Kevin Sene

Hydro-meteorology

Forecasting and Applications

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Preface

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 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 pre-defined 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 (for example, 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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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. There, I had the opportunity to work on a wide range of research and consultancy projects, with much of this work overseas. Moving to a large engineering consultancy, my focus turned to real-time applications, leading to publication of the book 'Flood Warning, Forecasting and Emergency Response' in 2008.

For this book, many people have helped with reviewing short extracts of text, and providing permission to use figures and to include a discussion of their projects. 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.

The book includes a number of short case studies in the form of text boxes, and text linked to figures, and the following people have helped by providing comments on these descriptions and/or permission to use the associated figures, including (with the box numbers shown in brackets): E. Blyth (11.4), J. Bromley and colleagues (8.2 and 11.2), M. Brown (8.3), R. O'Callaghan, P. Carter and Y. Chen (2.2), G. Charchun (5.3; part), R. Hartman (1.2, 9.2), M. Huttunen and colleagues (7.3, 10.1 and text linked to Fig. 10.7), M. McCartney (11.1), C. McPhail (10.4), G. Munoz (5.2), C. Obled (3.2), M. Potschin and R. Haines-Young (6.2), P. Sayers (6.1), E. Sprokkereef (7.2, 10.2), J. van Steenwijk (10.2), and M. Svoboda (8.1). I would also like to thank Clive Pierce for providing a significant re-write of Box 3.1, and Frank Weber for the description on which Box 11.3 is based. Heiki Walk also provided the text on short-term load forecasting in Box 5.3. Other people who allowed figures to be used (with the figure numbers shown in brackets) include B. Davey and M. Keeling (1.3), Y. Chen (2.2 and part of 2.8 and 9.1), T. Love (2.6), D.-J. Seo (1.1, 6.5), K. Stewart (2.9, 2.10), C. Stow and colleagues (10.5, 10.6), and A. Troccoli and M. Harrison (6.3).

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Where figures are from external sources, this is acknowledged in the captions; however, for completeness, the following figures (including those mentioned above) are from publications, presentations or websites produced by the following organisations:

- Australian Bureau of Meteorology (Fig. 3.4)
- BC Hydro (Figs. 4.10, 5.7, 5.8, 11.6–11.8)
- Cabinet Office (Fig. 3.1)
- CEM, University of Nottingham (Fig. 6.6)
- Centre for Ecology and Hydrology, Wallingford (Figs. 10.2, 11.9)
- ECMWF (Figs. 3.6–3.8)
- Environment Agency (Figs. 2.1, 2.2, 2.8, 4.11, 5.1, 7.4, 8.5, 9.1 (part), 11.5)
- Finnish Environment Institute (Figs. 7.10, 10.1, 10.7)
- Food and Agriculture Organization (Figs. 5.2, 5.4, 5.5)
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- HR Wallingford (Fig. 6.4)
- Institut National Polytechnique de Grenoble (Fig. 3.9)
- International Water Management Institute (Fig. 11.1)
- Joint Research Center (Fig. 8.6)
- Met Office (Figs. 1.4, 1.9, 2.3 (part), 2.5, 3.1, 3.5)
- National Drought Mitigation Center (Figs. 1.2, 8.1, 8.2)
- NOAA, Great Lakes Environmental Research Laboratory (Figs. 10.5, 10.6 and Table 10.2)
- NOAA, National Weather Service (Figs. 1.1, 1.5–1.8, 2.4, 2.6, 2.9 (part), 6.5, 9.6, 9.7)
- Office of Science and Technology (Fig. 7.2)
- Open University (Fig. 1.3)
- Rijkswaterstaat (Figs. 7.6, 7.7, 9.3, 10.3)
- SEPA (Fig. 10.8)
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- Tennessee Valley Authority (Fig. 5.6)
- Urban Drainage and Flood Control District (Figs. 2.9 (part), 2.10)
- United Utilities (Figs. 8.3, 8.4, 11.3, 11.4)
- U.S. Environmental Protection Agency (Fig. 9.8)

Contents

Part I Techniques

Part II Selected Applications

Chapter 1
Introduction

Abstract Hydrometeorological forecasts can be used to assist with emergency management, routine operations, and for longer-term strategic planning. The range of potential applications is large, and can include flood warning, drought forecasting, reservoir operations, hydropower and irrigation scheduling, pollution control, and river basin management. Users may require information in a range of formats, and at different lead times and spatial scales, meaning that the techniques which are used need to be adapted to each application. The approach to interpretation of forecasts can also vary widely, ranging from visual inspection of outputs through to risk-based and probabilistic decision support systems. This chapter presents a general introduction to these topics, and to some of the applications which are presented in later chapters. The areas which are discussed include user requirements for forecasts, approaches to decision-making, and the general techniques which are used in meteorological and hydrological forecasting, and for demand forecasting for water supply, irrigation and energy generation.

Keywords Hydrometeorology · Meteorology · Hydrology · Hydrologic · Demand · Forecast · Lead time · Decision support · Risk-based

1.1 Forecasting Applications

Hydrometeorological forecasts usually aim to provide an estimate of future catchment conditions, based on recent and forecast meteorological conditions, and hydrological observations. Some potential applications include flood warning, drought forecasting, the response to pollution incidents, hydropower operations, and longer-term planning for water resources, irrigation and flood risk management.

Forecasts can be required at a range of timescales, ranging from a few hours or less in flood warning applications, through to many years or decades ahead for long-term strategic planning. In hydrology, the distinction is often made between the following timescales for decision-making:

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- Tactical or Emergency – including flood warning, hydropower generation, irrigation scheduling, water supply operations, and predictive control for urban drainage systems
- Seasonal or Intraseasonal – including drought forecasting, planting/harvesting of crops, water resources management, and annual snowmelt forecasts
- Strategic or Inter-Annual – including river basin management, investment planning, climate change impact assessments, and the operation of reservoir and groundwater systems with large over-year storage

The boundaries between these timescales are not clear-cut and depend on the application.

The scale at which forecasts are ideally required is also an important consideration, and some typical categories include the field (or plot) scale in irrigation applications, through to farm, community, catchment, regional, continental and global scales. The focus also varies between users; for example, emergency managers and urban drainage system operators may be interested in information at a town or city scale whilst, for a wide-spread disaster, international disaster relief organizations are often interested in information across many countries.

The forecasting requirements for lead-time and spatial scale therefore vary and Table 1.1 provides an indication of the requirements for some of the applications which are described in later chapters. Some more detailed examples are provided – for example – by Meinke and Stone (2005) and Bellow et al. (2008), for agricultural applications, by Sene (2008), for flood warning applications, and by the National Research Council (National Research Council 2006) for a wide range of potential end-users in the USA. Here, a subcatchment is defined as the area to the point at which the forecast is required, which might be some way inland from the river outlet (and is often called a Forecasting Point, Flood Forecast Point, or Water Supply Point in real-time forecasting applications).

Of course, the lead time which can be provided in practice is constrained by factors such as catchment response times, and the accuracy of meteorological forecasts at the required lead times. Internationally, there is also much development work underway to develop seamless forecasts valid for a range of lead times, for a range of applications, with consistent estimates of uncertainty throughout. For example, Fig. 1.1 illustrates the range of potential benefits for applications in the USA using this approach (Seo and Demargne 2008).

It is also worth noting that, at longer lead times, the distinction between forecasts and simulation modeling becomes less clear-cut. However, forecasts are usually considered to apply to a specific date or time interval (no matter how uncertain), whilst simulation or prediction studies typically consider representative past, current and/or 'future' conditions (e.g. Nemec 1986, Tallaksen and van Lanen 2004). The modeling techniques which are used are often similar, although in forecasting applications there is the opportunity to improve the model outputs by making use of observations up to the time of the forecast; a process which is called

Table 1.1 Some examples of forecast requirements for spatial scale and lead-time for a range of hydrometeorological forecasting applications (where this is technically feasible)

Application	Spatial scale	Lead-time
Drought Early Warning	Typically regional, national or continental	Varies widely depending on the application, with types of drought including hydrological, groundwater, soil moisture and socio-economic, but typically from days ahead to seasonal, and possibly longer for severe droughts (see Chapter 8)
Ecosystem Forecasting	Field, catchment or lake basin; also for coastal waters	A wide range of timescales, varying from hours to days ahead for pollution incidents, days to months ahead for Harmful Algal Blooms, and longer term for ecosystem impacts (see Chapter 10)
Famine Early Warning	Regional, national or continental	Ideally seasonal, with information available before the start of the main crop growing season(s) (see Chapter 8)
Flood Warning	Subcatchment, catchment or regional	Can vary from a few minutes for flash flooding in canyons, through to hours or days ahead for lowland rivers, the evacuation of people from towns or cities, reservoir releases and emergency response planning. Also, longer term for major river basins and flood risk management (see Chapter 7)
Hydropower Operations	Catchment or regional	Hourly to daily for production scheduling; daily to seasonal or longer for water resources management; longer term for operating large reservoirs and multi-reservoir systems and investment planning (see Chapters 5, 9 and 11)
Irrigation Scheduling	Field to catchment to regional	Hours to days ahead for water allocation; intraseasonal for operational decisions (e.g. fertilization, pest control), seasonal for planting/harvesting decisions; longer range for investment decisions (see Chapters 5 and 8)
Navigation	River reaches, lakes and reservoirs	Hours to days 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 Chapters 4 and 7)
Pollution Incidents	Subcatchment, 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 Chapter 10)
Water Resources	Catchment or regional	Typically from hours to days ahead for operational management, through to weeks, years or decades ahead for river basin management, integrated water resources management, and climate change impact assessments (see Chapter 7 and 11)
Water Supply	Catchment or regional	Varies from 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 Chapters 5 and 9)

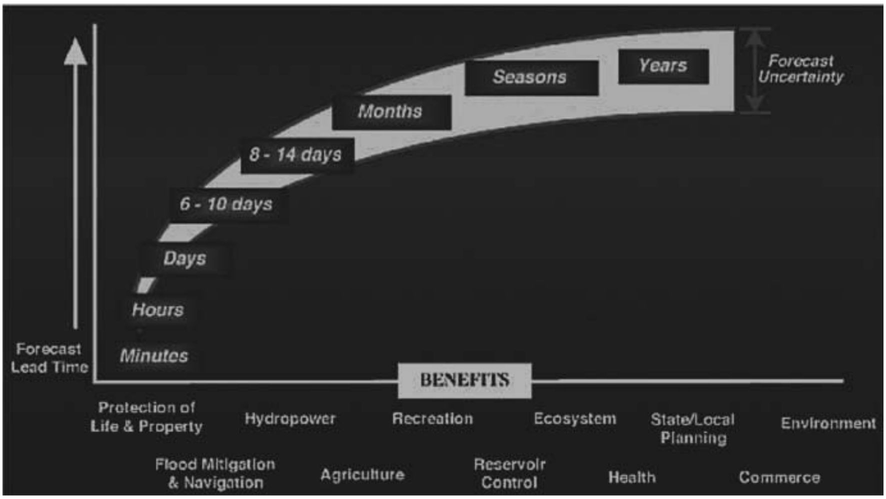

Fig. 1.1 Seamless probabilistic forecasts for all lead times (National Weather Service, Seo and Demargne 2008)

real time updating or data assimilation. Also, in forecasting applications (particularly for short lead times), models are often structured to make best use of the available real-time data, rather than around subcatchment features, such as river confluences.

A hydrometeorological forecasting system typically makes use of monitoring equipment, meteorological and hydrological forecasting models, and tools for post-processing forecasts into useful products. Demand forecasts may also be required for water supply, irrigation and hydropower operations and longer term planning. Recent decades have seen a gradual transition towards more automated, and more computationally-intensive approaches, although simpler or informal techniques still have a valuable role to play where budgets are limited, the risk is low, or as a back-up to more complex systems. Some examples include the use of informal techniques for flood warning (e.g. Parker 2003), community-based flood warning systems, and the expertise of farmers and pastoralists in recognizing the onset of drought.

The range of technologies available has also improved over the years, and developments include the increasing use of weather radar and satellite-based observations, the introduction of multimedia warning dissemination systems (e.g. for flood warning applications), and the widespread use of the internet for dissemination of forecasts. Geographic Information Systems (GIS) are also increasingly used for providing a spatial interpretation of forecasts. One notable example of the use of new approaches to the dissemination of forecasts is the international RANET initiative (Radio and Internet for the Communication of Hydro-Meteorological Information for Rural Development). The project uses a combination of satellite broadcasting, internet and mobile phone technologies to disseminate meteorological information to the public and between national meteorological services and other organizations in Africa, Asia, and elsewhere (http://www.ranetproject.net/). Scientific understanding of regional and global scale phenomena such as the El Niño-Southern Oscillation (ENSO) has also improved, making longer range seasonal forecasting a more realistic proposition in some locations (see Box 1.1). The modeling of climate change, and potential impacts, has also progressed significantly in recent years.

Table 1.2 summarises some significant milestones in the history of the development of hydrometeorological forecasting techniques, and many of these methods are discussed in later sections and chapters. Note that, for convenience, hydrodynamic modeling is considered as an aspect of hydrological forecasting, although is of course a major subject area in its own right.

Table 1.2 Some significant milestones in the development of hydrometeorological forecasting techniques

Period	General area	Description
1850–1900	Monitoring	First telegraphy of river levels and meteorological observations
	Meteorology	Launch of a Public Weather Service (US Army Signal Corps/Met Office)
	Hydrology	Rational method for runoff estimation (Mulvaney)
	Hydrology	St Venant hydrodynamic equations (St Venant)
1900–1929	Meteorology	Principles of Numerical Weather Prediction (NWP) (Bjerknes)
	Meteorology	Identification of the Southern Oscillation (Walker)
	Meteorology	Manual trials of the NWP approach (Richardson)
	Meteorology	Statistical seasonal (monsoon) prediction in India (Walker)
1930s	Hydrology	Unit hydrograph rainfall-runoff model (Sherman)
	Hydrology	Muskingum flow routing approach (Muskingum)
1940s	Meteorology	First trials of data assimilation in NWP (Panofsky)
	Hydrology	Penman evaporation equation (Penman)
	General	First general-purpose computer (ENIAC)
1950s	Monitoring	US NOAA WSR-57 weather radar network started
	Meteorology	First operational NWP models
	Meteorology	World Meteorological Organisation (WMO) established
1960s	Monitoring	First NASA TIROS satellite launched (polar orbiting/infrared)
	Monitoring	WMO World Weather Watch programme established
	Hydrology	Degree-day method for snowmelt (Martinec)
	Hydrology	Development of conceptual rainfall-runoff models
	Hydrology	Muskingum-Cunge flow routing approach (Cunge)
	Hydrology	Palmer Drought Severity Index (Palmer)
		Blueprint for physically-based distributed models (Freeze and Harlan)
	General	Kalman filter (Kalman)

Table 1.2 (continued)

Period	General area	Description
1970s	Monitoring	First geostationary earth observation satellite launched (SMS-A and B)
	Monitoring	European Space Agency (ESA) Meteosat I satellite launched
	Monitoring	NOAA/NASA GOES satellite programme started
	Hydrology	Development of time series models for hydrological forecasting
	Hydrology	Research on physically-based distributed rainfall-runoff models
	General	Introduction of email and internet protocols
1980s	Meteorology	First operational ocean-atmosphere coupled NWP models
	Hydrology	Ensemble Streamflow Prediction (ESP) method (Day)
1990s	Monitoring	TRMM space-borne precipitation radar launched
	Meteorology	First IPCC assessment report on climate change
	Meteorology	Four-dimensional variational data assimilation schemes (4D-Var)
	Meteorology	Operational ensemble meteorological forecasting (ECMWF, NCEP)
	Meteorology	Regional Climate Outlook Forums started (WMO)
	Hydrology	Hydrodynamic models publicly/commercially available
	Hydrology	Increasing sophistication of the land-atmosphere component in NWP
Since 2000	General	Multi-media warning dissemination systems available commercially
	General	Increasing use of coupled land-atmosphere simulation models
	Hydrology	Increasing use of probabilistic flood forecasting systems

The main reason for generating forecasts is to assist in decision-making, and the forecasting system is therefore often only one component in a wider operational framework. For example, Fig. 1.2 illustrates the role of prediction and early warning within the overall risk management and crisis management process for drought disasters, and a similar approach is often used for other types of natural hazards, such as floods. The key components in this process can include assessing the risk, typically through modeling, consultations, and reviews of historical events, preparing to deal with that risk, putting mitigation (risk-reduction) measures in place, issuing the early warning, responding to the disaster, and then a series of crisis management and recovery measures. For example, in famine early warning systems, hydrometeorological forecasts are often combined with other approaches, such as expert judgement on future trends, and observer and media reports on possible precursors of future problems, such as food shortages, and an increase in food prices.

Chapters 7, 8 and 10 provide further examples for warnings for floods, drought and pollution incidents, whilst Chapter 6 provides a general introduction to decision-making processes for emergencies, operational management and long term planning. Internationally, an increasing emphasis is also being placed on improving the way that disaster risk is prepared for and managed (e.g. UN/ISDR 2006a,

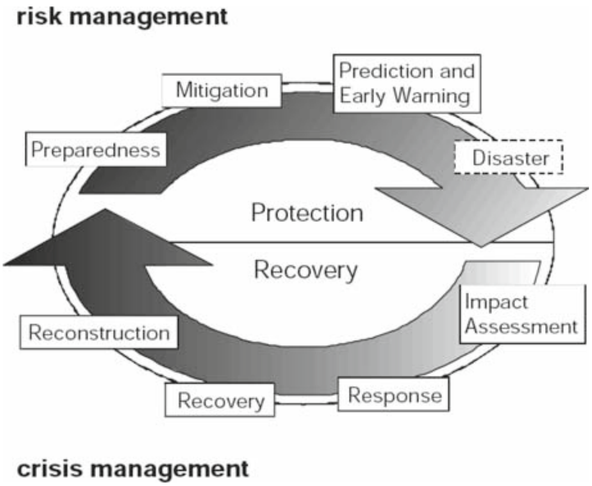

Fig. 1.2 The cycle of disaster management (National Drought Mitigation Center, University of Nebraska-Lincoln; Wilhite and Svoboda 2005)

2009), rather than on the ensuing emergency response and relief. This requires that all aspects of the process are given equal importance; not least the need to adopt a people-centred or community based approach (e.g. Emergency Management Australia 1999, Basher 2006). The point is also often made that the effectiveness of the response depends on a wide range of factors, including institutional capacity, social and economic factors and public awareness, so that what is a disaster for one country, causing many injuries and deaths, may only have economic consequences in another.

Risk management techniques are also widely used in decision making and Section 1.3 and later chapters discuss examples in hydropower operations, irrigation scheduling, water supply and a range of other applications, including examples which make use of probabilistic forecasts. For high risk (and high-value) applications, decision support systems are also increasingly used, combining Geographic Information System (GIS), optimization tools, and other computer-aided techniques for decision making.

1.2 Operational Forecasting

1.2.1 General Principles

As noted earlier, the main components in a hydrometeorological forecasting system typically include monitoring equipment, meteorological forecasting models, hydrological forecasting models, and possibly also demand forecasting models, and decision support tools. Table 1.3 illustrates some of the methods which are often used.

Table 1.3 Illustration of hydrometeorological forecasting tools and techniques

Component	Description
Monitoring	Techniques include raingauges, weather stations, weather radar, satellite observations, river gauges, and instrumentation for catchment conditions (e.g. soil moisture, snow cover); see Chapter 2
Meteorological forecasting	Techniques include nowcasting, Numerical Weather Prediction, and statistical methods, and may include statistical, weather matching or dynamic post-processing (downscaling) to the scales of hydrological interest; see Chapter 3
Hydrological forecasting	Techniques include statistical methods, water-balance methods, 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 Chapter 4 and Chapters 7–11
Demand forecasting	Empirical, statistical and deterministic methods for estimating the water demands for water supply, irrigation and energy generation (particularly related to hydropower generation) and for industrial and other applications; see Chapter 5
Decision support	Techniques to assist users in making decisions, including graphical, tabulated and map-based forecast products, decision support systems, and threshold-based approaches; see Chapter 6

The extent to which each component is required depends on the application and, in particular, the forecast lead time which is required, and the flow range of interest. For example, in flood forecasting applications, in a large river catchment, sufficient lead time may be possible simply from using observations of flows further upstream in the catchment as inputs to the hydrological forecasting models; however, for a flash flood forecasting application, rainfall forecasts (often combined with a rainfall-runoff model) may provide the only feasible way of obtaining sufficient lead time for an effective emergency response. Demand forecasts may also be of little interest for flood forecasting, but are often a key input to procedures for the forecasting of low flows for drought, water resources management and other applications.

The availability of data is also an important consideration. This can mean that, for operational applications, at short lead times, there is a need for information to be relayed automatically by telemetry or manually by observers whereas, for longer lead times, and for model calibration, it may be sufficient to collect information from record sheets, charts or data loggers during site visits. Later chapters describe the lead time and data requirements and forecasting approaches for a range of applications.

In some countries, the national meteorological and hydrological services are part of the same organization, whereas in others they may be distinct organizations, each operating separate observation networks. A variety of other organizations may also collect real-time and off-line data, including agricultural research stations, reservoir operators, hydropower suppliers, water supply companies, canal operators, and others. Some of this data may potentially be available for use for hydrological forecasting applications, depending on local data sharing arrangements and policies.

The availability of data and forecasts also varies widely between organizations and countries. For example, in flood forecasting applications, a survey of 86 countries (World Meteorological Organisation 2006a) suggested that, where flood forecasting capability was non-existent or insufficient, this was often due to insufficient observational data, and issues relating to technical or institutional capacity.

For National Meteorological and Hydrological Services, the arrangements for data sharing are facilitated by the World Meteorological Organisation, which provides standards for the collection and exchange of data and forecast products, and for feeding data into the Global Telecommunication System (GTS). The GTS is a component of the World Weather Watch programme, and 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 all over the world" (World Meteorological Organisation 2006b). It is the main route for the exchange of data for use in weather forecasting models and includes information collected by the WMO Global Observing System from approximately 16 satellites, hundreds of ocean buoys, aircraft, ships and some 10,000 land-based weather and other meteorological stations (World Meteorological Organisation 2006b).

Other United Nations organisations such as the Food and Agriculture Organization (FAO) and the ISDR (International Strategy for Disaster Reduction) also play an important role in sharing expertise and information between countries and, for climate change assessments, the UNEP/WMO Intergovernmental Panel on Climate Change (IPCC) of course plays a key role. There are also many examples of international cooperation between hydrological services for transboundary river systems; the International Commission for the Protection of the Danube (http://www.icpdr.org), and the Mekong River Commission (http://www.mrcmekong.org/)). Table 1.4 summarises some other examples of international cooperation in research and operational activities in meteorology and hydrology which are discussed in later chapters.

The World Meteorological Organisation is also leading the World Hydrological Cycle Observing System (WHYCOS; http://www.whycos.org) initiative, which is aimed at improving basic observation activities in National Hydrological Services, strengthening international cooperation, and promoting free exchange of data in the field of hydrology (Rodda et al. 1993, World Meteorological Organisation 2005). Regional projects have been implemented in the Mediterranean area (MED-HYCOS), southern Africa (SADC-HYCOS), and a pilot study in western and central Africa (AOC-HYCOS), with many other projects planned or in progress. New hydrological stations typically consist of satellite Data Collection Platforms (DCPs) equipped to measure precipitation, air temperature, humidity, water levels (river, lake/reservoir, groundwater, as appropriate), wind speed and direction, and solar radiation. Water quality variables such as conductivity, turbidity and dissolved oxygen may also be monitored in some locations. Data values are typically transmitted between centres using the WMO's Global Telecommunication System (GTS).

Table 1.4 Examples of international cooperation in meteorology and hydrology

Abbreviation	Description
FRIEND	Flow Regimes from International Experimental and Network Data; a UNESCO-initiated programme of research into low flows, floods, variability among regimes, rainfall/runoff modeling, processes of streamflow generation, sediment transport, snow and glacier melt and climate and land-use impacts involving more than 100 countries http://www.unesco.org/water/ (1984-ongoing)
GEWEX	Global Energy and Water Cycle Experiment, a key component of the WMO World Climate Research Programme, whose goal is to reproduce and predict, by means of suitable models, the variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases http://www.gewex.org/gewex (1990-ongoing)
HEPEX	The Hydrologic Ensemble Prediction EXperiment (HEPEX) is an international effort that brings together hydrological and meteorological communities from around the globe to build a research project focused on advancing probabilistic hydrologic forecast techniques http://hydis8.eng.uci.edu/hepex/ (2004-ongoing)
PUB	The Predictions in Ungauged Basins (PUB) programme is an International Association of Hydrological Sciences (IAHS) initiative for the decade 2003–2012, aimed at uncertainty reduction in hydrological practice http://pub.iwmi.org/
WWRP	The WMO World Weather Research Programme, which advances society's ability to cope with high impact weather through research focused on improving the accuracy, lead time and utilization of weather prediction, and includes the THORPEX (1 day to 2 week ahead high impact forecasting; 2003–2013) and TIGGE (global grand ensemble forecast) components http://www.wmo.int/

The following sections provide an introduction to meteorological and hydrological forecasting techniques, and further details are provided in later chapters. A basic understanding of the hydrological cycle is assumed (and a brief introduction is provided in Section 4.2 of Chapter 4). For hydrological forecasting in particular, but also for meteorological forecasting, the methods which are used depend on the local weather and climate, and Fig. 1.3 shows typical rainfall regimes around the world, including high latitude regions which may experience snow cover for several months of each year. The precipitation which is observed can range from desert regions with little or no annual rainfall, through to areas such as Cherrapunji in India, and the island of Kaua'I in Hawaii, which experience average annual rainfalls which are often quoted to be in the range 11–12 m/year, and have reached more than 26 m/year at Cherrapunji (e.g. World Meteorological Organisation 1994). Extensive snow cover may also be experienced in mountain

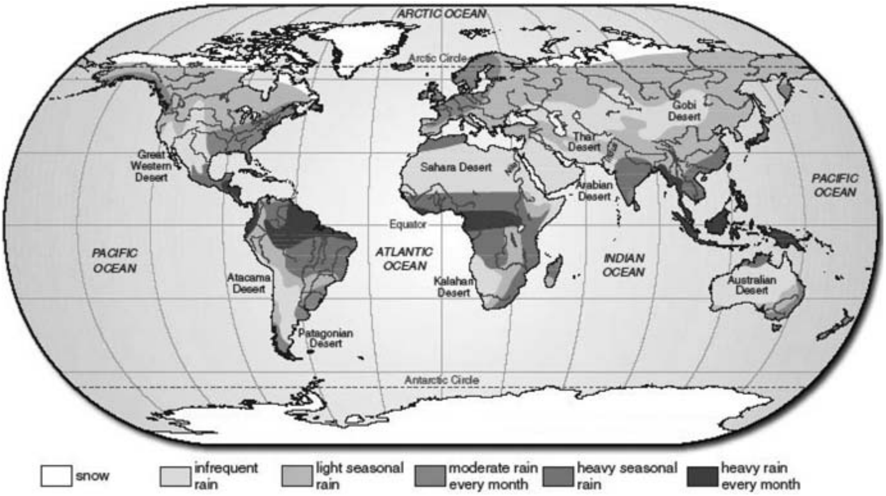

Fig. 1.3 Map showing world rainfall (© Open University, Halliday and Davey 2007) http://openlearn.open.ac.uk/mod/resource/view.php?id=293808&direct=1)

regions at mid-latitudes; for example, in the Western USA and Canada, the European Alps, the Andes, the Himalaya and, to a lesser extent, the high mountains of Africa.

1.2.2 Meteorological Forecasting

Meteorological forecasts are often classified as short-range for lead times up to 3 days ahead, and medium-range for 3–10 days ahead, whilst extended and long-range forecasts extend to seasonal and longer time periods (World Meteorological Organisation 1992). Forecasting techniques include nowcasting, Numerical Weather Prediction, and a range of statistical and hybrid techniques. These are described in Chapter 3 and are summarized in Table 1.5, together with two key approaches which can improve the usefulness of forecasts: post-processing and consensus forecasts.

Numerical Weather Prediction (NWP) models underpin many of these techniques and typically use global scale models to provide boundary conditions to regional and local models; for example, this approach is illustrated in Fig. 1.4, which shows the extent of the operational forecasting models operated by the Meteorological Office in the United Kingdom (the Met Office).

Data assimilation is also a key component in initializing model runs and, as indicated in the table, may include data from a wide range of observation systems. Also, since the 1990s, ensemble forecasting techniques have become standard practice in many meteorological services, and provide multiple realizations of future conditions, based on perturbations to the initial conditions of models to help to take

Table 1.5 Summary of key meteorological forecasting and post-processing techniques

Method	Typical maximum lead time	Basis of method
Nowcasting	0–6 h	Extrapolation of the motion of weather radar and/or satellite based rainfall intensity observations, possibly guided by the outputs from Numerical Weather Prediction models (in which case nowcasting can be regarded as a form of post-processing of NWP outputs). Also, manual or automated extrapolation of other parameters (e.g. fog, air temperature), and of the evolution of tropical storms (hurricanes, tropical cyclones, typhoons)
Numerical Weather Prediction (NWP)	0–10 days (deterministic), 0–15 days, seasonal (ensemble)	Three-dimensional modeling of the atmosphere on a horizontal grid and vertical layer basis, accounting for mass, momentum and energy transport and transfer at the land and (possibly) the ocean surfaces, and assimilating data from a wide range of land-based, oceanographic (buoys, boats etc.), atmospheric (aircraft, radiosonde) and satellite observation systems
Statistical methods	Weeks to seasonal	Multiple regression, canonical correlation analysis, and other techniques linking future weather to indicators or predictors such as sea surface temperatures, and indices for the El Niño-Southern Oscillation (ENSO) (and sometimes called Teleconnections)
Post-processing	As for Numerical Weather Prediction	Dynamic techniques, in which models are nested to provide finer resolution in locations of interest, and statistical techniques, which relate model outputs to ground conditions based on historical or recent observations. Also, analogue or weather matching techniques
Consensus forecasts or predictions	Typically intra-annual and seasonal	Forecasts agreed by experts in meteorology and other disciplines based on the outputs from a range of forecasting models and techniques. Examples include the WMO Regional Climate Outlook Forums active in several parts of the world, and the discussions which lead to the weekly updates of the US Drought Monitor (see Chapter 8)

account of uncertainty in current conditions, and possibly also the uncertainty in model parameters. Typically, 20 to 50 ensemble members are provided per time step. These outputs provide useful information to forecasters on uncertainty, and also open the way to wider use of probabilistic and risk-based decision making techniques. In some systems, performance statistics also show that the ensemble mean value improves upon the single-valued deterministic forecast, particularly at longer lead times.

In the short to medium-range weather forecasts issued to the public, the outputs from computer models are typically interpreted by operational forecasters

Fig. 1.4 Illustration of the spatial extent of the Met Office's UK, North Atlantic and European (NAE) and Global models (© Crown Copyright 2009, the Met Office)

who issue the forecast based on experience, comparisons with recent observations, synoptic charts, and the use of other tools to summarise atmospheric conditions. The outputs from models operated by other national meteorological services may also be taken into account, particularly for longer lead times, with the use of multi-model ensembles becoming increasingly widespread. Statistical and dynamic post processing techniques may also be applied to the raw model outputs, including tailor-made methods to produce forecast products to meet the needs of different users, including road-users, airports, farmers, businesses, industry and others.

For hydrological forecasting applications, the time series of model outputs are also of interest, particularly for flood warning and other short-term forecasting applications. Outputs can be obtained for a point location (e.g. a town centre) or spatially averaged (e.g. for a catchment) for input to hydrological models. Numerical Weather Prediction models can also provide a range of other outputs which can be useful in hydrological applications, including forecasts for evaporation, soil moisture, air temperature, and snow cover. More general information, such as that provided by consensus forecasts and statistical techniques, can also be used for sensitivity and 'what-if' studies.

Historically, one barrier to using forecasts in this way has been the coarse spatial resolution of model outputs, compared to typical hydrological scales of interest. For example, until recently, a typical grid-length for regional models was 10–20 km and, although nowcasting techniques can offer much higher resolutions (e.g. 1 km), this is typically only for lead times of up to a few hours at most for rainfall estimates.

However, due to improvements in computing power (typically using some of the world's fastest supercomputers), the resolutions of Numerical Weather Prediction models are now approaching those of nowcasting models for local (or limited) area, or regional, models. For example, models with grid scales of 1–5 km now becoming operational in some countries, typically at an hourly run interval (compared to 6 hourly or 12 hourly for global scale models). However, due to the additional computer time required, ensemble forecasts are still typically at a lower spatial resolution. The improvements in resolution have also contributed to improvements in forecast accuracy; for example, for the forecasts issued by the UK Met Office, 3-day forecasts are now as accurate as 1-day forecasts were 20 years ago (http://www.metoffice.gov.uk/science/). However, there are of course limitations on predictability from the non-linear, chaotic nature of the atmosphere. These arise since small disturbances from the land surface and atmosphere can grow rapidly and interact, which is often called the 'butterfly effect', and was first popularized by Lorenz (e.g. Lorenz 1993).

The development of seasonal and decadal forecasting techniques is also an area of active research. Approaches include statistical methods, and the operation of coupled atmospheric and ocean models out to lead times of several months to capture the influence of phenomena such as the El Niño-Southern Oscillation and other regional or global scale features (see Box 1.1). Approximately 10 national and international meteorological organisations are designated as World Meteorological Organisation Global Producing Centres (GPCs) of long-range forecasts, including the Bureau of Meteorology in Australia, the China Meteorological Administration/Beijing Climate Center, the European Centre for Medium-Range Weather Forecasts (ECMWF), the Japan Meteorological Agency/Tokyo Climate Center, and the UK Met Office. Similar techniques are also used for the General Circulation Models used in modeling the impacts of climate change for years to decades ahead.

Box 1.1 Regional and global scale features of the atmosphere

In many parts of the world there are distinct seasonal influences and large-scale features of the atmosphere which are in principle predictable, even if only to provide a general indication of the timing and location of events, and in probabilistic terms. Some key driving mechanisms include variations in solar radiation, atmospheric waves, heat and water transfer at the ocean boundary, and related factors, such as the strength and position of the jet stream at mid-latitudes, and blocking anticyclones. In particular, the timescales over which the oceans respond are slower than for the atmosphere, and the heat capacity larger, raising the possibility of forecasting atmospheric changes over longer timescales, if the links between changes in the atmosphere and oceans can be understood.

The investigation of these phenomena is a key area for research in meteorology, and also in the wider search for so-called ‘teleconnections’ which relate observations or forecasts in one part of the world to impacts in another. Some key mechanisms which have been identified as either primary or secondary driving factors (and which to some extent are all inter-related) include (e.g. Palmer and Hagedorn 2006, Troccoli et al. 2008):

- El Niño-Southern Oscillation – abnormal increases (beyond the usual seasonal variations) in sea surface temperatures (SST) in the eastern and central Pacific, over characteristic periods of 2–7 years, for durations typically of a few months or more, linked to variations in the surface and sub-surface circulations in the Pacific Ocean. El Niño episodes tend to alternate with cooling (La Niña) episodes and drive a global atmospheric pressure variation called the Southern Oscillation, leading to the widely used term El Niño-Southern Oscillation (ENSO). ENSO events in particular have a strong influence on sea level temperatures and pressures and tropical rainfall, and the northern hemisphere jet stream and the Madden Julian Oscillation, so the impacts can occur in many parts of the world (see later)
- Inter Tropical Convergence Zone (ITCZ) – the convergence zone between the trade winds in the northern and southern hemispheres, which results in an uplift of air and generation of heavy convective rainfall and thunderstorms around the equator. Over land, the north-south position follows a meandering path linked to the zenith of the sun, with widths of several hundred kilometres, typically reaching a latitude of about 10° north or south, but with effects extending as far as 45° north in parts of southeast Asia. This often leads to two wet seasons and two dry seasons near the equator, merging into single wet and dry seasons at the northern and southern limits
- Madden Julian Oscillation (MJO) – intraseasonal patterns of atmospheric circulation, and enhanced and suppressed tropical rainfall (Madden and Julian 1994), which progress eastwards from the Indian Ocean into the western Pacific Ocean, and to a lesser extent the Atlantic Ocean, variously described as having a timescale of approximately 30–60 or 40–50 days, but with strong variations from year to year. Areas affected include the western USA, the Pacific Northwest and southeast Asia, with impacts also on the Indian and Australian monsoons, and tropical cyclones, and the northern hemisphere jet stream, with the greatest impacts during weak La Niña years, and little activity during strong El Niño episodes
- Monsoon – linked to the seasonal variations in 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 on-shore, and affecting many regions where large land masses

are adjacent to the ocean (e.g. in parts of west Africa and Central America, and southeast Asia). Most notable in the form of the Asian Monsoon, which typically lasts from June to September, and for which the countries affected include Bangladesh, India, Nepal, Pakistan and Sri Lanka

- North Atlantic Oscillation (NAO) – a mainly atmospheric phenomenon, although 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). Affects the strength and tracks of storms across the Atlantic and into Europe (particularly in winter), with influences on air temperatures and rainfall from a region extending from southern Europe and North Africa (in weak NAO years) to central and northern Europe (in strong NAO years), and to a lesser extent the eastern USA and Canada (e.g. Hurrell et al. 2003)

Other 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 mid-latitudes of the Pacific Ocean (Mantua et al. 1997). The influence of the El Niño-Southern Oscillation is perhaps the most active area for research, and the impacts can be widespread, particularly in equatorial and tropical regions surrounding the Pacific Ocean, but also in other locations, as illustrated in Fig. 1.5 for both El Niño and La Niña events. For example, the 1982–83 and 1997–98 El Niño events affected countries in Africa, Asia, the United States and South America (e.g. Hoerling and Kumar 2003, NDMC 2009).

As noted in NDMC (2009) ‘In general, when El Niño conditions develop in the eastern Pacific, the first visible impacts include an increase in precipitation in the eastern Pacific, including parts of South America, and a decrease in precipitation for western Pacific locations such as Australia, Indonesia, Southeast Asia, and the Philippines. As the El Niño continues, other impacts include a significant decrease in tropical storm activity in the Atlantic Ocean and a corresponding drought in the Caribbean and Central America. Tropical storm activity increases in the eastern Pacific. Anomalously wet conditions are common across the southern United States and eastern Africa. Severe droughts can also occur in southern Africa and in northeastern Brazil’.

