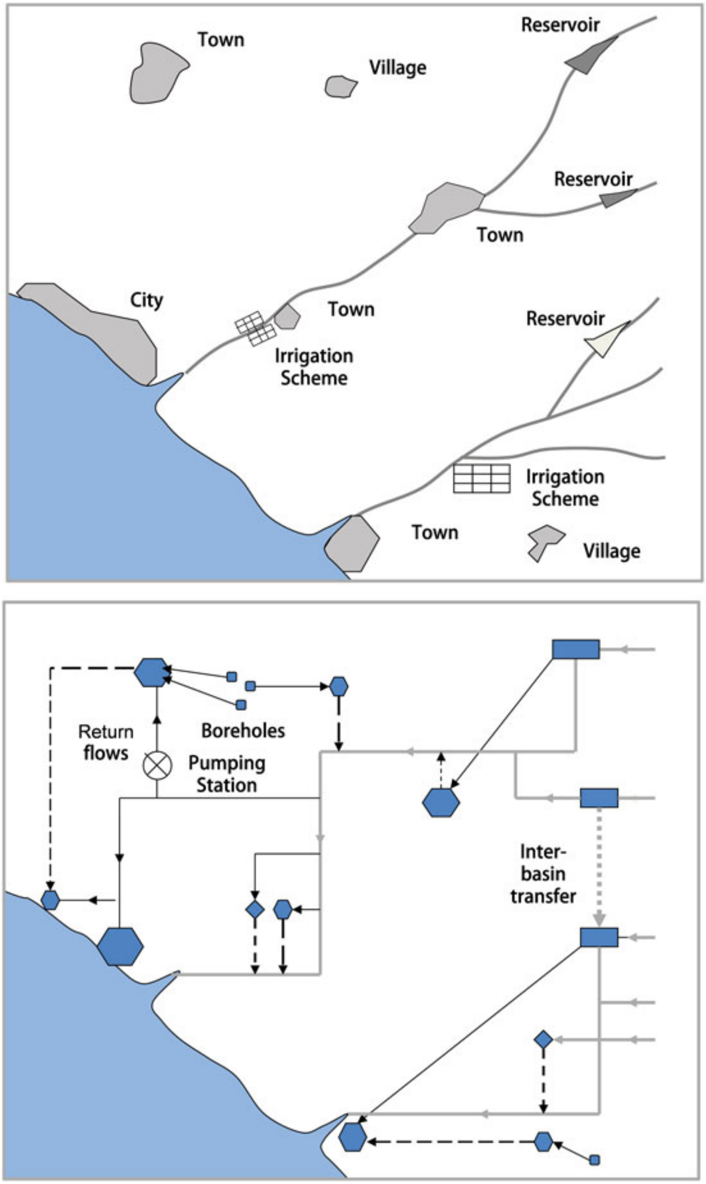

Fig. 13.1 Illustration of a supply demand model for a water supply network in a coastal region; this is a hypothetical example and water and wastewater treatment works and borehole pumps are omitted for simplicity. *Solid lines* = water supply routes, *short dashes* = interbasin water transfers, *long dashes* = discharges, *squares* = reservoirs, *hexagons* = demand centres, *diamonds* = irrigation schemes, *circles* = boreholes

13.2.2 Integrated Catchment Models

Integrated catchment models are widely used for short- to medium-range forecasting applications and increasingly for longer lead times, such as seasonal forecasts. The aim is usually to provide estimates for flows at specific forecasting points; for example, to assist with water supply and hydropower operations (e.g. Box 13.1).

As discussed in Chap. 5, one common approach is to represent a river system using a network of hydrological or hydrodynamic flow routing models. Conceptual or data-driven rainfall-runoff models then provide estimates for the inflows from the headwaters and tributaries, together with models to represent the runoff from ungauged catchment areas (e.g. Fig. 13.2). Additional modelling components are normally required for abstractions and discharges and sometimes for other features such as reservoirs, lakes and control structures.

In some applications river-groundwater interactions and transmission or seepage losses may need to be considered; for example, using simple conceptual models to relate infiltration to river flows and depths or making use of the groundwater flow estimates from any rainfall-runoff modelling components. However, these approaches are very approximate and more detailed conceptual or numerical models are normally required to assess groundwater availability (see Chap. 5).

In real-time operation, the main types of inputs required for this type of model typically include:

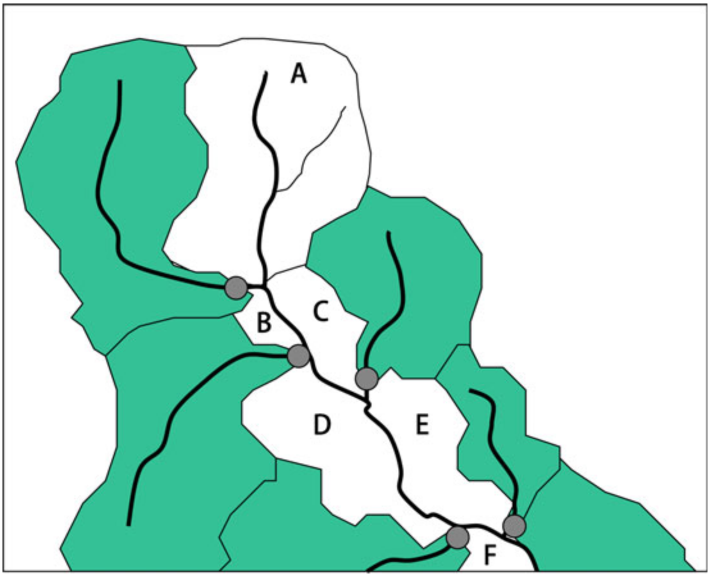

Fig. 13.2 Illustration of gauged (*shaded*) and ungauged (*A–F*) areas based on a catchment in NE England (not to scale); *circles* indicate telemetered river gauges (Adapted from Sene 2008)

- Rainfall observations – from raingauges, weather radar and/or satellite precipitation estimates (see Chap. 2)
- River observations – river level and flow observations from river gauging stations (see Chap. 3)
- Rainfall forecasts – inputs from nowcasting approaches and numerical weather prediction models in deterministic or ensemble form, possibly with some form of post-processing/downscaling applied (see Chap. 4)
- Abstractions and discharges – estimates or observed values for key water demands in the system and any return flows (see Chap. 6)

Depending on the application, some additional types of inputs could include gate settings at control structures, reservoir levels, and air temperatures for input to snowmelt models. Typically observations are received by telemetry although – as noted in Chaps. 5 and 8 – it is sometimes practicable to use a manual approach in which observers report values by cell phone or radio which are then typed into data entry screens. Model run frequencies are often based upon the intervals at which observations are received, with 5–15 min or hourly values typical in many telemetry systems.

As in flood forecasting applications, there is the potential to use real-time observations to reduce the uncertainty in model outputs and improve the accuracy of forecasts. This process is called data assimilation and normally provides significant improvements in forecast performance up to lead times comparable to typical catchment response times. Chapters 5 and 8 discuss the main approaches, and these are generally classified as input, state, parameter or output updating techniques; examples include error prediction and ensemble Kalman filter approaches. When data assimilation is required, normally at least some of the forecasting points need to be located at river gauges so that a real-time feed of observations is available. As illustrated in Fig. 13.2, this usually leads to a significantly different configuration when compared to off-line simulation models, in which subcatchments are normally defined to confluences rather than telemetry sites.

Regarding the flow routing component, this may be implemented internally to the model, as in some distributed approaches, or as a separate component (see Chapter 5). Hydrological routing approaches such as kinematic wave models are widely used; however, hydrodynamic models offer the potential to consider more complex issues related to flow control and water quality issues, such as gate and sluice operations or the impacts of saline intrusion. As for flood forecasting applications, hydrodynamic models developed for off-line planning studies often need some improvements to reduce model run times and improve the stability and convergence, particularly if zero flows are a possibility (see Chaps. 5 and 8).

The resulting models can be complex; for example, Huband and Sene (2005) describe a catchment-wide forecasting model which included 55 lumped conceptual rainfall-runoff models and more than 400 km of hydrodynamic model network. Almost 500 structures were represented including flood storage reservoirs, siphons, pumps, gates, bridges, weirs and culverts. The model was developed for a range of applications including flood forecasting and the management of raw water transfers, river flow support, drought and licence control, pollution incidents and navigation.

Box 13.1: Inflow Forecasting at BC Hydro

BC Hydro is the third largest electric utility in Canada and supplies power to approximately 1.9 million customers in British Columbia (BC) from 30 hydroelectric facilities and three thermal generating plants. Approximately 90 % of the power generated is from hydroelectric sources (CEA 2008). It is BC Hydro's mandate to provide low-cost, clean and reliable power while meeting environmental, social and financial goals.

Forecasts for water supply and electricity demand are two of the key drivers of BC Hydro's reservoir management and energy trading systems and provide key inputs to financial forecast models for the corporation. The significance of water supply forecasts is further underlined by the fact that the largest amount of variability in earnings stems from the variability in water supply, followed by financial risks and ambient air temperatures (BC Hydro 2005).

BC Hydro's Runoff Forecast Team issues short-term inflow forecasts and long-term seasonal forecasts using conceptual and statistical hydrologic models, weather forecasts and deterministic and probabilistic techniques. Depending on the forecast horizon and technique, forecasts are issued for up to 25 basins ranging in drainage area from 88 to 72,078 km^2, in a total area of almost 950,000 km^2. The climate ranges from maritime in the southwest to continental in the northeast of British Columbia, and the hydrology is strongly influenced by the building of a seasonal snowpack and snowmelt and, in some watersheds, glacier melt.

At the core of BC Hydro's inflow forecast system is the UBC Watershed Model (Quick 1995), which is a continuous hydrologic simulation model, developed to calculate streamflow from mountainous watersheds in data-sparse areas. It is a semi-distributed model, in which model input is calculated separately for lumped elevation bands. For a given watershed, the model simulates the various components of runoff using precipitation and temperature from manually operated and automatic weather stations and meteorological forecasts. Runoff components include surface runoff from rainfall, snowmelt and glacier melt, interflow and upper and lower groundwater flow. A hydrologic response unit (HRU) based implementation of the model is currently under development.

Models are operated on an in-house forecasting system called the River Forecast System (RFS), whose main components are illustrated in Fig. 13.3 for the case of short-term forecasts (Weiss 2001). The data flow for longer-term forecasts with the RFS system is similar, although with somewhat different inputs. Both input and state variable updating approaches are used and, when time is limited, an interactive manual output updating procedure can be used in which flows can be (1) offset in magnitude, (2) shifted in time, (3) tilted, (4) assumed to follow a recession or (5) manually overwritten. The RFS is in the process of being replaced with a Delft-FEWS based forecasting platform but the engine remains the UBC Watershed Model.

(continued)

Box 13.1 (continued)

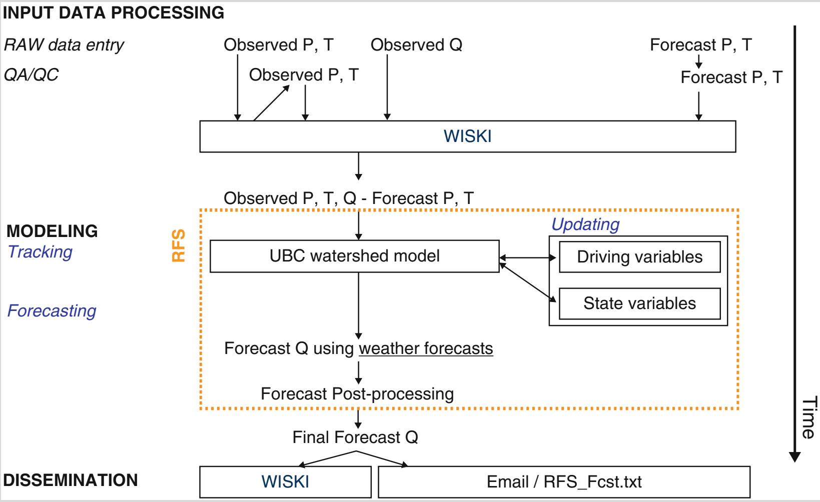

Fig. 13.3 River forecast system – data flow for short-term forecasts and links to the operational database (WISKI). *P* precipitation, *T* air temperature, *Q* inflow (BC Hydro)

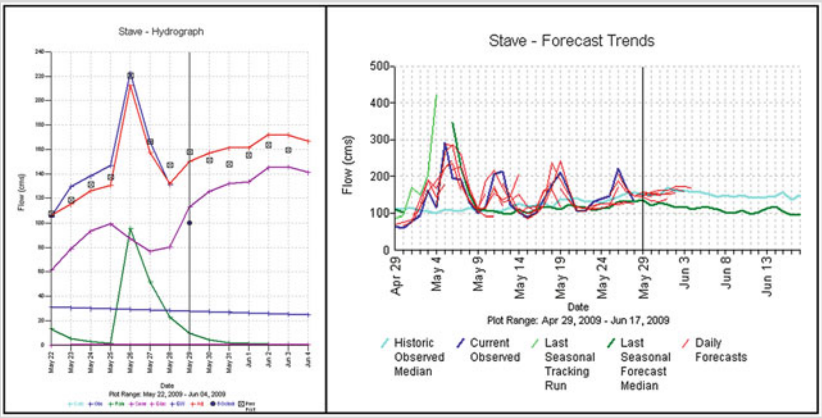

Fig. 13.4 River forecast system: (**a**) short-term forecast hydrograph with runoff components for a forecast (here issued on May 29) and (**b**) 30-day record of historical forecasts for Stave Reservoir (BC Hydro)

Deterministic five-day inflow forecasts for 20 reservoirs are issued in the morning of every workday (e.g. Fig. 13.4), if necessary, together with scenarios of 'reasonably' low and high inflow forecasts for use in operational planning. In routine operation, a daily time step is used, although this can be changed to hourly during high inflow events, and model parameter updating can also be used in this mode of operation.

(continued)

Box 13.1 (continued)

Model states for each forecast model run are initialised using simulated states from 8 days prior and updated using observations for the 7 preceding days. Forecasts for daily precipitation and maximum and minimum air temperatures are obtained from the Canadian Meteorological Center's (CMC) Regional Deterministic Prediction System (RDPS) operating with a horizontal grid spacing of 10 km for days 1–2. For days 3–8, median values from the North American Ensemble Forecast System (NAEFS) are used. This ensemble is comprised of members from the CMC and the US National Centers for Environmental Prediction (NCEP), run at ~50 km horizontal grid spacing.

To be used as inputs to the UBC Watershed Model, gridded forecasts are interpolated to forecast locations using a b-spline function and are subsequently bias corrected using the bias calculated from comparisons of observed and forecast values. For air temperature, an additive bias correction is calculated for a moving 21-day window that generally ends 2 days before the forecast date. For precipitation it's a multiplicative bias correction using a 60-day window (West 2015). Weather forecasts may be further adjusted by BC Hydro staff meteorologists if this proves necessary.

For longer-term forecasts, an Ensemble Streamflow Prediction (ESP) procedure is used (Day 1985), with a daily time step and with the option of using weather forecasts rather than historical data for the first 8 days of the model run. These forecasts, together with a statistical procedure (see later), form the basis for BC Hydro's 'official' seasonal water supply forecast. ESP-style forecasts are issued at the beginning of each month from January through August, together with ad hoc 'unofficial' forecasts at other times as required. Methods for incorporating uncertainties arising from model parameters and forcings are available in the current version but are only utilized on request due to limitations in the modelling infrastructure. On the other hand, uncertainties due to initial conditions, or model structural errors, are not considered at present.

The ability to forecast the seasonal runoff is assisted by the fact that runoff from melting of the mountain snowpack is a major component of the seasonal water supply for many BC Hydro reservoirs. Forecast adjustments, therefore, rely heavily on the assimilation of snow water equivalent data (for which long-term observational records are only available between February and May). BC Hydro's snowpack adjustment tool allows the forecaster to compare measured with simulated snow water equivalent for forested areas (noting that snow survey sites are typically located in lightly treed areas) and, if necessary, to adjust the simulated values accordingly.

Figure 13.5 shows an example of the snowpack adjustment plots for one watershed and one forecast date. The transfer functions are developed from data pairs of historical simulations and observations which have been optimized for seasonal residual runoff volume. Driving variables and other basin states are also adjusted in the long-term forecast mode but only infrequently.

(continued)

Box 13.1 (continued)

There is also the option to apply a bias correction based on comparisons of observed and forecast flows, which can be further adjusted manually based on a forecaster's experience.

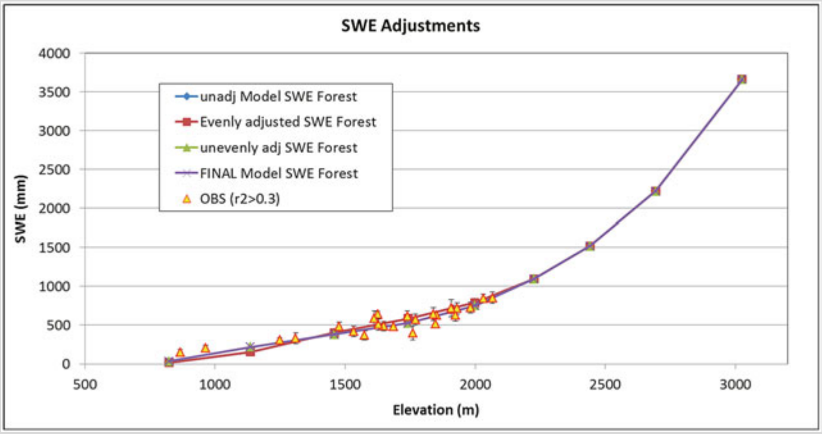

Fig. 13.5 Snow water equivalent data assimilation by elevation band, showing the unadjusted simulated, adjusted simulated and observed snow water equivalent (BC Hydro)

As a complement to the ESP approach, a statistical approach is used in which historical inflow volumes are related to key predictors for user-defined periods consisting of either single months or ranges of months in the period February to September. At the beginning of every month, from November to August, statistical water supply forecasts are issued for each of 25 basins.