Publicly available bulletins on the progression of El Niño events include the WMO El Niño/La Niña Updates issued through a collaborative effort between the 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/).

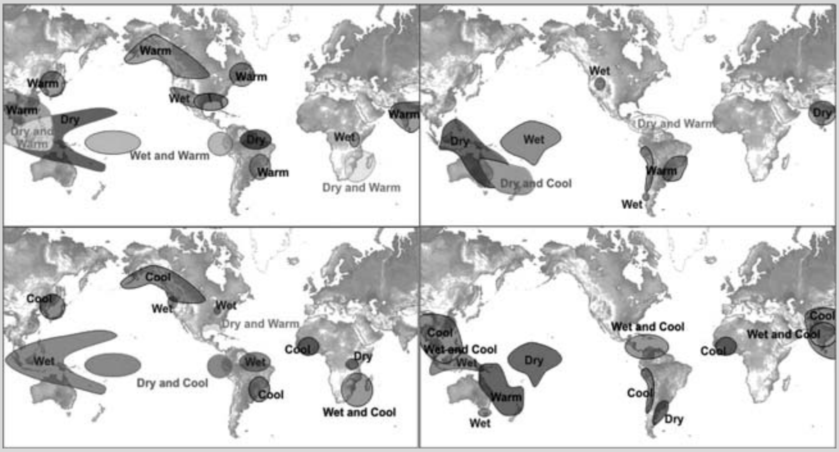

Fig. 1.5 The regions where the greatest impacts occur due to the shift in the jet stream as a result of ENSO. Top row: El Niño effect during December–February (*left*) and June–August (*right*), lower row: La Niña effect during December–February (*left*) and June–August (*right*) (Source: NOAA, http://www.riverwatch.noaa.gov/jetstream/tropics/enso_impacts.htm)

Seasonal forecasting techniques include the use of coupled ocean-atmosphere Numerical Weather Prediction models, and statistical and spectral techniques linking impacts to indicators and predictors such as sea surface temperatures, and latitudinal differences in sea surface air-pressure (e.g. the Southern Oscillation Index SOI and North Atlantic Oscillation Index). For example, sea surface temperatures can be forecast using ocean models, and observed by satellite and ocean buoys, and there are approximately 70 deep ocean buoys in the international Tropical Atmosphere Ocean (TAO/TRITON) array in the equatorial Pacific Ocean (http://www.pmel.noaa.gov/tao/). Some further description of seasonal forecasting techniques is presented in Chapters 3 (in general terms), 7 (for floods) and 8 (for droughts).

1.2.3 Hydrological Forecasting

Hydrological forecasts can be generated using a range of techniques; however, a typical approach is to use observation or forecasts of rainfall as inputs to conceptual, data-driven or distributed (grid-based) rainfall-runoff (hydrologic) models. These may in turn provide inputs to hydrological or hydrodynamic flow routing models, which translate flow through the river network. Simpler water balance techniques are also sometimes used, and demand forecasts may also need to be considered in some applications.

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 (World Meteorological Organisation 2008). Models may be operated at a local, catchment or regional scale, and sub-models may also be included for a range of influences, including urban drainage, reservoir control, water quality issues, and other factors. As for meteorological models, the availability of real-time data means that, at least at short to medium lead times, the outputs from hydrological forecasting models can be updated to help to account for the differences between observed and forecast values; a process which is often called real-time updating or data assimilation.

In addition to rainfall, a number of other meteorological variables may also be of use as inputs to hydrological forecasting procedures, and Table 1.6 shows some examples. Note that rainfall, snow, hail, drizzle etc. are often referred to collectively as precipitation, and that evaporation losses occur directly from open water, plant interception or soil surfaces, whilst transpiration arises from plants drawing up water from deeper soil layers. The combination of the evaporation and transpiration terms is often called evapotranspiration (although some definitions exclude the open water component). The use of coastal forecasts of surge and tidal levels can be relevant in some hydrological forecasting applications, such as in providing a downstream boundary condition for a river hydrodynamic model.

Meteorological variations can also affect the demand for water, both directly, by increasing the requirements for water consumption (e.g. for drinking water, or irrigation), and indirectly; for example, by increasing the demand for sources of electricity which rely on water either for power generation (e.g. hydropower plants) or for cooling (e.g. thermoelectric plants). Some typical demand forecasting techniques include multiple regression approaches, data-driven methods, such as artificial neural networks, process-based models (e.g. crop simulation models), and micro-component approaches, in which the total demand is estimated from the sum of individual types of use (e.g. drinking water, bathing water). Methods can

Table 1.6 Some examples of the use of meteorological inputs in hydrological forecasting applications

Parameter	Typical model components
Precipitation	Surface runoff, reservoir and lake levels, urban drainage, groundwater levels
Snow	Snow cover, snow depth, snow density
Air temperature	Snowmelt, evaporation, transpiration, evapotranspiration
Humidity	Evapotranspiration, snowmelt
Radiation	Evapotranspiration, snowmelt, ice break-up
Wind speed	Wave heights on lakes and reservoirs (and surge on large water bodies, and in estuaries), evapotranspiration, snowmelt
Wind direction	Wave directions on lakes and reservoirs and in estuaries

be very specific to the particular application, and Chapter 5 describes a range of approaches for water supply, irrigation and energy generating applications.

For short- to medium-term forecasting, National Hydrological Services and other forecasting centers typically operate models within a computer forecasting system. Systems of this type usually have the facility to receive real-time data and forecasts from a range of sources (e.g. raingauges, river gauges, weather radar, Quantitative Precipitation Forecasts), to operate the models, and then to post-process the outputs into map-based, graphical and other formats for a variety of users. Models are typically operated at least once per day, and more frequently during flood events. The system may be designed primarily for use during particular types of hydrological event (e.g. flooding), or cover a range of applications in flooding, droughts, water resources management, and other areas. For example, Box 1.2 describes the operational forecasting system used by the California-Nevada River Forecasting Center, which is part of NOAA's National Weather Service in the USA.

For longer term forecasting, the reduced pressure on lead times means that models can sometimes be operated off-line, although there are often good reasons for using a more formalized system, such as improvements to data quality control and record keeping, and operational efficiencies. Some typical modeling approaches at these lead times include supply-demand models, which can represent the main sources and demands for water to a high level of detail, simplified integrated catchment models, and distributed models, operating on a gridded basis. For example, supply-demand models are widely used in river basin management, hydropower and other applications, and often include a linear or dynamic programming component to help to optimize operating strategies.

Also, an increasing trend in forecasting applications is to develop models which consider all key meteorological inputs, flow pathways and artificial influences on flows from the headwaters to the coast. Some research examples include the 'clouds-to-catchment-to-coast' concept in the Flood Risk from Extreme Events (FREE) programme in the UK (http://www.free-uk.org/) and the 'Sky to the Summit to the Sea' approach in the Coastal and Inland Flooding Observation and Warning Project (CI-FLOW) in the USA (http://www.nssl. noaa.gov/).

The Source-Pathway-Receptor approach is also widely used in environmental applications to consider the impacts of flooding, pollution and other factors on people and the environment, and can be applied at a local level (e.g. for a point source of pollution affecting an aquifer) through to a catchment or regional scale. For example, Chapter 6 illustrates this approach for a flood risk management application. For longer term forecasts and prediction, and particularly for climate change impact assessments, process-based techniques are increasingly used and – as described in Chapter 11 – in addition to the water and energy fluxes between the land, atmosphere and oceans, may also consider additional factors, such as the carbon cycle, and the role of atmospheric chemistry in affecting meteorological and hydrological conditions. Some other factors which may be considered include urban drainage and pollution, changes in land use, vegetation, and ecosystems, and the effects of forest fires and volcanoes.

Box 1.2 California-Nevada River Forecast Center (CNRFC)

The California-Nevada River Forecast Center (CNRFC) is one of 13 River Forecast Centers (Fig. 1.6) in NOAA's US National Weather Service (NWS), whose main functions are (http://www.cnrfc.noaa.gov/):

- 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.

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

Fig. 1.6 National Weather Service River Forecast Centers in the United States (http://www.weather.gov/ahps/rfc/rfc.php)

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 raingauge telemetry systems.

The combined telemetry network in California and Nevada across these organisations includes more than 1,450 raingauges, 750 air temperature sensors, 750 river gauges, and 120 reservoir level gauges, where 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, and actual and scheduled releases from reservoir operators, together with rainfall observations from the NEXRAD network of weather radars, and from satellite-based precipitation measurements. Meteorological forecasts are provided by ten NWS Weather Forecast Offices in California, Nevada and Oregon, and the National Centers for Environmental Protection (NCEP). A steady state multi-layer 2D modelling approach (Rhea 1978, Hay 1998) is also used to provide estimates for watershed precipitation and snow levels in the Sierra Nevada for up to 5 days ahead.

The area covered by CNRFC is approximately 627,000 km^2, and catchment models have been developed for 230 river basins, with forecasts provided for approximately 90 Flood Forecast Points, 50+ Reservoir Inflow Points, and 50+ Water Supply Points. Flood forecasts are derived for a range of timescales, as illustrated in Fig. 1.7.

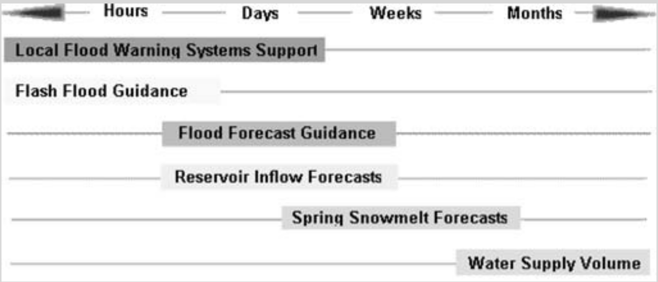

Fig. 1.7 Typical applications of flow forecasts for a range of timescales (California-Nevada River Forecast Center, http://www.cnrfc.noaa.gov/)

Models are currently operated on a real-time forecasting system called the National Weather Service River Forecast System (NWSRFS); however, the CNFRC is in the process of migrating their models into a more modern infrastructure called the Community Hydrologic Prediction System (CHPS). CHPS is based on Delft-FEWS 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) model (Burnash 1995), the SNOW-17 snowmelt model (Anderson 1968), unit hydrograph techniques, Muskingum and hydrodynamic flow routing models, and reservoir operation models. Long-term flow forecasts are also derived by sampling historical rainfall and air temperature records using the Ensemble Streamflow Prediction approach (Day 1985), together with simpler 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. ENSO). Shorter term ensemble forecasting techniques are also under development, together with the 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 (http://www.cnrfc.noaa.gov/publications.php).

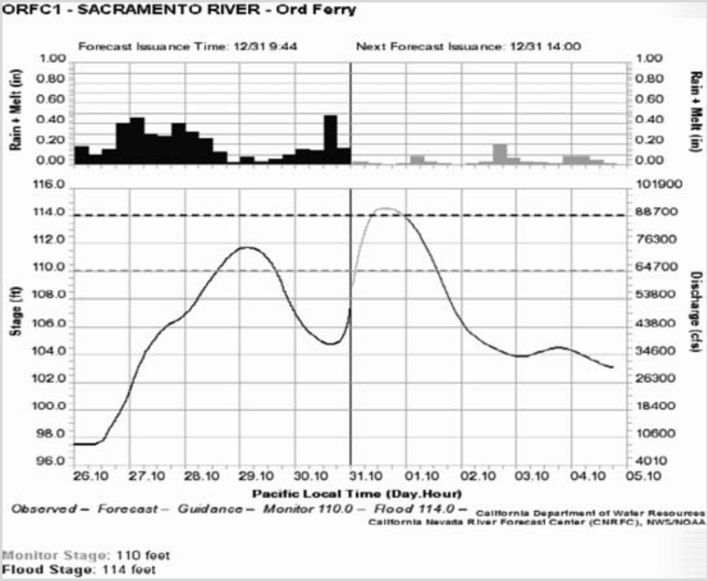

Fig. 1.8 Illustration of river stage forecast guidance for Ord Ferry on the Sacramento River (California-Nevada River Forecast Center, http://www.cnrfc.noaa.gov/)

The CNRFC provides a range of forecast products to different users (e.g. Fig. 1.8), including 5-day reservoir inflow forecasts to water management agencies, and Flash Flood Guidance based on current watershed conditions. In addition, the center issues 20-day Forecasts of Runoff Volumes during the Snowmelt Season, 90-day ensemble-based predictions (year-round), and seasonal (April through July) volume Water Supply Outlooks from January to May or June. During flood events, the center is staffed 24 h 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).

1.3 Decision Support

Hydrometeorological forecasts are usually made to support decision-making. The types of decisions can range from short-term emergency response actions such as evacuating people from areas at risk from flooding, or switching water supplies due to a pollution incident, through to longer term strategic and investment decisions, such as on which crops to plant, and the seasonal operation of reservoirs.

To support end users, forecast outputs are usually post-processed into a range of map-based, graphical, tabular and text-based formats, which provide information in a way which is useful and meaningful to the user. Other information can include the time of the forecast, the time of the next forecast and – for more expert users – information on the spatial and temporal scale of the forecast, the validity of the data used in initializing the forecast, the uncertainty in the forecast, and recent forecast verification statistics. The optimum approach can depend on a range of factors, including the application, the technical skills of users, the ways in which information can be accessed (radio, television, internet etc.), the authority level of recipients (technical specialists, advisors, policy makers etc.), and the risk tolerance of users (risk adverse, risk neutral, risk taking etc.).

Figure 1.9 shows some examples of forecast products produced by the UK Met Office (Met Office 2007), consisting of a composite image of rainfall intensity for the United Kingdom produced from the UK network of weather radars, and the associated surface pressure chart, for a frontal event during December 2005. Of course, the Met Office, in common with other meteorological services, also produces many other types of product, and these can include severe weather warnings, surge and wave forecasts, seasonal forecasts, monthly outlooks, on-demand forecasts in response to atmospheric pollution incidents and other crises (e.g. disaster relief), and a range of more specialised products for agriculture, business, aviation and other users.

Similar considerations about the design of forecast products also apply in hydrological forecasting. Forecast outputs and other decision support tools are therefore best designed as a collaborative effort between forecasters and end-users (e.g. Rogers et al. 2007). For example, in flood warning applications, it is more useful to the emergency response authorities to have a map of locations likely to flood,

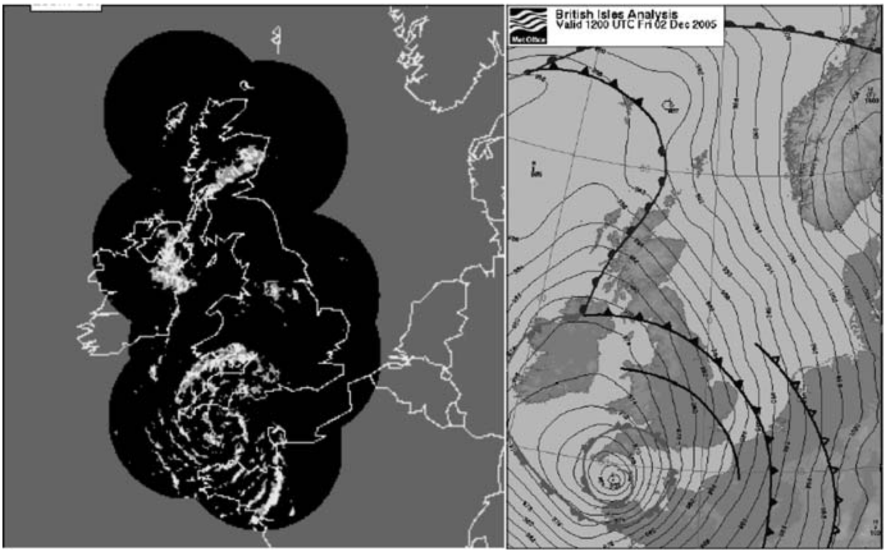

Fig. 1.9 Example of the weather radar output and corresponding surface pressure chart (55 min earlier) produced by the UK Met Office for a day in December 2005 in which a deep low pressure region was approaching the UK, and which illustrates how closely the rainfall was linked to the atmospheric circulation in this event (© Crown Copyright 2007, the Met Office)

with an indication of times and depths, than to know the maximum level which the forecasting model has predicted at a telemetry gauge.

Perhaps the most highly developed approach to warning and evacuation is for hurricane warning in the USA, and Fig. 1.10 shows an example of a hurricane evacuation map for the Louisiana coastline, in which colour coded zones are used with the colours depending on the lead time before the onset of tropical storm winds, ranging from 50 h at the coastline, to 40 h for the next region inland, and 30 h for the area immediately to the north of New Orleans (State of Louisiana 2009). Similar maps are also produced for river flood warning applications in many countries (e.g. EXCIMAP 2007). Later chapters present a variety of other purpose-made products, including graphs showing hydropower potential and pollution transport, and maps showing forecasts for drought severity, the locations of harmful algal blooms, and lake levels relative to long term values.

Chapter 6 describes some other widely used approaches to decision making, which include the use of thresholds, in which actions are taken when river levels, reservoir levels, pollution concentrations etc. exceed a pre-defined value and – particularly for high risk and/or high impact decisions – the use of decision support systems, often combined with Geographic Information Systems (GIS). For decision support systems, the forecasting model may either be embedded in the system, or used to provide one of a number of inputs. Some examples include systems for flood emergency management (Chapter 7), and for reservoir operation and the real-time control of urban drainage systems (Chapter 9).

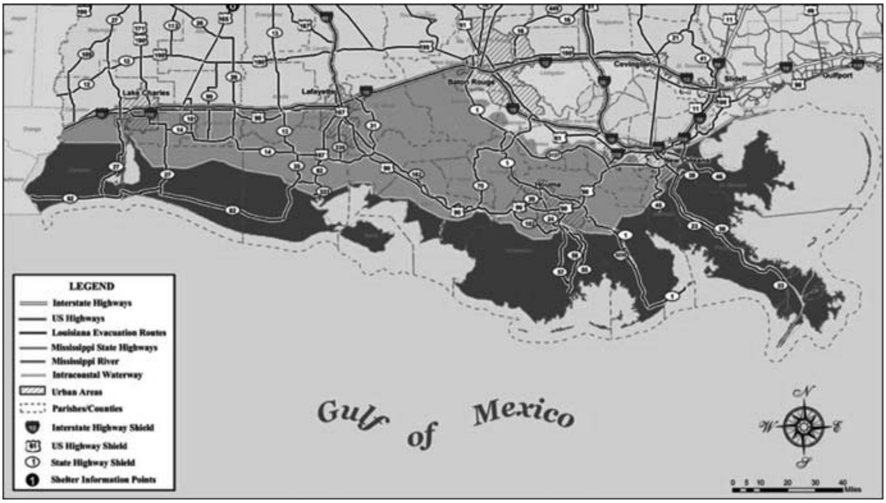

Fig. 1.10 Example of a hurricane evacuation map for the New Orleans and Baton Rouge area of the Louisiana coastline. Governor's Office of Homeland Security and Emergency Preparedness, (Louisiana)

Risk-based approaches are also increasingly used, which consider both the probability of an event occurring, and the consequences if it does occur, and examples are presented in later chapters for applications to agricultural risk management (Chapter 6), flood risk management (Chapter 7), and drought risk management (Chapter 8). The probability of occurrence can be estimated either off-line, based on historical data (e.g. using flood or low flow frequency estimates), or in real-time, starting from current conditions. Having assessed the risk, users can choose a number of actions, including avoiding, sharing, accepting, or mitigating the impacts. For example, in real-time applications, probabilistic techniques based on sampling of historical meteorological conditions, but using current conditions to initialize the forecast, have been used since the 1970s for seasonal water supply forecasting, and longer term planning (e.g. Day 1985). This approach is also increasingly used at shorter timescales, using the ensemble forecast outputs from meteorological models, and also considering other sources of uncertainty, arising from model parameters, boundary conditions, initial conditions, and input data (see Chapter 4 and 7).

More generally, probabilistic techniques are widely recommended as a way of advising users of the uncertainty in forecasts, arising from uncertainties in the input data, models, and other factors (e.g. Krzysztofowicz 2001, UN/ISDR 2006b, Beven 2008). Indeed, for seasonal forecasts, given the uncertainties at these longer lead times, outputs are usually presented in probabilistic terms. For example, the case for probabilistic forecasting in hydrology has been concisely summarised by Krzysztofowicz (2001), which is that:

- 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

A wide range of probabilistic forecasting applications is presented in later chapters, and Chapter 6 provides a more detailed discussion of the use probabilistic forecasting techniques in decision-making. A brief discussion is also included of the societal aspects of issuing forecasts and warnings, which is an active area for research in meteorology, flood warning, agriculture and other areas (e.g. Drabek 2000, National Research Council 2006, Troccoli et al. 2008).

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Part I

Techniques

Chapter 2
Monitoring

Abstract Historical and real-time observations have a key role in the calibration and operation of hydrometeorological forecasting models. Parameters which may be required include rainfall, air temperature and river flow values for rainfall-runoff models, and a range of variables for estimating water availability (e.g. river flows), catchment conditions (e.g. soil moisture, snow cover), and water demands (e.g. for irrigation) and losses (e.g. from evaporation). Additional information may also be required for water quality and ecological forecasting. Many meteorological and hydrological forecasting models also routinely use real-time observations to improve the accuracy of forecasts in a process called real time updating or data assimilation. This chapter discusses some of the main monitoring techniques which are used, including raingauges, weather stations, weather radar, and instrumentation for water quantity and quality in rivers, lakes and reservoirs. The role of satellite observations is also discussed, including remote sensing of precipitation, snow cover, and soil moisture. The chapter concludes with a brief introduction to the design of monitoring networks for forecasting applications, and real-time telemetry systems.

Keywords Raingauge · Automatic Weather Station · Weather radar · Satellite · River gauging station · Stage-discharge relationship · Rating curve · Telemetry · Instrumentation network

2.1 Introduction

2.1.1 Techniques

Real-time and historical observations underpin most hydrometeorological forecasting techniques, and are typically available at a range of spatial scales and time intervals. Due to technical, financial and other limitations, one of the challenges in hydrometeorological forecasting is often to provide satisfactory forecasts on the basis of a less than ideal range of data inputs.

K. Sene, *Hydrometeorology*, DOI 10.1007/978-90-481-3403-8_2,

When considering the types of information available, a distinction is often made between land-based and remote sensing techniques, and site-specific (point) and distributed observations. Remotely sensed or distributed observations, such as satellite observations of snow cover, provide a spatial view of conditions, but may lack detail or accuracy at individual locations, whilst point measurements can be highly accurate, but unrepresentative of the surrounding area. The time delay between successive measurements is also important, and some commonly used intervals for observations include 15-minute, hourly, daily, decadal (10-day), and monthly values, where 10-day values are widely used in agricultural applications, for example. Event-based monitoring is also sometimes used, in which observations are reported only when a threshold value is exceeded, such as a trace amount of rainfall, or river levels exceeding a given value.

Observations are increasingly relayed by telemetry, although manual observation systems are still widely used, often with recording intervals suited to the national or local work schedules of observers; for example, 0800, 1300, 1900. However, for input to the World Meteorological Organisation World Weather Watch programme (http://www.wmo.ch/), which supports operational meteorological forecasting worldwide, ground-based meteorological observations are usually reported at synoptic intervals (3-hourly, starting from 0000) or more frequently (e.g. hourly). The recording intervals are based on the UTC (Coordinated Universal Time) time standard which is – to within a second – the same as Greenwich Mean Time (GMT), and is also known as 'Zulu Time'.

Figure 2.1 provides a simple illustration of the differences between site-specific and remotely sensed techniques, and shows an idealized storm crossing a region, in which rainfall is monitored by three raingauges. Remotely sensed observations, in this case from weather radar, are also available on a grid-square basis. Each raingauge records a different time sequence of rainfall, whilst the weather radar values for the highlighted grid square record a spatially averaged representation of the rainfall which occurred. The values which are recorded will also depend on the progression of the storm, including changes in the velocity, rainfall intensity and spatial extent, and whether values are recorded at the end of each timestep, or following some other convention. Gauges B and C might also record small ('trace') amounts of rainfall during the third and fourth time intervals.

The timestep chosen for this example is also small enough to resolve the time evolution of the rainfall event as it passes over the region, whereas a longer time step (e.g. daily) would not provide this level of detail. Thus, each type of measurement technique provides a sample of the actual rainfall (and neither is 'truth'), and the forecasting approach would need to be tailored to the types of observations which are available, or are considered to be the most representative. There may also be the option of installing new equipment, or refurbishing existing instruments, if there is insufficient data available to provide the required forecasting performance.

A more general point is that all observation techniques have their own measurement uncertainties, and these need to be taken account throughout the forecasting process, as described in later chapters. Some other factors which may need to be considered include topographic influences (e.g. for raingauges and weather radar), and the lead times at which forecasts are required. For example, for a flood

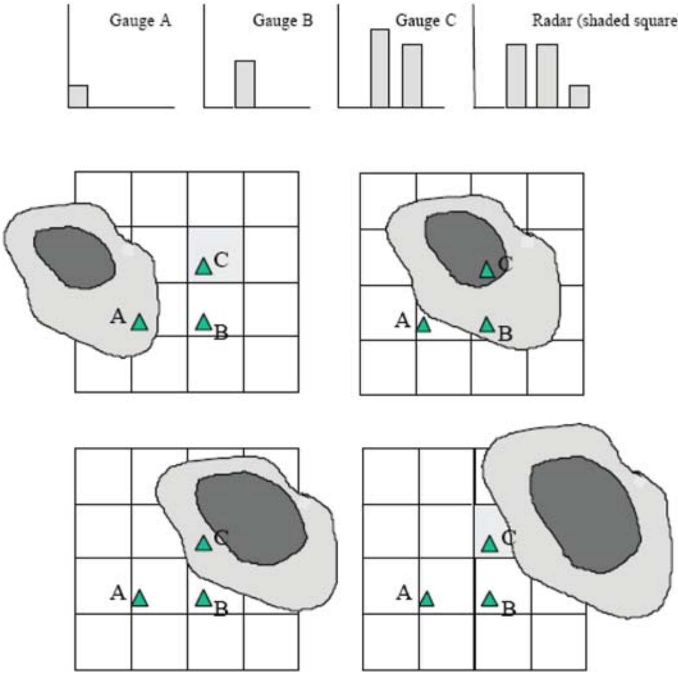


Fig. 2.1 Illustration of the differences between radar and rain gauge sampling (*darker shading* indicates a higher intensity of rainfall) (Environment Agency 2002, Copyright © Environment Agency 2009 all rights reserved)

forecasting application, the time between the heaviest rainfall and the flood peak might only be a few hours or less for a flash flooding event, and measurements would ideally be required at time intervals of less than an hour (e.g. 15 min). By contrast, droughts typically develop over periods of weeks or months, and daily or longer intervals are often sufficient for emergency planning and response, although are often too coarse for operations such as pumping and water treatment, in water supply applications, and irrigation and hydropower scheduling.

Later chapters discuss these issues of spatial resolution, temporal averaging and forecast lead-time in more detail, whilst this chapter considers the types of information which may be available, under the following headings:

- Meteorological Observations – raingauges, weather stations, weather radar, satellite rainfall estimation (Section 2.2)
- Hydrological Observations – water levels (river, reservoir, lake), river flows, water quality (pH, conductivity etc.), catchment conditions (soil moisture, snow cover etc.) (Section 2.3)

Section 2.4 also provides a brief introduction to the design of instrumentation networks, and telemetry systems. Note that the term hydrometry is often used to describe the monitoring of rivers, reservoirs, lakes and other aspects of the hydrological cycle.

The remainder of this section provides a general introduction to the satellite technology which supports both meteorological and hydrological satellite observations, and to the background to the global network of synoptic observations which supports weather forecasting operations worldwide. In the space available, it is only possible to provide a brief introduction to these topics, and some more comprehensive reviews include texts on precipitation measurement (Michaelides et al. 2008, Strangeways 2007), hydrometry (Boiten 2000, Herschy 1999), weather radar (Collier 1996, Meischner 2005), and satellite observations (World Meteorological Organisation 2000). The World Meteorological Organisation (http://www.wmo.int/) also publishes a number of guidance documents for observers, and standards for instrumentation, and more general summaries such as the Guide to Hydrological Practices (World Meteorological Organisation 1994). There are also international standards available for river flow monitoring, water quality monitoring and several other types of measurement (e.g. International Standards Organisation 1996, 1998).

2.1.2 Satellite Technology

Since the Sputnik 1 satellite was launched in 1957, many satellites have been launched by international and national organisations and the private sector for communications, defence, earth observation and other applications. These include polar orbiting and low earth orbit (LEO) satellites and – at a much greater distance from the earth – geostationary satellites, whose location in space appears fixed relative to a given point on the earth. Estimates vary but typically suggest that there are about 800–900 operational satellites orbiting the earth at any one time, with about 400 (each) in geostationary and low earth orbits (e.g. http://www.ucsusa.org/). Polar orbiting satellites in sun-synchronous orbits typically operate at an altitude of about 700–1,000 km whilst geostationary satellites are placed above the equator at a height of approximately 36,000 km, and low earth orbiting satellites are typically operated at altitudes from 300 to 800 km.

To achieve a good spatial coverage, low earth orbit satellite systems typically consist of groups (or constellations) of individual satellites, and are widely used for communications and in global positioning systems. However, for earth observation, most systems consist of polar orbiting or geostationary satellites (typically one, two or three). For hydrometeorological forecasting applications, a number of satellite systems are potentially of interest, or have been used operationally, and Table 2.1 summarises some examples:

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 improved systems and instrumentation (e.g. Landsat, GOES, Meteosat/MSG). Several of these systems, plus others not listed, also form part of the World Meteorological Organisation (WMO) World Weather Watch (WWW) Global Observing System (GOS) programme (World Meteorological Organisation 2003). The MetOp programme is also part of a joint collaboration with the NOAA-N satellite programme in the USA.

Many satellites carry a range of communications equipment and sensors, and sometimes also have secondary payloads, such as for search and rescue operations.

Table 2.1 Some satellite systems of interest to hydrometeorological forecasting applications (G = Geostationary orbit, P = Polar orbit)

Name	Country/operator	Orbit	First launch	Primary hydrometeorological applications
GOES	National Oceanic and Atmospheric Administration (NOAA)	G	1975	Weather forecasting, earth observation
GPM	International/multi-agency	P	2013-on	Precipitation measurement by active weather radar and other instruments (planned)
Landsat	National Aeronautics and Space Administration (NASA)	P	1972	Earth observation of vegetation, land use, flood extents etc.
MetOp	European Space Agency/EUMETSAT	P	2006	Operational Meteorology
Meteosat	European Space Agency/EUMETSAT	G	1977	Meteorological observations
RadarSat	Canadian Space Agency/private sector	P	1995	Earth observation by Synthetic Aperture Radar (SAR)
SPOT	Public/private sector (France/Sweden/Belgium)	P	1986	Earth observation including SPOT VEGETATION
TRMM	NASA/Japan Aerospace Exploration Agency (JAXA)	LEO	1997	Tropical rainfall measurement by active weather radar and other instruments

Some well-established types of sensor (again representing a series of improvements over the years) include the NOAA Advanced Very High Resolution Radiometer (AVHRR) instrument, which is carried on several satellite platforms, and the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, which is again carried on more than one platform. A distinction can also be drawn between passive and active systems, where passive systems simply record the radiation which is received from the atmosphere and land and ocean surfaces, whilst active systems transmit a signal and record the reflected signal. The main type of active systems of interest are space-borne Synthetic Aperture Radar (SAR) instruments, which reconstruct images from successive returns along the satellite track, to simulate an extremely large high resolution radar antenna, and space-borne weather radar, which operates on a similar principle to ground-based weather radar (see later), although with the difficulty of lower signal strengths due to payload limitations, and a moving field of view.

For hydrometeorological applications, some typical issues include the accuracy, time intervals and resolution at which observational products are available (and cost), and whether systems are affected by cloud cover. For example, polar orbiting satellites typically record data along a track with a width (swath) of a few 100 km or more, and orbit the earth every 100 min or so. Hence, a given area (e.g. a catchment) may only be observed every few hours or more, often making the outputs unsuitable for flood forecasting applications, for example. By contrast, higher altitude geostationary satellites remain within sight of a given point on the ground at all times but, due to their much greater altitude, offer a lower resolution of data which – despite continuous improvements in instrumentation and software – may be insufficient for the application of interest. However, despite these problems, satellite observations are increasingly used in hydrometeorological forecasting applications, and some examples which are presented in later chapters include rainfall estimation for flood forecasting (Chapter 7) and drought monitoring (Chapter 8), snow cover monitoring for flood forecasting (Chapter 7), vegetation and land use observation for drought monitoring (Chapter 8), and observations of harmful algal blooms (Chapter 10).

2.1.3 Global Observing System

The Numerical Weather Prediction and other models operated by many national meteorological services typically require data at a regional or global scale, which requires information to be exchanged between countries. In an excellent example of international cooperation, since 1963, as part of the World Weather Watch programme (http://www.wmo.int/), all participating countries (comprising 188 member states and territories since 24 January 2007), have adopted the standards set by the World Meteorological Organisation (WMO) for the recording and transmission of data. These include guidance on the synoptic times at which values should be recorded (see earlier), and the formats in which they should be exchanged (e.g. SYNOP, CREX, GRIB, BUFR).

For example, for land-based weather stations, the parameters which are recorded can include air temperature, humidity, wind speed and direction, atmospheric pressure, precipitation, cloud cover, cloud base, present weather, visibility, and (for manual stations) any local observations which may be relevant. Other locally applicable parameters may also be recorded at the same or less frequent intervals (e.g. daily), such as soil temperatures, soil moisture, sunshine hours, and snow depth.

To capture the best possible information on the current state of the atmosphere, a wide range of observational techniques is used and, in addition to the ground-based and satellite techniques already discussed, these can include:

- Radiosondes (Upper Air Observations) – instruments launched manually or automatically on helium-filled weather balloons which relay values for air pressure, temperature and humidity by radio transmitter. Each ascent provides a vertical profile of the state of the atmosphere above the observation site, up to heights of about 20–30 km. Windspeeds and direction can be inferred from the speed and direction of travel relayed by Global Positioning System (GPS) sensors, or observed from the ground. Worldwide, more than 1,000 launch sites are operated per day, and this information is shared between countries, and stored in archives for later research and operational studies
- Aircraft, Platforms, and Ships – many ships, oil and gas platforms, and commercial airliners are equipped with automatic recording equipment to relay key atmospheric variables by radio or satellite to ground stations for onward transmission to meteorological services. Manned and remotely controlled aircraft are also flown as required; for hurricane observations, for example

- Ocean Buoys – weather forecasting models often include representation of the exchange of water, momentum and energy between the atmosphere and oceans and many countries operate networks of tethered buoys which may be equipped with wave recorders, sea surface temperature sensors, automatic weather station and other equipment

WMO member countries exchange data using the WMO Global Telecommunication System (GTS). As discussed in Chapter 1, this is a network of ground-based, radio and satellite transmission systems in which common standards for data exchange have been adopted, and for which outputs are available to both national meteorological and hydrological services (World Meteorological Organisation 2006). The process of combining all of this information before every model run is called data assimilation, and this is discussed in Chapter 3, together with some examples of operational weather forecasting models.

2.2 Meteorological Observations

2.2.1 Raingauges

Raingauges are one of the simplest and most widely used instruments in hydrometeorological forecasting applications (e.g. World Meteorological Organisation 1994, Strangeways 2007, Michaelides 2008). Many countries operate networks of instruments for a range of purposes, including agriculture, flood forecasting, synoptic observations, and water resource applications. Both manual and automatic instruments are available, and Fig. 2.2 illustrates an example of each type for a site in southern England.

Manually operated (or storage) gauges accumulate rainfall in a container and, at a fixed time each day (or other period), an observer empties the accumulated water into a graduated measure to record the rainfall total since the last reading. Monthly-read gauges are sometimes used as a check on the accumulations at automated instruments. Some countries operate extensive networks of storage gauges which are read by both paid and voluntary observers; for example, in the

Fig. 2.2 Tipping bucket raingauge (foreground) and storage gauge (background) in southern England. Photo: Y. Chen (Copyright © Environment Agency 2009 all rights reserved)

United Kingdom, the voluntary component of the network includes several thousand gauges with volunteers including school teachers, members of the public, and others. The Community Collaborative Rain, Hail and Snow network (CoCoRaHS) network in the USA operates on a similar principle with more than 12,000 observers (http://www.cocorahs.org/).

As an alternative to storage gauges, automated, autographic or recording gauges are less labour intensive to operate (although more expensive to install), and allow data to be recorded more frequently, and relayed by telemetry. For example, automated gauges are used in many flood forecasting systems. The most common type is the tipping bucket raingauge (see Fig. 2.9), in which rainfall is passed from the funnel mouth into an open ended metal or plastic 'bucket' on a pivoted arm, which tips the lever mechanism when a certain weight is reached, equivalent to a certain depth of rainfall, raising the 'bucket' on the other side of the lever arm into a position where it can accumulate water. Each tip is recorded on a data logger or chart and, if telemetry is available, the record of the tip can be sent immediately, or accumulated if the number of tips, or rainfall depth, is to be sent at fixed time intervals. The rainfall depths recorded per tip are one of the design features of each instrument and are typically in the range 0.2–2.0 mm, with the larger sizes more appropriate for high rainfall locations (although with a standard size often defined at an organizational or national level).

Several other types of automated raingauge are also used, and the principles of operation include devices which detect individual droplets as they are funneled through the gauge (e.g. optical or electrode detectors), the weight of water accumulated (e.g. capacitance gauges, spring mechanisms, vibrating wire types), the depth of water accumulated (e.g. floats, electrodes), and the flux of water between two detectors (e.g. laser or ultrasound disdrometers). Many of these types have the advantage of being 'solid state' in the sense that there are no moving parts. On a much larger scale than disdrometers, microwave techniques operating over distances of several kilometers or more also show potential to estimate path averaged rainfall rates from the attenuation in the signal, and could potentially make use of the extensive transmitter networks used by cell phone operators (Rahimi et al. 2003, Leijnse et al. 2008).

Some issues which can occur with raingauges (depending on the type) include blockages (e.g. due to grass cutting around the gauge), wind-effects around the gauge and from surrounding obstacles (trees, buildings, hills etc.), splashing, flooding, and mechanical and electrical failures. In locations where snowfall occurs, gauges can also be affected, or blocked, by snow, with one partial solution being the use of heated raingauges, although there may be a time delay between the snow falling and the 'water equivalent' depth being recorded, with the actual value often being under-recorded. Measurements of air temperature can also assist with interpreting the outputs from raingauges likely to be affected by snow; however, some other methods for recording snow depth and/or cover include satellite observations, snow pillows, and manual observations, and these approaches are described in Section 2.3.4.

Also, since raingauges only represent the rainfall at a single location, for hydrological modeling applications, a common requirement is to combine the outputs

Table 2.2 Some examples of approaches to catchment averaging of raingauge data

Method	Description
Weighted values	The total rainfall consists of a weighted sum where the weights are based on trial and error, expert judgement, mean annual rainfall, or some other approach. 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 bisecting 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 also including elevation in the relationship, and 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 planes (TIN) methods
Geostatistical techniques	Methods based on the covariance structure of observations, seeking to minimize the variance in estimates, sometimes bringing in other factors, such as elevation, using a co-Kriging approach

from several gauges to obtain estimates for rainfall at a catchment or regional scale, and Table 2.2 summarises some of the techniques which are used (e.g. Creutin and Obled 1982, World Meteorological Organisation 1994, Goovaerts 2000).

Many of these methods can be implemented as part of an automated procedure (for example, in a flood forecasting system), although this can be problematic with approaches which ideally also include some expert judgement, such as isohyetal methods. As indicated, other secondary or auxiliary variables can also be included in some approaches, such as elevation, aspect, mean annual rainfall, and other factors.

For shorter timescales (e.g. hourly values), the simpler techniques are generally better suited to low lying areas and where widespread, relatively uniform rainfall is the usual feature of interest (e.g. frontal events). However, where topographic influences on rainfall are important, such as elevation, aspect, and slope, more complex approaches can be useful, provided that the facility exists to make these calculations within the operational environment. Similar considerations also apply at longer timescales, although raingauges are now likely to be recording storm totals, or a significant fraction, and the influences of spatial variability are less pronounced, although can still justify the use of more sophisticated approaches.

Some techniques which can assist with devising catchment averaging schemes include examination of sequences of weather radar or satellite data and images (if available) to see if there are any preferential paths or distributions for storms across a catchment, and the use of stochastic sampling techniques to assess the performance of a large number of possible weights in terms of catchment rainfall, or overall forecasting performance. For developing operational averaging schemes, linked to telemetered values, a review of the records from manually operated storage gauges can also be useful, since typically there are many more such gauges available in a catchment compared to the number of telemetered gauges. Manual gauges can provide an indication of storm totals, with each value including part of the event, the whole event, or multiple events, depending on the measurement time interval and storm scale. However, where raingauge networks are sparse, rainfall estimates from weather radar or satellite observations may provide higher accuracy than catchment averaged values from raingauges, and these approaches are discussed later in this chapter.

2.2.2 Weather Stations

Weather stations are a key component in synoptic networks and also in monitoring meteorological conditions for other applications, such as agriculture, water resources, and transport systems (road, rail, airports). As for raingauges, both manual and automatically operated stations are used, and the parameters which are recorded typically include air temperature, humidity, wind speed, wind direction, air pressure, solar radiation, and rainfall. A range of other parameters, such as soil temperature at various depths, soil moisture, grass temperature, and net radiation, may also be recorded, depending on the application. Types of sensors can include cup anemometers, wind vanes, barographs, sunshine hour recorders, and wet and dry bulb thermometers, with variations for automatic weather stations including hygrometers (for humidity), radiometers (for radiation), visiometers (for visibility), and thermistors (for temperature).

For a manually operated station, instruments are typically installed in a fenced enclosure, with the thermometers and some other instruments kept within a ventilated screen, which is often known as a Stevenson Screen. For automatic stations, instruments are typically installed on a single mast, which might also support a radio antenna, if a radio telemetry system is used. Figure 2.3 shows an example of a manually operated weather station, and an automatic weather station installed to monitor mountain weather on a 1,000 m high peak (Snowdon) in North West Wales

Fig. 2.3 Example of (**a**) a manually operated weather station and (**b**) an automatic weather station installed at the top of Mount Snowdon in Wales, including an antenna for radio telemetry of data (© Crown Copyright 2008, the Met Office)

(Met Office 2008). Box 2.3 also shows an example of a type of weather station which is widely used in the USA and elsewhere in local flood warning systems.

2.2.3 Weather Radar

One early observation when operational aircraft-tracking radar networks were introduced in the late-1930s and 1940s was that rainfall and other type of precipitation could be seen on the images. The potential for use in meteorology was quickly recognized, with the first operational applications of weather radar starting in the 1950s in the USA and elsewhere.

The main quantitative uses of weather radar data are in nowcasting, and in the data assimilation process for Numerical Weather Prediction models (see Chapter 3). Outputs are also used in rainfall depth-duration based alarms (see Chapter 6), and as inputs to rainfall-runoff models in flood forecasting applications (see Chapter 7) and for pollution incidents (see Chapter 10). More generally, the images of rainfall intensity are widely used (qualitatively) to provide visual information on the progression of storms. Historical (archived) rainfall intensity values also potentially provide a useful resource for a range of other applications, such as the detailed investigation of historical storms (e.g. when designing raingauge networks), and for estimating time series of catchment average rainfall for the calibration of rainfall-runoff models.

A weather radar installation typically consists of the radar dish, a radome to protect the dish, and a building which houses the computer and electrical equipment. For meteorological applications, devices usually operate at wavelengths of 3, 5.5 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 is shorter; however, a smaller, cheaper dish and installation is required. Most operational weather radars are either C-band or S-band, although X-band radars are sometimes used to fill in gaps locally in the national network, or near to high-risk locations, such as in the Local Area Weather Radar network in Denmark (Pedersen et al. 2007). X-band radars are also widely used in aircraft, with the shorter K-band for space-borne radar.

In the USA for example, a national network of more than 150 weather radars is operated by the National Weather Service. This is known as the Next Generation Radar, or NEXRAD, system, and consists of S-band Doppler installations (http://radar.weather.gov/). Figure 2.4 shows an example of this type of radar near to the city of Pueblo in Colorado, together with an example of the radar output, in the form of the Storm Total Precipitation product for a thunderstorm event in El Paso county, in which over five inches of rainfall fell in a 2 h period.

Figure 2.10 in Box 2.3 shows another example of NEXRAD radar output, this time from around Denver in Colorado. Many other countries also operate national systems of weather radars; for example, in Europe, the EUMETNET OPERA project (http://www.knmi.nl/opera/) maintains a database of key information, and a data hub to facilitate data exchange, for more than 190 radars in 30 countries.

Fig. 2.4 National Weather Service WSR-88D Doppler radar at Pueblo County, Colorado, USA and example of Storm Total Precipitation output (http://www.crh.noaa.gov/pub/?n=/radar_about.php)

Most weather radars work by transmitting a pulsed microwave beam and recording the strength of the reflected signal (giving a measure of precipitation amount) and the time taken for the signal to return (giving a measure of distance from the radar). The 'listening' time is typically far greater than the time spent transmitting the signal. The beam is rotated about a vertical axis to provide a 360° coverage, and may be inclined upwards at an angle to the horizontal. For radars installed in mountain regions, the beam sometimes scans horizontally, or at an angle below the horizontal. Many permutations exist of this basic configuration, including radars with multiple beams, or for which a range of pre-programmed scan strategies is available, from which the most appropriate can be selected depending on the prevailing meteorological conditions. Doppler radars are also widely used, in which the phase shift of the reflected signal provides a measure of the speed and direction of hydrometeors (rain drops, snowflakes etc.), and hence both of wind speed and direction, and type of precipitation, and to assist with removal of ground clutter. In the NEXRAD system, for example, a more sensitive mode, used in clear air conditions, can also be used primarily for wind profiling. Polarimetric, or dual polarization (horizontal and vertical) devices are also increasingly being used operationally, and can provide useful information to help with classifying the types of hydrometeors (rain, snow, hail etc.) and with the quality control of radar outputs.

To interpret the reflected signal, typically a relationship is used which relates the power of the signal to the drop size distribution and hence to precipitation intensity. Relationships are usually calibrated for typical local conditions, and may over- or under-estimate rainfall under very light or extremely heavy rainfall conditions. Rainfall accumulations are typically processed to 5, 15 min or hourly values when used in hydrological forecasting applications. The signal processing software usually also attempts to correct for a number of other factors, including anomalous echoes when the beam encounters terrain, or flying objects, such as insects, birds, and aircraft. Line of sight analyses, using digital terrain models, can also assist with identifying areas of ground clutter, and deciding how to interpret the reflected signal.

There are also the intrinsic limitations that, for precipitation distant from the radar installation, the power of the reflected signal is reduced by the spread of the beam and attenuation. Also due to the curvature of the earth, the beam height above ground level increases with distance from the radar, so may overshoot typical cloud heights. Weather radar outputs are therefore usually only available up to a maximum range, with a lower spatial resolution at longer ranges, which can influence the suitability of measurements for input to hydrological models. Typical maximum ranges for C-band radars might be 100–250 km, at a resolution of 5 km, although a higher resolution is often offered close to the radar (e.g. 1 km). The outputs from individual radars (single-site outputs) are also often combined into a composite or mosaic image, as illustrated in Fig. 1.9.

The accuracy of measurements can also be affected by meteorological conditions, such as rainfall at low levels, beneath the beam, and anomalous propagation of the beam due to density variations in the atmosphere (anaprop), causing it to strike the ground. Table 2.3 shows some examples of these sources of errors in weather radar measurements (e.g. Collier 1996, Meischner 2005) and Fig. 2.5 illustrates these various mechanisms (Met Office 2007). Most weather radar signal processing systems apply corrections for these factors; for example, based on estimates for the vertical profile of reflectivity, and sometimes linking with alternative sources of information (e.g. raingauges, satellite observations, Numerical Weather Prediction model outputs) to assess the probability of precipitation at a given pixel location.

Compared to raingauge observations, which only apply at a point on the ground, weather radar outputs provide more detailed estimates for the spatial variations in rainfall, although the rainfall at the ground can only be inferred. A natural development has been therefore been to attempt to combine these two complementary forms of observation to derive a raingauge-adjusted radar rainfall field. Various schemes have been developed and used operationally, and this is also an active area for research. Some examples of approaches which have been used include the use of bias adjustment factors which are adjusted periodically (e.g. every week), when the difference between raingauge and radar measurements exceeds a threshold, and real-time dynamic adjustments using Bayesian, multiquadric and other approaches (e.g. Todini 2001, 2005, Moore et al. 2004, Seo and Breidenbach 2002).

Table 2.3 Some examples of sources of errors in weather radar observations

Item	Influence on rainfall estimates (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 at low level due to topographic influences
Bright band	Overestimate	Strong echoes from melting snow flakes with large, wet reflective surfaces
Drop size distribution	Various	Smaller drop sizes (e.g. as in drizzle) or larger drop sizes (e.g. as in heavy showers) than used in calibrating the reflectivity relationship
Anaprop	Various	Diversion of the beam into the ground due to density variations in the atmosphere

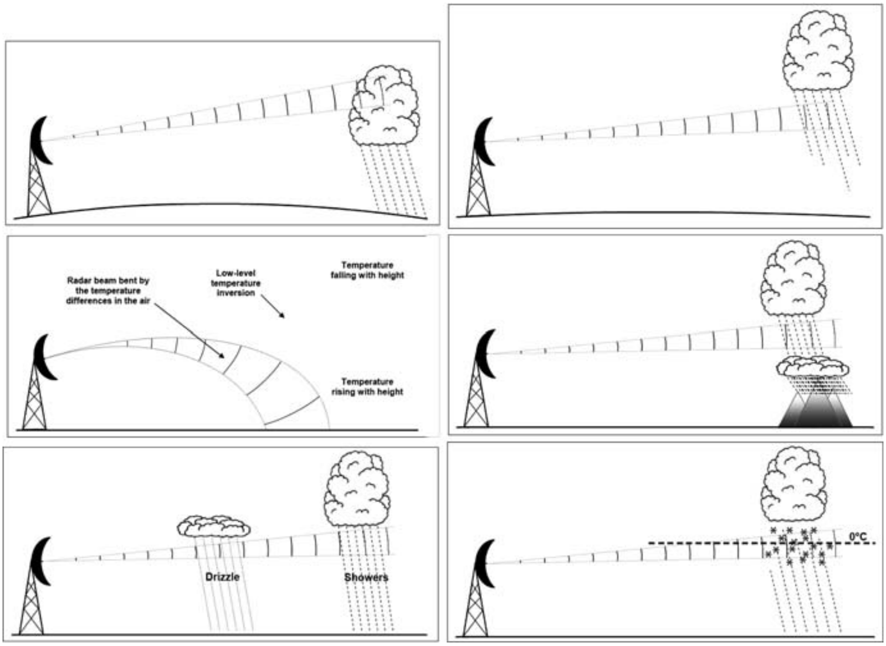


Fig. 2.5 Meteorological causes of errors in weather radar observations. From top left clockwise (**a**) radar beam above the precipitation at long distances (**b**) evaporation of rainfall at low levels beneath the beam (**c**) orographic enhancement of rainfall at low levels (**d**) bright band (**e**) varying drop sizes of precipitation (**f**) anomalous propagation (anaprop) (© Crown Copyright 2007, the Met Office)

Satellite observations, radiosonde information and the outputs from Numerical Weather Prediction models can also be used to help to improve the outputs from weather radars. This type of combined product, for current rainfall or 'rainfall actuals', is derived on a similar basis to forecasts derived using nowcasting techniques, and is discussed further in Chapter 3. As noted in the next section, space-borne weather radars are also under development, and an instrument has been used successfully on the TRMM satellite since 1997.

2.2.4 Satellite Rainfall Estimation

The main types of meteorological observations by satellites are of clouds and precipitation, although information on lightning location and intensity can also provide a useful indicator of thunderstorm activity, and temperature and wind profiles can also be inferred. Observations of this type are an increasingly important source of information in initializing operational Numerical Weather Prediction models (see Chapter 3). Observations of soil moisture, snow cover, land use and vegetation cover are also useful in both hydrological and meteorological forecasting applications, and are discussed in Section 2.3.

For hydrological forecasting applications, a historical limitation on the use of satellite-based precipitation estimates has been the accuracy and resolution of measurements, although this has improved significantly in recent years. For short-term forecasting, particularly for flood warning applications, the need for constant surveillance also means that geostationary satellites are often more use than polar orbiting satellites but, due to their greater orbit heights, the accuracy and resolution is lower. However, some practical applications which are discussed in later chapters include providing flash-flood guidance at a regional scale, flood forecasting in large river basins, and regional monitoring of rainfall for drought and famine early warning systems.

One widely used approach to estimating rainfall is to consider so-called cold cloud durations, since deeper cloud formations are more likely to lead to intense rainfall and, due to their greater altitudes, will tend to have lower temperatures at their upper limit. To estimate rainfall, some key sources of information include both visible and multi-channel infrared observations of the cloud cover, morphology and extent, and cloud top temperatures. Methods may use single images (cloud indexing methods), or sequences of images (life history methods) to assess the cloud development, which can then be related to rainfall intensity (e.g. World Meteorological Organisation 2000, Scofield and Kuligowski 2003). Some algorithms also make use of the outputs for available humidity and other factors from Numerical Weather Prediction models to guide the interpretation of the observations.

The precipitation at the ground surface can be inferred by combining this information, and using empirical relationships calibrated from historical satellite and raingauge or weather radar observations. Table 2.4 provides some examples of algorithms of this type, selected to illustrate the range of approaches which have been used or evaluated. Several of these products fall into the category of so-called multi-sensor precipitation estimates, or High Resolution Precipitation Products (HRPP), which combine satellite observations (visible, infrared, microwave), weather radar data, raingauge data, and other information, such as from lightning detection systems.

For the CMORPH approach, for example, precipitation estimates from a number of polar orbiting satellites are combined, and then propagated during the periods between satellite overpasses, based on geostationary satellite observations. Where raingauge data are used, some typical areas for development include improving estimates to account for spatial variations in the density of raingauge networks, and for topographic influences, and to make use of additional manually recorded raingauge data which is available with a few hours time delay. In addition to much active research in this area, the CGMS/WMO International Precipitation Working Group was formed in 2001 to provide a focus for the development and comparison of satellite-based precipitation measurement techniques (e.g. Ebert et al. 2007). A number of locations in Australia, Europe, South America, Japan and the USA have been chosen for routine daily comparisons with raingauge and weather radar data (http://www.isac.cnr.it/∼ipwg/IPWG.html).

Active space-borne radar systems also have the potential to provide a more direct way of measuring rainfall, and the first such instrument was the 2 cm-band Precipitation Radar on the NASA Tropical Rainfall Measuring

Table 2.4 Examples of satellite-based rainfall estimation algorithms with an indication of the main sources of data and other information

Method	Satellite	Main inputs to method	References
CMORPH (NOAA)	Various	Combines polar orbiting passive microwave and geostationary infrared outputs	Joyce et al. (2004)
MPE (EUMETSAT)	Meteosat, others	Combines polar orbiting passive microwave and geostationary infrared outputs	Kidd et al. (2008)
Hydro-Estimator (NOAA/NESDIS)	GOES	Geostationary infrared temperature observations, Numerical Weather Prediction model outputs	http://www.star.nesdis.noaa.gov/
MPA-RT (NASA)	Various	Multiple microwave and infrared inputs from geostationary and polar orbiting satellites	Huffman et al. (2003)
PERSIANN algorithm	GOES, TRMM, others	Uses artificial neural network techniques based on infrared brightness temperatures	Sorooshian et al. (2008)
RFE2 (NOAA/CPC)	Various	Combines information from three satellite systems and raingauge data	See Box 2.1
TAMSAT algorithm	Meteosat	Geostationary infrared observations	Grimes and Doiop (2003)

Mission (TRMM) satellite, which was launched into low earth orbit in 1997 (http://trmm.gsfc.nasa.gov/). The orbit is at an altitude of about 350 km over the tropics, and the challenge in developing systems of this type is not so much the distances involved, but the need to carry sufficient transmitter power to generate the signal within the available payload. The principles of operation for space-borne radar are similar to those for ground-based weather radar which are described in the previous section, although with the limitations of a lower resolution, and lower sensitivity (e.g. to lighter precipitation), and without Doppler or dual polarization (so far). Also, images are sampled along a path, rather than in a volume. A next generation precipitation measurement satellite, the Global Precipitation Mission (GPM), is expected to be launched in 2013 (see Table 2.1).

Box 2.1 Rainfall Estimation Algorithm (RFE 2.0)

The Rainfall Estimation Algorithm (NOAA 2009) was developed by the NOAA National Weather Service Climate Prediction Center, and has been used since 1995 to estimate daily precipitation for use in the FEWS-NET Famine Early Warning System in Africa, which is described in Chapter 8. Recently, the system has been extended for use in southern and western Asia. A faster, more accurate version (RFE 2.0) was introduced in 2001 which uses a merging technique (Xie and Arkin 1996) to combine precipitation estimates from the following four 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-B) 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 5 and 7 infrared cloud top temperature measurements using the GOES Precipitation Index with a threshold of < 235 K at half hourly intervals and a resolution of 4 km (Arkin and Meisner 1987)

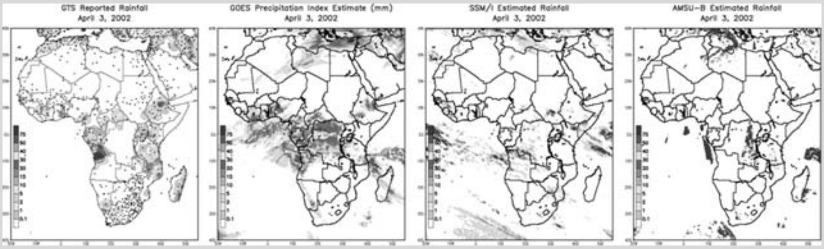


Fig. 2.6 Illustration of the 4 sources of precipitation estimates for RFE 2.0 for 3 April 2002 (http://www.cpc.ncep.noaa.gov, Love 2002)

The satellite estimates of precipitation are merged (Fig. 2.6) using predetermined weighting coefficients based on a maximum likelihood approach, using an inverse weighting scheme. The single combined value is then adjusted using the raingauge data, again using an inverse weighting scheme. For FEWS NET, output files are produced daily for the whole of Africa with a resolution of 0.1°, which corresponds to a distance of approximately 10 km at the equator. Some sources of errors from day to day can include variations in the number of raingauges available, which can be less than 500 on some days due to problems with station maintenance and erroneous data, and the inherent gaps in the temporal coverage offered by the satellite data. However, tests during development of the algorithm have shown that, when compared to climatological estimates of rainfall, the merged estimate has considerably lower bias and higher correlation coefficients than any of the individual products.

2.3 Hydrological Observations

2.3.1 Water Levels

Measurements of river levels, and of reservoir and lake levels, are often required for the calibration and operation of hydrological forecasting models. Information on borehole levels may also be useful for the groundwater component of models, and on tidal levels for the downstream boundary of hydrodynamic models.

The measurement techniques are similar in most cases (e.g. World Meteorological Organisation 1994, Herschy 1999), and include the following methods:

- Bubbler Gauges – which measure the pressure required to release a compressed-gas (typically air or nitrogen) from a submerged orifice, from which the water level can be inferred, and which are sometimes called pneumatic gauges
- Downward Looking instruments – radar or ultrasonic devices suspended from purpose-made frames or existing structures (e.g. bridges) which record the time taken for a pulsed signal to travel to and from the water surface, from which the water level can be inferred
- Float recorders – floats which rise and fall with water levels, and are suspended from a pulley by a wire or tape, with the angular movement of the pulley converted into an electrical signal by a transducer, or recorded on a chart, hence giving the distance moved by the float, and hence the water level
- Pressure Transducers – which use a submerged solid state probe to measure the water pressure, from which the water level can be inferred
- Satellite Monitoring – estimation of levels on larger rivers, reservoirs and lakes using satellite altimetry (e.g. Benveniste and Berry 2004, Xu et al. 2004, Zakharova et al. 2005)
- Staff Gauges – manual readings of values from a graduated board (or series of boards) on the river bank or attached to an existing structure

Pressure transducers are also used in the developing area of low-cost sensor networks – which are sometimes known as pervasive or grid networks – in which self-contained sensors with integral microprocessors and transmitters (maybe the size of a house brick) can be submerged, and are programmed to form networks, resilient to the loss of any part of the network due to damage, electrical failure etc. (Hughes et al. 2006).

Figure 2.7 shows two examples of pressure transducer installations; the first for a river location, with a data logger and telephone-based telemetry, and the second for a reservoir location, with radio-based telemetry. Box 2.3 shows another example of a river level recorder.

For automated approaches, typically the levels recorded are still checked occasionally during site visits against the value shown by a staff gauge, or gauge board, which can be read manually. The resulting levels may be expressed in local gauge values, or converted to a national or regional datum based on a nearby benchmark

Fig. 2.7 Examples of pressure transducer installations with associated gauge boards (**a**) river level gauge (**b**) reservoir gauge (Sene 2008)

elevation. The issue of measuring datums, and keeping them up to date (e.g. as instruments change), is a continuing requirement, and is particularly important for measuring river flows using stage-discharge relationships (see Section 2.3.2) and in developing hydrodynamic models of river systems.

With the exception of staff gauges and most downward looking devices, a metal or plastic conduit is usually required to protect either the pulley wires or tape (for float in stilling well devices) or the electrical cable or tube as it passes through the water. Typically, the down pipes are attached to bridges or structures on the river bank, or are built into the river bank with an inlet pipe to the river to transmit the pressure to the device. For float in stilling well devices, values may be recorded on a clockwork-driven chart, with no electrical power required (unless a data logger is included), and instruments of this type are still widely used due to their reliability and ease of maintenance. Where a source of power is required, typically mains electricity is used, if easily available, or solar panel and battery systems. If data are required in near real-time, power may also be required for the telemetry system (see Section 2.4). Where there is no telemetry, readings are typically collected at regular intervals by hydrometry staff from charts and/or a data logger.

Each measurement method has its own advantages and disadvantages; for example, bubbler devices are mechanically simple, but require a source of compressed gas from a compressor, or from storage tanks which periodically need refilling, whilst float in stilling well devices may suffer from problems with wires jamming, breaking or falling off the pulley system. Downward looking devices have the advantage of having no parts within the water, although the outputs can be affected by debris on the water surface, whilst for pressure transducers the accuracy and reliability varies between different types of designs. Manual readings from a staff gauge provide the simplest method of all, although are obviously reliant on the skills and commitment of observers. For all types of device, there can also be problems with damage from debris during high flow events, from vandalism, and from theft of components such as solar panels (if used). Electrical components for data loggers or telemetry systems can also be at risk in high flow events unless – following good practice – the installation has been designed to be resilient to events up to (at least) a likely maximum level (e.g. the 1 in 100 year flood).

Some related applications are in monitoring the position of devices such as gates, barriers and other river and reservoir flow control structures, and of the movement of ice, in situations where ice break-up and ice jams are a concern. A wide range of methods is available, typically relying upon detecting a rotational movement (e.g. shaft encoders), internal stresses (e.g. strain gauges), or a change in location or a flow blockage (e.g. transducers, CCTV, webcams).

2.3.2 River Flows

For hydrological forecasting, it is often more useful to know the river flow than the river level. This can provide information for use in water balance estimates, and for the development and operation of rainfall-runoff models, and flow routing and hydrodynamic models. The most widely used approaches to monitoring river flows include:

- Electromagnetic devices – a coil buried in the river bed which generates an electromagnetic signal whose strength depends on the water river velocity as it passes through the electromagnetic field generated by the instrument, and which can be detected by electrodes in the river bank
- River Gauging Structures – purpose-made structures, such as weirs or flumes, which provide a well-defined flow regime in which flows can be estimated from levels using a theoretical or modeled relationship, or an empirical relationship (see Fig. 2.8 for an example)
- Stage-Discharge Relationships – occasional measurements of flows for later conversion of levels to flows using an empirical stage-discharge relationship, which is also often called a rating curve (see Fig. 2.8 for an example)
- Ultrasonic devices – which measure flow velocities at one or more depths from the differences in transmission times for ultrasonic pulses transmitted in an upstream and downstream direction (the time differences arising from the river flow velocity)

Where velocities are measured, these can be integrated across the river cross section to provide an estimate for the flow.

Of these methods, stage-discharge relationships are probably the most widely used, followed by river gauging structures, ultrasonic gauges and (least often) electromagnetic devices. In part this is due to the greater cost of structures and ultrasonic and electromagnetic instruments compared to the cost of simply installing a river level recorder in a river channel, and the practical limitations on installation in large rivers. However, these approaches do avoid the difficulties with developing stage-discharge relationships which are discussed later. Note, though, that the accuracy of ultrasonic devices can be affected by high sediment loads, and electromagnetic instruments can be affected by nearby sources of electromagnetic radiation. River gauging structures can also suffer from issues with erosion, weed growth, damage from debris, and other factors. In some cases, structures may also drown at high river levels/flows due to high downstream river levels, ideally requiring measurements of both upstream and downstream levels to deduce flows.

Whichever approach is used, it is advisable to make occasional measurements of river flows to check the accuracy of flow measurements, and this is of course intrinsic to monitoring flows using a stage-discharge relationship. The most widely used approaches to measuring flows – or making ‘spot gaugings’ or ‘discharge measurements’ – are to use a current meter, or an Acoustic Doppler Current Profiler (ADCP) device. Current meters are typically suspended from a cableway, bridge or boat, or carried by an observer across the river when levels are low. Velocities are measured by automatically counting the revolutions of a propeller in given time, and are recorded at several locations across the river, and typically at one or two depths at each location. The flow can then be estimated by integrating these values across the cross section. A single measurement of flow can take many hours, or even days, on a large river. ADCP devices are a newer and faster approach, in which the depth integrated velocity is measured using Doppler ultrasound transmitted from an instrument installed on a floating platform which can be towed across the river, or operated from a boat. These devices operate on a similar principle to the more expensive fixed ultrasonic installations mentioned earlier.

Other methods which are sometimes used include (a) dilution gauging, in which a tracer (typically a fluorescent dye) is released into the river, and the concentration measured further downstream, from which the flow can be estimated using theoretical formulae and (b) slope-area methods, in which the slope of the water surface is measured, again giving an indication of flows from hydraulic formulae. Slope-area methods are particularly useful in post flood event assessments when considering the trash, or wrack, marks left at the high water line during flood flows. For a quick, indicative estimate of surface velocities, purpose-made floats, or any convenient floating object, can be dropped onto the water surface, and the time to cover a given distance noted. Hydrodynamic models (in one-, two- or three-dimensions) can also be calibrated to known flows, and then used to extrapolate rating curves to higher flows, as illustrated in Box 2.2 for a river gauging station operated by the Environment Agency in England and Wales. Extrapolation is sometimes also required at the low flow end of curves for water resources applications.

Typically, when following International Standards (International Standards Organisation 1996, 1998), a power law relationship is used for stage-discharge relationships, with associated confidence limits, with multi-part curves if the river channel cross section changes significantly with depth. Polynomial relationships are also sometimes used. Rating curves must also be periodically checked and updated to account for changes which may occur to instrumentation, river channel characteristics, and for other factors, such as weed growth, and ice cover, and can have seasonal or other periods of validity. The establishment and maintenance of rating curves is typically a major and ongoing activity for any hydrological service, and is described in more detail in many textbooks and guidelines (e.g. Herschy 1999, International Standards Organisation 1996, 1998).

Box 2.2 Cowbeech Gauging Station

Hydraulic modelling studies can also assist with extending rating curves beyond the range for which spot discharge measurements are available, and for gauges which experience non-modular flows. This can also include developing ratings for periods when a station is bypassed by flows on the floodplain (if this occurs). The extent of survey data required depends on the distance over which hydraulic influences affect the station, and the features of the gauge, the local floodplain, and any other structures which need to be included in the model, such as bridges and culverts. For example, Fig. 2.8 summarises the results from a one-dimensional model with 12 cross sections which was developed for the Cowbeech gauging station in southern England, together with the resulting high flow rating curve which is now used in an operational flood forecasting model.

The catchment area to the gauge is approximately 19 km^2 and the highest spot discharge measurement made over the period 1995–2008 was approximately 8.3 m^{3}s^{-1}, compared to an estimated maximum flow of about 28 m^{3}s^{-1} since records began. The gauge is a compound Crump Weir which was commissioned in 1939 primarily for monitoring low flows for water resources applications, and which is equipped with float in stilling well and downward looking ultrasonic level sensors. The divider in the weir creates separate channels for monitoring low flows up to a value of about 0.3 m^{3}s^{-1}, and medium flows of up to about 10–15 m^{3}s^{-1}. At higher flows, the station is bypassed on the left bank by flows on the floodplain and, for flows above about 5–6 m^{3}s^{-1}, the weir is also affected by backwater influences from a road bridge and pipe-crossing further downstream, resulting in non-modular flows.

The hydraulic model was designed to represent these effects, and was built on the basis of survey data for the river channel and floodplain, and the as-built drawings for the weir. Using a range of inflow hydrographs, the rating curve was extended up to a flow limit of about 36 m^{3}s^{-1}, which exceeds the estimated 1 in 100 year return period (1%) flow at this location. The rating curve plot in Fig. 2.8 also shows the results of sensitivity tests which were performed regarding the values assumed for the roughness coefficient, bridge soffit height, and downstream slope, which showed little influence at low to medium flows, and about a ±10% variation in flow estimates at higher flows. The use of a two-dimensional hydraulic model was also considered but was not thought to be justified for this application.

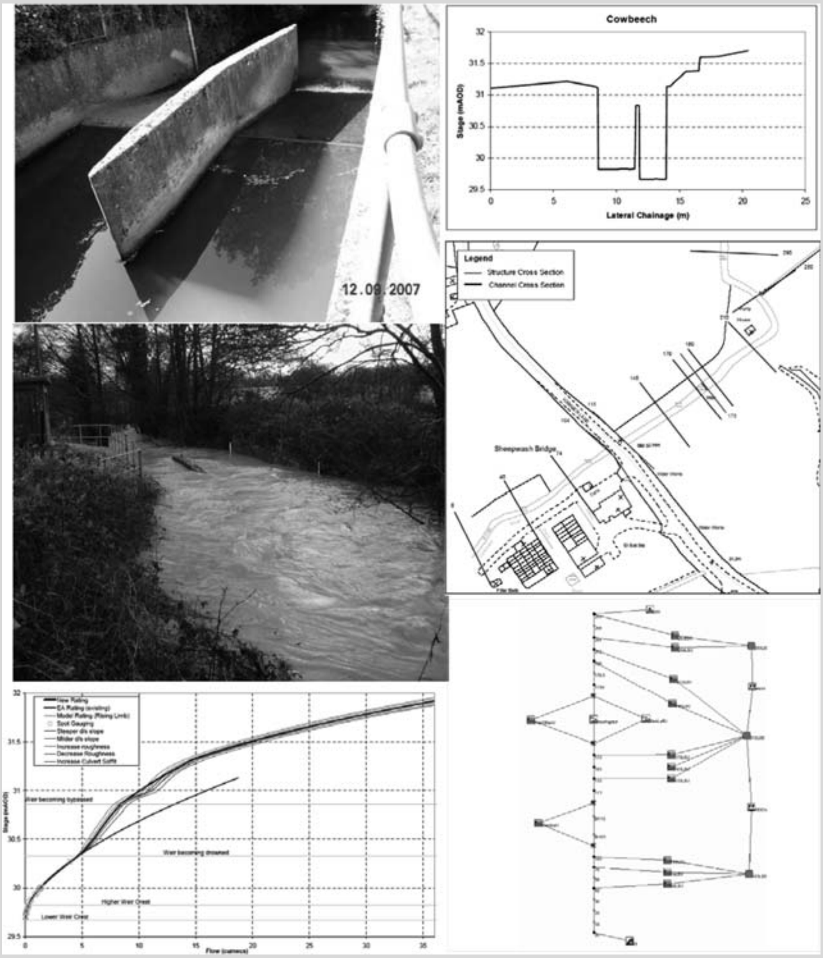


Fig. 2.8 Cowbeech gauging station. From top left clockwise (**a**) station at low flows (**b**) cross section through station (**c**) survey locations (**d**) hydrodynamic model schematic (**e**) extended rating curve (**f**) station drowned at high flows (photograph **a**) Y. Chen; photograph (**f**) Environment Agency (Copyright © Environment Agency 2009 all rights reserved)

2.3.3 Water Quality

For pollution and ecological forecasting applications, measurements of river, reservoir and lake water quality are often required, and parameters can be continuously monitored, sampled in the field, or analysed at a later date in a laboratory. For short-term forecasting applications, ideally measurements would be available in near real-time, and historically the reliability of equipment was one issue. However, this issue has largely fallen away with modern instrumentation, at least for the most commonly monitored parameters.

The range of parameters which might need to be monitored is large. For example, the United Nations Global Environment Monitoring System Water Programme (http://www.gemswater.org/) recommends more than 60 core water quality variables that the GEMS/Water monitoring programme should endeavor to collect, and identifies the following issues at global and/or regional or sub-regional 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 salinization and polluted irrigation return waters
- Agro-chemical use, fertilizers 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.

Table 2.5 summarises some of the more common types of parameter which may need to be monitored, with an indication of some typical sources of pollution or contaminants.

Continuous monitoring approaches are now available for a wide range of parameters, with multi-parameter instruments available, and results can be relayed by telemetry, if appropriate, for input to forecasting systems. However, some parameters intrinsically require some time to measure; for example, the Biochemical Oxygen Demand (BOD) is typically measured in a laboratory as the difference in dissolved oxygen between the start and end of a 5-day period within a sealed container at 20°C. Note that, in some cases, a surrogate or secondary parameter is monitored, as an indication of the presence, or otherwise, of the primary cause (as with BOD, for example).

Perhaps the most widely sampled parameters are as follows (World Meteorological Organisation 1994, UNEP/WHO 1996, Hargesheimer et al. 2002):

Table 2.5 Some examples of typical indicators of water quality

Type	Typical source	Examples of typical indicators or contaminants
Fuels/hydrocarbons	Oil industry, road vehicles	Depends on compounds
Heavy metals	Industry, mining	Cadmium, mercury, copper, zinc, lead etc.
Nutrients	Fertilisers	Nitrogen, phosphorus, chlorophyll
Organics	Industry, mining	Many possible chemical substances (and 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 temperature

- Conductivity – provides a measure of the ability of a water sample to carry an electrical current, and hence of the ionized chemical content, and total dissolved solids and salinity. Usually measured by filtration, evaporation and weighing, or by applying an alternating voltage between two immersed electrodes and measuring the electrical resistance of the sample. Typically reported in units of microSiemens/centimeter and depends on water temperature, so is usually referenced to a standard value
- Dissolved Oxygen – when performed manually, sampling typically involves adding one reagent to fix the oxygen sample, then adding another until a colour change occurs. More automated approaches measure the electrical current generated by the dissolved oxygen as it reacts with the coating on the cathode in an electrode system. Typically reported in units of milligrams per litre or parts per million and depends strongly on water temperature (and to a lesser extent atmospheric pressure)
- Faecal Coliforms/Streptococcus – laboratory tests for these and other pathogens typically involve membrane filtration with particular pore sizes to separate out the organisms, then cultivation of the organisms on a petri dish to determine concentrations. Typically reported as the number of colonies per 100 ml
- pH – a measure of the concentration of hydrogen ions, and of acidity and alkalinity. 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. Reported on a numerical scale from 0 to 14, with 7 indicating a neutral solution
- Suspended Solids – a range of methods can be used to measure different aspects of sediment load, including filtering and drying a sample of the sediments from a known volume of water, lowering a Secchi disk (a black and white coloured disk) into the water until it disappears from view to measure transparency, and turbidity meters which measure the scattering of light caused by the suspended sediment. Sediment loads are typically reported in milligrams per litre, with more specialized units for turbidity

- Water Temperature – measured manually using conventional thermometers or continuously sampled using thermistors

The World Meteorological Organisation (World Meteorological Organisation 2008) in addition defines the following ‘Basic Parameters’ to monitor, depending on whether a river, lake or groundwater source is being considered: Nitrate, Nitrite, Ammonia, Calcium, Magnesium, Sodium, Potassium, Chloride, Sulphate, Alkalinity, BOD, Chlorophyll a, Orthophosphate and Total phosphorus (unfiltered).