The forecast equations are based on a principal components regression analysis and an optimal search for variables (Garen 1993) whilst maintaining hydrological consistency between successive regression periods. Current predictor variables are (a) soil moisture proxies, like antecedent inflows and autumn precipitation; (b) winter precipitation (i.e. November to March), conditional precipitation (i.e. precipitation that fell on days when the daily maximum temperature was less than +2°C), snowpack to date; and/or (c) climate indices, specifically the previous year's June through September values of the Southern Oscillation Index (SOI) and Multivariate ENSO Index (MEI).

The values of input variables can also be updated in real time if observations are considered unrepresentative of basin-wide conditions or forecasts are deemed incorrect based on hydroclimate information and/or other forecasts. With respect to total volume predictions, climate indices tend to play a more important role in early-season water supply forecasts, with a generally declining influence as the forecast season progresses.

(continued)

Box 13.1 (continued)

Both the short-term and long-term inflow forecasts are periodically verified against observed values using statistical scores and skill scores for deterministic forecasts of continuous variables and statistical scores for deterministic forecasts of discrete variables and for probabilistic forecasts of continuous variables (Weber et al. 2006). Water supply forecasts are also compared on a regional basis and tracked throughout the forecast season, which helps to put forecasts and the associated uncertainty into context with the natural variability of water supply.

Note: the text in this box is adapted (with permission) from a description provided by Frank Weber at BC Hydro.

13.2.3 Distributed Models

Distributed (grid-based) models provide another forecasting option and are increasingly used in real-time applications. Chapter 5 discusses the hydrological background to this type of model and Chap. 9 describes some flood forecasting applications.

For short-range forecasts, typically a physical-conceptual modelling approach is used based on conceptual representations for key components, rather than attempting to model physical processes in detail using partial differential equations. The distributed approach facilitates linkages to other distributed sources of information, such as meteorological forecasts and weather radar observations or spatially averaged raingauge inputs. In contrast, where model run times are less of a constraint, more physically based approaches are sometimes used.

As discussed in Chap. 5, data assimilation has the potential to improve forecast outputs, using techniques such as variational and ensemble Kalman filter approaches, although this is a developing area. In some cases these make use of satellite observations of snow cover and soil moisture. As for supply demand and integrated catchment models, subcomponents are often required to represent the influences of abstractions, discharges, reservoirs and other features which could potentially influence flows and water availability.

In some applications in addition to mass conservation, it is desirable to consider the energy balance and radiation terms, and perhaps the most highly developed examples of this approach are for:

- Operational weather forecasting – the land-surface models in numerical weather prediction models, which are included to represent land-atmosphere interactions
- Climate change impact assessments – regional or continental scale (macroscale) models for estimating the hydrological impacts corresponding to climate change projections

Increasingly a single modelling suite is used for both applications and many models of this type have been developed; for example, in one benchmarking study, 13 land-surface models were considered, provided by a number of national agencies and research centres (Best et al. 2015).

In the early days of numerical weather prediction, a key focus was on the vertical exchange of water vapour and energy over timescales comparable with the time steps in atmospheric models, which are typically of the order of a few minutes (e.g. Shuttleworth 1988, Garratt 1993). Longer-term variability due to soil moisture changes and surface runoff was either represented in a very simple way or not at all. However, the latest models typically consider some or all of the following processes:

- Soil moisture – representation of the key terms in the water balance including infiltration, percolation, evaporation and evapotranspiration from crops and natural vegetation
- River flows – representation of the runoff resulting from rainfall and snowmelt, in some cases allowing for the influence of reservoirs, lakes and other types of storage

Typically land-use types are classified in some detail; for example, relating to bare soil, urban areas and various types of crops and vegetation (e.g. Best et al. 2011, Clark et al. 2011). So-called SVAT (Soil Vegetation Atmosphere Transfer) models are also widely used to represent water and energy fluxes due to plant interception, transpiration and other processes (e.g. Shuttleworth 2012; see Chap. 6 also). For operational weather forecasting, there is the option to use energy-related terms such as satellite radiances for data assimilation (e.g. Liu et al. 2012) in addition to adjustments to the mass balance terms.

For climate change impact studies, climate projections are normally downscaled to the scales of interest and post-processed to help to account for any systematic (and other) differences between forecast values and long-term observations (see Chap. 4 and Box 13.3). Normally there is some representation of the mass balances for carbon, phosphorus and nitrogen and factors such as the influences of forest fires, atmospheric pollution/aerosols and changes in ice and vegetation cover. This often includes the use of dynamic vegetation models (or crop simulation models) of the types described in Chap. 6 to help to understand the feedback effects between climate, land use and vegetation cover (e.g. Wilby and Wigley 1997, Xu 1999, Shapiro et al. 2007).

13.3 Selected Applications

13.3.1 Seasonal Flow Forecasting

Although this is a developing area, many meteorological services now provide seasonal forecasts for a range of prognostic and diagnostic variables, including rainfall and air temperatures and sea surface temperatures. Typically these are based on long-range ensemble forecasts from coupled ocean-atmosphere global-scale models and/or statistical techniques which relate meteorological variables to indices linked to oceanic phenomena. Chapter 4 discusses these approaches, and Chap. 1 considers the predictability of large-scale features such as the El Niño-Southern

Oscillation or El Niño for short. Due to the many uncertainties involved, forecasts are normally probabilistic in nature and for monthly or longer intervals. Also, as discussed in Chap. 4, the forecast skill for rainfall is generally less than for some other variables, such as air temperatures.

At an international level WMO has designated a number of Global Producing Centres (GPCs) for long-range forecasts. These are listed in Chap. 4 and are required to adhere to a set of well-defined standards, and as a minimum (http://www.wmo.int/) provide the following on a fixed forecast production cycle:

- Predictions for averages, accumulations or frequencies over 1-month periods or longer (typically anomalies in 3-month-averaged quantities *are* the standard format for seasonal forecasts, and forecasts are usually expressed probabilistically)
- Lead time: between 0 and 4 months
- Issue frequency: monthly or at least quarterly
- Delivery: graphical images on GPC website and/or digital data for download
- Variables: 2m temperature, precipitation, Sea Surface Temperature (SST), Mean Sea Level Pressure (MSLP), 500hPa height, 850hPa temperature
- Long-term forecast skill assessments, using measures defined by the SVSLRF

Here SVSLRF is the WMO Standard Verification System for Long-Range Forecasts.

Many national services also issue seasonal forecast products, although in some cases – particularly in temperate regions – this is only on an experimental basis or to expert users. However, these are more closely integrated into operational procedures in regions where predictability is higher, such as the tropics, and are a key aspect of the Regional Climate Outlook Forums discussed in Chaps. 1 and 10.

There is increasing interest in translating these types of forecasts into quantitative estimates for flows and this is often termed Extended Hydrological Prediction or EHP (e.g. WMO 2011). Some potential applications include drought forecasting, reservoir management and irrigation and hydropower scheduling. For example, in Australia the Bureau of Meteorology (2010a) notes that ‘reliable seasonal streamflow forecasts for weeks to several months ahead can influence important decisions such as:

- water allocations
- cropping strategies
- water market planning
- environmental watering
- operating a diversified water supply scheme
- restricting water supply
- managing drought’

Usually in long-term flow forecasting, the focus is on estimating mean flows or volumes, rather than flood flows, unless there is a distinct prolonged flood season, such as that due to seasonal snowmelt. The main techniques include:

Table 13.2 Some examples of seasonal forecast products in the USA

Example	Description
Lake Powell, Colorado Basin, USA	Use of a combination of multiple regression techniques and rainfall-runoff forecasting models using Ensemble Streamflow Prediction techniques to generate inputs, with outputs adjusted based on climate forecasts and indices, to provide seasonal outlooks of flow volumes into Lake Powell (Brandon 2005). More generally the Colorado Basin River Forecast Centre maintains a website with a wide range of examples of water supply, reservoir condition and other long-range forecasts http://www.cbrfc.noaa.gov/, and monthly telephone conference calls and web-based presentations are held for the benefit of water managers from December to June and more frequently if required
California-Nevada River Forecast Centre	Use of Ensemble Streamflow Prediction techniques and statistical approaches to produce seasonal forecast products; in the latter case for estimates of spring runoff 'where the independent variables include monthly snow course, snow pillow, precipitation and, occasionally, streamflow observations' (Hartman and Schaake 2014; http://www.cnrfc.noaa.gov/); see Box 1.3 also
Natural Resources Conservation Service (part of the US Department of Agriculture)	Water supply forecasts are issued for several hundred points in the western USA every month between January and June and at other times as requested. Most forecasts are based on statistical relationships between streamflow volume and predictors such as snowpack, precipitation, antecedent streamflow and large-scale climate indices, such as the Southern Oscillation Index. These are developed using principal component analysis and other techniques (e.g. Garen 1993). Catchment simulation models are used for some locations. Forecasts are presented in probabilistic terms to reflect uncertainties in future weather conditions, models and observations (http://www.wcc.nrcs.usda.gov/)

- Statistical approaches – relationships relating river flows to indicators of current catchment and climate conditions plus the use of time series analysis techniques (e.g. Box 13.2)
- Ensemble Streamflow Prediction (ESP) – an approach in which historical precipitation and air temperature records are sampled and used as inputs to rainfall-runoff models, with model runs initialised based on current catchment conditions (e.g. Box 13.1)
- Numerical Weather Prediction – in which long-range ensemble meteorological forecasts are used as inputs to data-driven, conceptual or distributed rainfall-runoff models

Regarding the first two of these approaches, some of the first operational applications were in the USA (e.g. Wood and Lettenmaier 2006, Pagano et al. 2009), and Table 13.2 shows examples of the types of forecast products generated. For statistical techniques some typical climate indicators include indices relating to phenomena such as El Niño and the Indian Ocean Dipole and Chap. 4 provides further examples. Chapter 5 also discusses ensemble streamflow prediction techniques in more detail.

Regarding the use of meteorological forecasts as inputs, some examples of operational applications include the national flow forecasting system in Finland (Vehviläinen et al. 2005) and a medium- to long-range ensemble flow forecasting system for the Ganges and Brahmaputra rivers in Bangladesh (Webster and Hoyos 2004; Hopson and Webster 2010). Combined approaches provide another option; for example, blending short- to medium-range meteorological forecasts with an ensemble streamflow prediction approach as illustrated in Box 13.1, or selective sampling of ensemble traces based on climate indices or forecasts.

For hydrological systems with significant storage influences, it is sometimes possible to produce operationally useful forecasts for lead times of weeks or even months ahead, in particular where some (or all) of the factors shown in Table 13.3 are applicable. Other examples might include forecasts for catchments with seasonally extensive wetlands or annual glacial melt. Indeed it is worth noting that in some catchments and seasons, particularly at shorter lead times, forecast skill can be attributed mainly to the hydrological component (e.g. Robertson and Wang 2012, Shukla and Lettenmaier 2011) rather than the meteorological or oceanic aspects.

As in most types of hydrological modelling one key issue to consider (see Chap. 5) is that models should be calibrated using long record lengths that include a number of the types of events of interest, such as floods or droughts. Also since the forecast products generated are usually in probabilistic terms, users often need assistance in interpreting the outputs. For example, the Natural Resources Conservation Service (see Table 13.2) provides the following definition of a '30 Percent Chance of Exceedance Forecast':

> There is a 30 percent chance that the actual streamflow volume will exceed this forecast value, and there is a 70 percent chance that the actual streamflow volume will be less than this forecast value.

Table 13.3 Some examples of slowly responding hydrological systems and potential hydrological indicators

Example	Potential indicator	River flow characteristics
Large aquifers	Borehole levels, spring flows	Rivers where – with the exception of flood events – flows are dominated by groundwater outflows from large aquifers
Large lakes and reservoirs	Lake or reservoir levels, net inflows, lake rainfall	Catchments with large lakes and/or multiple reservoirs whose levels respond slowly to variations in rainfall or inflows and whose outflows dominate flows further downstream
Large river basins	Current river flows, soil moisture conditions, cumulative observed rainfall	Major river basins where it takes several days to weeks for water to flow from the headwaters to the sea
Snowmelt	Snow water equivalent, snow depth, snow cover	Catchments whose headwater regions are usually at least partly covered by snowpack for part of the year which then melts during the spring months as air temperatures and solar radiation increase

Web-based guidance notes (http://www.wcc.nrcs.usda.gov/) provide several examples of ways to make use of this information; for example, noting that to decrease the chance of having less water than planned for:

> A user might determine that making decisions based on a 50 percent chance of exceedance forecast is too much risk to take (there is still a 50% chance that the user will receive less than this amount). To reduce the risk of having less water than planned for, users can base their operational decisions on one of the forecasts with a greater chance of being exceeded such as the 90 or 70 percent exceedance forecasts.

Chapters 1, 5 and 7 discuss this topic in more detail including a range of risk-based approaches to decision-making. The area of sub-seasonal to seasonal forecasting (or S2S) is also an active area for research and aims to bridge the gap between medium- and long-range forecasts; for example, exploiting linkages to phenomena which show some predictability in that timeframe, such as the Madden-Julian Oscillation (Robertson et al. 2014; see Chapter 1).

Box 13.2: Seasonal Streamflow Forecasting Service, Australia

To help with water resources management in Australia, the Bureau of Meteorology has offered a seasonal streamflow forecasting service since 2010 (http://www.bom.gov.au/water/ssf/). This seeks to address some of the typical questions faced by water managers (Tuteja 2015) which include:

- How much water is available in the dams and the water conductor system?
- How much is the water demand and what is its spatial distribution?
- How much are the water entitlements and what are the associated priorities?
- How much loss to evaporation is likely?
- Given the current hydrologic condition of the river basin, how much water loss can be anticipated in the water conductor system, and what is the likely spatial distribution of the losses?
- How much is the likely inflow – Next week? Next month? Next season? And next year?
- What is the range of uncertainty of the likely inflow and how best can knowledge of forecast uncertainty be integrated into water allocation and water delivery planning?

The service has been developed on the basis of research conducted in partnership with the CSIRO and is based primarily on a Bayesian Joint Probability (BJP) approach. This assumes that the relationship between streamflows and the chosen predictors can be described using a Box-Cox transformed multivariate normal distribution. Some advantages of the Bayesian formulation are that this allows multiple sites and predictors to be considered including

(continued)

Box 13.2 (continued)

missing, non-concurrent and intermittent records, such as flows recorded on ephemeral streams (Robertson and Wang 2012; CSIRO 2012). Forecast probabilities are based on the 5000 member ensemble outputs generated by the statistical BJP model.

Operationally the main predictors used include catchment-based indicators such as streamflows in the previous 1 to 3 months and climate indicators such as the Southern Oscillation Index. Monthly updates of likely streamflow volume over the next 3 months are issued on around the 7th working day of each month and are displayed in a range of map-based and graphical formats (Fig. 13.6; Table 13.4). The outputs are used in a variety of ways by water managers; for example, to estimate 3-month ahead median and 10 % and 90 % exceedance inflows to reservoirs based on site-specific monthly disaggregation factors (Bureau of Meteorology 2014).

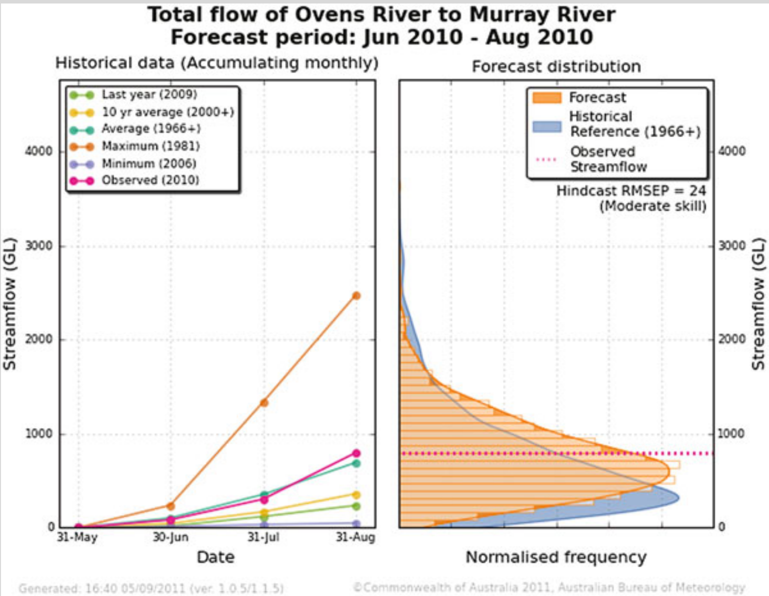

Fig. 13.6 Example of the 'historical and probability distribution' product for the total flow of Ovens River to Murray River for the 3-month period June–August 2010 (*right*) and comparisons with the historical record (*left*) (© Commonwealth of Australia 2011, Australian Bureau of Meteorology, http://www.bom.gov.au/water/ssf/)

(continued)

Box 13.2 (continued)

Table 13.4 Summary of key products in the Seasonal Streamflow Forecasting Service (Adapted from Bureau of Meteorology 2010b)