Chapter 10 provides several additional examples of monitoring equipment for water quality, including a continuous monitoring approach in the Netherlands which makes use of biomonitors (daphnids and algae) as indicators of hazards from herbicides and pesticides, phosphorus monitoring and satellite observations of harmful algal blooms in Finland, and the use of acoustic vertical profiling equipment for turbidity in the USA and Canada.

2.3.4 Catchment Monitoring

For hydrological forecasting, a number of other variables can be useful at a catchment scale. These include the distributions of soil moisture, evaporation, and snow depth, density and cover, and information on land use and vegetation cover.

Satellite observations provide one possible route to measuring many of these parameters, although sometimes with issues relating to the frequency of observations, whether measurements are affected by cloud cover, and the overall resolution of the post-processed products. Also, some types of variable cannot be observed directly, and must be inferred from post-processing algorithms and/or models. Nevertheless, the outputs are useful in many applications, particularly in situations where ground-based measurements are sparse, or parameters vary over timescales of days or more. Some examples include (e.g. Shunlin 2008):

- Snow Cover – visible, near-infrared or infrared, 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.
- Soil Moisture – infrared, passive and/or active microwave measurements with algorithms to interpret the signals from different types of land surface including open areas, forest, water, ice, snow and urban areas (although with the issue that only a shallow surface layer, a few centimeters in depth, is sampled). Algorithms are sometimes also included for estimating evaporation
- Vegetation Cover – 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 infrared and near infrared channels
- Water Surfaces – monitoring of the extent of lake and reservoir boundaries as levels rise and fall, and also satellite altimetry to estimate levels, as discussed

earlier. Also, flood extents can be monitored, although may not necessarily show the maximum flood extent

For example, Chapter 7 describes the use of polar orbiting satellite observations of snow cover in a data assimilation procedure for a flow forecasting model, and Chapter 8 describes the use of observations of vegetation cover in drought and famine early warning systems. Chapter 3 also discusses the use of satellite data in the data assimilation schemes for Numerical Weather Prediction models.

Ground-based observations provide the main alternative to satellite-based observations and, although generally more accurate, may not be representative of wider catchment conditions, particularly where there are significant changes in elevation or land cover across the catchment. Some widely used techniques include (e.g. World Meteorological Organisation 1994, 2000):

- Evaporation – evaporation pans, in which the reduction in levels is measured in a prescribed type of container, for which various designs are available. Also, specialized meteorological equipment, such as eddy correlation devices, may be used to measure evaporation via observations of instantaneous values of horizontal and vertical wind speed and fluctuations in humidity and air temperature
- Soil Moisture – neutron or capacitance probes, or tensiometers, installed at one or more depths in the soil, or manual sampling of the water content of soil samples
- Snow Depth – manual observations using ablation stakes or by weighing snow cores to estimate snow water equivalent values. Also, automated techniques using heated raingauges (see earlier), radioisotype methods, downward looking ultrasonic sensors, and snow pillows

For evaporation measurements, evaporation pans are widely used but often show large day to day variations in evaporation due to local heating and other factors, whilst turbulence-monitoring techniques are not often used operationally. This has led to the widespread use of the Penman (Penman 1944) and Penman-Monteith (Monteith 1965) equations to provide indirect estimates of evaporation for open water, and vegetation, respectively. The input variables are the air temperature, wind speed, humidity and solar or net radiation from automatic weather stations (or related variables such as wind run, and sunshine hours). Penman-Monteith values are often calculated for a reference grass surface, with values for other types of crop or vegetation estimated using empirical crop coefficients, as described in Chapter 5, for example (FAO 1998).

Similarly, there are many practical difficulties with obtaining representative measurements of soil moisture at a catchment scale, which has led to the widespread use of values estimated from soil moisture accounting schemes. In this approach, typically a water balance model is used to keep account of the net changes in soil moisture arising from rainfall and evaporation (usually estimated from Penman-Monteith methods), and allowing for variations in land cover and vegetation types. Estimates for surface runoff are often neglected in this approach. Alternatively, the soil moisture outputs from conceptual or distributed rainfall-runoff models are sometimes used, either operated specifically for this purpose, or as one of the products available from the land-atmosphere component of Numerical Weather Prediction models (see Chapter 3). However, some organizations do operate large scale networks of ground-based soil moisture monitoring sites; for example, the United States Department of Agriculture (USDA) operates a network of more than 150 automated stations. These combine soil monitoring with a dielectric constant measuring device with additional sensors for soil temperature monitoring, snow depth and water content, and meteorological conditions (e.g. Schaefer et al. 2007).

For snow depth and cover, the extent to which ground-based measurements are useful can depend on many factors, including the nature of snowfall in the area, and the topography. For locations with extensive seasonal snow cover, spot measurements by observers, or automated measurements by snow pillows, are widely used, where a snow pillow is a device which measures the internal pressure changes due to snow accumulating on top of a flexible container filled with a non-freezing fluid. For example, in the USA, the USDA also operates a network of more than 700 SNOTEL (SNOwpack TELemetry) snow pillow instruments in the western USA and Alaska (Schaefer and Paetzold 2000). A network of snow pillows is also used in Norway, supplemented by satellite and manual observations, to monitor snow conditions for flood forecasting and other applications (Røhr and Husebye 2005). Chapter 7 also briefly describes the approach to snow monitoring in Finland.

2.4 Monitoring Networks

The installation and upkeep of a network of monitoring stations can represent a considerable undertaking, and can require detailed investigations to determine the optimum locations of instruments for the application under consideration. Compromises may also be required due to limitations on cost, constraints on access to equipment (nearby roads etc.), power supplies (if not using solar power or batteries) and telemetry links (particularly for telephone and radio telemetry). Other factors may also need to be considered, such as permissions from land owners, and the security of equipment from theft and vandalism. The costs for maintenance and repair can also be a significant factor, and in a number of countries have led to a decline in networks in recent years.

For short- to medium-term forecasting applications, some key factors to consider in designing an instrumentation network can include:

- Catchment Response – the features and locations in a catchment or region which have the greatest influence on hydrological conditions (e.g. reservoirs, headwater catchments, river control structures, groundwater conditions, water quality)
- Forecasting Point(s) – the location(s) where forecasts are required in the catchment, considering both local influences at these locations (e.g. control structures, braided channels, the degree of mixing for water quality applications), and features of the catchment upstream
- Lead Time Requirements – the minimum lead time required for the application, and the recording timestep which is ideally required to resolve the evolution of the event as it occurs (this particularly applies to emergency response applications)

- 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 flooding, drought, pollution and other incidents
- Meteorological Conditions – the scale, intensity and types of event for which the hydrometeorological forecast is required (widespread frontal events, thunderstorms, hurricane related flooding etc.)
- Operational Requirement – the decisions and actions that the forecast will support, and associated risks; for example, 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, evacuation of a city
- Resilience – the consequences if an instrument or telemetry link fails in terms of the backups available (and how representative they are) and the consequences on data assimilation for forecast updating (where relevant)

For example, in flood warning applications, for providing warnings to a major city, the level of risk could justify at least one river gauging station within each main area at risk from flooding, possibly with backups in case of failure. Also the time needed to evacuate large numbers of properties might justify the installation of raingauges and river gauges at locations further upstream in the catchment to provide additional lead time (and this would also allow the outputs from rainfall-runoff and flow routing forecasting models to be updated in real-time). The need for up to date information can also require all gauges to be on telemetry, with recording intervals possibly as low as 5 min, although 15 min or hourly is more usual, depending on the typical rate of rise of river levels.

By contrast, for long-term (seasonal) drought forecasting, the emphasis might be more on accurate monitoring of low flows from the main contributing areas in each subcatchment, and at major abstraction and discharge points, and in monitoring rainfall across a whole region. Values might only be recorded on a daily basis, with some data collected by observers from charts or data loggers on a weekly or less frequent basis (although it is worth noting that telemetry values are often required to support day to day water supply and other operations during drought conditions). Indeed, a common problem which arises in flood forecasting applications is that only a subset of the available river gauges is suitable for use with a forecasting model. This situation can arise since, at high flows, gauges originally installed for low flow and water resources applications may be affected by problems such as flows bypassing the gauge, backwater from tributaries further downstream, and flooding of electrical equipment. Similarly, issues due to weed growth and shifting river channel beds may be an issue at low flows, but not significant at high flows.

There are many guidelines available on the design of instrumentation and telemetry networks for different applications, and the related cost-benefits. Table 2.6 summarises some examples which cover flood warning, water resources, and water quality applications. Analysis of historical raingauge data and weather radar and satellite data and images (if available) can also help with identifying typical storm paths and types when considering new instrument locations. Also, analyses using

Table 2.6 Some examples of guidelines on the design of instrumentation networks

Application	References
Flood warning	USACE (1996), NOAA/NWS (1997)
Water quality	World Meteorological Organisation (1994, 2008), UNEP/WHO (1996)
Water resources	World Meteorological Organisation (1994)

hydrological and hydraulic models can provide useful insights into local and catchment wide response at potential gauge locations, as can the use of digital elevation models to visualize gauge and telemetry locations and the line of sight for radio telemetry (if applicable). In some situations, it may also be useful to install temporary gauges to assess the suitability and security of a site, before proceeding to install telemetry and other infrastructure (e.g. kiosks, cableways). Ultimately of course, cost may be the critical factor, and cost benefit and other analyses are often used to justify the installation of new equipment.

For short to medium lead time applications (but also other applications), another key factor is the approach used to telemetry of data values. The main options include telephone lines (PSTN), cellular/mobile telephone (GSM, GPRS), VHF or UHF radio, satellite, internet connections, and meteorburst. Data may be transmitted at fixed time intervals, on demand, or when values exceed a threshold (e.g. river levels above a certain critical value). Manual methods, in which an observer relays values by telephone, radio, fax or email, are also widely used in situations where this provides information sufficiently frequently for the application. Links may also be required to locally operated systems, such as the SCADA (Supervisory Control and Data Acquisition) systems which are sometimes used in water supply, reservoir and hydropower schemes. Normally, the polling and receipt of telemetry data will be controlled by a dedicated computer system, or by a module within a forecasting system, with associated database, data validation, data display and data output tools. These items may also be integrated with, or have links with, a hydrometric database system, which is a key tool in most national hydrological services, and many other organizations.

Each approach to telemetry has its own limitations; for example, for telephone and internet links, there may be no convenient telephone connection near the instrument, possibly requiring an expensive additional run of cable. Radio-telemetry systems, by contrast, rely upon a clear line of sight for the signal, and hence may require repeater and booster stations, and may also suffer from interference from other transmitters. Satellite and cell phone approaches may have significant connection charges, and restrictions on the timing and volumes of data transferred imposed by the operator, whilst meteorburst systems (which rely upon the ionization trails caused by meteors in the atmosphere), although generally reliable, may have transmission delays whilst waiting for suitable atmospheric conditions. The issue of control of the network may also be important, with radio and meteorburst networks being the only approaches with the option to be completely within the control of the operator, although sometimes at a significantly higher initial cost than other options (although possibly with lower operating costs). The disadvantage, of course, is the need to operate and maintain the network, which is not an issue with telephone-based systems.

Many organizations operate telemetry networks for hydrometeorological forecasting applications, and some examples include:

- ALERT – the Automated Local Evaluation in Real Time approach which mainly uses radio telemetry (see Box 2.3)
- Environment Agency – an extensive raingauge and river gauge instrumentation network in England and Wales which mainly uses land-line telephone (PSTN) telemetry
- SNOTEL – the US Department of Agriculture SNOwpack TELemetry network which was described earlier and which mainly uses meteorburst telemetry
- WHYCOS – the WMO World Hydrological Cycle Observing System (WHYCOS) initiative which mainly uses Data Collection Platforms to transmit data via satellite (see Chapter 1).

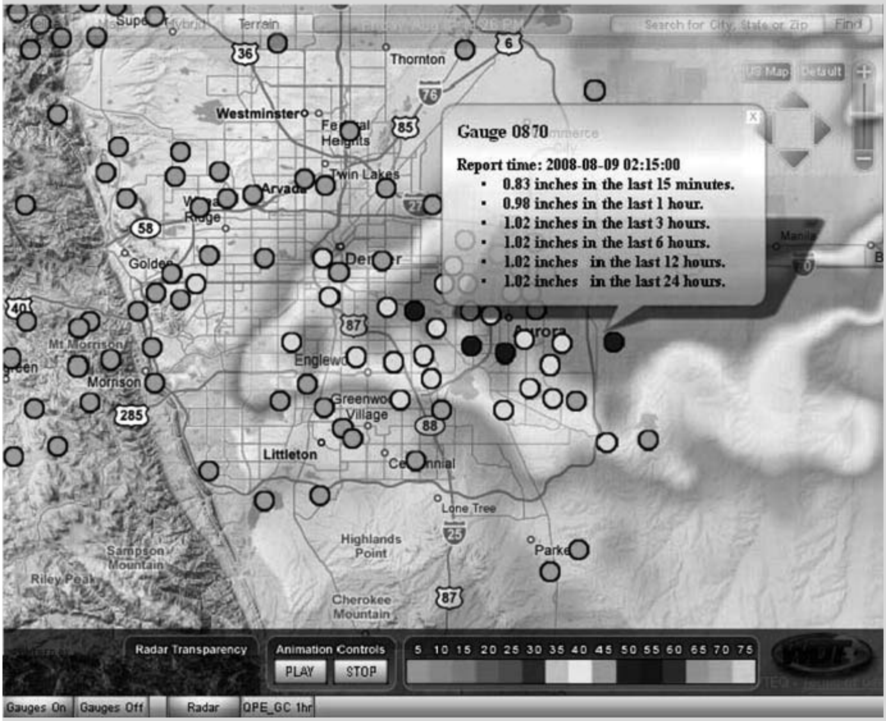
Box 2.3 Automated Local Evaluation in Real Time (ALERT)

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 river flood warning systems (Fig. 2.9), although other uses include monitoring of water quality, river control structures, and coastal conditions.

Fig. 2.9 Principles of operation of a radio-reporting raingauge (NOAA/NWS 2005) and illustration of an ALERT weather station and combined raingauge and streamflow gauge (Stewart 2009)

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/NWS 2005), 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 with national coordination provided by the National Hydrologic Warning Council (NHWC) and regional user groups. 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 also be used, such as automatic weather stations, and gauges for monitoring reservoir levels, pumping station operations, 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, possibly with repeater stations.



Gauge 0870

Report time: 2008-08-09 02:15:00

- 0.83 inches in the last 15 minutes.
- 0.98 inches in the last 1 hour.
- 1.02 inches in the last 3 hours.
- 1.02 inches in the last 6 hours.
- 1.02 inches in the last 12 hours.
- 1.02 inches in the last 24 hours.

Fig. 2.10 Illustration of a combined internet based display of raingauge and NEXRAD weather data (Urban Drainage and Flood Control District, Denver, Colorado; Stewart 2009)

Recent developments have included an enhanced ALERT-2 protocol for data transmission, the use of ever more sophisticated internet based tools for displaying and mapping data, and the increasing use of ALERT systems with optical and other sensors for monitoring water quality parameters, such as blue green algae, dissolved oxygen, chlorophyll, conductance, water temperature and turbidity. For example, Fig. 2.10 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. Rainfall locations are also colour coded according to rainfall depth-duration values, and the sequence of radar and raingauge values can also be animated.

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Chapter 3
Meteorological Forecasting

Abstract Meteorological forecasts provide a basis for extending the lead time provided by hydrological forecasting models, beyond that available from observations of rainfall and other parameters. In addition to the general weather forecasts provided to the public, meteorological services often provide a range of more specialized products tailored to different users, and a number of these are potentially of use in hydrological modeling. Examples include short-range forecasts of rainfall for flood forecasting and water supply operations, seasonal forecasts for drought and agricultural applications, and air temperature and other inputs for demand forecasting. This chapter provides an introduction to the main techniques used in meteorological forecasting, including nowcasting, Numerical Weather Prediction, and statistical methods. Several approaches are also discussed for post-processing outputs to the scales of hydrological interest, including dynamic downscaling, statistical post-processing and weather matching. An introduction is also provided to the topics of data assimilation and forecast verification.

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

3.1 Introduction

Meteorological forecasts play a key role in many aspects of the hydrometeorological forecasting process, particularly for lead times beyond the natural response times of hydrological systems. The types of meteorological forecasting outputs which are potentially useful include Quantitative Precipitation Forecasts (QPF), and forecasts for a range of other parameters, including air temperature, soil moisture, wind speed, and humidity. Meteorological forecasting techniques include:

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- Nowcasting – short-range local or regional forecasts based on recent and current observations, which can include weather radar, raingauge, weather station, satellite and other observations
- Numerical Weather Prediction (NWP) – three-dimensional models of the atmosphere at a local, regional or global scale
- Statistical Methods – techniques which use regressions and other statistical approaches to estimate future conditions, particularly for longer range forecasts

Techniques may often be combined; for example, Numerical Weather Prediction model outputs are increasingly used to improve the accuracy of nowcasting techniques. As noted in Chapter 1, consensus forecasts or predictions are also used for long-range forecasting in some regions, and are based on expert opinion from meteorologists and other experts, based on model outputs, experience and observations.

In meteorology, 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. The World Meteorological Organisation defines the following meteorological forecasting ranges (World Meteorological Organisation 1992): 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). For nowcasting, current conditions (or ‘actuals’) are included since, as discussed in Chapter 2, the merging or ‘data fusion’ process which is often used in generating forecasts can also improve the estimates for present conditions beyond those provided by any individual observing system, such as weather radar, satellite or raingauges.

Spatial scales which are defined include the microscale, mesoscale and macroscale, where mesoscale phemomena are defined as ‘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’ (AMS 2009).

One development in the past 1–2 decades which has significantly improved medium- to long-range forecasts has been the introduction of ensemble forecasting techniques (e.g. Molteni et al. 1996, Toth and Kalnay 1997). These are now widely used to help to assess the uncertainty in forecasts, particularly at longer lead times, and are used in addition to deterministic (single-valued) forecasts. Due to the non-linear and chaotic nature of atmospheric processes, small differences in initial conditions can, at longer lead times and/or for certain types of weather event, lead to significantly different outcomes, which – as noted in Chapter 1 – is the so-called ‘butterfly effect’ or ‘sea-gull’s wing’ influence popularised by Lorenz (e.g. Lorenz 1993). Indeed, it is widely held that, for some types of forecast, such as the rainfall caused by thunderstorms, or seasonal forecasts, it is only meaningful to provide information in probabilistic terms.

Ensemble approaches aim to take account of the inherent uncertainty in current (initial) conditions, and sometimes in model parameters, and can also be of value in decision making for hydrometeorological forecasting applications. For example, at the simplest level, when the spread in ensemble values is small, or significant clustering of ensembles occurs, a forecaster will often be more confident in the forecast. When used as inputs to a hydrological model, the probabilistic information can also assist with risk-based and other approaches to decision making, as described in Chapter 6 and later chapters. Several examples of ensemble outputs are provided later in this chapter, and in other chapters (see, for example, Fig. 3.8).

Table 3.1 Some typical lead time and resolution characteristics for meteorological forecasting techniques (typical values in the period 2005–2010)

Method	Lead time	Horizontal/grid resolution (km)	Time step for model outputs (h)	Comments
Nowcasting	0–6 h (rainfall)	1–5 km	5 or 15 min	Maximum lead times may be only 0–2 h or less for thunderstorms and some other types of event
	0–10 days (tropical cyclones)	100–1,000 km	Hourly or more	Typical values for tropical cyclone, typhoon and hurricane forecasting
Numerical Weather Prediction	0–3 days	1–25 km	1–6 h	Higher resolution models may have limited spatial extent (e.g. limited area models, mesoscale models)
	3–10 days	25–100 km	6–12 h	Models are typically global in extent
	10 days+	25–100 km	12 h to monthly	May be operated for lead times of several months or more ahead
Statistical methods	Weeks to months ahead	Depends on application	Depends on application	Probabilistic estimates of timing, magnitude and location

Due to improvements in modeling techniques and observation methods, the lead times at which forecasts show skill are constantly improving. Model resolutions are also nowadays much closer to the scales of interest in hydrological forecasting, particularly for large catchments and/or at short lead times (Table 3.1). For Numerical Weather Prediction Models, some examples of recent and ongoing areas of improvement include:

- Computing Power – general increases in processor power, and use of parallel and distributed processing, with some of the world's fastest supercomputers being used in operational meteorological forecasting

- Data Assimilation – improved techniques for the assimilation of ground-based, atmospheric and ocean observations into model runs, and increasing use of weather radar and satellite data
- Atmospheric Processes – increased understanding of key processes, in particular for local (mesoscale) phenomena, and land-atmosphere and ocean-atmosphere interactions

The grid length available can have a significant influence on the ability of a model to resolve the detail of an event, and is often constrained by the available computing power. Also, the smallest feature (and wavelength) which can be resolved without attenuation is typically of the order of 3–5 grid lengths (e.g. Lean and Clark 2003, Persson and Grazzini 2007).

To illustrate the effect of an order of magnitude change in resolution, Fig. 3.1 shows an example of forecasts at a 12 and a 1.5 km resolution for a major rainfall event in northwest England which resulted in flooding to approximately 3,000 properties in the city of Carlisle during January 2005. This analysis was performed after the event by the UK Met Office to assess how accurate the higher resolution model would have been if it had been available at the time of the event; the enhancement with this model is very apparent, and a 1.5 km model has subsequently been implemented operationally for the whole of the UK.

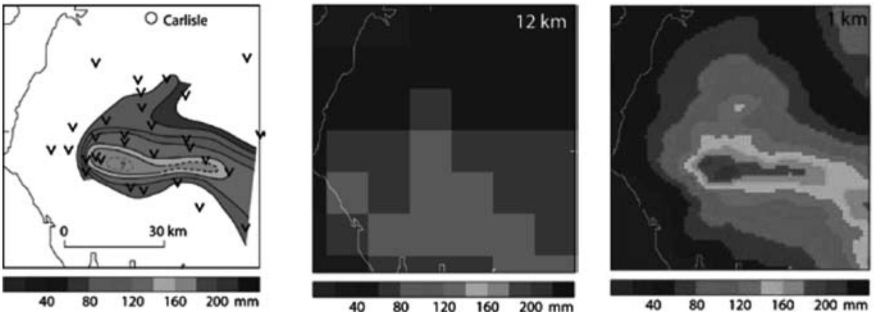

Fig. 3.1 Benefits of improved resolution for the Carlisle flooding in 2005. From left to right (**a**) observed rainfall (**b**) 12 km resolution (**c**) 1.5 km resolution (Cabinet Office 2008; © Crown Copyright 2008, the Met Office)

More generally, when developing Numerical Weather Prediction models, given the computer resources required, a balance is required between the model complexity and resolution, the number of ensemble members, and the frequency of model runs. Typically lower spatial resolutions and less frequent model runs are used at longer lead times. Usually, the additional computational requirement for ensemble forecasts also means that the ensemble runs are at a lower spatial resolution than the deterministic (or control) run. One active area for research is into how to blend these various forecasts at different lead times and resolutions into a single, internally consistent ‘seamless’ suite of products, covering both deterministic and ensemble forecasts. Another consideration is the time required to initialize model runs based on current and recent observations of the atmosphere, land surface and oceans, such as those provided by weather stations, aircraft, weather radar, ocean buoys and satellites. This data assimilation stage can account for a significant proportion of the time interval between model runs, and may also make use of the forecasting outputs from previous model runs (see Section 3.2.2).

For Numerical Weather Prediction models, outputs are usually generated on an hourly or longer basis and are typically issued at times linked to the main and intermediate synoptic reporting hours specified by the World Meteorological Organisation (0000 UTC, 0300 UTC, 0600 UTC and so on) or multiples of those periods (e.g. at 0000 and 1200 UTC for medium-range forecasts, or weekly or monthly for long-range forecasts). Outputs are usually post-processed into a range of formats, depending on the requirements of individual users. Examples can include synoptic charts, heavy rainfall alerts, and severe weather warnings. The raw gridded model outputs for rainfall and other parameters are also widely used, particularly in short-range operational hydrological forecasting models.

Another aspect to post-processing can include downscaling of results to better meet the requirements of end users, including hydrological forecasters. The three main approaches which are used are statistical post-processing, dynamic (or dynamical) downscaling, and weather matching or typing. Statistical techniques include the Model Output Statistics (MOS) approach of the National Weather Service in the USA (see Section 3.3), and Kalman Filter and other approaches which make use of real-time observations from individual meteorological stations. Stochastic weather generators are also used in climate change modeling. By contrast, in dynamic (or dynamical) downscaling, a more detailed local model is operated, based on the boundary conditions provided by a regional or global scale model, whilst weather matching involves the identification of similar conditions from the historical record to use as a basis for forecasting future conditions. The topic of post-processing is also closely linked to that of forecast verification, as discussed later.

This chapter provides a general introduction to these various topics, at an introductory level. More detailed information can be found in the references which are cited, and in the many texts on this topic, including World Meteorological Organisation (2000), Kalnay (2002), Palmer and Hagedorn (2006) and Troccoli et al. (2008). Section 3.2 discusses the main forecasting techniques which are used operationally, and Section 3.3 describes a range of practical considerations when the forecast outputs are used as inputs to hydrological models, including post-processing techniques, re-analysis or hindcasting studies, and forecast verification. Figure 3.2 illustrates how these various components are typically linked within a national or regional hydrometeorological forecasting system, although note that, in some applications, some steps may not be required, or omitted, such as post-processing of outputs. In some cases, a coastal forecasting component may also provide forecasts for surge and tidal levels for input to the hydrological component (although is not shown in the figure). Chapter 4 and later chapters provide more detail on the decision support aspects and the hydrological forecasting components which are shown in the figure.

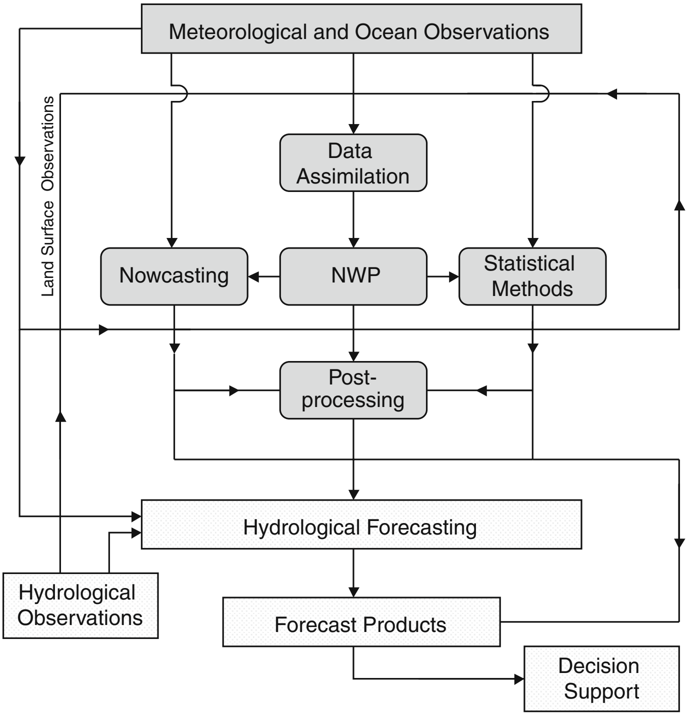

Fig. 3.2 Typical information flow in a national or regional hydrometeorological forecasting system. Note that the hydrological forecasting component may also include pre-processing of meteorological forecasts, data assimilation and post-processing stages (see Chapter 4). The post-processing step can include joining or blending of forecasts at different lead times into a seamless ensemble.

3.2 Forecasting Techniques

3.2.1 Nowcasting

Nowcasting techniques aim to estimate the future location, extent and characteristics of features of the atmosphere, such as storms and clouds, based on the current location, track, and speed, and possibly other considerations, such as the rate of growth or decay. Although nowcasting techniques are often associated with weather radar applications, they are also applied to satellite observations of cloud formations, and are widely used in forecasting for tropical cyclones, hurricanes and typhoons, and in forecasting for snow and fog. Nowcasting was one of the earliest meteorological forecasting techniques, although the original manually-based techniques are nowadays often superseded by automated methods.

When used with weather radar outputs, the aim is to estimate how a storm might move and evolve in the next few hours, based on its current (and recent) location, extent, speed and track. The lead times at which forecasts show skill depend on the local climatological conditions and topography, the type of rainfall event under consideration (isolated thunderstorm, widespread frontal rainfall etc.), and the resolution of the radar rainfall data; however, maximum lead times of up to 3–6 h ahead are often quoted for widespread events, although less for convective events. Compared to Numerical Weather Prediction models, the computing requirements are relatively modest, allowing values to be provided at a higher resolution and more frequent intervals, with model run intervals of 5–15 min and grid resolutions of 1–5 km typically used. The methods are also often more accurate at short lead times (up to 1–3 h, say).

The earliest approaches to radar nowcasting only allowed for advection or extrapolation of rainfall, in which the storm was simply translated based on its current speed and direction of travel. However, some more recent techniques allow for the initiation, growth and dissipation of storm cells, and the response to the underlying synoptic conditions, such as the wind field, and topographic influences. Many of the latest nowcasting techniques make use of the wind fields, pressure fields and other outputs from Numerical Weather Prediction models, together with satellite, ground-based, and lightning observations, to produce a combined product for short-range forecasts of rainfall and other parameters (e.g. Golding 2000, 2009, Mueller et al. 2003, Ebert et al. 2004, Wilson 2004). This approach to nowcasting can therefore be regarding as a form of post-processing (or ‘data fusion’) of NWP outputs, which adds skill to forecasts at short lead times. Typically, at longer lead times, the information content of the observed data decreases, and nowcasts rely increasingly on the NWP outputs.

Figure 3.3 illustrates these two nowcasting approaches for an idealized example of a single storm cell approaching a town. The location of the storm is shown for the current time (time now), and for the forecasts for 1- and 2-h ahead. For the simplest case (advection only) only minor rainfall would be forecast in part of the town, whilst the more complex approach forecasts the change in path of the storm as it approaches the town, and the development of a more intense rainfall band.

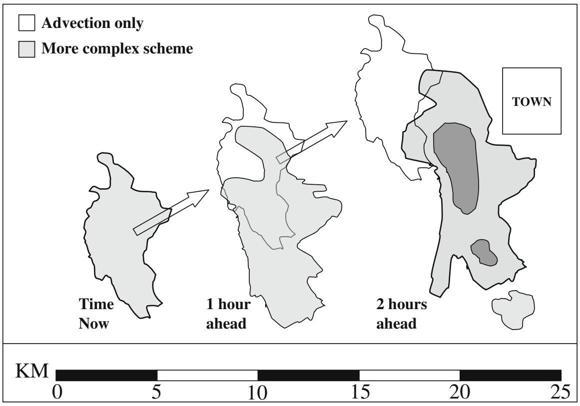

Fig. 3.3 Illustration of two approaches to nowcasting; simple advection or extrapolation, and allowing for storm growth and response to synoptic conditions and topographic influences

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, fuzzy logic, cell-tracking and other approaches (e.g. Wilson 2004).

There are also significant scale influences to consider in forecasting the evolution of precipitation, and this has led to the development of nowcasting techniques that take account of this effect. One operational example is, the approach developed jointly by the Met Office in the UK and the Bureau of Meteorology in Australia which became operational in the UK during 2007, and is described in Box 3.1.

As noted earlier, another widespread application of nowcasting is in forecasting the progression of tropical cyclones, typhoons and hurricanes, based on satellite and other observations of the position, speed and track. Methods include trajectory tracking, statistical and expert systems (Holland 2009). Due to the strong pressure and other gradients, and the difficulties in obtaining observations, Numerical Weather Prediction models cannot always represent the complexities of motion, so nowcasting approaches are presently the main forecasting technique which is used operationally. These methods can provide useful forecasts at lead times of up to several days ahead, although with considerable uncertainty in the location of landfall at those lead times. A probabilistic approach is therefore often used, in which the uncertainty is represented in forecasts to the public by a forecast plume or cone of uncertainty for the projected track. However, the ability of numerical models to forecast this type of event is improving and they are increasingly being considered for operational use (e.g. Sheng et al. 2005).

Nowcasting techniques are also used in some satellite rainfall estimation techniques, and complement the Quantitative Precipitation Estimation (QPE) procedures described in Chapter 2. For example, the 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, allowing for growth and decay (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.

Box 3.1 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). The system became operational in the UK in 2007 (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).

Products based upon two forecast configurations are currently generated: 5 min, 2 km resolution nowcasts of rain rate with a range of 1 h, and 15 m, 2 km resolution nowcasts of rain rate with a range of 6 h. Accumulation products for a range of accumulation periods are generated from these. Single scenario (deterministic) forecast realisations of both configurations are produced every 15 min. A 48 member ensemble of the second configuration is generated once an hour.

The STEPS approach acknowledges that precipitation fields exhibit both fractal (scaling) and dynamic scaling properties. 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 with their size. Consequently, the evolution of a field of instantaneous rain rate can be modelled effectively using a cascade framework (Fig. 3.4). 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 features at scales lacking skill are replaced by synthetically generated precipitation (noise) with appropriate statistical properties.

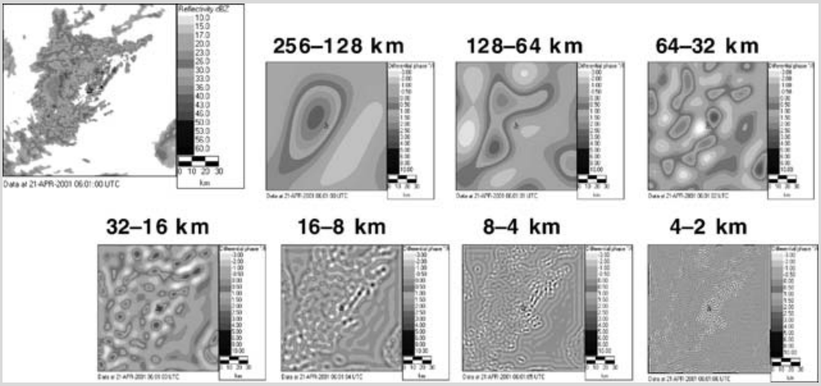

Fig. 3.4 Comparison of a STEPS cascade decomposition with the original radar inferred precipitation field (*top-left*) (© Australian Bureau of Meteorology)

In operational use in the UK (Fig. 3.5), STEPS blends precipitation observations from a network of C-band weather radars (mosaic) with NWP forecasts from the Met Office's Unified Model (hereafter MetUM). The model domain has horizontal dimensions of 1,024 × 1,024 km.

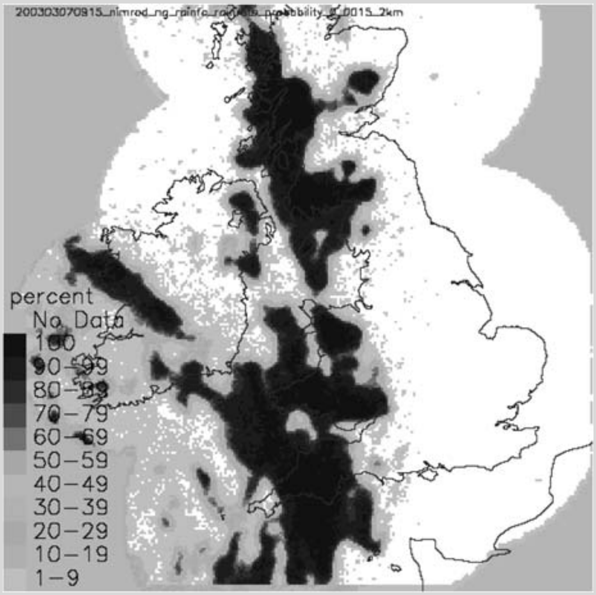

Fig. 3.5 Example of a STEPS probability of precipitation output; semi-circular boundaries indicate the extent of coverage for the UK and Ireland weather radar network (© Crown Copyright 2009, the Met Office)

Unlike most 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.

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 as measured against a recent radar inferred precipitation field. Since larger scale precipitation features tend to be most predictable, the weights applied to the model forecast components will increase with increasing scale. Noise is added to the blend to ensure that the statistically properties of the blended forecast closely follow those of the radar. This implies adding more noise at the small scales where least weight is given to the model forecast components.

Verification (Bowler et al. 2006) suggests that, under UK conditions, the forecast skill, in terms of a Brier skill score, is increased compared to NWP forecasts for lead times of up to about 3 h, whilst reliable forecasts for the probability of precipitation are obtained for lead times of up to about 6 h. 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.

3.2.2 Numerical Weather Prediction

Numerical Weather Prediction models are typically operated by National Meteorological Services and a small number of international, research and other organisations. Model outputs can include forecasts for rainfall (Quantitative Precipitation Forecasts; QPF), air temperature, humidity, and wind speed, and a range of other derived variables which may be useful in hydrometeorological forecasting, such as soil moisture conditions and snow cover.

A typical configuration is to use a detailed local or limited area model for the location of interest, nested within a coarser regional and/or global scale or general circulation model. Figure 1.4 shows an example of this approach. The global scale model provides boundary conditions to the regional scale model (if used), which in turn provides boundary conditions to the local, or limited area, model. Models with a global extent can of course provide forecasts world-wide, although higher resolution models may be available locally. Some other types of model which may be available include convective or storm-scale models, and non-hydrostatic mesoscale models. Storm scale models represent the evolution of individual storms (typically thunderstorms) using object oriented, life-cycle and other approaches, and may be embedded in other models, whilst mesoscale models are often capable of representing factors such as sea breezes and other local microclimates, such as around large lakes and reservoirs, and in mountainous regions. Some meteorological services also have the facility to configure regional models on demand for any part of the world; for example, in support of disaster relief efforts.

Many countries operate limited area or regional models, with boundary conditions provided by a smaller number of global scale models operated by regional or international centres. For example, for long-range forecasts, the WMO XVth Congress in Seoul in November 2006 recognized nine officially designated Global Producing Centres (GPCs) and these are summarized in Table 3.2. As described in Chapter 2, the initialization of models, and post-processing and sharing of outputs, is facilitated by the World Meteorological Organisation's Global Telecommunication System (GTS), which distributes a wide range of ground-based, atmospheric, satellite and oceanic data, and forecast products, to participating National Meteorological and Hydrological Services.

Table 3.2 WMO Global Producing Centres of long-range weather forecasts (see http://www.wmo.int/pages/prog/wcp/ for the latest updates)

Country	Organisation	Location
Australia	Bureau of Meteorology	Melbourne
Canada	Meteorological Service of Canada	Montreal
China	National Climate Center of China Meteorological Administration	Beijing
France	Meteo France	Toulouse
Japan	Japan Meteorological Agency	Tokyo
Korea	Korean Meteorological Administration	Seoul
UK	Met Office	Exeter
USA	NOAA Climate Prediction Centre	Washington
International	ECMWF (supported by 31 Member States)	Reading, UK

For each model run the main stages in deriving forecast outputs typically include:

- Data Collection and Validation – from a wide range of sources, including ground-based stations, aircraft, ships, ocean buoys, radiosondes and satellites
- Data Assimilation – initialization of model runs based on recent and current observations
- Model Runs – operation of the model, or suite of models, often performing multiple runs to obtain an ensemble of forecasts
- Post-processing – processing of outputs into forecast products suitable for a range of potential users

Models typically solve the three-dimensional equations for mass, momentum and energy conservation in the atmosphere, and run at a timestep of a few minutes or more. For example, Fig. 3.6 illustrates the main physical processes represented in the general circulation model operated by the European Centre for Medium-Range Weather Forecasts (ECMWF). The deterministic version of this model, introduced in 2006, has a horizontal resolution of approximately 25 km, and 91 vertical levels. (see http://www.ecmwf.int/ for the latest information).

Table 3.1 shows the typical horizontal resolutions for the current NWP models which are used world-wide whilst, in the vertical plane, between 20 and 100 layers is typical, with closer spacing near to the land surface. Models may also include

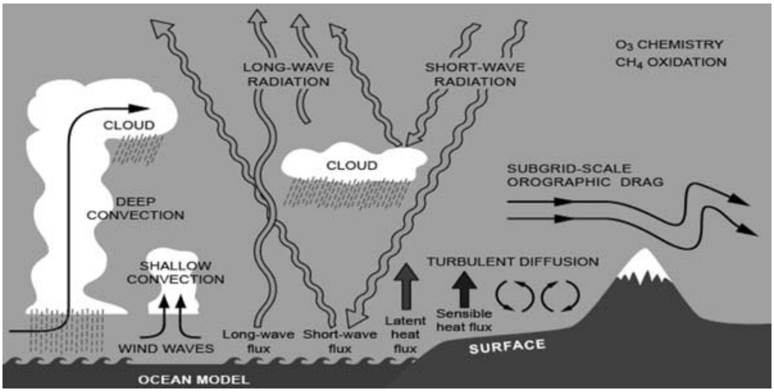

Fig. 3.6 Main physical processes represented in the ECMWF model (Persson and Grazzini 2007; Source: ECMWF)

several soil layers and, particularly for medium- to long-range forecasting, an ocean model may also be included. Ocean models typically include wave models (e.g. Komen et al. 1994, Tolman 1999) to allow for the two-way interactions of the wind field and waves. Wave models are of the phase averaging type, and describe the rate of change of the wave energy spectrum due to factors such as the wind field, and dissipation due to wave breaking and non-linear wave-to-wave interactions.

For the atmospheric component, separate models or parameterisations are also normally included for boundary layer, radiative and other processes such as cloud formation and dissipation, turbulent diffusion, orographic effects, and water and radiation transfer at the land surface, as illustrated in Table 3.3. In many cases, the simplification of hydrostatic equilibrium is made, which reduces the ability to forecast localized effects with significant vertical accelerations due to topographic and convective influences.

The approach which is used for data assimilation is another distinguishing feature of models (e.g. Kalnay 2002, Park and Liang 2009). In any atmospheric model, or coupled ocean-atmosphere model, the challenge is to interpret a relatively sparse set of measurements, when compared to the number of model grid points and vertical levels, to provide an estimate of the initial conditions at the start of each model run. This may require spatial interpolation of values, extrapolation in time (to account for different measurement times), corrections to account for measurement errors, and other adjustments, guided by the forecast outputs from the previous model run. The resulting initial conditions also need to avoid any sharp discontinuities or other anomalies which might set off unrealistic transient behaviour in the model runs, and to be consistent with the initial stages of the previous forecasting run. Indeed, there is generally a spin-up period whilst the model state adjusts to the initial conditions, particularly regarding the precipitation generation components.

In recent years, the availability of satellite data has significantly changed the approach to data assimilation, and to some extent has overcome the issues with

Table 3.3 Illustration of some typical sub components in a Numerical Weather Prediction model

Item	Description
Cloud Physics	Models for uplift and descent, convection, boundary layer turbulence, cloud top entrainment, precipitation (rainfall, snow, hail, ice), evaporation, radiative heat transfer etc., distinguishing between different types of cloud, fog, and precipitating and non-precipitating cloud, and including the influence of aerosols on radiation and heat transfer
Orographic influences	Use of key features such as orientation, aspect ratio, height, slope etc. to represent key influences on the wider circulation. More detailed representations are used in some local and mesoscale models using digital elevation models and non-hydrostatic formulations
Land-atmosphere interactions	A mosaic of land, soil and vegetation types, possibly with individual energy balances, and more dynamic parameters such as snow cover, linked to conceptual models for soil moisture storage, typically with Penman-Monteith evapotranspiration estimates (see Box 11.4 for example)
Radiation	Models for influences at the land surface, and on air temperature, absorption by aerosols etc., and in particular the influence of clouds on the radiation balance
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

sparse data, although the observations still need to be interpreted in terms of conditions at the ground or in the atmosphere. For example, both infrared and microwave data can be used to provide information on temperature and humidity fields, cloud cover, wind speeds (via cloud motion), and sea surface temperatures and elevations. Weather radar data for rainfall rate and Doppler wind speeds (if available) can also be used during the assimilation process.

Historically, the most widespread approaches to data assimilation were optimal interpolation and 1-D or 3-D variational (3D-Var) approaches (Kalnay 2002). For example, variational approaches involve the minimization of an objective function (cost function) in terms of the differences between observed and forecast values. These approaches are increasingly being superseded by methods which also allow for the differing times of observations, and particular features of the current conditions, using short-range projections of values, such as the 4D-Var approach, and developments of the ensemble Kalman Filter (EnKF) approach.

The validation and assimilation of data can represent a considerable proportion of the time between model runs, and involve large volumes of data. For example, Fig. 3.7 shows a summary of the observations received at ECMWF in a 24 h period on 5 July 2004 from a wide range of sources, where the values indicate the number of individual items of information received.

Different approaches are also taken to the generation of ensemble forecasts. The most widespread approach is to generate ensembles which account for the uncertainty in the state of the atmosphere, and hence in initial conditions. There

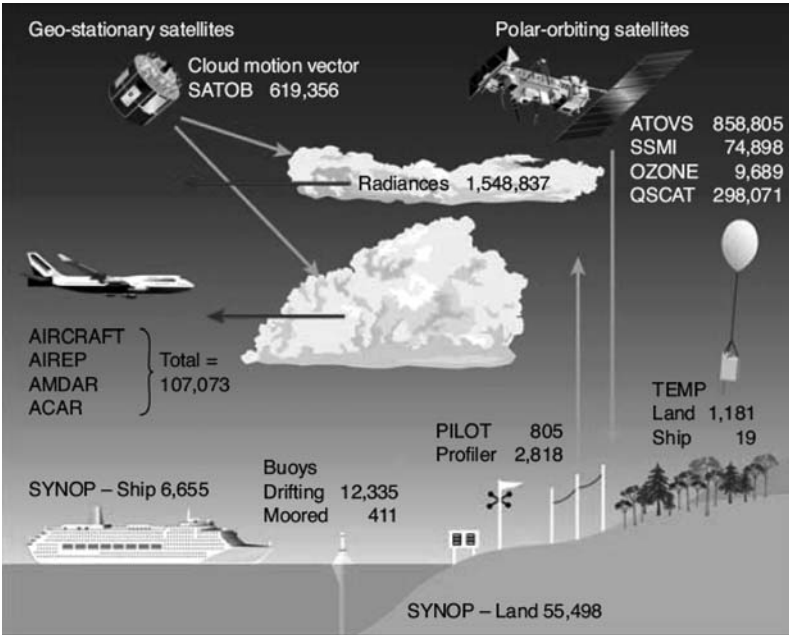

Fig. 3.7 24 h summary of observations received at ECMWF, 5 July 2004 (Persson and Grazzini 2007; Source: ECMWF)

is therefore a close connection with the data assimilation process, for which the errors in observations and past forecasts also need to be considered. Due to computing limitations, it is not possible to sample the full probability density functions for all variables, so a sample is drawn to achieve a set of equally likely ensembles. Typically, between about 20 and 50 ensemble members are generated per model run and, as noted earlier, due to the longer computing times typically a lower grid resolution is used than for the deterministic forecast. Some organizations also allow for model uncertainty; for example due to the finite model grid resolution and/or model parameters (e.g. Persson and Grazzini 2007). Multi-model ensembles are also increasingly used to provide an insight into modeling uncertainty, in which the outputs from several forecasting centres are compared, and sometimes combined using Bayesian Model Averaging techniques (Raftery et al. 2005). The THORPEX Interactive Grand Global Ensemble (TIGGE) experiment, which is a component of the WMO World Weather Research Programme (http://www.wmo.int/), is also investigating the performance of multiple global model ensemble outputs from a number of different operational centres for lead times from 1 to 14 days (Park et al. 2008).

The general approaches used for short- to medium-range numerical weather prediction are also used for longer-range forecasting to a month or more ahead, with ensemble and multi-model runs normally used (e.g. Doblas-Reyes 2005, Troccoli et al. 2008). At longer timescales, the representation of ocean processes becomes more important, and initialization for the ocean component of the coupled model, using satellite, wave buoy and other data. A general problem for data assimilation for the ocean component is the lack of data on sub-surface conditions (temperature, currents, salinity etc.), and the relatively sparse data at the sea surface, compared to that available for land surfaces. Long-range forecasts are typically issued in probabilistic terms, as average values over periods of a month or more, and model runs may only be performed weekly, or less frequently. The development of NWP models for use in seasonal forecasting is an active research area, and the use of the outputs for hydrological applications is discussed in several later chapters, including Chapter 7 (seasonal flood forecasting), Chapter 8 (droughts), and Chapter 11 (water resources applications). Also, given the uncertainties in the approach, these techniques are often supplemented by statistical methods, as described in the following section. Combined methods have also been proposed, in which the outputs from several coupled ocean-atmosphere models are combined with statistical estimates using Bayesian techniques (e.g. Coelho et al. 2006).

For decadal (10–30 year) and longer predictions, statistical linkages are largely unproven, so Numerical Weather Prediction is again the preferred approach, often at comparable grid resolutions to medium- or long-range forecasting models. For this type of simulation, the land-atmosphere component is often improved to represent additional mechanisms, such as through the use of dynamic vegetation models, and models for atmospheric chemistry and the carbon cycle (see Chapter 11 for example). Results are usually presented for the latest WMO climatological standard period (e.g. 1961–1990), and subsequent 10- or 30-year periods, using the outputs from several models to help to take account of modeling uncertainty. Models runs are usually perturbed based on the scenarios developed by the Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/), and local interpretations of those scenarios. Various scenarios are considered for atmospheric emissions, considering population growth, economic development, adaptation to climate change and other factors. Downscaling issues are of particular importance in climate change impact assessments, and similar techniques are used to those discussed later for operational forecasting models.

3.2.3 Statistical Methods

Historically, the main approach to seasonal forecasting was through statistical approaches; for example, by developing linear regression relationships between parameters at the site of interest (predictands, or dependent variables), such as air temperature or cumulative rainfall, and variables or indices for the atmospheric and/or oceanic phenomena believed to be the main influence (predictors). These relationships are sometimes called teleconnections. An early example was the approach developed by Walker in the early twentieth century for forecasting the Indian Monsoon (Walker 1997).

These techniques still have a useful role to play, and may perform as well as, or better than, some NWP-based approaches, particularly for regions where strong relationships can be demonstrated between cause and effect (e.g. Goddard et al.

2001, Mason and Baddour 2008). One limitation though is the assumption that the historical data are representative of future conditions, whereas this may not always be the case due to climatic variations and other factors. Other more recent developments include the use of time series analysis methods to extrapolate observed trends into the future (e.g. autoregressive moving average approaches), and artificial neural network techniques, which derive an estimate for future conditions based on a range of possible indicators.

Many statistical approaches focus on the use of predictors for the following phenomena, which are described in more detail in Chapter 1:

- 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 typically of a few months or more, also linked to cooler La Niña episodes
- Madden Julian Oscillation (MJO) – intraseasonal 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 a timescale variously estimated to be 40–50 or 30–60 days, but with strong variations from year to year (e.g. Madden and Julian 1994)
- Inter Tropical Convergence Zone (ITCZ) – the convergence zone between the trade winds in the northern and southern hemispheres, which results in an uplift of air and generation of heavy convective rainfall and thunderstorms around the equator, and which moves north and south with the progression of the seasons
- Monsoon – linked to the seasonal variations in 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 on-shore, and affecting many regions where large land masses are adjacent to the ocean (e.g. in Africa, the Americas, and particularly in Asia)
- North Atlantic Oscillation (NAO) – a mainly atmospheric phenomenon, although 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)

Table 3.4 summarises some examples of the more widely known indices which are used in seasonal and longer term forecasting. Other more complex indices, involving multiple parameters, such as the Multivariate ENSO Index (MEI), are also used, together with indices for longer-term phenomena, such as the Pacific Decadal Oscillation (PDO).

Linear regression is probably the most widely used statistical approach, sometimes in transformed coordinates, and sometimes using multiple regression relationships. Standard regression theory can also be used to assess confidence limits, and the statistical significance of relationships. Often, parameters need to be averaged over periods of a month or more, and a time delay built into the relationship to reflect the lag between cause and effect. As in any modeling exercise, care needs to be

Table 3.4 Examples of indices that are widely used in seasonal and longer term weather forecasting

Phenomenon	Abbreviation	Name	Description
El Niño	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 normalized difference in mean sea level pressure between Tahiti and Darwen e.g. SOI, EQSOI
North Atlantic Oscillation	NAO Index	North Atlantic Oscillation Index	Normalised sea level pressure difference between an observation station in the Azores, and a station in Iceland

taken to identify and correct or remove instrumental and other errors in the records used for the analysis. Exploratory analyses using Numerical Weather Prediction model outputs are also sometimes performed to examine the likely reasons for, and likelihood of, any relationships which are hypothesized.

More advanced techniques, such as principal component analysis, canonical correlation analysis, redundancy analysis or maximum covariance analysis can also be used to provide estimates across multiple sites. Typically, these approaches involve identifying spatial patterns or modes across the region of interest, and then superimposing the outcomes to obtain the forecast (Mason and Baddour 2008). Related techniques include empirical orthogonal functions, wavelet banding and constructed analogue techniques (e.g. Webster and Hoyos 2004, Wilks 2006, van den Dool 2007). Some examples of the use of ENSO Indices in operational flow forecasting systems, as a supplement to more physically-based modeling approaches, are presented in Boxes 1.2 and 11.3, for locations in the USA and Canada. An example of the use of Canonical Correlation Analysis is also presented in Box 8.3 for a drought early warning system in Africa.

Currently, much research into longer term forecasting focuses on the influence of the El Nino-Southern Oscillation (ENSO). The 1972/1973 event was probably the first to prompt significant work on world-wide linkages, which was reinforced by the 1982/1983 event (e.g. Harrison et al. 2008). This development work accelerated following the 1997/1998 event, which was one of the most significant on record (see Chapter 1), and 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

3.3 Operational Considerations

Previous sections have discussed the generation of meteorological forecasts but, when these are used as inputs to hydrological models, some additional considerations include the format of those outputs, whether the outputs need to be post-processed before use, and the general suitability of forecasts, at the scales and lead times for which they are required. This section discusses these three inter-related topics under the headings of forecast products (Section 3.3.1), post-processing (Section 3.3.2) and forecast verification (Section 3.3.3). Later chapters include similar discussions for a range of hydrological forecasting outputs and applications.

3.3.1 Forecast Products

For hydrometeorological applications, the outputs from meteorological forecasting models often need to be processed into a form which can be used operationally. Often this may need a collaborative approach between meteorological and hydrological forecasters to develop bespoke products and delivery mechanisms suitable for the application.

At the simplest level, information may just be provided in the form of situation reports or bulletins. However, for quantitative forecasts, a real time feed of information often needs to be established, particularly for short-range forecasts. Some examples could include delivery of ensemble quantitative precipitation forecasts for use in flood forecasting models at 15 min or hourly intervals, provision of rainfall and air temperature forecasts for use in hydropower scheduling, and daily transfer of a range of parameters for input to crop simulation models (e.g. air temperature, precipitation, humidity, windspeed, soil moisture). However, particularly for medium- to long-range forecasts, manually prepared products, based upon NWP outputs, observations, and the expertise of forecasting duty officers, have a valuable role to play (and this approach forms the basis of the forecasts issued to the public in most meteorological services).

For automated transfer of data, although internet or ftp delivery is one possibility, the need for a real-time feed often places some constraints on the viability of the approach. For example, the steps needed may include establishing a robust telecommunications link, specifying level of service agreements, provision of training and round the clock support, and a range of other issues. Ideally, hydrological models also need to be calibrated to the specific meteorological outputs which are delivered, and a system of version control established so that any changes in the product can be assessed in terms of the impacts on the hydrological component. For National Hydrological Services, as discussed earlier there is also the possibility that some forecast information can be accessed through the World Meteorological Organisation's Global Telecommunication System.

Another constraint may be the availability of suitable outputs for the location of interest. For example, not all countries operate Numerical Weather Prediction models, which leaves the choice of whether to use the outputs from a global or regional scale model directly and/or to develop a more locally applicable approach, using statistical and other techniques. By contrast, for some countries, such as in mainland Europe, the location of interest may fall within the domain of the high resolution models operated by several nearby countries, perhaps suggesting use of a multi-model approach. In some cases, there may also be the choice of using a relatively coarse global scale model, incorporating the latest data assimilation and modelling techniques, or a simpler local model, but with outputs calibrated and developed specifically for the locations of interest.

These factors are all part of the model design and decision-making process, which is discussed in more detail in Chapter 4 and Chapter 6. Often the first stage is to consider whether the current forecast performance is sufficient, at the lead times and scales of interest, and the topics of forecast post-processing and forecast verification are discussed in the following sections.

3.3.2 Post-processing

3.3.2.1 Introduction

Numerical Weather Prediction models provide values on a three-dimensional grid, whose node points will often not coincide with the locations of interest, and the model outputs are also subject to many uncertainties. In particular, whilst models may provide a good representation of the large-scale features of the atmosphere, such as frontal systems and jet streams, they may not represent local features such as thunderstorms, and sub-grid processes due to topography, variations in land cover, coastal influences, and other effects. Also, as noted earlier, the lower limit to the size of atmospheric features which can be resolved without attenuation may cover several grid lengths.

It can therefore be desirable to post-process the model outputs to a finer scale and/or to better match the statistical (climatological) characteristics of the historical record at the site(s) of interest. This process – which is increasingly used operationally – is often called post-processing or downscaling, and is an active area of research. Some techniques which are used include:

- Statistical post-processing – use of regression relationships, time series analysis and other techniques to relate model outputs to values at the site(s) of interest
- Weather Matching, Weather Typing or Analogue Techniques – identification of similar conditions from previous observations and forecasts, often guided by current forecasts, to provide an estimate of likely future conditions

- Dynamic (or Dynamical) Downscaling – use of additional models at a finer resolution and/or including more local detail

The following sections describe these techniques in more detail, which may be applied at various stages in the forecasting process. For example, at one extreme, post-processing may be performed entirely by the meteorological service (and not apparent to hydrological forecasters) or, at the other extreme, used by hydrological forecasters alone on receipt of the raw, unadjusted meteorological forecasts. Alternatively some post-processing options may be offered by forecast providers as an additional, enhanced (or 'value-added') service. The approach used will depend on organisational arrangements, the application, and other factors.

Note also that, in the hydrological modeling literature, meteorological post-processing is often described as a form of pre-processing with respect to the hydrological modeling component, and Fig. 4.7 uses this terminology.

Similar approaches are also used in climate change prediction studies (e.g. Fowler et al. 2007). 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. Stochastic techniques are described briefly in Chapter 4, and have also been used in some shorter-range hydrological applications.

One useful resource for developing post-processing techniques and hydrological models is an archive of forecast values which has been generated using the suite of meteorological forecasting models in its current form, including the data assimilation component. Generating such an archive – a process which is usually called hindcasting, reforecasting or reanalysis – can be a time consuming task, and usually it is necessary to allow for the fact that the instrumentation available for data assimilation will almost certainly have changed over the period of the reanalysis; for example, in terms of the number of ground-based sites, the increasing availability of satellite-based data, and changes in recording methods and intervals. However, major hindcasting exercises have now been performed by several organizations, including the ongoing programmes at ECMWF, NCEP in the USA, and the Japan Meteorological Agency (e.g. Uppala et al. 2006, ECMWF 2007). The results which are available date back to the 1940s, in some cases, and have a wide range of potential applications. For example, Hamill et al. (2006) note that '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'.

3.3.2.2 Statistical Post-processing

Statistical post-processing of model outputs is widely used by some meteorological services to achieve a better match between model forecasts and surface observations at the locations of interest. For specific applications, this approach can also be used to predict variables which are not calculated within the model.

The techniques which are used can include multiple regression relationships, autoregressive relationships, transfer functions, and artificial neural networks, sometimes using the assumption of perfect prognosis (the Perfect Prog. Method) to estimate additional variables (Klein et al. 1959). Methods are typically calibrated off-line on the basis of historical data and forecasts, and the coefficients can then be used to adjust the forecast outputs in real-time.

Many different types of predictor have been considered, including precipitable water, area averaged temperature, relative vorticity, geopotential heights, categorical values relative to a threshold, and other approaches, in some cases using values from many grid points in the model. If measurements are available in real-time, such as from an automatic weather station, Kalman Filter and other time series analysis techniques can also be used to update the forecast based on observations in the past few days to weeks. This approach has similarities to the error prediction and state updating approaches used in hydrological forecasting applications (see Chapters 4 and 7).

One advantage of statistical post-processing techniques is that they are relatively simple to develop and apply operationally. With some approaches, probabilistic estimates can also be derived based on the estimated uncertainty in the relationships. In the past, this was the main route to producing probabilistic short- to medium-range meteorological forecasts, before the introduction of ensemble forecasting techniques. Where methods are calibrated to long-term historical records, the outputs are also usually consistent with the long-term data (climatology) at the site of interest; however, this has the disadvantage of the need for recalibration if there are changes to models or instruments. Also, in some approaches, the forecast variables are not necessarily consistent (correlated) spatially, or at a given site (e.g. for multiple variables), which can be important if they are subsequently used in a hydrological model or a decision support system. One way to reduce the need for recalibration if the NWP model changes is to use a virtual grid, and to calibrate additional relationships from the model grid points to that grid, with a second set of relationships to the observation points.

Perhaps the most highly developed form of statistical post-processing is the method of Model Output Statistics (MOS) developed by the National Weather Service in the USA and used since the 1970s (Glahn and Lowry 1972, Antolik 2000). Using a national database of observations for a range of variables at several thousand stations, and historical forecasts, multiple regressions and other approaches are used to establish adjustment procedures. These are then routinely applied to the outputs from Numerical Weather Prediction models following each model run. Relationships may vary with season, lead time, time of day, and other factors. Non-linear relationships can also be included through statistical transformations of outputs.

A more recent development has been to perform the calculations on a gridded basis, using interpolations for the observed values where these are only available at a point (i.e. excluding weather radar and satellite observations). Forecast verification studies generally show a significant increase in forecasting skill compared to the raw model outputs, both for point estimates, and interpolated fields based on those estimates. Probabilistic estimates, with estimates of uncertainty, can also be derived for each site of interest.

Statistical post-processing techniques can also be applied to ensemble forecasts so that, over the long-term, the estimates provide a better match to the statistical characteristics of the historical data. Adjustments of this type are required because ensemble members typically represent only a sample of the full probability distribution at each model run, and do not necessarily account for all sources of uncertainty, such as the uncertainty in model parameters. Perhaps the simplest approach is to apply the same adjustment to each ensemble member as used for the deterministic (or control) run, whilst being mindful of the impact that non-linear adjustments may have on the statistical characteristics of the ensemble. A wide range of regression, quantile matching, distribution matching and other approaches has also been considered to account for differences between the observed and forecast probability distributions over a hindcast period (e.g. Bremnes 2004, Wilks and Hamill 2007).

As an example, Fig. 3.8 shows the impact of application of a statistical post-processing approach to a 10-day ensemble air temperature forecast, before and after application of the correction (Persson and Grazzini 2007). For the adjusted ensemble, the spread of the plume has been significantly reduced, whilst retaining the substantial minority of ensemble members which indicated that the cold weather at the start of the forecast period would continue.

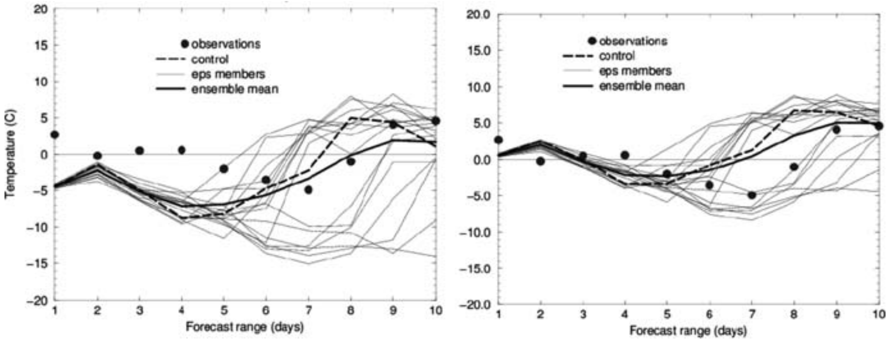

Fig. 3.8 Example of application of a statistical post-processing technique to a 10-day ensemble air temperature forecast, showing the original (*left*) and adjusted (*right*) forecast (Persson and Grazzini 2007; Source: ECMWF)

As noted in Section 3.2, when using the outputs from several models (i.e. a multi-model ensemble), another post-processing option is to use Bayesian Model Averaging (Raftery et al. 2005). This approach assesses the performance of each ensemble member in real-time in the recent past, and then combines the estimates to produce a new distribution in a way which assigns a higher weighting to better performing ensemble members. However, perhaps the most comprehensive approach of all is to perform the entire analysis within an overall Bayesian uncertainty processing framework (Krzysztofowicz 2004).

3.3.2.3 Analogue Techniques

Analogue or weather matching/typing techniques are another form of post-processing, and seek to identify similar atmospheric conditions to those which are currently forecast by searching through an archive of forecasts and/or observations. This can include matching both of ground-based data (e.g. from weather stations) and atmospheric data, with the atmospheric values obtained from previous Numerical Weather Prediction model runs or historical radiosonde ascents.

Often the approach used is to seek to find one or more variables which, in principle, are more predictable than the parameter of interest; for example, using surface atmospheric pressure values or geopotential heights, rather than precipitation fields (e.g. van den Dool 2007). Matching techniques include principal component analyses, pattern matching, and more qualitative techniques, such as identification of similar general classes of weather system, and may take account of current short-, medium- and long-range forecasts. One advantage is that the spatial and temporal variability of the estimate is preserved, since values are extracted from the historical record. The overall performance depends on the suitability of the predictors chosen, and the search algorithms used to identify analogous conditions.

For example, this approach has formed the basis of an operational method which has been used successfully for rainfall forecasting for reservoir operations in southern France since the 1970s. There have been many improvements and developments since that time, and these are described in Box 3.2.

Box 3.2 An Analogues Approach to Rainfall Forecasting

Quantitative Precipitation Forecasts, combined with rainfall-runoff models, provide the possibility of extending the lead-time available for estimating inflows for reservoir operations, or to anticipate a flood event. However, although major improvements have been made to Numerical Weather Prediction (NWP) modelling techniques in recent years, the accuracy and resolution of rainfall forecasts is still sometimes insufficient at lead times of 1–3 days ahead or more, particularly for small, fast response catchments.

By contrast, forecast verification studies suggest that the uncertainty surrounding parameters such as air temperature and pressure is generally lower, and that the predictive value of forecasts extends to longer lead-times. To take advantage of this additional performance, for more than 30 years the main electricity supply company in France, Electricité de France, has used an adaptation process for identifying analogous situations from the past to provide estimates of daily rainfall for up to 7 days ahead to assist in managing reservoirs for water supply and hydropower generation (Duband 1970, Obled and Datin 1997, Obled, personal communication).

The so-called ANALOGS model complements nowcasts (0–6 h) and NWP model outputs (6–72 h ahead), and has been progressively improved since its introduction in the 1970s, with a significant upgrade implemented in 1999 (Obled et al. 2002, Djerboua and Obled 2002). The underlying assumptions (e.g. Obled et al. 2002) are that:

- there have been synoptic situations in the past that were not necessarily identical but similar, over a certain domain, to the current one for which a forecast is required
- during such situations, local variables, such as precipitation over a medium-sized mountain catchment, react partly in response to the synoptic situation, but also to more local features (e.g. orography, wind channelling, etc.), which are embedded in the historical data
- for this given day, the part explained by regional circulation will be similar to that observed in the analogous situations, and can be associated with a conditional distribution of the rainfall observed in similar synoptic situations

In operational use, a meteorological archive of more than 50 years of reanalysed/hindcast situations is used (merged with stored radiosonde measurements of geopotential heights, ground and satellite data etc.). The current process is performed in two steps.

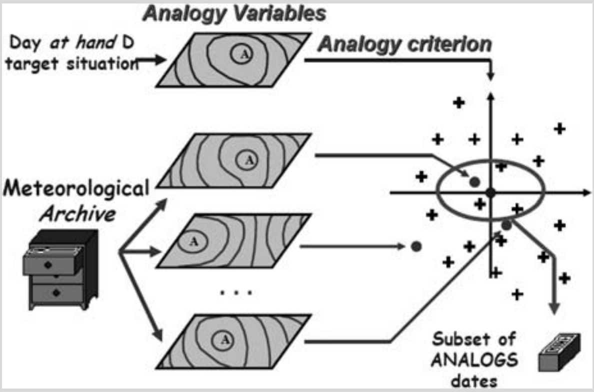

Fig. 3.9 Illustration of principles of the ANALOGUES model (Obled et al. 2007)

Firstly, the target situation considered (e.g. the NWP forecast for one of the next few days) is searched for in the archive to find the days which most closely match current forecasts for the 1,000 hPa and 500 hPa values at 0000 UTC, over a domain of about 1,500 km centred on the catchments (which are in southern France in this case). For lead times up to 72 h, forecasts can be taken from the Meteo-France ARPEGE numerical weather prediction model, whilst the ECMWF European model is used for longer lead times, or the NOAA Global Forecasting System. A first set of 50–70 days is selected, which are analogous in terms of the general situation. The search criterion (Teweless and Wobus 1954) takes account of the south–north and west–east gradients in geopotential and, by implication, the synoptic circulation, with a limit of 2 months either side of the current date to allow for seasonal effects (Fig. 3.9).

In the second step, a subset of 30–35 days is selected from the initial set which, beyond having a rather similar circulation, share similar humidity conditions close to the catchment. Given the quality of the forecast for those humidity variables, this second step is restricted to the next 72 h of the forecast, while the first can be applied up to 10 days ahead.

The daily catchment rainfall amounts for those days are then extracted from a hydrological archive for the catchments of interest, and a probability distribution fitted to the resulting values (with an incomplete gamma function used). Probabilistic estimates for future rainfall can then be generated by sampling from this distribution. Research has suggested that a sample of about 50 analogs for a single step procedure, and 35 out of 70 for a two-step procedure, provides the best performance, assessed in terms of a Ranked Probability Score (Obled et al. 2002, Obled, personal communication).

The method is used to provide forecasts of daily rainfall at lead times of up to 7 days for more than 70 catchments with areas in the range 200–2,000 km^2. The probabilistic nature of the forecasts allows users to better understand the likelihood of critical levels or flows being reached, and the uncertainty associated with the forecast at different lead times. Information can also be used in decision support systems, and to assist with decisions to draw down reservoirs to provide additional storage in advance of heavy rainfall and runoff.

Current research is focussing on the use of reanalyses/hindcasts of numerical weather prediction model outputs to provide a more consistent meteorological archive for the region, and to allow for a wider range of possible predictors (e.g. humidity, temperature, wind speed, potential vorticity). Multi-model approaches are also under development (Obled et al. 2007). The derivation of catchment rainfall values at shorter time intervals than daily (e.g. 12 hourly) is also being investigated, either by disaggregating daily values, or using ground-based data, although with the difficulty of only a limited coverage of autographic raingauges, compared to manually operated daily raingauges. The method is an adaptation method to be applied downstream of a NWP, providing either single deterministic or ensemble forecasts. One main advantage is that it is unbiased in that the adapted rainfall forecasts have the same climatology as the observed rainfall.

3.3.2.4 Dynamic Downscaling

Another post-processing technique is to operate local numerical weather forecasting models, calibrated specifically for the region of interest, using the outputs from a coarser scale model to provide the boundary conditions. This is a form of dynamic (or dynamical) downscaling of outputs which, in principle, should be able to account for a wider range of conditions than simpler statistical approaches. However, the success with this approach depends on the suitability and calibration of the model which is used, and of any data assimilation techniques. Nowcasting techniques (see Section 3.2.1) are also sometimes described as a form of dynamic downscaling when the rainfall extrapolation is guided by the outputs from Numerical Weather Prediction models.

Of course, the process of nesting local, regional and global models is also routinely used in operational weather forecasting, as described in Section 3.2 and – with some meteorological services now routinely operating models at a grid resolution of 1–2 km – there may be no requirement for operation of a more detailed model. However, other possibilities include running specific types of model on demand (e.g. when a major storm event is forecast, or following a major atmospheric pollution incident), or organizations running their own models based on boundary conditions provided by regional or global scale models.

For example, as discussed earlier, during the unusually wet summer of 2007 (Cabinet Office 2008), the UK Met Office ran a 1.5 km scale research model for a brief period to test its capabilities, and a development of this model is now implemented operationally for the whole of the UK. By contrast, in the western USA, a steady state multi-layer 2D model (Rhea 1978) is operated by the California-Nevada River Forecast Centre (CNRFC) in Sacramento to provide estimates for watershed precipitation and snow levels in the Sierra Nevada for up to 5 days ahead (see Box 1.1). Another example is for a project in New York City which included routine operation of a high resolution non-hydrostatic mesoscale model on behalf of the city authorities (Treinish and Prano 2006).

Compared to some other post-processing approaches, some advantages of dynamic downscaling are that values are internally consistent, and can potentially account for a wider range of meteorological conditions (subject to the functionality in the model) Some disadvantages can include the considerable technical expertise required to operate some models, the telecommunications infrastructure required (e.g. for data assimilation), and the computationally intensive nature of some approaches (although some models are capable of being operated on personal computers). Also, as for any model, the accuracy of the results is ultimately limited by the extent to which the model represents natural processes. The model outputs are also affected by the quality of the coarser resolution model used to provide the model boundary conditions although this can to some extent be mitigated by use of a higher resolution data assimilation scheme; for example, using additional sources of information such as Doppler radar winds, aircraft-based data, nowcasting model outputs, additional ground-based stations, and high resolution satellite images.

3.3.3 Forecast Verification

Meteorological services routinely assess the performance of forecast outputs, and are often required to report on key measures to government and other organizations. Performance measures also provide a guide to the need for future improvements, and where to target effort in research, data assimilation and model development, and also allow comparisons with the forecasts produced by other organizations. Many different approaches to verification have been developed covering both deterministic and ensemble forecasts (e.g. Stanski et al. 1989, Jolliffe and Stephenson 2003, Casati et al. 2008). For example, Murphy (1993) identified the following three characteristics of a good forecast:

- Consistency – the correspondence between forecaster's 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. Chapter 6 discusses the concept of value in more detail whilst, to assess the usefulness of a meteorological forecast in hydrological applications, some key attributes include:

- The forecast performance at a range of and scales compared to the parameter of interest (e.g. catchment average rainfall)
- Performance relative to critical thresholds, such as the depth and duration of rainfall which might cause flooding (often called categorical statistics)
- The decay in forecast performance with increasing lead time, giving an indication of the maximum lead time at which the forecast is of value
- The shape, spread and consistency (from run to run) of the distributions implied by ensemble forecasts (if used), their interpretation in probabilistic terms (compared to the climatological probabilities), and the correspondence with the deterministic or control run (if used)

In addition to simple statistical measures such as the maximum, minimum, average and cumulative values, a number of other parameters are of interest in meteorological applications, and Table 3.5 summaries some widely used examples. However, more than one measure is required to adequately describe the forecast performance, particularly for ensemble and probabilistic forecasts.

Many other types of skill score have been devised, and typically express the difference in performance compared to a reference forecast, such as the assumption that recent conditions will persist, or that the best guess for the future is to base the estimate on past climatological conditions. Values are normally expressed as a ratio to the value for the reference forecast.

Table 3.5 Examples of meteorological forecast performance measures relevant to hydrometeorological forecasting applications

Performance measure	Characteristic of the forecast which is quantified
Bias	Mean of the errors in the forecast
Brier Skill Score (BSS)	A skill score based on the Brier score, which is the mean squared probability error (i.e. based on the difference between the probability of ensemble members exceeding a threshold, compared to 0 if not exceeded, and 1 if exceeded)
Correlation coefficient	A measure of how close forecast values are to a regression line of forecast and observed values on a scatter plot
False Alarm Ratio (FAR)	The proportion of forecasts when a forecast for a threshold exceedance was incorrect
Probability of Detection (POD)	The proportion of events when a forecast for a threshold exceedance was correct
Ranked Probability Score (RPS)	A mean Brier Score for continuous variables (e.g. air temperature) across a full range of threshold values. Can be calculated in both discrete and continuous forms
Reliability	One interpretation is as a mean square error measure of the closeness to a 1:1 line on a plot of forecast and observed probabilities (based on exceedance of a threshold value)
Relative Operating Characteristic (ROC)	A plot of the Probability of Detection against the Probability of False Detection for a range of probability thresholds; the ROC is the area under the curve (in the range 0–1, and 0.5 for climatology)
Root mean square error (rmse)	The square root of the sum of the squares of the errors in forecast values

Table 3.6 Example of a 2 × 2 contingency table (showing the number of times that the event occurred in each category)

		Event observed	
		Yes	No
Event forecast	Yes	A	B
	No	C	D

As indicated, some measures are used primarily for ensemble and probabilistic forecasts, whilst contingency measures such as POD and FAR can be used in a wide range of applications and are usually estimated from a 2 by 2 contingency table, as shown in Table 3.6 (POD = A/(A +C), FAR = B/(A + B)). Many other measures can be devised from this simple table, and higher order tables can also be constructed; for example, with a range of different threshold values.