Product	Description
Tercile summary map	The forecast sites are presented as a tercile or three-part pie chart on the map. The pie chart represents the probability of getting low flow, near median flow and high flow for each of the sites. Shading and greyscale are used to indicate forecast performance over the verification period (retrospective forecasts). This appears in the legend at the bottom of the map
Tercile forecast	Based on historical data, the probabilities of high, near median and low flows for each location are defined as 33 %. The graphic describes the shift in probability of each flow category for the forecast period
Historical and probability distribution	The forecast and historical distributions are compared with historical data. The historical data chart shows the streamflow recorded last year and the minimum and maximum streamflow total recorded for the same 3-month period in history. It also includes the 10-year and long-term average for this period and site
Historical and exceedance probability	The exceedance probability is the forecast probability that a particular streamflow value will be exceeded. This can be compared to the exceedance probability based on the historical reference or record

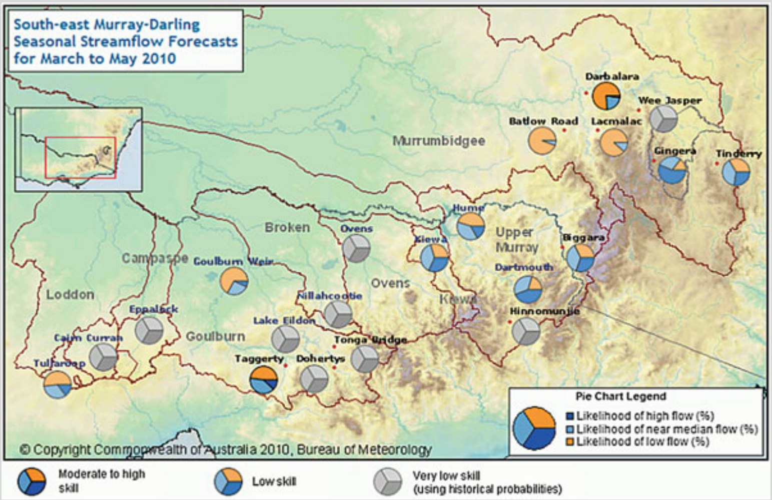

Fig. 13.7 Example of a tercile summary map showing South-east Murray-Darling Seasonal Streamflow Forecasts for March to May 2010 (© Commonwealth of Australia 2011, Australian Bureau of Meteorology, http://www.bom.gov.au/water/ssf/)

Forecast verification statistics are routinely made available including a range of skill scores. Forecast performance typically depends on both the location and the season, and this needs to be considered when using the outputs operationally; for example, in the case of tercile summary maps (Fig. 13.7), an indication of the reliability of the forecasts appears in the map

(continued)

Box 13.2 (continued)
legend, with grey shading used to indicate sites with very low additional skill for that season with respect to the reference forecast.

Since 2015 dynamic techniques have been used operationally for some locations. These are based on the outputs from conceptual rainfall-runoff models driven by downscaled long-range outlooks from the Bureau of Meteorology's Predictive Ocean Atmosphere Model for Australia (POAMA). Hybrid products are also under development consisting of a blend of the outputs from the dynamic and statistical approaches.

13.3.2 Water Resources Planning

In water resources planning studies, the objectives can range from investigations of performance of a single asset, such as a reservoir, through to basin-wide or regional studies considering a wide range of social, economic and environmental factors. Planning horizons typically range from a few years ahead to several decades, depending on the application.

For example, in England and Wales (EA/NRW 2013) water companies 'are required to produce a water resources management plan (WRMP) every five years. The plan sets out how a water company intends to maintain the balance between supply and demand for water over a 25-year period and is complemented by a water company drought plan, which sets out the short-term operational steps a company will take as a drought progresses'. Table 13.5 provides some examples of the topics which are usually considered as part of the annual review process.

For the hydrological aspects of these types of study, water balance techniques are widely used, taking account of possible changes in both supply and demand. Additional more specialised models are sometimes required to study particular issues; for example, relating to reservoir operations (see Chap. 11) or water quality (see Chap. 12). Long-term hydrometeorological records are normally required for model calibration, preferably spanning several decades, although synthetic values provide another option when only short periods of observations are available and are typically based on stochastic and/or rainfall-runoff modelling techniques (see Chap. 5). Some key interests are often in the sensitivity to uncertainties in the assumptions regarding future supply and demand and the impacts of climate change (e.g. Fig. 13.8, Box 13.3).

Some typical outputs from this type of study include estimates for flow reliability for different development or investment scenarios, with associated estimates of costs if these are required. Regarding water quality and environmental issues, WMO (2012b) notes that:

> Contamination of water sources, whether by natural or human-induced pollutants, can significantly affect the resources available for effective use and so must be factored into resource assessments. The quality of groundwater also varies. In addition, it is increasingly recognized that there are minimum flow regimes required to support and maintain many

Table 13.5 Some examples of items to be considered in annual reviews of a water resources management plan

General area	Examples
Supply	Target level of service, deployable output, outage-related issues, bulk supply agreements, potential climate change impacts
Demand	Demand forecasts, per capita consumption, sustainability reductions, household metering, leakage, water efficiency

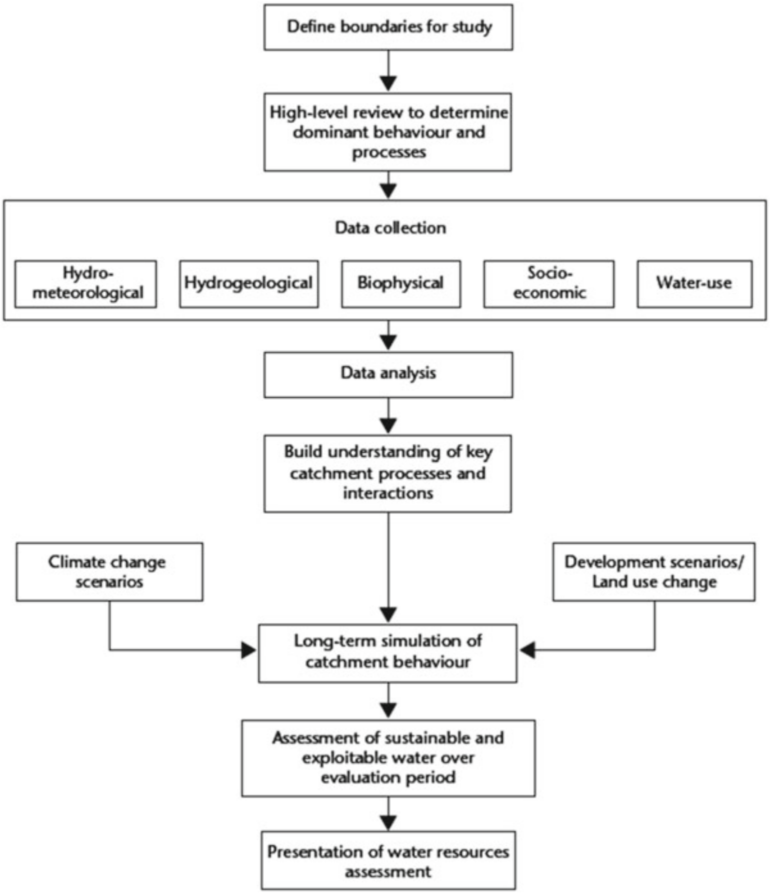

Fig. 13.8 Outline schematic of the water resources assessment development process (WMO 2012b, courtesy of WMO)

> valuable aquatic habitats that are important for the support of both animal and human populations, for example, fish spawning. These are often referred to as environmental allocations or environmental flows. These must also be factored into any analysis of water availability.

For studies at a catchment or basin-wide scale, the term Integrated Water Resources Management (IWRM) has become widely used in recent years and one definition (Global Water Partnership 2000) is that:

> IWRM is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

The term river basin management has a similar meaning and in Europe the Water Framework Directive is a key driver for this type of study. This legislation was adopted at European level in 2000 and the timetable for implementation (http://ec.europa.eu/) includes the following key deadlines:

- 2009 – Finalise river basin management plan including programme of measures
- 2015 – Meet environmental objectives, First management cycle ends, Second river basin management plan & first flood risk management plan
- 2021 – Second management cycle ends
- 2027 – Third management cycle ends, final deadline for meeting objectives

In these types of studies, consultations are a crucial part of the process, and some approaches to stakeholder engagement include workshops; community-level meetings in villages, towns and cities; volunteer programmes; and web-based consultation exercises. Key consultees often include representatives from government departments, local authorities, industry, businesses and voluntary and community-level organisations. Hydrological models often play a central role in helping to explore possible outcomes with map-based outputs a particularly useful way to present results to a non-specialist audience. More generally Pegram et al. (2013) note that the following goals characterise strategic basin planning:

- Trade-offs between alternative economic, social and environmental objectives and between existing and potential future demands
- A sophisticated approach to recognizing environmental water needs and the importance of aquatic ecosystem functioning in providing goods and services
- Understanding basin interactions, including the range of hydrological, ecological, social and economic systems and activities at work within a basin
- Robust scenario-based analysis to address uncertainty in future development and climate, by assessing alternative hydro-economic scenarios
- Prioritisation, to identify which of many demands are the key needs for economic development, social justice and environmental protection

There are several guidelines which give more information on these topics including publications by the Global Water Partnership (2015), UNESCO (2009) and WMO (2012b).