Some other approaches to forecast verification include spectral decomposition of the errors, and approaches which take account of the spatial variability and structure of precipitation, using pattern matching, object oriented and other techniques. Simple graphical or ‘eyeball’ comparisons are also widely used. For many measures, performance is ideally reported using forecasts over a sufficiently long period that the statistics are representative of the longer term climatology. In some cases this can require hindcasts or reanalyses using the model and data assimilation system in its current state, as described earlier in Section 3.3.1. The findings from meteorological intercomparison experiments are also of interest; for example, the THORPEX Interactive Grand Global Ensemble (TIGGE) experiment which was mentioned in Section 3.2.

Compared to hydrological forecasting, the techniques for meteorological forecast verification are perhaps better established and have been developed to a greater degree, although many of the key ideas are now used in hydrological model verification, particularly for flood warning and forecasting applications (see Chapters 4 and 7). There are also some key differences between meteorological and hydrological forecasting applications, which can influence the choice of verification measures. One example is the case of null forecasts, in which no event is forecast, and none occurs, which can count towards success criteria for meteorological forecasts (e.g. no ice on roads overnight, as expected), but are often not considered in hydrological forecasting applications. Another is the need to consider extremes which may only occur a few times in the observational record, such as some types of flood and drought events.

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Chapter 4
Hydrological Forecasting

Abstract Hydrological forecasts typically aim to translate meteorological observations and forecasts into estimates of river flows. Techniques can include rainfall-runoff (hydrologic) and hydrological and hydrodynamic flow routing models, and simpler statistical and water-balance approaches. Additional components may also be required for water quality applications, and for modeling specific features of a catchment, such as reservoirs, and lakes, and the influence of snowmelt. Particularly for short lead times, models may also need to be embedded in a forecasting system, which controls the gathering of data, the model runs and the post-processing of outputs. The availability of real-time data also provides the option to update the model states or parameters or to post-process the outputs to improve the accuracy of the forecast; a process which is often called data assimilation or real-time updating. For operational use, appropriate performance measures also need to be adopted for forecast verification. This chapter presents an introduction to these various topics, and to the general issues of forecast uncertainty, and probabilistic and ensemble flow forecasting.

Keywords Rainfall-runoff · Hydrologic · Flow routing · Hydraulic · Hydrodynamic · Data assimilation · Performance measures · Forecast verification · Forecast uncertainty · Probabilistic forecast

4.1 Introduction

4.1.1 Modeling Techniques

River flow forecasts can be used in a wide range of applications, including flood warning, drought early warning, water resources management, and providing warnings of pollution incidents.

Hydrological forecasting models have many similarities to the types of simulation models developed for off-line studies for design, planning and other applications. One of the first such approaches was the unit hydrograph (Sherman

K. Sene, *Hydrometeorology*, DOI 10.1007/978-90-481-3403-8_4,

1932), in which a linear relationship is assumed between a unit depth of effective rainfall falling in a given time, and the resulting runoff. The combined river flow hydrograph is then estimated from the sum of these incremental contributions. This approach is still widely used in flood estimation studies although, for real-time use, other types of rainfall-runoff (or hydrologic) models are generally preferred, within the general categories of physically-based, conceptual or data-driven models.

For design applications, statistical analyses of historical data are also widely used, such as frequency analyses, flow duration analyses, and threshold ('run-sum') analyses. These methods, although not directly applicable to forecasting applications, can be useful in assessing the performance of a model during calibration, and in providing a historical context within which forecasts can be evaluated and outputs presented. As described in Chapter 6, the resulting values are sometimes also useful in setting thresholds for decision making; for example in some flood and drought forecasting applications. Box 4.1 provides a brief introduction to these techniques, whilst more details can be found in most hydrological textbooks.

Once water (or runoff) enters the river system, then the resulting flows can be translated to locations further downstream; a process which is often called flow routing. For example, Fig. 4.1 shows an example of how rainfall-runoff and flow routing models might be combined into a flood forecasting model for a town in the lower reaches of a catchment, and another town at a river confluence in the middle reaches of the catchment. Additional models (not shown) would normally also be included to represent the ungauged inflows to the flow routing reaches (and other configurations could also be envisaged). This integrated catchment modeling approach is widely used in flood forecasting and water resources applications, with the main alternatives consisting of distributed, grid-based, representations of the catchment, and simpler water balance approaches, as described later.

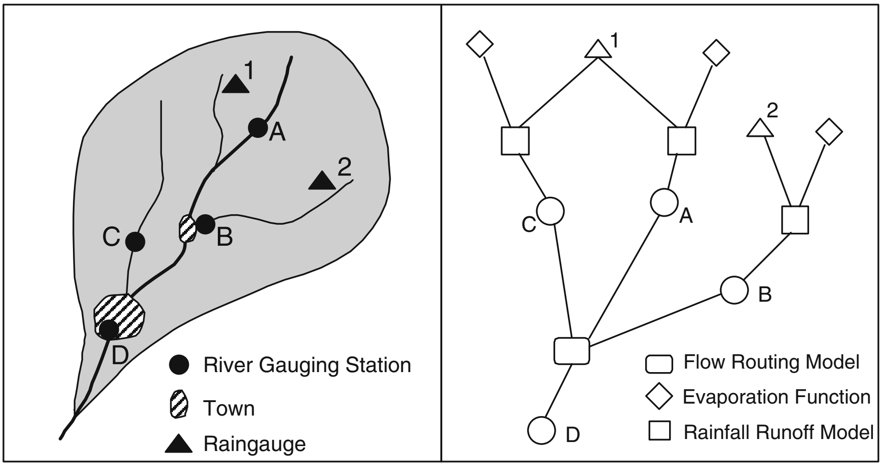


Fig. 4.1 Example of model configuration in a flood forecasting system (Sene 2008)

Flow routing models typically consider mass conservation (continuity of flow), and may also consider the conservation of momentum and/or energy. The basic governing equations for fluid flow were first established in the nineteenth century, in the form of the Navier Stokes equations, and in simpler forms, such as the St Venant equations for shallow water. Hydrodynamic models, based on these equations, and simpler approaches (see below), are widely used in real-time forecasting applications, and are often coupled to rainfall-runoff models for the headwater and tributary inflows. The transport of contaminants such as pollutants can also be included in the model formulation, either as passive 'tracers' or allowing for the interactions with both the river flow through dilution and chemical reaction and – for ecological applications – the life cycle of organisms. Similar types of model are also used in environmental forecasting applications for major lakes and reservoirs, and in surge forecasting for coastal waters.

More empirical approaches, such as the Muskingum method and storage routing approaches, are also widely used due to their relative computational simplicity and modest data requirements, and are sometimes called hydrological flow routing models. Indeed, some forms, such as the kinematic wave and Muskingum-Cunge approximations, are a simplified form of the equations of motion (Lighthill and Whitham 1955, Cunge 1969). Also, for longer lead times, it can be reasonable to consider a mass or water balance alone, as in the supply-demand modeling techniques which are widely used for water resource applications, and which are discussed in detail in Chapter 11. Many studies have also sought to forecast seasonal and longer-term flows using similar statistical approaches to those described in Chapter 3 for meteorological conditions. Some possible predictors include snow water equivalent, sea surface temperatures, and sea surface pressure and indices linked to the El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) (e.g. Chiew and McMahon 2002, Troccoli et al. 2008, Palmer and Hagedorn 2006). Some examples of these approaches are described in Boxes 1.1 and 1.2, Box 11.3, and in Chapter 8.

Section 4.2 provides a brief introduction to these various forecasting techniques, and to a range of more specialized models for snowmelt and water quality, and further details can be found in many hydrological textbooks and review volumes (e.g. Anderson and Bates 2001, Anderson and McDonnell 2009, Bedient et al. 2008, Beven 2001, Chanson 2004, Chow 1959, Singh 1995, Singh and Frevert 2002 and World Meteorological Organisation 1994). When used in an operational forecasting environment, particularly for short lead times it is also important to consider how data will be received, the scheduling of model runs, and the post-processing of model outputs, and this topic is discussed in Section 4.3. As with meteorological forecasts, in a real-time application, models can be initialized based on recent observations, and model inputs, outputs or parameters can be adjusted based on the performance of the model in the recent past (up to 'time now'). This process, called data assimilation or real-time updating, is another feature which distinguishes forecasting models from their off-line simulation counterparts, and is particularly important for short to medium lead times. Models can also be calibrated, and/or the performance evaluated, on the basis of the forecasts for a given lead time, such as the 3- or

6-h ahead forecast, which is a particularly useful approach in flood forecasting applications (see Chapter 7).

As with many other types of models, hydrological forecasting models are subject to many sources of uncertainty, including uncertainties in the input data, model parameters, initial conditions, and boundary conditions. The model structure may also be inappropriate or less than ideal for the situation under consideration. The extent to which these factors influence the model performance should be evaluated during the model calibration, and in subsequent monitoring of the operational performance, and ideally in real-time operation. Also, particularly where the lead time required exceeds the response time of the hydrological system, meteorological forecasts may also be used as an input to the models, which introduces another source of uncertainty, particularly for longer lead times. These issues have long been recognized (e.g. Day 1985, Yeh 1985, Krzysztofowicz 2001, Beven 2008), with a wide range of approaches developed to help to assess the uncertainty in forecasts. These include sensitivity tests, Monte Carlo sampling, Ensemble Streamflow Prediction (ESP) methods, and use of the ensemble outputs from Numerical Weather Prediction models. These topics are discussed briefly in Section 4.3, with a more detailed discussion in Chapters 6 and 7. These issues also arise in meteorological forecasting, and are discussed in more detail in Chapter 3.

Box 4.1 Statistical Techniques in Hydrology

Statistical techniques are widely used in hydrology to provide long-term estimates of river flows for flood, drought and other applications, and are described in most hydrological textbooks. In addition to the mean, maximum and minimum flows, some parameters of interest for flood-related applications include the flow of a given duration with a given return period or annual probability of flooding (e.g. the 1 in 100 year or 1% value) whilst, for low-flow applications, some useful indicators include the flow of a given duration which is exceeded for a given percentage of the time (e.g. the daily mean flow exceeded for 95% of the time, Q95) and the maximum cumulative volume (or deficit) below a threshold. Hydrograph separation techniques are also used to estimate the baseflow and surface runoff components, represented by parameters such as the Base Flow Index (BFI).

The usual approach to deriving estimates of this type is through statistical analysis of long term flow records, sometimes combined with stochastic generation of synthetic flows to extend the period available for analysis. Conceptual rainfall-runoff models are also sometimes used to extend flow records, using continuous simulation approaches. The main statistical techniques which are used include:

- Frequency analyses – transformation of a sequence of high or low-flow values assuming an underlying probability distribution, then fitting a straight line to the transformed values using standard statistical techniques
- Flow Duration Analyses – analyses of the flows which are exceeded for a given proportion of time in the observational record
- Threshold Analyses – in which the cumulative flow deficits below a given threshold are calculated, with the resulting values sometimes interpreted using frequency analyses

Analyses of trend can also be useful, both to check the consistency of long-term observations, and to identify any actual trends which may be occurring (e.g. due to changes in abstractions and discharges in a river reach, or long-term variations in climate). Some typical approaches to detecting trend include regression analyses, spectral decomposition, comparisons of total or mean values for different time periods, and significance tests using stochastically generated time series assuming some underlying trend or cyclical behaviour.

For frequency analyses, some widely used distributions for high flows include the Gumbel, Generalised Extreme Value and Log-Pearson Type III distributions, with the Weibull, Gumbel, Pearson Type III and Log-Normal distributions widely used for low-flows (e.g. Smakhtin 2001, Tallaksen and van Lanen 2004). Curve fitting techniques include Method of Moments, Maximum Likelihood and Probability Weighted Moments approaches. However, internationally, the number of distributions used is large, with one survey (World Meteorological Organisation 1989) listing some 10–20 types of distributions used for flood frequency analysis by national hydrological services and other organizations. Also, having estimated flood or low flow values using a frequency analysis, regression relationships are often developed which incorporate catchment characteristics, meteorological parameters, and other factors. For example, both catchment area and mean annual rainfall are sometimes useful predictors for floods of a given return period.

For flood-related analyses, frequency analyses are often performed in terms of the time series of annual maximum flow values (ideally based on sub-daily data). However, a common problem is that, at a given river gauging location, there may only be a short period of record and/or only a few flood events since records first began. Two widely used approaches for increasing the amount of data points available for analysis are peaks-over-threshold methods, in which all values above a threshold are selected, and regional or pooling group analyses, in which values from a number of gauges in hydrologically similar catchments are combined. Normalised regional or growth curves can also be derived for application to similar catchments, where typical parameters for normalization include the mean annual flood or the median annual maximum flood. Censored (or bounded) values are also sometimes used in situations where records are incomplete or uncertain to provide a measure of the uncertainty in the outputs.

By contrast, for low-flow analyses, it is often the cumulative shortfalls in water which are of interest, and analyses are typically performed in terms of daily, weekly or longer values. Stochastic flow generation using Monte Carlo and other techniques can also work well at longer timesteps, such as for monthly or annual values. This is because the serial (auto-) correlation in successive flow values is of less importance than for sub-daily values, and so can more easily be modeled using conventional time series analysis techniques. It may also be possible to assume statistical independence between successive values, although both serial and spatial correlations can be included in the analysis if required. Also, additional statistical sub-models can be introduced to disaggregate values estimated at a longer time interval (e.g. annual or monthly) to shorter time intervals.

For reservoir design, estimates are also often required for the Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF). The World Meteorological Organisation defines PMP as theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year. For PMP values, typically an approach of storm transposition and maximization is used, in which maximum observed storm depth-area-duration values, of the required duration(s), are transferred to the site of interest from meteorologically similar areas (World Meteorological Organisation 1986). These values are adjusted (maximized) by a factor which depends on the maximum observed precipitable water based on long term records at the site of interest, and representative values for each storm. Typically dew point observations from weather stations are used as a surrogate for atmospheric precipitable water values. Other factors can also be applied for wind speed and elevation differences. However, more complex approaches are often required for mountainous regions to take account of topographic influences, and can include atmospheric modeling and/or use of additional empirical adjustment factors. Simpler approaches using frequency analyses, regression relationships or regional maps and charts are also used in some studies.

Once the PMP has been estimated, estimates for the Probable Maximum Flood can then be derived using rainfall-runoff models. Typically, a unit hydrograph or conceptual rainfall-runoff modeling approach is used, with allowances for the influence of extreme rainfall on the infiltration component of the model, and the relative lack of importance of soil moisture conditions. Storm maximization or frequency analysis techniques based on precipitation and snow depth can also be combined with empirical (e.g. degree-day) or conceptual snowmelt models to estimate the Probable Maximum Snowmelt.

4.1.2 Model Design Issues

In developing a hydrological forecasting model, the choice of approach can depend on the catchment characteristics, the lead-time requirement, the spatial scale which is to be considered, and a range of other factors, including the availability of real-time data (where relevant), the budget available and the operational requirement. In particular, it is important to consider how forecasts will be used in the decision-making process, such as for issuing a flood warning, or providing early warnings for a pollution incident. The optimum approach often depends on the specific application, and later chapters discuss a range of examples. Conceptual frameworks can also assist with model design, such as the 'Source-Pathway-Receptor' approach. This approach is widely used in environmental applications, and considers the problem in terms of sources (e.g. diffuse pollution), pathways (e.g. the land surface), and receptors (e.g. rivers), with separate models required for each component. Section 5.3 provides an example of this approach for a flood risk management application.

The choice of modeling approach is also often tailored to the level of risk, where risk is defined as the combination of the probability of an event occurring (e.g. a flood), and the consequences if it does occur (e.g. damage to property, loss of life). For example, in flood warning applications, for a major city in the tidal reaches of a river, an integrated catchment modeling approach might be justified, combining meteorological, rainfall-runoff, hydrodynamic and coastal forecasting components. By contrast, for lower risk areas such as farmland and riverside footpaths, a simpler approach, such as a level to level correlation, might be sufficient. Similar decisions also arise in drought, flow control, water quality, ecological and water resources applications, and are discussed in more detail in Chapter 6 and later chapters. The development of integrated meteorological, hydrological, hydrodynamic and coastal models is also an active research area, and is sometimes called a 'Clouds-to-Catchment-to-Coast' (NERC 2007) or 'Sky to the Summit to the Sea' (NOAA 2008) approach. The term 'End-to-End' modeling is also sometimes used, although more often applies to the full decision making chain, from observations to forecasts to warnings and response.

As discussed in Chapter 1, the lead-time requirement for hydrological forecasts can range from a few hours or less for flood warning applications, through to weeks, months or even years for more slowly developing events, such as droughts, and in situations with a large volume of water in storage, such as for large reservoirs, lakes and aquifers. For short lead time applications, the model time step is often set equal to the shortest interval at which real-time data is available; for example, in the United Kingdom, a standard interval of 15 min is used for polling of river level and flow data by telemetry. However, at longer lead times, such as in drought forecasting applications, there is often the option of using longer timesteps since sub-daily variations in flows are of less interest. Other factors might also place constraints on the approach which is used include the availability of real-time data (which might only be available on a daily or longer basis), the need to maintain a strategic overview of seasonal water use (e.g. in reservoir forecasting applications), and limitations on computing power. Meteorological forecasts (when used) may also only be available at particular times of day, for short- to medium-range forecasts, or even only on a weekly or monthly basis, for seasonal forecasts, and may need to be disaggregated to the timescale of interest (see Chapter 3 and Section 4.3). The forecast scale is also an important consideration; for example, with current technology, the grid resolution of nowcasting and Numerical Weather Prediction models is typically 1–10 km for short-range forecasts, and increases to 10–100 km as the lead time increases.

To illustrate the influence of the choice of timestep, Fig. 4.2 shows the relationship between rainfall and river flows for three different time intervals, using a sub-daily (hourly) flow record as a starting point. The values are hypothetical, but illustrate that different modeling approaches may be appropriate in each case, with a greater emphasis on physically-based runoff generation mechanisms at shorter time steps, and in maintaining a long-term water balance at longer timescales. These points are discussed further in later sections and chapters, whilst most hydrological textbooks provide a more detailed discussion of this point.

The issue of data availability is particularly important at shorter lead times due to the need to use telemetered data values (or values relayed by observers). This may lead to a model configuration which is very different to that which would be used for longer term applications, such as drought forecasting, for which all available river flow gauges might be used, provided that regular site visits can be made to collect

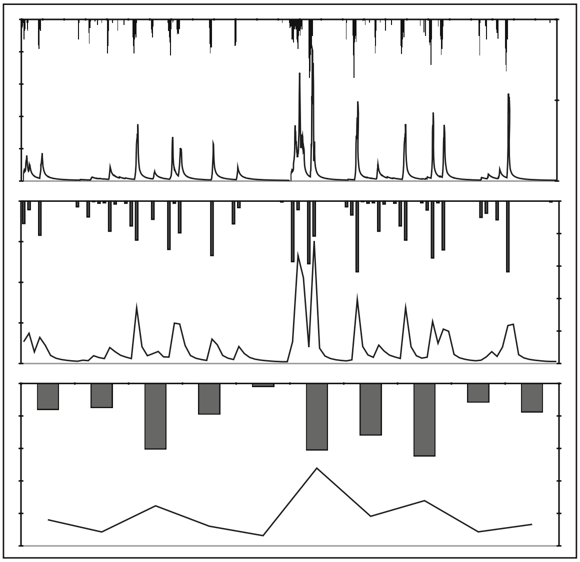


Fig. 4.2 Illustration of the relationship between rainfall and river flows for a range of model timesteps over a 100-day period (**a**) hourly (**b**) daily (**c**) 10-day

data. This point is illustrated in Fig. 4.1, and is discussed further in Chapter 7 for the case of flood forecasting models. The need to handle real-time data can also restrict the range of modeling approaches which can be used since, as noted earlier, this may require investment in a computer-based forecasting system, which may only be capable of operating a certain number of model types. These various model design issues are discussed in more detail in Chapters 7 to 11 for flood, drought, flow control, environmental and water resources forecasting applications.

4.2 Forecasting Techniques

4.2.1 Rainfall-Runoff Models

Rainfall-runoff, or hydrologic, models, form a key component in many hydrometeorological forecasting systems, and aim to translate observations and/or forecasts of rainfall into estimates for river flows. Sub-models, or separate models, may also be included for snowmelt, where this is relevant, and other factors, such as reservoirs and groundwater storage.

Table 4.1 summarises some of the main components which may need to be included in a rainfall-runoff model, and which collectively make up the hydrological or water cycle. Note that, for land surfaces, the evaporation and transpiration components are often considered as a single parameter called the evapotranspiration, although some definitions exclude the open water evaporation component. Some methods for estimating this quantity are discussed briefly in Chapters 2 and 5. The precipitation inputs (rainfall, snow etc.) may be obtained from raingauge, weather radar or satellite-based inputs and/or nowcasts or other Quantitative Precipitation Forecasts. For some applications, it may be possible to obtain sufficient lead time from observed rainfall values alone whilst, for longer lead times, rainfall forecasts may provide the only option. Where raingauge values are used, it may also be necessary to include a model for the catchment average rainfall, and Chapter 2 describes some examples of the types of approaches which are used. These include Thiessen polygons, inverse distance methods and geostatistical techniques. Where meteorological forecasts are used, then some statistical or other pre-processing may be desirable to improve and (possibly) to downscale the estimates, and this topic is discussed in Section 4.3.2.

The importance of each contribution to the water balance varies between catchments and geographic location, and some factors may not always be relevant (e.g. snowmelt), or may be small compared to other influences (e.g. abstractions). Flow control is also often included as part of the flow routing component of a catchment model, rather than in the rainfall-runoff model component. Therefore, as part of the model calibration, careful consideration is required of the extent to which flows are influenced by abstractions, discharges, flow control and other factors and, if these are significant, the recorded flows are sometimes adjusted to 'naturalise' the

Table 4.1 Some of the main processes which may need to be represented in a rainfall-runoff model in response to precipitation inputs

Layer	Item	Description
Surface	Runoff	Runoff from the soil surface 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. Also the accumulation and melting of ice
Soil	Evaporation	Evaporation from bare soil areas, rainfall intercepted by vegetation, and 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 and the water table/aquifer
Sub-surface	Recharge	Recharge to the water table/aquifers from deep percolation and, to a lesser extent, from surface flows
	Baseflow	Outflow of water into the river network from aquifers. Sometimes called groundwater flow or discharge
Contaminants	Point and Diffuse (non-point) pollution	Pollution inputs from farms, urban areas etc., particularly during and following heavy rainfall events (see Chapter 10)
Artificial influences	Abstractions	Abstraction of water for public water supply, irrigation, energy generation, industry etc. (see Chapter 5)
	Discharges	Discharge of treated effluents and other return flows (e.g. from irrigation schemes) (see Chapter 5)
	Flow control	Influences from reservoir operations and other control structures (see Chapter 9)

record before it is used in model calibration, with the influences then allowed for in the real-time application. Later chapters provide a more detailed discussion of the main factors which need to be considered in flood, drought, environmental and other applications.

The terminology which is used varies, but – in general terms – rainfall-runoff models may be distinguished by the way that they represent physical processes, and how they represent flows at a catchment scale. Scale issues are discussed later, whilst the main approaches to modeling rainfall-runoff process are:

- Physically-based Models – which typically use partial differential equations to describe the main processes by which rainfall is translated to runoff, are usually operated on a grid-basis, and are sometimes called process-based, deterministic or distributed models
- Conceptual Models – which typically use simpler, conceptual approaches to represent the conversion of rainfall to runoff, such as stores which fill and empty due to rainfall and evapotranspiration, and which represent surface runoff, infiltration, percolation, groundwater discharge, and other processes

- Data-Driven Models – which use transfer function, artificial neural network, and related approaches to estimate river flows given the available rainfall and other data, and are sometimes called black-box or data-based models

Here, a transfer function rainfall-runoff model is typically a time-series model which relates flows at the current timestep to observations of rainfall and levels or flows at previous timesteps. Various hybrid forms have also been developed, such as physically-based models which include conceptual components, which are sometimes called physical-conceptual models, and models which combine both conceptual and data-driven components. Figure 4.3 shows some simple examples of the use of physically-based, conceptual and data-driven models to represent the same catchment, and further examples of all three categories of models can be found in Chapter 1 and Chapters 7–11, with examples of how they are used in operational forecasting applications.

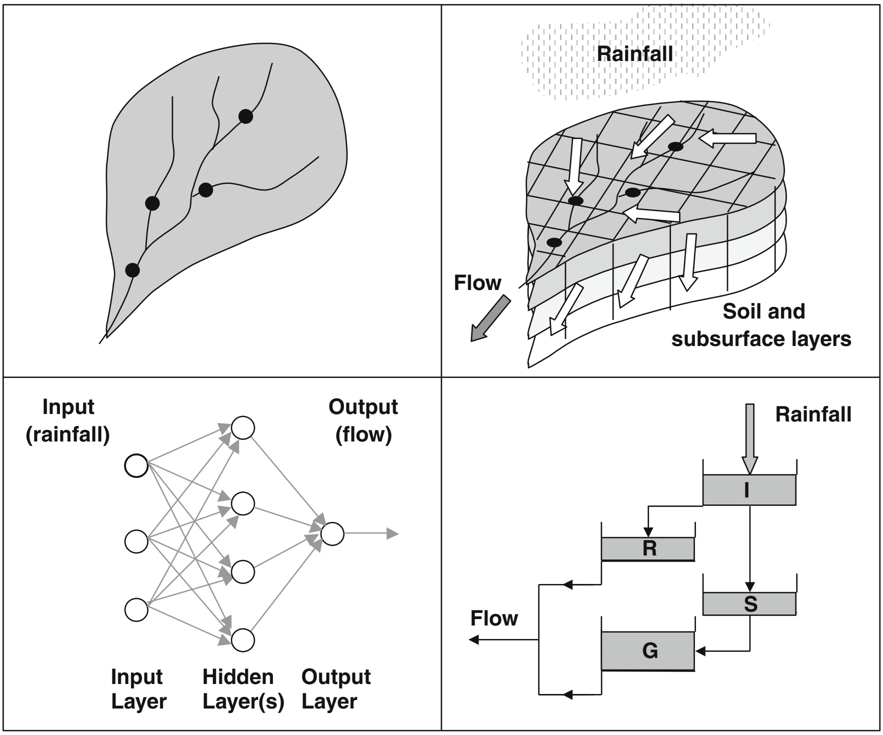


Fig. 4.3 Some simple examples of physically-based, conceptual and data-driven rainfall-runoff models (evapotranspiration components not shown). From top left clockwise (**a**) plan view of catchment with four river gauging stations (**b**) physically-based model with three soil and subsurface layers (**c**) conceptual model with interception, soil, surface runoff and groundwater stores and (**d**) artificial neural network model (adapted from Sene 2008)

For physically-based approaches, models may include a number of vertical layers, representing various aspects of the surface, soil and sub-surface runoff processes. Flows may be routed between model grid cells using approximations to the general equations of fluid flow, such as the kinematic wave equation. When used in forecasting applications, models are typically formulated to make use of readily available real-time data, including satellite observations of vegetation and snow cover, and gridded estimates for rainfall from rainguage, weather radar, and/or satellite observations and rainfall forecasts. Model parameters are typically obtained from laboratory and field experiments, and sometimes from the values used in other hydrologically similar catchments, with some further fine-tuning during the calibration stage. Spatial (GIS) analysis techniques are widely used to relate the model parameters and configuration to soil types, land cover, flow paths, geology, and digital elevation datasets. Coupled land-atmosphere models perhaps represent the most sophisticated form of this type of model, and can represent a wide range of processes, including vegetation growth, soil hydraulics, snowmelt, and energy transfer by radiation, conduction and advection (see Chapter 11). However, for short-term forecasts (e.g. in flood forecasting), given the constraints on data availability and model run times, simpler physical-conceptual formulations are perhaps the most widely used approach (see Chapters 7, 8 and 10).

For conceptual models, by contrast, model parameters are usually estimated primarily from a comparison of observed and estimated flows, although may be constrained to remain within a given range; for example, based on findings from similar catchments, or physical considerations. The results from regionalisation studies are also sometimes used, which seek to relate model parameters to catchment characteristics. Automated fitting techniques are often used to provide an initial estimate for the parameters, and typically aim to minimise measures such as the R^2 Efficiency or the root mean square error. The resulting model fit is usually assessed in terms of the shape, magnitude and timing of the hydrograph, and possibly other measures, such as the timing of the crossing of threshold values, or the performance at a range of lead times. Multi-objective optimization techniques may also be used, and empirical time delays introduced to better represent the delays between rainfall and runoff.

For data-driven models, a range of times series analysis techniques and other methods may be used to optimize the model performance. 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 can be calibrated (or 'trained') by adjusting the weighting factors and adding or removing neurons, using a range of approaches including Bayesian methods, genetic algorithms, and stochastic approaches, such as simulated annealing. The use of artificial neural network models has been considered in many hydrological applications, including flood forecasting, drought forecasting and environmental applications (e.g. ASCE 2000, Dawson and Wilby 1999), with some operational applications, particularly in short to medium-term demand forecasting (e.g. see Section 5.3). Similarly, for transfer function models, powerful techniques are available for identifying the model structure and parameters, including stochastic approaches, and can be guided by a physical interpretation of the underlying modes and timescales inherent in the catchment response, whilst preserving the data driven nature of the model (e.g. Young and Ratto 2009).

Later sections and chapters provide several examples of operational rainfall-runoff models (in particular, Chapter 7), whilst more detailed descriptions can be found in the various references cited, including Beven (2001), Bedient et al. (2008), Singh (1995), and World Meteorological Organisation (1994). There is much debate about the relative merits of each type of model (e.g. Arduino et al. 2005, Sivakumar and Berndtsson 2009, Todini 2007), and Table 4.2 summarises some of the advantages which are often stated for each approach. A multi-model approach can also be used, in which the outputs are compared from several types of model (e.g. Zappa et al. 2008), providing an indication of the uncertainty arising from model structural issues, as well as from the uncertainty in meteorological forecasts.

Intercomparison studies can also provide useful insights into the strengths and limitations of different types of model within each category although with care needed in the design of the experiment, and interpretation of the results (e.g. Reed 1984, Clarke 2008). Some international examples include a series of studies by the World Meteorological Organisation (e.g. World Meteorological Organisation 1992), the NOAA/NWS Distributed Model Intercomparison Project (Smith et al. 2004) and a subsequent follow-on phase (DMIP2), and an intercomparison component within the wider European Flood Forecasting System project (European Flood Forecasting System 2003).

Table 4.2 Some potential advantages of different rainfall runoff modelling approaches (adapted from Sene 2008)

Type	Description
Physically-based	Well suited to operate with spatially distributed inputs (weather radar, satellite, Numerical Weather Prediction model outputs, multiple inflow locations etc.) Can represent variations in runoff with both storm direction and distribution over a catchment Parameter values are often physically based and can be related to catchment topography, soil types, channel characteristics etc., including (possibly) the potential to represent events outside the range of calibration data
Conceptual models	Fewer parameters to specify or calibrate than in the physically-based approach Fast and stable for real time operation Easier to implement real time state updating than for physically-based models
Data driven models	Parsimonious, run times are fast, and models are tolerant to data loss Can be 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

For operational use, as noted earlier, some other factors which may influence the feasibility of applying a given approach include the availability of real-time data, the forecasting system used for model operation, and the approach used for model calibration and performance monitoring (see Section 4.3). The familiarity of users with the model type and approach can also be a factor in how well a model is calibrated, and performs in an operational environment. Also, increasingly, a toolkit approach is used for model development, in which the various components which are required can be configured according to the application. Additional components may also be included for modeling artificial influences, such as reservoirs, and for specific applications, such as irrigation schemes.

Another item which is often included in high elevation or high latitude regions is a snowmelt module. Several modelling approaches can be used, including simple empirical methods which relate cumulative heating (degree-days) to snowmelt, conceptual models, which include stores for snowpack, melting snow, and other components, and physically-based models, which account for both the mass and energy balance of a snow layer. Figure 4.4 shows an example of the components which may need to be considered in models of this type.

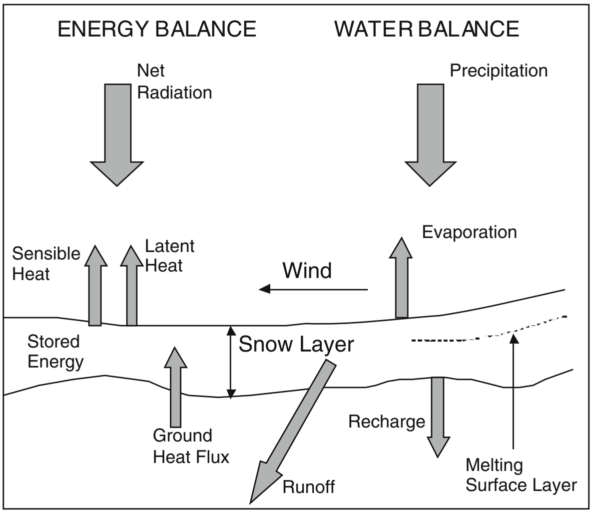


Fig. 4.4 Some key features in the energy and water balance for a melting snow layer ; directions of fluxes may vary (Sene 2008)

Some features which may need to be represented include the energy inputs from net radiation, advection losses, evaporation, runoff to streams and rivers, and recharge to subsurface layers. Models may also include some representation of the spatial variations in snow depth with topography, elevation, and other factors, as described in more detail in Chapter 7. The main challenge in using this type of model for forecasting applications is to obtain sufficient data to initialize the model, and Box 7.3 describes one approach to data assimilation for snowmelt models at a national scale. Phase 2 of the Snow Model Intercomparison Project (SnowMIP2) has also compared the performance of 33 models from 11 countries for forested areas in the northern hemisphere (Essery et al. 2009).

Rainfall-runoff and snowmelt models can be applied to part of a catchment, or to a whole catchment, either alone, or linked to models for the river network (see Fig. 4.1 for example). The main approaches are to use lumped, semi-distributed or distributed (grid-based) models. Figure 4.5 illustrates the difference between the lumped and semi-distributed approaches; note that, in this example, as is often the case for short- to medium-term forecasting models, the sub-catchment boundaries for the semi-distributed model are defined to the telemetry gauging stations, rather than to river confluences. Smaller sub-catchment areas or hydrological response units might also be defined based on considerations of soil types, land use, geology and other factors.

The distributed approach and, to a lesser extent, the semi-distributed approach, can allow for the influence of rainfall distribution, and the direction of storm travel, on flows, which can be particularly important at short lead times (e.g. in flood forecasting applications). Physically-based or physical-conceptual models are normally used in distributed form, whilst conceptual and data-driven models are usually used in lumped or semi-distributed forms. For the distributed approach, the grid may be regular, or irregular, with the grid resolution tailored to the individual features of interest. and may adopt a grid-to-grid (cell-to-cell) or source-to-sink approach (e.g. Moore et al. 2006).

For the semi-distributed approach, estimates for runoff are also required for any ungauged catchment areas. Also, for distributed models, there is the general issue of how to assess the variability in runoff response and model parameters across the catchment, based on any gauged flow data available. The issues of model parameter estimation, and ungauged flow estimation, have been considered in several international studies, including the Model Parameter Estimation Experiment (MOPEX; Andrssian et al. 2006) and the Flow Regimes from International Experimental and Network Data programme (FRIEND; for example, Servat and Demuth 2006). Some approaches to estimating flows for ungauged areas include:

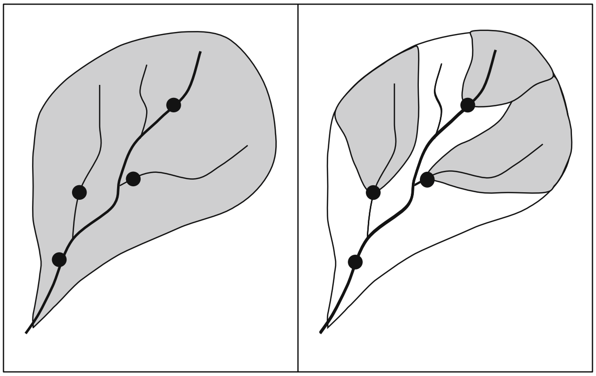


Fig. 4.5 Illustration of lumped and semi-distributed rainfall-runoff models (gauged areas shown shaded)

- Transferring parameter values for a model calibrated for a nearby hydrologically similar gauged catchment, or searching for regional regression or other relationships between the model parameters and catchment characteristics
- Use of a physically-based model with model parameters derived from laboratory or field-scale experiments and spatial datasets
- Scaling of flows measured at a telemetered gauge in a nearby hydrologically similar catchment based on catchment area, and possibly other factors (e.g. average annual rainfall), with an appropriate time delay or difference (a ‘scale and lag’ approach)

Each method has its strengths and limitations; for example, scale and lag approaches have the advantage of using real-time, observed data, but assume that the ungauged catchment experiences the same rainfall regime as the gauged catchment, with a similar response, thereby to some extent losing the influence of spatial variations in rainfall around the catchment. Transfering parameter values helps to avoid this limitation, but relies on the values which are used being representative of the catchment. In practice, an iterative or trial and error approach is often used to model fitting, treating the ungauged flow contributions as another source of uncertainty in the overall catchment model.

4.2.2 Flow Routing Models

Flow routing models translate river flows through a river network, and can include reservoir and lake routing components. The types of model can range from simple correlation approaches, which relate levels and/or flows at an upstream location to values further downstream, through to one-, two- or three-dimensional hydrodynamic models. Additional components may also be included for modeling the transport of contaminants and sediment, and for ecological applications. The approach which is used can depend on a number of factors, including the lead time and accuracy required, the flow mechanisms to be considered, and the availability of real-time data and meteorological forecasts. Indeed, for longer term applications, it may not be necessary to consider dynamic effects at all, and a simple water balance may be sufficient; for example, supply-demand models, which consider all key inflows and outflows, including artificial flows such as abstractions and effluent discharges, are widely used in water resources applications, and are described in Section 11.2.

Corrrelations or regressions are perhaps the simplest approach, to the extent that they are sometimes not even considered under the category of ‘flow routing’. The result is usually a simple scaling and translation of upstream flows, without accounting for factors such as floodplain storage and flow attenuation, which can sometimes have a major effect on the flow hydrograph further downstream. Figure 4.6 illustrates the use of a peak to peak or crest stage correlation to estimate flows at a downstream location from values which are measured or forecast at an upstream

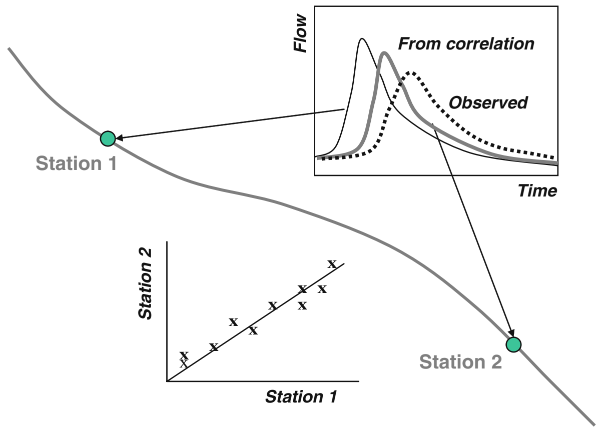


Fig. 4.6 Illustration of a peak to peak flow correlation, and derivation of downstream flows. For this example, the correlation-based forecast did not fully account for the flow attenuation which was subsequently observed

location. In this case, the correlation has been applied to the full flow range, with a typical time delay, although it was derived only from peak values, which can introduce some additional errors. Other factors, such as tributary inflows between the gauges, and snowmelt, can also influence the accuracy of the relationship. However, multiple sets of curves, or multiple regressions, with more than one input, can sometimes be used to help to account for these factors (e.g. World Meteorological Organisation 1994). Correlations can also be derived in terms of levels where this is required operationally, as in some flood warning applications, for example, or where no flow estimates are available at a gauging station (e.g. where there is no stage-discharge relationship available). Whilst level-to-level correlations avoid the uncertainty in deriving flow estimates, other factors can influence the accuracy of the relationship, such as downstream influences from tidal levels, or backwater effects from operations at a flow control structure.

Data-driven methods such as transfer functions or artificial neural network models, with single or multiple inputs, can also be used to provide a form of flow routing, in which flows at a downstream location are related to inputs at one or more other locations further upstream. The models could also include locations further downstream, such as a tidal boundary in an estuary or coastal waters. For example, transfer function routing methods have been used in operational flood forecasting (Lees et al. 1994), and also show promise in emulating the performance of more complex hydrodynamic models in probabilistic forecasting applications, where model run times can sometimes be a constraint (e.g. Young et al. 2009).

The remaining approaches to flow routing consist mainly of hydrological and hydrodynamic techniques, which seek to preserve a mass balance along the river reach (or reservoir or lake), and in some cases also consider the conservation of momentum and/or energy, including losses due to friction at the river bed, and at control structures and other obstacles to flow (e.g. Chanson 2004, Chow 1959, Novak et al. 2006, Ji 2008). 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 approach. Both approaches express the mass balance for the reach as a differential equation, relating the rate of change of volume to the difference between the inflow and outflow to the reach. In the reservoir routing approach, it is assumed that the storage can be derived from the reservoir or channel dimensions, whilst the Muskingum method conceptualizes the flow hydrograph as consisting of rectangular (prism) and triangular (wedge) storage components. Computational solutions are typically obtained by dividing the river reach into sections, and the inflows from tributaries and losses due to spills over embankments etc. can also be included in some formulations. Later studies (Cunge 1969) showed that, with the choice of a suitable grid length and timestep, the Muskingum equation is an approximation to a simplified form of the St Venant equations.

Some key parameters in the resulting Muskingum-Cunge formulation are the wavespeed, which influences the travel time in a river reach, and an attenuation parameter. In practice, both parameters vary with flow, particularly in situations in which the river goes out of bank onto the floodplain, and later developments (e.g. Price 1977, Tang et al. 1999) have considered variable parameter values to help to allow for this effect. Similar approaches are also used in other approximations to the St Venant equations, such as the kinematic wave and convective-diffusion equation approaches.

These methods are widely used in operational flood forecasting systems (see Chapter 7), and some techniques, such as kinematic wave routing, are also used within distributed rainfall-runoff models to route flows between adjacent cells (see Section 4.2.1). Calculations are normally performed in terms of river flows, and river levels (if required) are estimated from application of a stage-discharge relationship. Models are typically calibrated using automated optimization routines, to maximize the value of an objective function although, in some approaches, parameters such as the wavespeed can be estimated from survey data for just a few river channel cross-sections.

Although hydrological flow routing methods work well in many situations, one general limitation is that often these methods are not able to take account of the influences on river levels from downstream factors, such as tidal influences or tributary inflows, particularly for shallow sloping rivers. Also, it may be difficult to include the influence of other complicating factors, such as operations at flow control structures, or spills over flood defences (levees or dikes) and embankments. In these situations, flows can be particularly sensitive to the accuracy of the estimates for levels, and in some cases there may be parallel and return flows to consider. Some examples of river forecasting applications might include providing flood warnings for a major city in the lower reaches of a catchment, or forecasting levels in an ecologically sensitive wetland. Also, for reservoirs and lakes, hydrological flow routing approaches cannot provide the detail on currents, vertical circulation and other factors which are required for many applications.

These considerations have led to the increasing use of hydrodynamic models in forecasting applications. Also, limitations on computing power, which at one time constrained their use for short lead-term applications, are nowadays less of a consideration, particularly if models are tuned for real-time use, and simplified in locations distant from Forecasting Points (e.g. Chen et al. 2005). For river forecasting models, the usual approach is to divide the reach under consideration into a number of discrete sections, represented by nodes along the main river channel. Each section should cover a reach with hydraulically similar response, with nodes positioned along the river channel every few hundred metres or less (typically), and at locations where there is a change in flow characteristics, such as at changes in cross section, river bed characteristics or slope. Additional survey information may also be required for features which can influence river levels and flows, such as hydraulic structures (weirs, barrages, culverts etc.) and flood defence systems. As described in Chapter 7, in cold climates, the effects of river ice may also need to be considered, both in terms of the restrictions on river flows when the surface is frozen, and other factors such as ice jams and break-up (e.g. Morse and Hicks 2005, White 2003).

Models are typically calibrated using pre-defined values for key parameters such as loss coefficients and bed friction coefficients (e.g. Manning's n), followed by fine tuning of parameters and ungauged inflows to obtain a good fit between observed and forecast flows. The river channel dimensions are typically obtained from survey data, measured using traditional ground-based and boat survey, perhaps supplemented by information from Global Positioning System (GPS) devices, and also Digital Terrain Model data if the model is to be extended onto the floodplain. Information on structures is ideally obtained from the as-built drawings, supplemented by information on the current condition obtained from site surveys. The equations of motion are then solved computationally for each subsection, using the observed or forecast inflows into the main river channel and significant tributaries, to drive the model. Figures 2.8 and 7.4 show examples of schematics for models of this type.

Flows on the floodplain can be represented by parallel channels, a network of interconnected cells or reservoir units, or using a two-dimensional modeling approach. For example, in the UK, one-dimensional hydrodynamic flood forecasting models are widely used (e.g. Werner et al. 2009), with models typically having several hundred to several thousand node points, and being required to run reliably within the 15 min available between each update from the national telemetry network. There is also increasing interest in coupling river forecasting models to urban drainage models to represent the interactions between river and urban flows, and this topic is discussed further in Chapter 9.

A similar approach is also used to building hydrodynamic models for reservoirs and lakes, except that the main driving influences may now include wind shear at the water surface, and the thermally driven circulation. Depending on the relative volume size of the water body compared to typical annual inflows, these factors may be more significant than the circulation driven by tributary inflows. Models are often three-dimensional, so that run times are usually longer than for a river forecasting application, and it may only be possible to run the model occasionally, such as on a daily or weekly basis. The model grid may be regular, or irregular in both the horizontal and vertical directions, to capture key shoreline and depth-related processes, such as thermal stratification and surface currents. The key sources of survey information now include bathymetry data captured by depth or acoustic sounders, and digital terrain data for the shoreline. However, to simplify the model, and reduce run times, a two-dimensional model may be sufficient for shallow water bodies when the water depth is small compared to horizontal length scales. Chapter 10 provides some further description of the use of models of this type for water quality and ecological forecasting applications, for timescales from a few days ahead to months or years. Typically, the contaminant or organism can be represented either as a passive tracer, or sub-models can also be included for dilution and chemical reactions, and growth and decay (as appropriate).

Shallow water hydrodynamic models are also widely used in coastal forecasting applications, typically using the outputs from Numerical Weather Prediction models to provide the wind and pressure fields required at the ocean boundary. The outputs of surge and tidal levels from this type of model are often used to provide the downstream boundary condition for hydrodynamic river flow forecasting models. Wave forecasts may also be provided, typically using 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, which relates the input of energy from the wind to the dissipation of energy by wave–wave interactions, wave-current interactions, and wave breaking (e.g. Komen et al. 1994, Tolman 1999). Models of this type may also be useful for large lakes.

Groundwater numerical models also use a similar modeling approach, in which the subsurface flows are again modeled on a two- or three-dimensional grid, which is tailored to provide a high resolution around the main features of interest, such as boreholes and line sources (e.g. rivers), and the main hydraulic controls on subsurface flows. The main components in the water balance for subsurface flows typically include recharge from surface water sources and rainfall, and outflows at springs, wells and boreholes, and into the river system. Aquifers may be confined or unconfined, and considerable detail may be included for the main geological features. A contaminant transport component may also be included. Simpler conceptual models are also sometimes used, in which groundwater flows are estimated from the subsurface stores in a rainfall-runoff model, or from a water balance considering recharge, abstractions and outflows.

In operational use, groundwater models can be 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, and models of this type are more usually used for forecasting for water resources or drought applications (and may only be used on an occasional basis). However, Box 7.3 describes a national flow forecasting and water resources modeling system which is operated several times per day, and includes a conceptual groundwater component, and Chapter 8 describes a coupled river and groundwater forecasting system for the Netherlands, which is operated on a daily basis. Box 11.4 also describes a coupled land-atmosphere simulator for modelling over longer timescales which includes detailed soil and subsurface models.

4.3 Operational Considerations

When using a hydrological forecasting model in an operational environment, a number of factors need to be considered, including forecast verification, data assimilation and forecast uncertainty. Also, particularly for shorter lead times, models may be operated within an automated forecasting system, which can impose some constraints on the types of models which can be used. As in meteorological forecasting applications (see Chapters 1 and 3), some additional processing of outputs is often required to convert the forecasts into operationally useful products, and later chapters, and Chapter 1, provide examples for a wide range of map-based, graphical and tabulated outputs, and of the use of forecasts in decision support systems. The remainder of this chapter provides an introduction to some of the operational considerations regarding forecasting systems, data assimilation, forecast uncertainty and forecast verification.

4.3.1 Forecasting Systems

In operational use, a hydrological forecasting model is typically driven by inputs from a wide range of sources, including meteorological observations and forecasts, river observations, and other data types. Whilst at long lead times it can often be practicable to operate models as required (on demand), using one-off transfers of data, at shorter lead times some degree of automation becomes useful, particularly when a telemetry system is used (e.g. as in many flood warning applications). An automated system can also provide initial data quality control, reduce the time spent on routine data processing and manipulation, and assist with the maintenance of an audit trail of forecasting model runs. The main tasks performed by an automated system can include some or all of the following items:

- Data Gathering – receipt of data from instruments such as raingauges and river gauging stations, and possibly weather radar and satellite observations, and forecasts from meteorological services
- Pre-processing – initial validation of data using checks on range, rate of change etc., and intercomparisons with nearby records, and possibly also automated infilling of short gaps in records, and application of pre-defined correction factors
- 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
- Data Assimilation – use of observed data to initialize model states and/or improve the forecast outputs (see Section 4.3.2)

- Post-processing – post-processing of the forecast outputs into map-based, graphical and tabulated formats, and for onward transmission to other systems, such as decision support systems
- Data Management – storage of both input data and forecast results for subsequent review and analysis and training

This process is similar to that used in meteorological forecasting, and Fig. 4.7 illustrates how a meteorological and hydrological forecasting system might exchange information. Many organizations operate systems of this type, either developed in-house, or based upon commercially available systems. Also, as discussed in Chapter 7, in flood forecasting systems there are often additional components to allow for alarm handling, and the automated dissemination of warnings. Note that the term 'decision support' is used here in the widest sense, and can range from visual inspection of outputs through to automated decision support systems of the type described in Chapter 6.

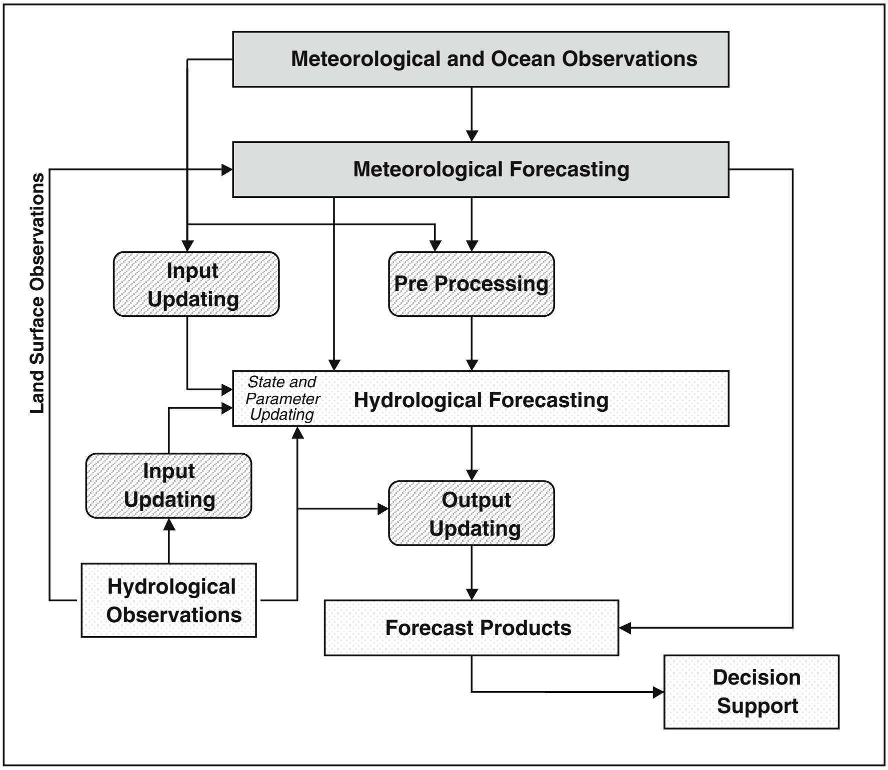


Fig. 4.7 Illustration of some typical linkages between meteorological and hydrological forecasting systems. Note that not all components and links may be used or required; in particular the items shown with cross-hatching. Also, usually only one form of updating would be used. Ocean observations can include coastal and estuary levels

Chapter 3 provides more detail on the meteorological forecasting component and, as noted, often some form of post-processing is applied to Numerical Weather Prediction (NWP) model outputs before delivery to hydrological forecasters and other users. Techniques can include statistical post-processing, using methods such as non-linear regression and Kalman Filtering, weather matching/typing/analogue approaches, and dynamic (or dynamical) downscaling. Ideally NWP and other outputs would be made available under a system of version control, so that any improvements to meteorological forecasts (resolution, representation of sub-grid processes, ensemble generation processes etc.) can be notified and the impacts on hydrological model performance assessed.

Before use in a hydrological model, some additional processing or calibration is sometimes performed and, from a hydrological perspective, this is often called meteorological or hydrological pre-processing, or calibration or conditioning of meteorological forecasts. Where this involves the use of observed (real-time) data, rather than being based on the historical forecasting performance, this pre-processing step can be regarded as a form of data assimilation, which is described in the following section.

The requirement to use these techniques depends largely on the quality and resolution of the meteorological forecasts which are provided. For deterministic forecasts, this can best be determined through analysis of the performance of forecasts over a range of events or number of years, at the forecast lead times of interest. However, as discussed in Chapter 3, one barrier to performing this type of analysis is that this requires access to an archive of rainfall forecast values, ideally produced with the meteorological forecasting component in its current form (models, data assimilation etc). Hindcasting or re-analysis exercises of this type have been performed by a number of meteorological services, although can be a considerable undertaking. For ensemble forecasts, the probabilistic content of the forecast also needs to be considered and, as discussed later, this is a particular area where some form of pre-processing is often required (e.g. Schaake et al. 2007b). Of course, the view could be taken that any bias or other issues with meteorological forecasts can be absorbed in the hydrological model calibration and data assimilation components; however, as with all components in the modeling chain (e.g. rating curves, catchment averaging procedures), it is better to reduce uncertainties at source if possible.

Similar considerations also apply for long-term forecasting for climate change and other applications, where statistical, dynamical (regional climate model) and other downscaling approaches are also a major area of research, together with the related topic of temporal disaggregation of results to shorter timescales, using stochastic weather generators and other approaches (e.g. Wilby and Wigley 1997, Xu 1999). Stochastic approaches have also been used in downscaling for short-term flood forecasting applications (e.g. Ferraris et al. 2003, Rebora et al. 2006).

Although there are many valid reasons for using forecasting systems, one other consideration is the resilience to failure of any one component, such as a model, a computer server, an instrument, or a telemetry connection, and the safety or other implications of that failure. This issue is particularly important in flood and pollution forecasting applications, and there are various strategies for coping with problems of this type. These can include the use of alternative simpler models, or manual methods (e.g. correlation plots), and using computer systems running in parallel. Other options include using a hierarchy of data inputs, and maintaining alternative routes (or manual approaches) for feeding data into the system. For example, a common data hierarchy for raingauge inputs is to switch automatically to an alternate gauge in case of failure, and then to use a pre-defined profile if that gauge fails also. This issue is discussed further in Chapter 7 for flood forecasting applications, but is also relevant to a number of other short- to medium-term applications, such as providing warnings for pollution incidents, hydropower scheduling, water supply operations, and reservoir operations.

It is also worth noting that it can be feasible to implement quite sophisticated and low cost approaches which are entirely, or mainly, manually based. Some situations where this might be the preferred approach include applications where the resources or infrastructure are not available to support a more complex system, where data input requirements are modest and the lead-time requirement long, and/or where the risk is low and a more complex system is not justified. For example, in the early days of forecasting for flood warning and water resources applications, many systems relied on observers feeding back information by telephone, radio or fax (or telegraph) to a central location where paper-based or computer-based forecasting methods could be used, with that information then transmitted to the emergency response or operating authorities. Real-time updating, if used, could also be performed manually, or interactively on a computer screen; for example, by adjusting forecasts by shifting values along the time axis, applying scaling corrections, and other adjustments to make forecasts blend more smoothly with the observed values up to the present time ('time now').

With a network of observers either living on site, or making observations around other duties, it can be feasible to receive data several times per day and perform the associated analyses. This approach is still used in some countries, and can also provide a basis for back-up procedures to more complex systems. Of course, for very short lead time applications, such as flash flood warning, this approach may not be practical. A balance is therefore required between meteorological forecast accuracy, catchment response times, and the time required for an effective emergency response.

4.3.2 Data Assimilation

Data assimilation is the process of using recent observations of river flows or levels, and possibly catchment conditions, to improve forecast outputs and, in flood forecasting applications, is often called real-time updating or adaptation. The main motivation for using data assimilation techniques is to help to account for uncertainties in the model parameters, rainfall and other inputs (including meteorological forecasts), and model initial and boundary conditions. Some data assimilation techniques simply provide an improved (single-valued or deterministic) estimate for the forecast, whilst others also provide a measure of the uncertainty in the forecast, based on the recent and/or long-term model performance. Data assimilation is often recommended as best practice, provided that the data quality and availability is sufficient to support the method which is used, without degrading the forecast performance. Some examples of the 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

Indeed, for a chain of models in an integrated catchment model, as noted earlier, whenever possible it is generally better to resolve issues at each model input and boundary (e.g. with rainfall forecast inputs, weather radar data, or stage-discharge relationships), rather than to rely on data assimilation or the model calibration to compensate for these issues. This is particularly relevant to models which seek to preserve continuity of mass (and momentum, if applicable); for example, in rainfall-runoff models, over the course of a rainfall event, a stage-discharge relationship which is considerably in error at high flows might imply an event runoff coefficient much greater than unity, which would adversely affect the model calibration, and performance during real-time operation. These considerations also apply to the post- or pre-processing (or conditioning) of meteorological forecasts based on historical performance, as discussed in the previous section.

Figure 4.8 shows a simple example of data assimilation for a flow forecasting application, in which the forecast flows from the time of the most recent observation are adjusted based on the time series of errors in the forecast in the recent past. In this case, the forecasting model overestimates flows when compared to the observed values up to the present time ('time now'), and the resulting adjustment reduces these flows throughout the flow range; note also that, at longer lead times, the magnitude of the adjustment decreases, as the information content of the observed data decreases, which can be typical for this type of approach. This type of data assimilation is often called error correction or error prediction, and is a form of output updating, which is only one of the following general approaches to updating (e.g. O'Connell and Clark 1981, Rungo et al. 1989, Serban and Askew 1991, World Meteorological Organisation 1992, 1994, Refsgaard 1997, Moore 1999):

- Input Updating – adjustment of the input data or forecasts to the model
- State Updating – adjustment of the initial model states

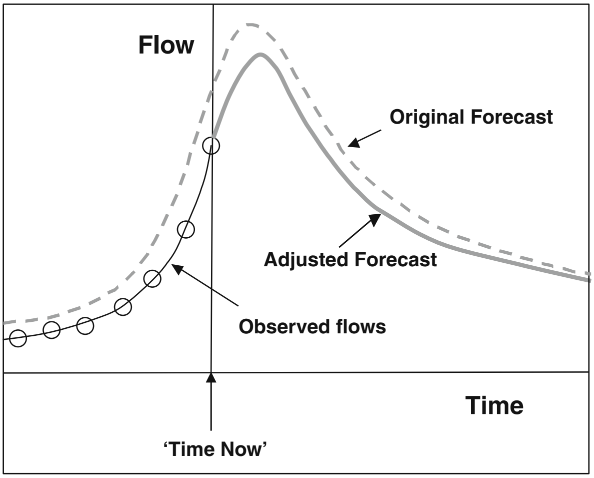


Fig. 4.8 Example of an error prediction approach to data assimilation (adapted from Sene 2008)

- Parameter Updating – adjustment of the parameters of the model
- Output Updating – adjustment of the outputs from the model

Figure 4.7 shows examples of where input updating and output updating appear in the information flow for a hydrological forecasting model, whilst state updating and parameter updating routines are usually internal to the model.

Input updating techniques are occasionally used for adjusting rainfall observations, and in hydrodynamic modeling applications; for example, when distributing model errors into the inflow components Some of the meteorological post-processing techniques discussed in Chapter 3 might also be viewed as a type of input updating when real-time observations are used as part of the process. One difference though is that, in meteorological forecasting, it is often necessary to relate forecasts at a location (or locations) distant from the point of interest (e.g. from a Numerical Weather Prediction model grid node) whereas, in hydrological applications, a forecast is often available at the location of interest (e.g. a Forecasting Point). However, this situation does also arise in some distributed and hydrodynamic modeling applications; for example, when translating coastal surge forecasts to a downstream model boundary in an estuary.

State updating is another widely used technique, particularly for the initialisation of conceptual rainfall-runoff models, including snowmelt stores (e.g. Bell et al. 2000). However, this approach can be more challenging to apply for distributed rainfall-runoff models, since the forecast errors observed at gauge locations need to be distributed over the whole model domain. Other types of measurements might also need to be considered, such as satellite and ground-based observations of soil moisture and snow cover. In this case, variational techniques are sometimes used, as described in Chapter 3 for meteorological applications (e.g. Le Dimet et al. 2009, Seo et al. 2009), together with a range of model-specific approaches (e.g. see

Boxes 7.3 and 11.3). Similar issues of distributing errors over a domain also arise for hydrodynamic models; for example, in real-time inundation mapping. Some approaches to updating in this situation include making adjustments to inflows from tributaries, and interpolation of levels between gauged locations.

For parameter updating, when using physically-based and conceptual models, views differ on whether it is meaningful to change the parameters of a model in real-time, since parameter values should have some physical meaning. However, in some situations, restricting any adjustments to a likely range is an option (e.g. for the river channel and floodplain roughness coefficients in a hydrodynamic model). Output updating techniques are more widely used and typically a time series analysis model is fitted to the sequence of errors between forecasts and observed flows up to time now, as a basis for estimating the likely future variations in those errors (and hence the required forecast adjustments). This approach is analogous to some of the statistical post-processing methods used in meteorology which are described in Chapter 3. Indeed, as already noted, and there are many parallels between data assimilation in meteorology and hydrology, with some terminology in common, as illustrated in Table 4.3.

Table 4.3 Examples of some alternative terms used for data assimilation in hydrological forecasting applications for deterministic and ensemble forecasts. Techniques developed primarily for ensemble forecasts are indicated by the letter (e)

Type	Alternative terms	Examples of methods
Input updating	Meteorological post-processing, hydrological pre-processing	Kalman Filtering (including extended and ensemble versions), Bayesian Model Averaging (e), manual (forecaster) adjustments (see Chapter 3)
	State updating	Redistributing model errors into tributary inflows in hydrodynamic models, adjusting raingauge weights in catchment rainfall estimates
State updating	Real time updating	Often model specific, but can include changing the states (store contents) in conceptual rainfall-runoff models and snowmelt models; also Kalman Filtering (including extended and ensemble approaches), Particle Filtering, variational techniques for distributed (grid-based) models, and simple substitution of observed values up to 'time now'
Parameter updating	None known	Model specific, but can include adjustment of roughness coefficients in hydrodynamic models, runoff factors in rainfall-runoff models, and other parameters, using empirical, Kalman Filter and other approaches
Output updating	Error correction, error prediction, output correction, real-time adjustment, real-time updating	Time series analysis techniques (e.g. Autoregressive Moving Average; ARMA), artificial neural network, gain updating, and manual (forecaster) adjustments, such as blending and scale and lag approaches

As for meteorological forecasts, some additional post-processing may also be performed based on analyses of the historical performance of the model, as well as (or instead of) making use of real-time data, using techniques such as regression relationships and quantile regression (see Chapters 3 and 7). Also, for data-driven models, there are several more sophisticated time series analysis techniques beyond those described in Table 4.3, which can also provide a measure of the uncertainty in forecasts (e.g. Young and Ratto 2008).

Whilst one of the main reasons for using data assimilation is to reduce the intrinsic uncertainty in forecasts, the benefits which are obtained to some extent also depend on the hydrological response time of the system under consideration since, at longer lead times, the ‘memory’ of any initial adjustments tends to decrease. For catchments with large or multiple reservoirs and lakes, or large aquifer storage, the dependence on initial conditions can extend for many months and sometimes across years. However, even for small fast-response catchments, the magnitude of flood events can depend strongly on the antecedent soil moisture conditions, and snow cover (if relevant), which respond on a slower timescale than the surface runoff.

Due to the short lead times which are often required, data assimilation techniques are perhaps most highly developed for flood forecasting applications, and this topic is discussed further in Chapter 7. Later chapters also present examples of the use of data assimilation in snowmelt forecasting (Chapters 7 and 11), reservoir modeling (Chapter 9), and water resources applications (Chapter 11).

4.3.3 Forecast Uncertainty

As in meteorological forecasting, it is widely acknowledged that the uncertainty in the forecasts from hydrological models should be recognized and estimated, both operationally, to advise users on the uncertainty in forecasts (e.g. Krzysztofowicz 2001), and more generally to drive future model and data improvement programmes. In particular, this information is potentially of value to forecasting duty officers, who can assess the confidence to be placed in forecasts, and may, in some cases, decide not to issue a forecast on the basis of that information, or at least to wait until the next model run, when hopefully the uncertainty will have reduced.

The extent to which information on uncertainty should be communicated to the public and other end users is an active area for research in both meteorology and hydrology, with a balance required between providing useful information to assist with decision making, and the potential for confusion on receipt of a probabilistic forecast (e.g. National Research Council 2006, Demeritt et al. 2007, Demuth et al. 2007). However, it is often found that basic probabilistic concepts are widely understood, and that many users would actively welcome information on uncertainty in forecasts. For example, the uncertainty in the tracks of hurricane and tropical cyclone forecasts has for many years been presented to the public in the form of ‘plumes’ or ‘cones of uncertainty’. Many meteorological services also now attach probabilities to events such as thunderstorms, or heavy rainfall (e.g. there is a 60% or greater confidence that there will be heavy rainfall in your district this afternoon). This topic is discussed further in Chapter 6, and in Chapter 7 for flood forecasting applications.

More experienced users may also be able to use the raw information on uncertainty in their own decision making processes and decision support systems (where available). For example, as described in Box 4.2, and in Chapters 9 and 11, many water resource managers and hydropower operators in the USA and elsewhere routinely make use of long-term ensemble streamflow predictions of river flows to assist in operations, particularly during the spring snowmelt season. For flood forecasting applications, there is also much development underway internationally into providing real-time estimates of uncertainty in flood extent maps, and river flow forecasts, based on ensemble meteorological forecasts.

There are many approaches to estimating uncertainty in model outputs, which are typically classified as arising from the model structure, model parameters, initial conditions and boundary conditions. To some extent, the approach which is used depends on the main sources of uncertainty which are of interest which, for an integrated catchment model, can include:

- Meteorological Forecasts – uncertainty in Quantitative Precipitation Forecasts, and other meteorological forecasts, with increasing uncertainty at longer lead times
- Observations – uncertainty in measurements of rainfall, river levels, river flows, and other relevant parameters, both when used as inputs, and in data assimilation
- Model Parameters – uncertainty in the most appropriate values to use for the parameters of the model
- Model Initial Conditions – uncertainty in initial catchment, river, reservoir etc. states, and their representation in the model

The importance of each source depends on the location in the catchment, the catchment response time, the forecast lead time requirement, and other factors. For example, Fig. 4.9 illustrates some typical sources of uncertainty in an integrated catchment model which combines rainfall-runoff and flow routing components. For this example, several possible scenarios are shown for a storm approaching the catchment, and the uncertainty arising from these sources could be combined with the uncertainty in catchment soil moisture conditions, and in the flow estimates derived from stage-discharge relationships.

In operational forecasting, some techniques which can be used to estimate the uncertainty in forecast outputs include:

- Probabilistic Techniques – Monte Carlo or other sampling from a probability density function for the parameter, variable etc. of interest
- Ensemble Techniques – generating a set of ensemble members as a representation of the full distribution of values

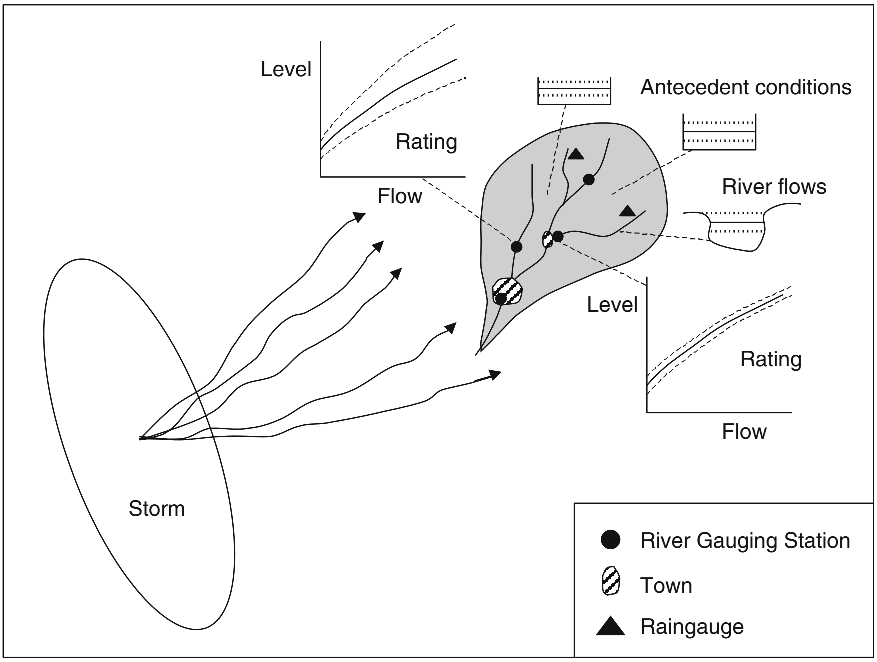


Fig. 4.9 Illustration of some sources of uncertainty for a catchment flood forecasting problem (Sene 2008)

- Sensitivity Tests – assessments of the model sensitivity to changes, typically using manually defined scenarios for future rainfall, catchment conditions, parameter values etc.
- Multi-Model Techniques – use of several models operated in parallel, and comparing the outputs to assess the uncertainty arising from model structure etc.
- Data Assimilation – choice of data assimilation techniques which also provide an estimate of predictive uncertainty, conditional on forecast performance

The first three of these methods are all forms of forward uncertainty propagation analysis (Beven 2008), in which the various estimates are fed through the hydrological model (or models) to assess the impacts on river flows and other outputs, thereby providing a measure of uncertainty from those sources. Some studies have also considered approaches for generating ensemble meteorological forecasts from single-value deterministic forecast model outputs (e.g. Schaake et al. 2007a). Methods may also be combined; for example, ensemble estimates of river flows may be updated using data assimilation techniques, and the individual models which contribute to a multi-model ensemble may also use a mixture of techniques. Note that when several deterministic model outputs are obtained from other organizations, this is sometimes called a poor man's ensemble.

More generally, both sensitivity testing and ensemble techniques can be regarded as a simplified from of probabilistic approach, with the number of samples usually limited by the available time and/or computing power. For short- to medium-range forecasts, the main focus for research in recent years has been the propagation of ensemble rainfall forecasts (Quantitative Precipitation Forecasts) through hydrological models, and the resulting techniques have been implemented in several pre-operational and operational flow forecasting systems world-wide (e.g. Cloke and Pappenberger 2009). This has included a number of international test beds within the Hydrological Ensemble Prediction Experiment initiative (HEPEX) which is described in Chapter 1 (Schaake et al. 2007b). Some other active areas of research include investigations into the uncertainty arising from model parameters, data inputs, model structure and other sources (e.g. Beven 2008).

Some examples of operational ensemble flow forecasting systems include medium- to long-term flow forecasting system for the River Ganges and Brahmaputra in Bangladesh (Webster and Hoyos 2004), and the European Flood Alert System EFAS, which "aims at increasing preparedness for floods in trans-national European river basins by providing local water authorities with medium-range and probabilistic flood forecasting information 3–10 days in advance" (Thielen et al. 2009).

For all uncertainty estimation techniques, there is of course the question of the statistical meaning of the outputs, and this depends on the uncertainty estimation techniques which are used, the characteristics of the hydrological modeling component, and whether, and to what extent, data assimilation is used. It is therefore increasingly recognized that the uncertainty component of the forecast also needs to be calibrated based on historical performance. For example, some of the statistical post-processing techniques described in Chapter 3 for meteorological applications have been considered for this application (e.g. Wood and Schaake 2008).

Bayesian techniques also show promise in providing an overall forecasting framework incorporating data assimilation and uncertainty estimation (e.g. Krzysztofowicz and Maranzano 2004, Todini 2007). Here, the overall aim is to estimate the predictive uncertainty, conditional on all of the information available at the time of the forecast (observations, past model performance etc.). As noted in Chapter 3, Bayesian Model Averaging approaches are also potentially useful in weighting the outputs from a collection of ensemble members based on their recent forecasting performance when compared with observed flows (Raftery et al. 2005); in particular for multi-model outputs.

For some approaches, an evaluation of long-term performance requires a re-analysis, re-forecast or hindcast of model performance over a number of years, ideally using the current model configuration and the same network of instruments as are presently used in the operational model. Where changes to instrumentation have been made in the hindcast period and incorporated into the current operational model (e.g. raingauges moved, river gauges installed), then estimates are required for the data values that would have been provided if those changes had been in place over the whole period. For hydrological forecasting models, this requirement has many similarities to the various stages performed in model calibration, and is not necessarily too onerous. However, if meteorological forecasts are also used then, as discussed earlier, hindcasting exercises of this type can be a considerable undertaking if no such re-analysis is already available.

For operational hydrological forecasting, the use of uncertainty estimation techniques is perhaps most advanced for flood forecasting and reservoir operation applications, and Chapters 7 and 9 provide a more detailed discussion of the methods which are used. Examples of ensemble and probabilistic outputs are also provided in a number of chapters, including in Chapter 3 (for meteorological forecasts), Chapter 5 (for demand forecasts), Chapter 7 (for river flow and groundwater level forecasts), and Chapter 10 for lake level forecasts.

Box 4.2 Ensemble Streamflow Prediction (ESP)

One approach to estimating the uncertainty in flow forecasts arising from metorological conditions is to sample historical meteorological records for input to the hydrological component of the model, but to use the current model state as the starting point for the model run. This approach forms the basis of the Ensemble Streamflow Prediction approach which has been used operationally by the National Weather Service in the USA since the 1980s (Day 1985, Ingram et al. 1998). A key application is to assist water supply and reservoir operators with assessing the likely flows arising from the Spring snowmelt, whilst other applications include providing forecasts to assist with flood control, drought management, navigation, and recreation. Other examples of the application of this general approach, and similar methods developed by other groups, are presented in Chapter 7 (flood forecasting), Chapter 8 (drought forecasting), and Chapter 11 (reservoir inflow forecasting). In many cases, these long-term ensemble estimates are now complemented by short- to medium-range ensemble meteorological forecasts from Numerical Weather Prediction models (see Chapter 3).

In real-time use, flows are typically derived by running multiple meteorological scenarios through the same catchment models which are used for operational flow forecasting. The ensemble inputs are derived by sampling historical meteorological records for rainfall, air temperature and (in some cases) potential evaporation data, with typically a period of at least 30–40 years of data used, to sample a representative range of conditions. The underlying assumption is that each year in the historical record is equally likely to occur, and that the historical record includes the full range of extremes that are likely to occur. The resulting ensembles are then post-processed to provide estimates for peak flows, flow/runoff volumes for different durations, water supply outlooks, river stages, and statistical distributions. Figure 4.10 presents an example of the outputs from the BC Hydro implementation of this approach in Western Canada (see Chapter 11 for more details).