Box 13.3: Climate change projections

In most long-range water resources studies, it is necessary to assess both the resilience of proposed options to climate variability plus the potential impacts of climate change.

At an international level, climate change assessments have been issued by the Intergovernmental Panel on Climate Change (IPCC) since 1990 and the fifth such assessment report (AR5) was issued in 2014. Some key findings from the synthesis report (IPCC 2014) regarding the climate system were:

> Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems

and:

> Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen

Climate change projections are made using a hierarchy of climate models and a standard set of scenarios for greenhouse gas and aerosol emissions and other factors – called forcing agents – such as land-use change. These correspond to a range of assumptions about future economic development and population dynamics. The climate models (IPCC 2014) range from 'simple idealized models, to models of intermediate complexity, to comprehensive General Circulation Models (GCMs), including Earth System Models (ESMs) that simulate the carbon cycle. The GCMs simulate many climate aspects, including the temperature of the atmosphere and the oceans, precipitation, winds, clouds, ocean currents and sea-ice extent'. Many of the findings are expressed in probabilistic terms, and the reports include detailed analyses of the evidence from observational records (e.g. IPCC 2013).

At a national or regional scale, downscaling techniques are widely used based on statistical, weather-matching or dynamic approaches (see Chap. 4). Outputs are usually expressed in terms of changes relative to a baseline period, which at present is typically – although not always – the most recent WMO climatological standard normal of 1961–1990 (WMO 2012c). For example, in the UK following the fourth IPCC assessment issued in 2007 (AR4), probabilistic climate change projections were derived based on a combined dynamic and statistical downscaling approach (Murphy et al. 2009). The spatial resolution of the projections was 25 km, and, for most variables, such as precipitation and air temperature, outputs were provided in the form of probability density functions and cumulative distribution functions for monthly, seasonal and yearly values. The emission scenarios were based on the IPCC assessment and projections were provided for 30-year periods, extending from the 2020s (2010–2039) to the 2080s (2070–2099), and on a decadal (10-year) basis.

(continued)

Box 13.3 (continued)

A software tool – called the UKCP09 Weather Generator – allows synthetic values for key variables to be simulated over land on an hourly and daily basis at a spatial scale of 5 km. The resulting values were designed to be consistent with the 25 km probabilistic projections, with some allowance for topographic influences. For water resources applications, a typical use of the outputs is as inputs to supply demand and distributed rainfall-runoff models. For future projections of water availability, impacts on water demand usually also need to be considered (e.g. Parker and Wilby 2013).

13.4 Summary

- In water resources applications, some examples of artificial influences on flows include those due to reservoir operations, abstractions for water supply and irrigation and discharges of treated or contaminated water. The extent to which these factors are considered depends on the application and in some cases includes water quality and ecological issues.
- Forecasting requirements range from short-term forecasts to support operational decision-making to long-term forecasts for water resources planning. The main techniques used are supply demand models, integrated catchment models and distributed models.
- Supply demand models typically aim to maintain a water balance but do not represent the flow dynamics, other than possibly considering lag times. Many systems include optimisation routines to guide users towards solutions; for example, regarding options for reducing operating costs or improving system reliability. The most common application is in long-term planning studies and sometimes to support day-to-day reservoir and water supply operations.
- In contrast, integrated catchment models are normally developed expressly to provide forecasts at specific locations (forecasting points) to help in areas such as water supply, reservoir and hydropower operations. The general approach is similar to that for flood forecasting models although greater account needs to be taken of factors which affect low flows such as abstractions and discharges. However, there are many potential benefits in developing full flow forecasting systems for use in a range of applications.
- Distributed models provide a grid-based or sub-basin representation of a catchment or region and for real-time use are often of the physical-conceptual type. These are used in operational flow forecasting and numerical weather prediction applications and for climate change impact studies. In the latter two cases, additional processes and energy balance and radiation terms are normally included,

together with factors such as the carbon and nitrogen balance for climate change projections.

- Seasonal flow forecasts have the potential to provide operationally useful information at lead times from weeks to months ahead, particularly in basins where due to storage influences there are significant delays between precipitation and runoff at the points of interest. Statistical and ensemble streamflow prediction techniques have been used for many years, whilst a more recent development has been to use long-range ensemble meteorological forecasts as inputs to flow forecasting models. Flow estimates are usually probabilistic in nature so users normally require some assistance in interpreting how best to use the information provided.
- In water resources planning studies, estimates for the balance between supply and demand are often required for planning horizons of years or more ahead and are typically derived using a water balance approach. Normally a wide range of social, economic and environmental factors must be taken into account, plus climate change projections. Extensive consultations are usually required in these types of studies and map-based and other model outputs often play a key role in helping to explore different development scenarios.

References

BC Hydro (2005) BC Hydro Service Plan – 2005/06 to 2007/08 Service Plan Update. http://www.bchydro.com/

Best MJ, Pryor M, Clark DB, Rooney GG, Essery RLK, Ménard CB, Edwards JM, Hendry MA, Porson A, Gedney N, Mercado LM, Sitch S, Blyth E, Boucher O, Cox PM, Grimmond CSB, Harding RJ (2011) The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes. Geosci. Model Dev., 4: 677–699

Best MJ, Abramowitz G, Johnson HR, Pitman AJ, Balsamo G, Boone A, Cuntz M, Decharme B, Dirmeyer PA, Dong J, Ek M, Guo Z, Haverd V, van den Hurk BJJ, Nearing GS, Pak B, Peters-Lidard C, Santanello Jr. JA, Stevens L, Vuichard N (2015) The Plumbing of Land Surface Models: Benchmarking Model Performance. J. Hydrometeor, 16:1425–1442

Brandon DG (2005) Using NWSRFS ESP for making early outlooks of seasonal runoff volumes into Lake Powell. AMS Forum: Living with a Limited Water Supply, San Diego, 9–13 March 2005

Bureau of Meteorology (2010a) Streamflow forecasting: days to seasons. Water Information, Information Sheet 9, Australian Government

Bureau of Meteorology (2010b) Product Factsheet: Seasonal Streamflow Forecasts. Australian Government

Bureau of Meteorology (2014) Enabling better water management: case study ACTEW Water, Australian Government

CEA (2008) Canadian Electricity Association 2008: Electricity 08, 79(1)

Clark DB, Mercado LM, Sitch S, Jones CD, Gedney N, Best MJ, Pryor M, Rooney GG, Essery RLH, Blyth E, Boucher O, Harding RJ, Huntingford C, Cox PM (2011) The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics. Geosci. Model Dev., 4: 701–722

CSIRO (2012) Seasonal and Long-term Water Forecasting and Prediction. Factsheet, Commonwealth Scientific and Industrial Research Organisation, Canberra

Day G N (1985) Extended streamflow forecasting using NWSRFS. J.Water Resources Planning and Management, 111: 157–170

EA/NRW (2013) Annual review of Water Resources Management Plans guidance, June 2013. Developed by the Environment Agency and Natural Resources Wales, Bristol/Cardiff

Garen D (1993) Improved techniques in regression-based streamflow volume forecasting. J. Water Resources Planning and Management, 118(6): 654–670

Garratt J R (1993) Sensitivity of climate simulations to land-surface and atmospheric boundary-layer treatments - A Review. J. Climate, 6(3): 419–448

Global Water Partnership (2000) Integrated Water Resource Management. Technical Advisory Committee Background Paper No. 4, Stockholm

Global Water Partnership (2015) Toolbox: Integrated Water Management. http://www.gwp.org/

Hartman R, Schaake J (2014) Case Study: Decision Making for Flood Forecasting in the US National Weather Service. In Applied Uncertainty Analysis for Flood Risk Management (Eds. Beven K, Hall J), Imperial College Press, London

Hopson TM, Webster PJ (2010) A 1–10 Day Ensemble Forecasting Scheme for the Major River Basins of Bangladesh: Forecasting Severe Floods of 2003–07. Journal of Hydrometeorology, 11: 618–641

Huband M, Sene KJ (2005) Integrated catchment modelling issues for flow forecasting applications. Scottish Hydraulics Study Group, Catchment Modelling for Flood Risk Management, 18 March 2005

IPCC (2013) Climate Change 2013: The Physical Science Basis Summary for Policymakers, Technical Summary and Frequently Asked Questions. Part of the Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva

Liu Y, Weerts AH, Clark M, Hendricks Franssen H-J, Kumar S, Moradkhani H, Seo D-J, Schwanenberg S, Smith P, van Dijk AIJM, van Velzen N, He M, Lee H, Noh SJ, Rakovec O, Restrepo P (2012) Advancing data assimilation in operational hydrologic forecasting: progress, challenges, and emerging opportunities. Hydrol. Earth Syst. Sci. Discuss., 9: 3415–3472

Loucks D P (1996) Developing and implementing Decision Support Systems: A Critique and Challenge. Journal of the American Water Resources Association, 31(4): 571–582

Loucks D P, Stedinger J R, Haith D A (1981) Water Resource Systems Planning and Analysis. Prentice-Hall, Englewood Cliffs, NJ

McKinney D C, Cai X C, Rosegrant M W, Ringler C, Scott C A (1999) Modeling water resources management at the basin level: Review and future directions. SWIM Paper 6. Colombo, Sri Lanka. International Water Management Institute

Millington P, Olson D, McMillan (2006) Integrated River Basin Management from Concepts to Good Practice. Briefing Note 6. System Modelling in River Basin Management

Murphy JM, Sexton DMH, Jenkins GJ, Boorman PM, Booth BBB. Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts RA, Brown SJ, Howard TP, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R, Wood RA (2009), UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter

Pagano TC, Garen DC, Perkins TR, Pasteris PA (2009) Daily updating of operational statistical seasonal water supply forecasts for the Western U.S. Journal of the American Water Resources Association 45(3): 767–778

Parker JM, Wilby RL (2013) Quantifying Household Water Demand: A Review of Theory and Practice in the UK. Water Resources Management 27(4): 981–1011

Pegram G, Li Y, Le Quesne T, Speed R, Li J, Shen F (2013) River basin planning: Principles, procedures and approaches for strategic basin planning. UNESCO, Paris

Quick M C (1995) The UBC watershed model. In Singh VP (ed.), Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, CO

Robertson DE, Wang QJ (2012) A Bayesian Approach to Predictor Selection for Seasonal Streamflow Forecasting. Journal of Hydrometeorology, 13(2):155–171

Robertson AW, Kumar A, Peña M, Vitart F (2014) Improving and promoting subseasonal to seasonal prediction. Bulletin of the American Meteorological Society, 95(3): 49–53

Sene K (2008) Flood Warning, Forecasting and Emergency Response. Springer, Dordrecht

Shapiro M, Hoskins B, Shukla J, Church J, Trenberth K, Beland M, Brasseur G, Wallace M, McBean G, Caughey J, Rogers D, Brunet G, Barrie1 L, Hendersen-Sellers A, Burridge D, Nakazawa T, Miller M (2007) The Socioeconomic and Environmental Benefits of a Revolution in Weather, Climate and Earth-System Analysis and Prediction A Weather, Climate and Earth-System Prediction Project for the 21st Century http://wcrp.wmo.int/

Shukla S, Lettenmaier DP (2011) Seasonal hydrologic prediction in the United States: understanding the role of initial hydrologic conditions and seasonal climate forecast skill. Hydrol. Earth Syst. Sci., 15:3529–3538

Shuttleworth W J (1988) Macrohydrology - The New Challenges for Process Hydrology. J. Hydrology, 100: 31–56

Shuttleworth WJ (2012) Terrestrial Hydrometeorology. Wiley-Blackwell, Chichester

Tuteja NK (2015) The Case for Extended Hydrologic Prediction Services for Improved Water Resource Management. WMO Bulletin 64(1)

UNESCO (2009) IWRM at River Basin Level: Part I: Principles. UNESCO, Paris

Vehviläinen B, Huttunen M, Huttunen I (2005) Hydrological forecasting and real time monitoring in Finland: the Watershed Simulation and Forecasting System (WSFS). ACTIF International conference on innovation advances and implementation of flood forecasting technology, 17–19 October 2005, Tromsø, Norway

Weber F, Perreault L, Fortin V (2006) Measuring the Performance of Hydrological Forecasts for Hydropower Production at BC Hydro and Hydro-Québec. 18th Conference on Climate Variability and Change, 86th AMS Annual Meeting, Atlanta

Webster PJ, Hoyos C (2004) Prediction of monsoon rainfall and river discharge on 15–30 day time scales. Bulletin of the American Meteorological Society, 85:1745–1765

Weiss E (2001) Integrating the UBC watershed model into a river forecast system. Presented at the BC Branch CWRA, 9 May 2001

West G (2015) Hydromet Point Forecast System Documentation. University of British Columbia, Weather Forecast Research Team, May 2015. Unpublished report

Wilby R L, Wigley T M L (1997) Downscaling general circulation model output: a review of methods and limitations. Progress in Physical Geography, 21(4): 530–548

WMO (2009) Guide to hydrological practices, 6th edn. WMO-No. 168, Geneva

WMO (2011) Experts Meeting: Extended Hydrological Prediction, 7–9 July 2011, Melbourne, Australia

WMO (2012a) Climate and Meteorological Information Requirements for Water Management: A review of issues. WMO-No. 1094, Geneva

WMO (2012b) Technical material for water resources assessment. Technical Report Series No. 2, WMO-No. 1095, Geneva

WMO (2012c) Technical Regulations Basic Documents No. 2: Volume I - General Meteorological Standards and Recommended Practices. WMO-No. 49, Geneva

Wood AW, Lettenmaier DP (2006) A test bed for new seasonal hydrologic forecasting approaches in the western United States. Bulletin of the American Meteorological Society, 87: 1699–1712

Wurbs E B, Wurbs R A (1995) Water Management Models. Prentice Hall, Englewood Cliffs, NJ

Xu C (1999) From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. Progress in Physical Geography 23(2): 229–249

Yeh W W-G (1985) Reservoir Management and Operations Models: A State-of-the-Art Review. Water Resources Research, 21(12): 1797–1818

Glossary

A

Action table A table of actions to take as meteorological, river and/or coastal conditions exceed predefined threshold values

Antecedent conditions The state of wetness of a catchment prior to an event or period of simulation (Beven 2012)

Antecedent Precipitation Index *The* weighted sum of past daily precipitation amounts, used as an index of soil moisture (WMO 2012)

Automatic Weather Station (AWS) An instrument for automatically measuring meteorological information in real-time including (typically) wind speed and direction, solar radiation, air temperature, humidity and rainfall and possibly other parameters, such as soil temperature and snow depth

B

Baseflow Discharge which enters a stream channel mainly from groundwater but also from lakes and glaciers, during long periods when no precipitation or snowmelt occurs (WMO 2012)

Basin Area having a common outlet for its surface runoff (*syn. drainage basin, catchment, river basin, watershed*, WMO 2012)

Boundary conditions Constraints and values of variables required to run a model for a particular flow domain and time period (*continued)* (Beven 2012)

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C

Calibration Process whereby the parameters of a model are adjusted to obtain a satisfactory agreement between model-generated results and measured variables (see *model calibration* in WMO 2012)

Catchment See *Basin*

Climatology The description and scientific study of climate in all its aspects. Often the term is used to refer to the observed distribution of a meteorological parameter, or set of parameters, over a number of years (typically a 30-year period) (Troccoli et al. 2008)

Conceptual model Simplified representation of a real situation, described by diagrams, flow charts, governing relationships or natural laws (WMO 2012)

Cost-benefit analysis A decision-making technique which compares the likely costs of an action or investment with the expected benefits

Cost loss An analysis technique which compares the cost of taking an action with the likely losses if that action is not taken

D

Degree day Algebraic difference, expressed in degrees Celsius, between the mean temperature of a given day and a reference temperature (WMO 2012)

Deltas See *Estuaries*

Demand forecast In hydrometeorological applications, a forecast for future water use for a range of possible applications, including water supply, irrigation and power generation

Deterministic model A model that, with a set of initial and boundary conditions, has only one possible outcome or prediction (Beven 2012)

Dike See *Flood defence*

Dissemination In emergency response, the issuing of warnings by a range of direct, community-based and indirect methods

Distributed model A model that predicts values of state variables varying in space (and normally time) (Beven 2012)

Downscaling The translation of a forecast from one spatial and/or temporal resolution to a finer resolution. In spatial downscaling, the term is frequently applied to the translation of a forecast from a gridded average to a local point (Troccoli et al. 2008)

Drainage basin See *Catchment*

Drought A broad definition of drought is a deficiency of precipitation over an extended period of time, usually a season or more, which results in a water shortage for some activity, group or environmental sectors (UN/ISDR 2007)

E

Effective rainfall (1) In surface hydrology, that part of the rainfall which contributes to runoff. (2) In groundwater, that part of the rainfall which contributes to groundwater recharge. (3) In agriculture, that part of the rainfall which remains in the soil and contributes to the growth of crops (WMO 2012)

El Niño Southern Oscillation (ENSO) A complex system of interactions between the atmosphere and the oceans, specifically across the equatorial Pacific Ocean. The strongest known internal forcing mechanism of climate variability through atmospheric teleconnections to many parts of the globe (Troccoli et al. 2008)

Ensemble Streamflow Prediction (ESP) An ensemble forecasting technique originally developed in the USA (Day 1985) in which historical meteorological conditions are sampled and used as inputs to operational hydrological forecasting models using current conditions as a starting point

Estuary The tidal reaches of a river as it outfalls to the sea, where fresh and seawater mix. Sometimes called a delta or river delta (although this term more usually describes the sediment deposited by some rivers within the tidal zone)

Evapotranspiration Combined processes by which water is transferred to the atmosphere from the soil by evaporation and from the vegetation by transpiration (WMO 2012)

F

False alarm A warning which is issued but for which no subsequent event occurs

Finite difference The approximate representation of a time or space differential in terms of variables separated by discrete increments in time or space (Beven 2012)

Flood defence See *Levee*

Flood Fighting Emergency response actions to reduce or prevent flooding, including reinforcing levees, sandbagging and installing demountable defences

Forecasting system A computer system for managing the operation of one or more forecasting models, including automated collection and validation of real-time data, post-processing of model outputs and possibly automated alerting facilities if thresholds are exceeded

Flood routing Technique used to compute the movement and the change in shape of a flood wave moving through a river reach or a reservoir (WMO 2012)

Forecasting Point A location at which it is useful to have a forecast of future flow conditions

G

General Circulation Model A set of equations describing the three-dimensional evolution of the system to be modelled (e.g. the atmosphere) in a numerical form. The equations include those of the dynamics and energy of the system, as well as those of any other relevant process (e.g. chemical reactions) (Troccoli et al. 2008)

Geographic Information System (GIS) Computer software for the presentation and analysis of spatial datasets

Glacial Lake Outburst Flood A flood caused by the sudden release of water from a lake formed by moraine, ice or similar

H

Hurricane See *Tropical cyclone*

Hydro-scheduling Planning the operation of a hydropower generation system over a range of timescales, from sub-daily to weekly or longer

Hydrodynamic Model A solution to the equations expressing mass, momentum and energy conservation of water, sediment, heat and other parameters (as required) in a river, estuary or coastal reach

Hydrograph Graph showing the variation in time of some hydrological data, such as stage, discharge, velocity and sediment load (WMO 2012)

I

Initial conditions Values of storage or pressure variables required to initialise a model at the start of a simulation period (Beven 2012)

Integrated Water Resources Management IWRM is a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership 2000)

Intertropical Convergence Zone (ITCZ) A belt of high rainfall near the equator. It is formed by the vertical ascent of warm, moist air converging from the north and south. It is usually found a few degrees to the north of the equator but moves north and south with the seasons (Troccoli et al. 2008)

L

Long-range weather forecast In meteorology, a forecast from 30 days to 2 years ahead (WMO 2010)

Lead time Interval of time between the issuing of a forecast (warning) and the expected occurrence of the forecast event (see *forecast (warning) lead time*, WMO 2012)

Levee Work used to confine streamflow within a specified reach or to prevent flooding due to waves or tides (*syn. bund, dike (US), dyke, embankment*, WMO 2012)

M

Medium-range weather forecast In meteorology, a forecast from 72 to 240 h ahead (WMO 2010)

Mesoscale model Pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometres, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones and topographically generated weather systems such as mountain waves and sea and land breezes (AMS 2015)

Monte Carlo simulation Simulation involving multiple runs of a model using different randomly chosen sets of parameter values or boundary conditions (Beven 2012)

N

North Atlantic Oscillation (NAO) An atmospheric see-saw of pressure across the North Atlantic Ocean with two standard 'centres of action', one over Iceland and the other on the Azores. Swings from one phase to another produce large changes in the mean wind speed and direction over the Atlantic. Influential on European and North African climate (Troccoli et al. 2008)

Nowcast A meteorological forecasting technique based on extrapolation of current conditions, typically observed by weather radar or satellite

Numerical Weather Prediction (NWP) A meteorological forecasting technique which obtains approximate solutions to the mass, momentum and energy conservation equations for the atmosphere, including transfer processes at the land and ocean surfaces

O

Objective function A measure of how well a simulation fits the available observations (Beven 2012)

Orographic precipitation Precipitation caused by the ascent of moist air over orographic barriers (WMO 2012)

P

Parameter A constant that must be defined before running a simulation (Beven 2012)

Polder Mostly a low-lying area, artificially protected from surrounding water and within which the water table can be controlled (WMO 2012)

Public Switched Telephone Network (PSTN) The telecommunications equipment and infrastructure which connects landline telephones

Q

Quantitative Precipitation Estimate (QPE) An estimate for current precipitation which is typically based on weather radar or satellite observations. When outputs are combined and other sources included, this is often called a multisensor precipitation estimate

Quantitative Precipitation Forecast (QPF) A forecast of rainfall and other types of precipitation, typically based on nowcasting or numerical weather prediction techniques

R

Rainfall-runoff model A model which is used to estimate flows from observed or forecast rainfall

Rating curve See *Stage-discharge relationship*

Resilience The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UN/ISDR 2009)

River gauging station A measuring location where observations of water level and discharge are made

S

Short-range weather forecast In meteorology, a forecast from 12 to 72 h ahead (WMO 2010)

Situation report A brief report that is published and updated periodically during a relief effort and which outlines the details of the emergency, the needs generated and the responses undertaken by all donors as they become known (IDNDR 1992)

Snow pillow Device filled with antifreeze solution and fitted with a pressure sensor which indicates the water equivalent of the snow cover (WMO 2012)

Soil Moisture Deficit (SMD) A state variable used in many hydrological models as an expression of water storage. SMD is zero when the soil is at field capacity and gets larger as the soil dries out. It is usually expressed in units of depth of water (Beven 2012)

Stage-discharge relation Relationship between water level and discharge for a river cross section, which may be expressed as a curve, a table or an equation (WMO 2012)

Stochastic A model is stochastic if, for a given set of initial and boundary conditions, it may have a range of possible outcomes, often with each outcome associated with an estimated probability (Beven 2012)

Surge Or storm surge – a sudden rise of sea as a result of high winds and low atmospheric pressure; sometimes called a storm tide, storm wave or tidal wave. Generally affects only coastal areas but may intrude some distance inland (IDNDR 1992)

T

Threshold A decision-making criterion based on a parameter exceeding or dropping below a predefined value. Sometimes called triggers, criteria, warning levels, alert levels or alarms

Trigger See *Threshold*

Tropical cyclone Generic term for a non-frontal synoptic-scale cyclone originating over tropical or subtropical waters with organized convection and definite cyclonic surface wind circulation (*syn. hurricane, typhoon*, WMO 2012)

Typhoon See *Tropical cyclone*

U

Ungauged catchment A catchment or sub-catchment in which flows are not recorded to the extent required for the application

V

Vulnerability The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. *Comment: There are many aspects of vulnerability, arising from various physical, social, economic and environmental factors. Examples may include poor design and construction of buildings, inadequate protection of assets, lack of public information and awareness, limited official recognition of risks and preparedness measures and disregard for wise environmental management. Vulnerability varies significantly within a community and over time. This definition identifies vulnerability as a characteristic of the element of interest (community, system or asset) which is independent of its exposure. However, in common use the word is often used more broadly to include the element's exposure* (UN/ISDR 2009)

W

Watershed See *Basin*

Weather radar An instrument for detecting cloud and precipitation using microwaves typically with wavelengths in the range 3–10 cm

References

AMS (2015) American Meteorological Society, Glossary of Meteorology

Beven K J (2012) Rainfall Runoff Modelling – The Primer. 2nd edition, Wiley, Chichester

Day G N (1985) Extended streamflow forecasting using NWSRFS. Journal of Water Resources Planning and Management, 111(2): 157–170

Global Water Partnership (2000) Integrated Water Resource Management. Technical Advisory Committee Background Paper No. 4, Stockholm, Sweden

IDNDR (1992) Internationally agreed glossary of basic terms related to Disaster Management

Troccoli A, Mason S J, Harrison M, Anderson D L T (2008) Glossary of Terms in 'Seasonal Climate: Forecasting and Managing Risk' (Eds. Troccoli A, Harrison M, Anderson D L T, Mason S J), NATO Science Series IV: Earth and Environmental Sciences, Vol. 82, Springer, Dordrecht

UN/ISDR (2007) Drought risk reduction framework and practices: Contributing to the implementation of the Hyogo framework for action. United Nations Secretariat of the International Strategy for Disaster Reduction (UN/ISDR), Geneva, Switzerland

UN/ISDR (2009) UNISDR terminology on disaster risk reduction. United Nations International Strategy for Disaster Reduction, Geneva

WMO (2010) Manual on the Global Data-Processing and Forecasting System. Volume I – Global Aspects. WMO-No. 485, Geneva

WMO (2012) WMO/UNESCO International Glossary of Hydrology, WMO-No. 385, Geneva

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