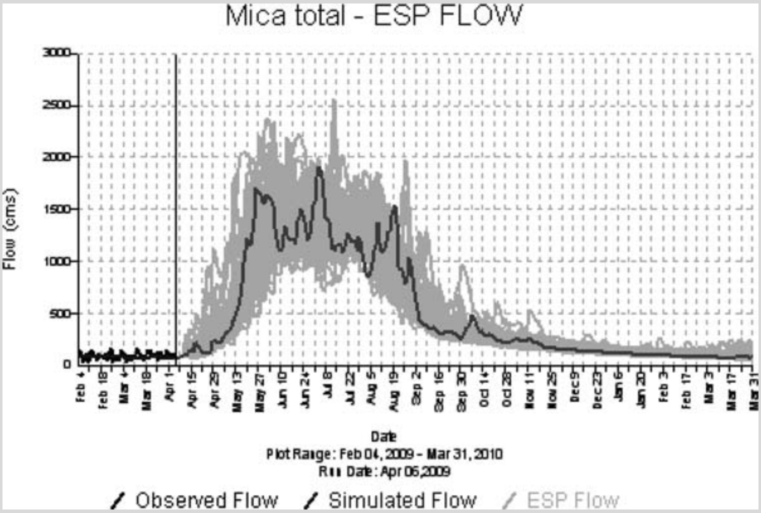


Fig. 4.10 River Forecast System: ensemble streamflow prediction issued on 6 April 2009 for Mica Reservoir with the 2008 ESP trace highlighted (BC Hydro)

Internationally, ongoing research includes the development of adjustment schemes to take account of medium- to long-range forecasts from meteorological services, and of conditioning approaches to improve the estimates, and identification of analogue years in the historical records. For example, approaches which have been evaluated include weighting techniques and Quantile Regression, with the general aim to improve the mean and spread in the forecasts, whilst preserving the space-time characteristics of the hydrometeorological variables (e.g. Demargne et al. 2007, Wood and Schaake 2008).

4.3.4 Forecast Verification

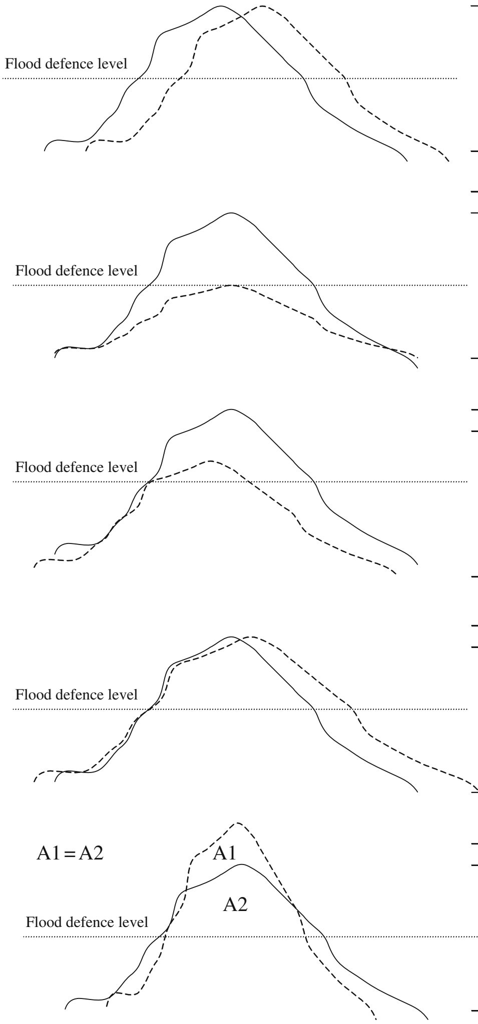
When a hydrological model is used operationally, a process is usually required by which the accuracy of forecasts can be evaluated (and performance monitored), both off-line and in real-time, by a range of potential users. For example, for the National Weather Service river forecast verification service (Demargne 2009), verification products "will be generated for a variety of users, such as scientists, forecasters, hydrology program managers, emergency managers, as well as everyday users of hydrologic forecasts". In flood forecasting applications, some particular areas of interest can include peak values, success at forecasting the crossing of thresholds (and associated false alarms), and the timing of crossing of thresholds. By contrast, some useful diagnostic measures for water resources applications can include flow duration statistics, mean flows, and cumulative volumes in terms of absolute values, and flow deficits beneath a threshold. The way that verification results are presented can also vary, with options including graphical, tabulated and map-based outputs, and more advanced visualization approaches, such as animated time sequences, and interactive map-based outputs.

The process of forecast verification, or performance monitoring, can be performed both in real-time (prognostic verification), to help to decide whether to issue a forecast, and the confidence to attach to the forecast, and over the longer term, as part of model maintenance and improvement procedures (diagnostic verification). For example, in flood forecasting applications, in addition to deciding on whether to issue a forecast during a flood event, there is also often a need to report on model performance as part of the general post-event reporting, and more generally as a guide to the requirements for future model development and improvements to instrumentation etc. The various uncertainty estimation techniques described in the previous section therefore also have a role to play in this process.

The usual approach to forecast verification is to select one or more performance measures, relevant to the application, and to calculate these values from observed and forecast flows (or other parameters of interest). For example, for river flows, performance measures might include the root mean square error (RMSE), the bias, R^2 Efficiency (sometimes called the Nash-Sutcliffe Efficiency), errors in the timing and magnitude of the peak flows, and other parameters. For real-time applications, these and other performance measures can also be calculated for different lead times, such as the error in peak flows at a 3-h lead-time, or the R^2 Efficiency at a 12-h lead-time, both with and without the use of data assimilation, and this can be particularly useful in short-term forecasting applications. For example, in flood forecasting applications, it is useful to know the model performance, with data assimilation, at the lead times at which flood warnings would be issued, in addition to the usual off-line performance measures used for model calibration. Indeed, some forms of data-driven model are optimized 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 can also be convenient to normalize values by statistical measures of flow of the types described in Box 4.1, such as the flow which is exceeded for 95% of the time, or the flood with an estimated return period of 1 in 100 years.

Table 4.4 Example of a 2 by 2 contingency table for flood warning applications

	Threshold crossed (observed)	Threshold not crossed (observed)
Threshold crossed (forecast)	A	B
Threshold not crossed (forecast)	C	D



Whole hydrograph		Threshold crossing	
Bias	L	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	L	CAR	H
Peak error (timing)	H	Crossing time error	H
Duration error	L	Duration above error	L
Volume error	L	Volume above error	L

Whole hydrograph		Threshold crossing	
Bias	H	CSI	L
Rmse	H	POD	L
R^2	L	FAR	L
Peak error (level)	H	CAR	L
Peak error (timing)	L	Crossing time error	H
Duration error	L	Duration above error	H
Volume error	H	Volume above error	H

Whole hydrograph		Threshold crossing	
Bias	H	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	H	CAR	H
Peak error (timing)	H	Crossing time error	L
Duration error	H	Duration above error	H
Volume error	H	Volume above error	H

Whole hydrograph		Threshold crossing	
Bias	L	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	L	CAR	H
Peak error (timing)	H	Crossing time error	L
Duration error	H	Duration above error	H
Volume error	H	Volume above error	H

Whole hydrograph		Threshold crossing	
Bias	H	CSI	H
Rmse	H	POD	H
R^2	L	FAR	L
Peak error (level)	H	CAR	H
Peak error (timing)	L	Crossing time error	L
Duration error	H	Duration above error	H
Volume error	L	Volume above error	L

Fig. 4.11 Examples of performance measures for fixed lead-time forecasts (*solid line* – observed levels; *dashed line* – forecast levels [L=Low, H=high] (Environment Agency 2002, Copyright © Environment Agency 2009 all rights reserved)

Where decisions are taken on the basis of crossing of a threshold value (see Chapter 6 for examples), the time of crossing of the threshold is also of interest, and the timing error, as is the lead time that this would provide for issuing a warning. Contingency measures, of the type described in Chapter 3 for meteorological forecasts, are also of interest; for example, Table 4.4 shows a typical 2 by 2 contingency table for flood warning applications (and higher order tables can be devised by introducing percentile ranges, for example). Some performance measures which can be defined from this table include the Hit Rate or Probability of Detection (POD = A/(A+C), the False Alarm Ratio (FAR = B/(A+B)), the Correct Alarm Ratio (CAR = 1 – FAR) and the Critical Success Index or Threat Score (CSI = A/(A+B+C)). For flood warning applications, it may be useful to only accumulate statistics for values within a given lead time of the threshold being crossed (e.g. Werner and Self 2005).

More generally, the choice of measures to use depends on the application and there are various advantages and disadvantages to each approach. For example, some methods give information on the magnitude of the error, but not the sign, or whether the errors occur at high or low flows, whilst others are sensitive to timing errors, or to outliers. This can be a disadvantage when other factors, such as instrumentation errors, have caused the outlier, but also an advantage where extreme values are of interest, such as in flood forecasting applications. These issues have been the subject of many studies in hydrology and meteorology for both deterministic and ensemble/probabilistic forecasts (e.g. Stanski et al. 1989, Jolliffe and Stephenson 2003, Laio and Tamea 2007, Casati et al. 2008, Clarke 2008, Pappenberger et al. 2008, Bartholmes et al. 2009).

Figure 4.11 shows some examples of indicative scores for a range of performance measures for some hypothetical river flow forecasts. It can be seen that in some cases a low score is obtained when, visually, the forecast looks acceptable and, conversely, that poor forecasts can lead to an unduly high score for some measures. Note that, for the threshold crossing measures, it is assumed that values would be accumulated across a number of similar events. Also, as discussed in Chapter 3, a range of additional measures can be useful for assessing the performance of probabilistic or ensemble forecasts, typically focusing on the range or spread, distribution, consistency with frequency and other analyses of historical data, and consistency with the deterministic model run (if available). Some examples of this type of measure include the Brier Score, Brier Skill Score, Ranked Probability Score (in continuous or discrete forms), Reliability, and Relative Operating Characteristic, and these are described in more detail in Section 3.3.

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Chapter 5
Demand Forecasting

Abstract Many hydrological forecasting applications require an assessment of water demand as well as water supply, and demand forecasts can require consideration of the water requirements for a wide range of applications. Examples include the availability of raw water for irrigation, hydropower generation and industrial water supply, and of treated water for public water consumption. Some applications, such as hydropower generation, may only store water temporarily, returning it to river flows at a later time (with minor evaporation and seepage losses), whilst other demands can represent a permanent loss to the river system. Forecasts also often need to provided at a range of timescales, from short-term values for tactical decision making, through to seasonal and longer term values for strategic planning. This chapter discusses a range of techniques for estimating and forecasting water demand, with applications in water supply, irrigation and power generation. Some typical approaches to decision making are also introduced, with a more detailed discussion in later chapters.

Keywords Abstractions · Demands · Discharges · Demand forecast · Water supply · Agriculture · Irrigation · Power generation · Hydropower · Thermoelectric

5.1 Introduction

In many hydrological forecasting applications, it is important to consider the abstractions and discharges by key water users, particularly under low flow conditions. This can require an understanding of the likely demands for water across a range of applications, including water supply, agriculture, and power generation, and of return flows or discharges of treated water and effluent/waste-water. The need to include these influences will depend on the magnitude of the artificial component of the flows, compared to main river flows and other parameters of interest, such as reservoir volumes.

For example, in flood forecasting applications, these influences may be relatively small compared to flood flows, and are often ignored (although can be important for

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forecasting the onset of an event) whilst, for forecasting during drought conditions, they can be crucial to consider. Later chapters include several examples of operational systems which include forecasts for abstractions and discharges, including drought forecasting models (Chapter 8) and water resources models (Chapter 11). The underlying techniques typically include supply-demand models, integrated catchment models, and distributed models. As discussed in Chapter 4, supply-demand models maintain a water balance throughout the simulation, whilst integrated catchment models typically combine rainfall-runoff, flow routing and other modeling components, and distributed models use physically-based equations for rainfall-runoff and other processes, and operate on a gridded basis. Other artificial influences on flows may also need to be considered, such as from reservoirs, sluices, barriers and other structures, and this topic is discussed in Chapter 9.

The potential uses of water are many and varied, and the volumes of water required can also vary widely. Table 5.1 shows some examples of the major types of river abstractions and discharges which can occur, and the potential impacts on river flows.

For example, for England and Wales, which covers an area of approximately 150,000 km^2 with a population of more than 50 million people, the Environment Agency manages about 20,000 abstraction licences (Environment Agency 2008a). Approximately 50% of freshwater (i.e. raw water) abstractions are for public water supply, and about 30% are used to support electricity generation (Fig. 5.1). In the USA, estimates for the year 2000 under the categories of public supply, domestic (self-supplied), irrigation, livestock, aquaculture, industrial, mining, and thermoelectric-power suggested that approximately 40% of freshwater abstractions (surface water and groundwater) were for irrigation, 39% were for thermoelectric-power, and 13% were for public water supply (Hutson et al., 2004). In both examples, a significant proportion of the abstractions for water supply and power generation are returned to the river system as treated waste-water or as used cooling water. By contrast, figures from the Food and Agriculture Organisation's AQUASTAT database show that, in some parts of Africa, Asia and South and Central America, the proportion of water withdrawn for agriculture can reach well over half of the total freshwater use (http://www.fao.org/nr/water/).

Later sections in this chapter present a detailed discussion of water demands for three of the largest potential influences on river flows: water supply, irrigation, and power generation. Note that some users, such as power station operators and desalination plants, may also make use of seawater, although this topic is not considered. Also, for some types of use, such as hydropower generation, there may be no net loss of water to the river system, other than minor losses due to evaporation, seepage and other factors; that is, the demand is non-consumptive. More generally, water may be discharged back to rivers in its freshwater (raw) state or in contaminated form, although often following treatment, as for waste-water treatment works and some industrial and mining uses, for example. The influences of changes in water temperature, sediment load and water quality may also need to be considered.

The process of estimating water requirements is often called demand forecasting, which is a term which is also widely used in other sectors, such as electricity

Table 5.1 Some examples of freshwater abstractions and discharges

Type of end-user	Typical water sources	Typical influences on river flows
Canal operators	Rivers	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 diversion schemes. Losses due to seepage and evaporation from reservoirs
Industry	Rivers, reservoirs, groundwater	A wide range of potential uses, both consumptive and non-consumptive. Major users include 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 can be influenced by irrigation schedules, possibly with return flows from pumped or gravity drainage. Groundwater abstractions may also influence river flows
Mining	Rivers, reservoirs, groundwater	Water may be required for cooling, the conveyance, washing and flotation of mined rock and other material, dust control, wastewater treatment, and other purposes, possibly with some return of treated or contaminated flows
Rural	Rivers, reservoirs, groundwater	Abstractions for subsistence farming, domestic water supply, livestock watering, fish farming etc.
Thermoelectric power stations	Rivers, reservoirs, and occasionally groundwater	Abstractions for cooling water, which is either lost in natural or forced draft cooling systems, or returned to the river system when using once-through cooling systems
Water supply	Rivers, reservoirs, groundwater	Major abstractions to water treatment works, and possibly for inter-basin transfers, and minor abstractions for local domestic use (including for livestock). Also return flows of treated waste water. Groundwater abstractions may also influence river flows

supply, marketing and telecommunications, to describe the estimation of future requirements by end-users. Examples of end-users might include householders, schools, shops, factories, farmers (e.g. for irrigation), power station operators (e.g. for hydropower, and cooling water), and canal operators. The general categories of residential, commercial and industrial users, and agricultural and transportation users, are also widely used.

At short timescales, the techniques used for forecasting day-to-day fluctuations in demand typically include trend and regression analyses, artificial neural network

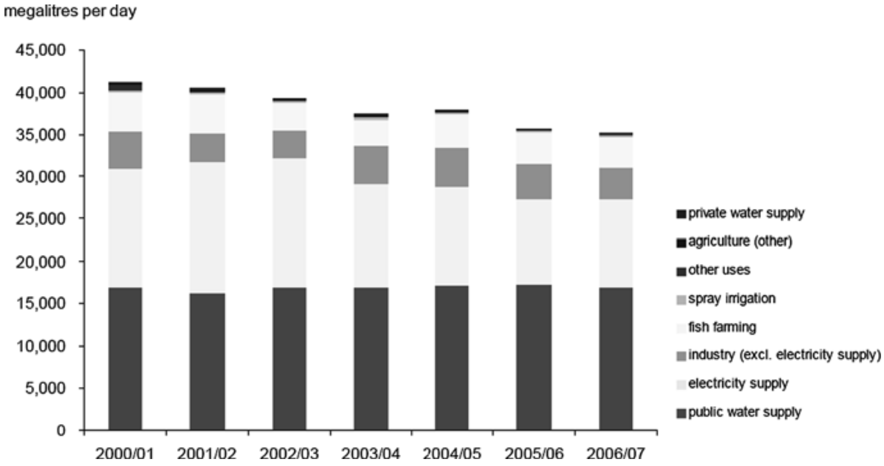

Fig. 5.1 Water abstraction (non tidal) in England and Wales (Copyright © Environment Agency 2009 all rights reserved)

techniques, and time series analysis methods. Similar methods are also used for forecasting longer-term changes in demand but are often complemented by detailed analyses of the requirements of individual types of user, and how these might change in future in response to factors such as:

- Economic Change – such as in Gross Domestic Product, employment, pricing, competition
- Regulation – for example, regarding permitted uses, water efficiency and leakage reduction measures
- Demographic Influences – such as changes in population, patterns of work and travel

For the benefit of users further downstream, or ecological and other reasons, abstractions may also be subject to the requirement not to allow river flows to drop below a specified value, variously called the residual, prescribed or hands-off flow. For some applications, such as hydropower generation, the initial analyses might also need to be performed in terms of a type of demand other than water, such as electricity demand, before expressing requirements in terms of water usage. In general, there is often a need to estimate both typical demands, and peak demands, when designing or operating any system.

Demand forecasting analyses traditionally also make use of sampling techniques both spatially and over time. For example, to make the analyses feasible, it may be necessary to introduce demand or command zones or areas, in which individual users are aggregated according to various criteria, such as general categories (e.g. residential, commercial), the type of water or electricity use, census blocks, socioeconomic status, the main sources of water, and other factors. Smaller abstractions or discharges may also need to be considered as single units; for example, when there are multiple gravity-fed or pumped irrigation off-takes along a river reach. Later sections provide several examples of these approaches. Geographic Information Systems (GIS) are widely used for this type of analysis.

The influence of meteorological variations also needs to be considered, both at short time scales, and in the medium to longer term. For example, increases in air temperature can cause increases in drinking water requirements (due to increases in water consumption), irrigation demands (due to increased crop water use), and hydropower demands (due to more electricity being required for air conditioning and other types of cooling). Changes in air temperature may also cause changes in the losses from irrigation schemes, and open water evaporation from reservoirs.

Other factors to consider can include solar radiation, humidity and wind speed, which may variously influence evaporation losses, cooling and heating requirements, water consumption, and other aspects of water demand (or related electricity demands). In some cases, such as when estimating crop water requirements, the combined effect of these three parameters, and air temperature, can be aggregated using the Penman or Penman-Monteith formulae for estimating open water evaporation or crop evapotranspiration, as discussed in Section 5.3. Later sections in this chapter also provide some additional examples of the influences of meteorological conditions on water demand.

The influence of adaptation strategies may also need to be considered, and these can include the following responses:

- Tactical/Short-Term – changes to the timing and magnitude of abstractions, temporary restrictions on abstractions by major users, use of emergency supplies
- Medium to Long-Term – drought orders (e.g. hosepipe bans, restrictions on spray irrigation), augmentation from other sources such as reservoirs and groundwater
- Strategic/Long-Term – improved water efficiency measures, revised water resources regulations, introduction of new water sources and new technologies, water efficiency measures

The distinction is sometimes also made between tactical measures, planned within a strategic framework, and emergency measures in response to unexpected circumstances (e.g. USACE 1994). Decision support systems, as described in later chapters, can also help with deciding on approaches to minimize the use of water subject to the various physical, economic, regulatory, environmental and other constraints which may exist.

For medium and longer term planning, the use of low flow estimation techniques can also assist with understanding the main users of river water in a catchment (e.g. World Meteorological Organisation 1994, Smakhtin 2001). Examples include the use of flow duration curves, low flow frequency analyses, baseflow and other indices, and estimates for the overall catchment water balance (see Chapter 4 and Chapter 8). Another simple technique is to visualise the influence of abstractions and discharges on flows using residual flow diagrams, which show the cumulative flow along a river reach, and how this varies with outflows due to abstractions, and inflows due to discharges. The international FRIEND (Flow Regimes from International Experimental and Network Data) initiative, which has involved scientists from more than 100 countries (UNESCO 2006), has also made major advances in developing methods for the estimation of low flows, and techniques for allowing for artificial influences on flows.

5.2 Water Supply

Demand forecasting for water supply is important in the design of water supply systems (including reservoirs), and water and wastewater treatment works. Abstractions for water supply can also have a significant influence on river flows and, in some countries, water may be re-used several times before it reaches the sea, with treated water discharged to rivers and then re-abstracted for water supply further downstream.

The main approaches to forecasting water demand include (e.g. McMahon 1993, Wurbs 1997, Butler and Memon 2006):

- Data-Driven (or Black Box) Methods – use of autoregressive time series analysis, artificial neural networks, expert systems, fuzzy logic, Kalman Filter and other techniques to forecast future water use based on recent or historical water consumption
- Per Capita Approaches – multiplication of typical water uses 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, and predictors such as climate, employment, income, price and other factors
- Micro-Component (or End Use) Analysis – derivation of estimates for a wide range of uses (e.g. washing machines, showers), and for the extent of ownership and frequency of use within each end user category

To limit the extent of the analyses, some level of simplification is usually introduced, and can include the following forms of aggregation:

- Sector (residential, commercial, industrial etc.)
- Housing Characteristics (e.g. age, value, type, size, occupancy)
- Pricing (e.g. metered/unmetered)
- Spatial (e.g. catchment, state, town, region, household, zone)
- Season (e.g. summer, winter, average)

Also, for some major categories of water user (industry, businesses etc.), analyses may need to be performed 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 in cases where insufficient information is available for a more complex approach. Per capita methods are also used in assessing likely future changes in demand in climate change impact studies.

For short- to medium-term demand forecasting, data-driven and regression approaches are often used over timescales from a few hours to weeks ahead, and may allow for factors such as recent water use, air temperature and rainfall forecasts, and diurnal and seasonal variations in water use. These techniques are also used in some aspects of meteorological and hydrological forecasting, such as data assimilation, seasonal forecasting, and rainfall-runoff modeling, and Chapters 3 and 4 provide a brief introduction to the underlying approaches.

For longer term planning, the usual approach is to use statistical or micro-component techniques (see Box 5.1). These more complex approaches can, of course, consider a wider range of factors affecting water use, and do not rely simply on historical data, as with trend analyses for example. Combinations of approaches are also used; for example, developing regression relationships for the frequency of use of micro-components in strategic and climate change impact studies.

When using per capita methods, some typical sources for per capita water use for drinking, hygiene and sanitation include historical data, and national and World Health Organisation standards. For domestic use, consumption can range from a few litres per day in low income countries, to about 150–300 l/day in Europe, Japan and the USA (e.g. Butler and Memon 2006). Where the required information is available, locally applicable values are typically obtained from a combination of industry guidelines, census data, household surveys, metering, billing information and another approaches. New technologies can also help with refining estimates; for example, intelligent metering systems have been developed to allow water volumes and frequency of use to be monitored for selected households for a wide range of types of appliance.

For regression approaches, some factors which can be included in the relationships include marginal prices, household incomes, net rainfall, and temperature degree days (e.g. Arbués et al., 2003, Wurbs 1997, Horn et al., 2008). Models which exclude economic considerations are sometimes called requirements models, rather than demand models (Wurbs 1997). Usually, both typical and peak likely demands need to be considered. Both static and dynamic relationships are used where, in this context, a dynamic model also includes an allowance for the demand at the previous timestep, and is typically used for shorter term forecasting.

Methods of this type can consider a wide range of categories of water user, responses to climate, and other factors, such as the elasticity of demand (e.g. reductions in demand with increases in price), and the impact of water conservation measures. For example, in addition to price, some other factors which can influence residential demand include tastes and preferences (e.g. for lush gardens, lengthy showers), the price of substitutes (e.g. recycled water), the number and closeness of substitutes, income, the price of complementary goods and services (e.g. swimming pools), climate (rainfall and temperature), population, and the number of actual and potential uses (Agthe et al. 2003). Often it is found that meteorological influences tend to arise mainly from non-essential uses such as watering gardens, and swimming pools, although also affect factors such as the use of showers, and drinking water consumption.

Demand forecasting can be a complex task, requiring historical information on water use, projections of key factors such as population, industrial activity and economic growth, and assumptions about responses to changes in climate, regulations, pricing and other factors. Allowances also need to be made for leakage and other losses, and Monte Carlo or 'what if' studies are often performed to assess the sensitivity of results to the assumptions that are made and the various uncertainties in the analyses. The impacts of demand management, leakage reduction programmes, appliance replacement (e.g. washing machines), plumbing codes, technological improvements, and passive and active water conservation measures also need to be considered. As noted earlier, Geographic Information Systems (GIS) can also facilitate this type of analysis, and typical planning units can include census blocks, resource zones, and towns and cities.

Box 5.1 Demand Forecasting in England and Wales

In England and Wales, water companies publish and revise Water Resources Management Plans at least once every 5 years, for a planning horizon of 25 years. These plans describe how companies intend to supply water to the public and other consumers, accounting for increases in demand and the possible impacts of climate change and whilst protecting the environment, particularly at Habitats Directive Sites. Some key aspects to assess in each plan include:

- The balance between demand management (e.g. leakage control, water metering, improved water use efficiency), and developing new water supply sources (e.g. reservoirs, boreholes)
- The level of service which will be achieved; for example, for the worst-case frequency of drought orders or hosepipe bans

For the demand forecasting component, several guideline documents are available to assist with forecasting future demands, including:

- UKWIR 1995 – a best practice manual providing a common methodology for UK water suppliers and their regulators to forecast water demands, following a transparent approach in which the various types of demand are separated into agreed, well defined components
- UKWIR 1997 – a best practice manual which recommends that household demand should be estimated by considering different groups of householder (in terms of types of water use), and that demand for industrial and other non-household uses should be linked to economic forecasts

- Environment Agency (2008b) – guidelines for water companies on preparing a Water Resources Management Plan, which provide recommendations on approaches to maintaining and forecasting the balance between supply and demand, including allowances for climate change

One of the key requirements in each plan is that estimates must be provided for the baseline demand for a dry year, and for a critical period if applicable (e.g. a few months). Targets for water efficiency and leakage reduction, and other factors, such as the optional uptake of water meters, also need to be considered. To account for a wide range of possible conditions and known historical drought years, it is recommended that analyses should be performed using several decades of historical meteorological and other data.

The dry year assumes a period of low rainfall and/or high temperatures, with the demand increased using adjustment factors based on a recent normalised baseline year. Estimates are derived in terms of individual resource zones which are defined so that, due to the water sources which are used, most consumers experience a similar risk of failure of water supply. Sensitivity analyses and maximum likelihood estimates are also required to assess the uncertainty in estimates and to reconcile discrepancies in the water balance.

To estimate water requirements, values are derived at resource zone level for the number of properties and metered and unmetered households, assumed occupancy rates, and the non-household population (e.g. farms, hospitals, prisons, educational establishments, industrial users). Typical per-capita consumption values are available for each category of water user. At a resource zone level, breakdowns are also provided for the following items (or ‘micro-components’): toilet flushing; bath; shower (standard and power shower); hand basin; clothes washing (by machine and by hand); dish washing (by machine and by hand); garden use (sprinkler, held hand hose and watering can); car washing (by hose and by bucket); miscellaneous use (e.g. Environment Agency 2008b).

Projections for future changes in the population, and numbers of properties, are made using both extrapolation of recent demographic trends (births, deaths, migration), and a more detailed analysis taking account of household projections in regional planning policies. Calculations should again be at micro-component level, taking into account how socio-economic changes might influence water use and appliance ownership.

Estimates for the impacts of climate change typically consider the effects of changes in temperature, precipitation, radiation, relative humidity and wind speed on households and other users (Herrington 1996, Downing et al., 2003) using the appropriate UK Climate Impacts Programme (UKCIP) climate change scenarios. Again, estimates of uncertainties are an important component in this type of analysis, with a complex interplay to consider between changes in climate, household choices regarding water use, and the regulatory environment (Downing et al., 2003).

5.3 Irrigation

Irrigation schemes are typically used where rainfed or dryland agriculture is not sustainable or economically beneficial, and can abstract significant quantities of water from rivers, reservoirs and groundwater sources. Demands are typically linked to the growing cycles of crops, and tend to be seasonally dependent (although multiple types of crops may be planted throughout the year). The main types of irrigation scheme include (e.g. FAO 2002; Fig. 5.2):

- Surface Irrigation Systems – in which water is provided overland via canals and pipes, then distributed at field scale using furrow, borderstrip or basin systems
- Sprinkler Irrigation Systems – in which water is sprayed onto the crop via fixed or mobile pressurized pipe systems (also known as Spray or Overhead Irrigation Systems)
- Localized 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

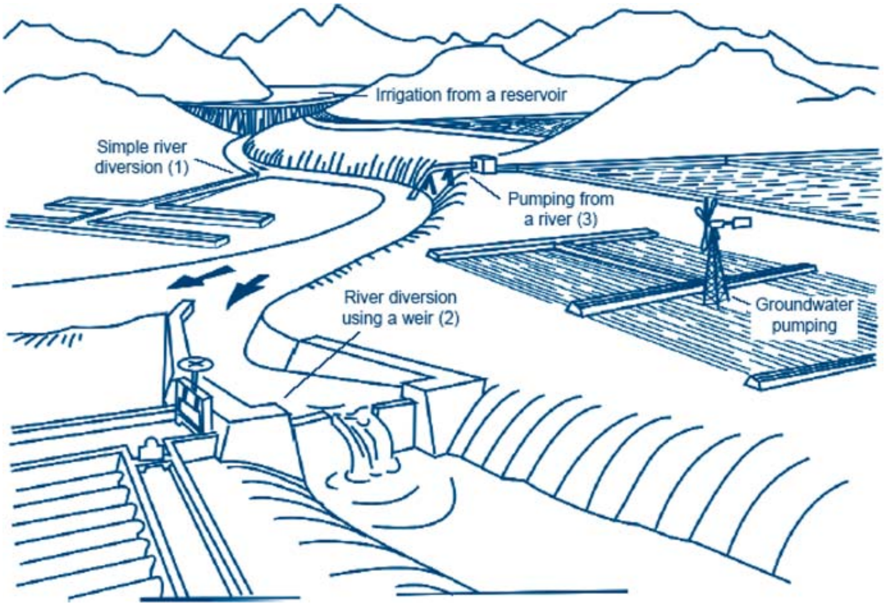

Fig. 5.2 Schemes irrigated from different sources (Food and Agriculture Organization of the United Nations; FAO 1992a, 2002)

Water can be abstracted from reservoir, river, lake or groundwater sources using gravity fed or pumped schemes. Pumped schemes often have higher capital and operating costs, with limitations on flow volumes, but can allow greater precision in the supply of water, and can continue to operate when river or reservoir levels are low. Treated wastewater and desalinated seawater sources are also sometimes used where other sources are not readily available.

Surface irrigation schemes are the most widely used world-wide. In furrow and borderstrip 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 localized systems allow greater precision in the timing and volumes of water applied, with lower losses to infiltration and evaporation, although can be 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 typical field application efficiencies might be 55–80% for a surface water scheme (but lower for rice), 60–85% for sprinkler systems, and 85–95% for localized irrigation schemes. However, values can depend upon weather conditions, the general management, operation and maintenance of the scheme, and other factors, such as whether canals are lined, rates of sedimentation, and the effectiveness of drainage systems (FAO 1992b, 2002).

The water requirements for an irrigation scheme depend primarily upon the crop water demand (i.e. evapotranspiration), 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 (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. The demand values can be estimated from past experience, or more detailed analyses performed using direct estimates for evapotranspiration and a soil water balance, allowing for leaching requirements (to control soil salinity) and irrigation efficiency. Multiple regression techniques are also sometimes used in longer-term forecasting to relate crop yield and other parameters to predictors such as air temperature, rainfall, solar radiation, season, price and type of crop. Simpler descriptive ('non-parametric') approaches are also widely used; for example linking crop yield to El Niño-Southern Oscillation indices, or cumulative rainfall, and expert systems using artificial intelligence are also under development which attempt to encapsulate this knowledge (e.g. World Meteorological Organisation 2009).

Crop evapotranspiration values are often estimated relative to a reference crop, 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 can then be expressed as a ratio to that of the reference crop, using a crop coefficient determined from field observations. The reference crop evapotranspiration is usually estimated from meteorological data (temperature, humidity, windspeed/wind run, solar radiation/sunshine hours), using the Penman-Monteith equation, although sometimes adjusted pan evaporation measurements are used. In some irrigation schemes, several types of crop may be planted, with the planting and harvesting dates staggered, and some areas lying fallow (and crop rotation is one strategy for reducing the risk to crop yields from drought and other factors, such as crop diseases; see Chapter 8).

The crop coefficient typically varies during the growing season, as the height, albedo, aerodynamic properties, and soil evaporation contributions change, reaching a maximum when plants reach maximum height and cover, then remaining at about that value until the crop reaches the mature stage, then reducing towards harvest time or full senescence. Values may vary considerably from day to day, so weekly or 10-day averages are often considered, and also under different climatic conditions; in particular, values are sensitive to the availability of water during the initial part of the growth cycle. An allowance may therefore also be made for departures from ideal conditions by introducing water stress and other coefficients, to allow for factors such as water shortages, waterlogging, and the influence of pests and diseases. A soil evaporation coefficient may also be included to allow for direct soil evaporation, such as from sparse crops, which have significant gaps between individual plants.

For a given type of crop, the overall irrigation scheduling requirements can then be estimated from a water balance calculation which takes account of rainfall, crop evapotranspiration, irrigation efficiency, soil characteristics, plant rooting depth, plant area coverage, and other factors. This approach forms the basis of the widely used FAO CROPWAT methodology, for example (see Box 5.2). Irrigation scheduling calculations of this type are usually performed as part of the scheme design, using historical climate data, and are sometimes also used with real-time meteorological observations or forecasts to forecast irrigation demand. A wide range of complicating factors may also need to be considered, such as influences from the water table (if any), water use by weeds, the changes in microclimate due to the presence of the scheme, return flows from drainage, and local practices regarding the use of fertilizers, ploughing etc.

A number of process-based crop simulation models have also been developed for operational use, and are gradually being adopted or considered for operational use. The main applications to date have been primarily for large-scale commercial farming, and for regional monitoring of drought by research and other organisations. The starting point for the analysis is often a consideration of the water and energy balance of the crop, as illustrated by the example shown in Fig. 5.3. 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, some additional components in models of this type can include (e.g. Thornley and France 2007, World Meteorological Organisation 2009):

- Aerodynamic Module – to simulate the turbulent and diffusive transfer of water and energy within and above the plant canopy
- Soil Hydrology Module – allowing for rainfall, irrigation, infiltration, percolation, leaching, capillary rise, evaporation, surface runoff, tillage effects, transpiration by plants and weeds etc.
- Vegetation Growth Module – simulating photosynthesis, respiration, senescence, stomatal resistance, uptake of nutrients from fertilizers etc., the carbon balance, disease, weed growth, plant competition, management practices etc.

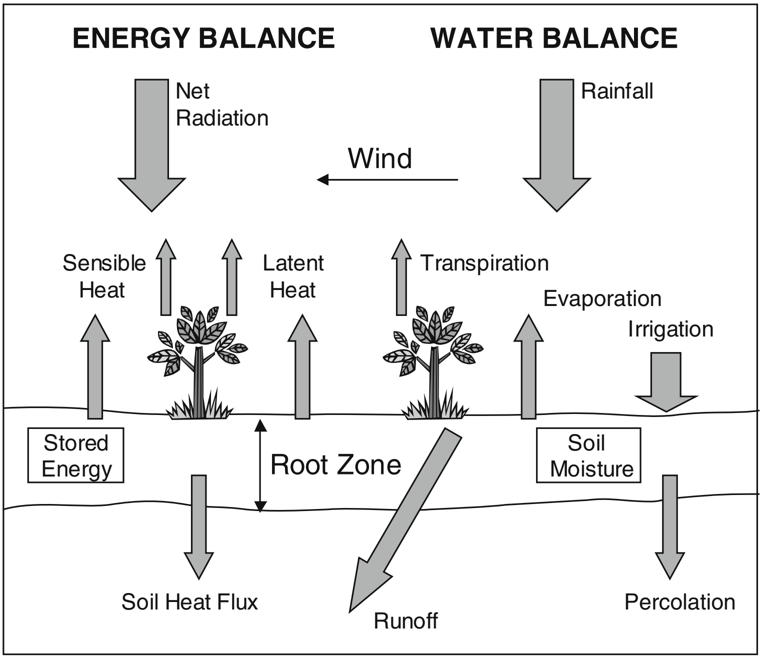

Fig. 5.3 Illustration of the water and energy balance of an irrigated sparse crop (infiltration and interception components not shown)

The evapotranspiration is often represented using the concept of aerodynamic and stomatal resistances, as in Soil Vegetation Atmosphere Transfer (SVAT) models (e.g. Shuttleworth and Wallace 1985, Shuttleworth 2007). This general approach is also often used in the land-atmosphere schemes in Numerical Weather Prediction models (see Chapter 3).

Crop simulation models generally have many parameters, which are typically based on the results from laboratory and field experiments and monitoring, and can be formulated at a range of scales (field/plot, farm, region etc.), depending on the application. Multi-layer models may also be required for some components, such as the soil component. Typically, the main inputs to models of this type consist of rainfall, solar radiation, air temperature, wind speed, humidity, and soil moisture conditions. Also, for application at a regional scale, satellite remote sensing often plays an important role in providing the input data required to operate such models. The model outputs can include estimates for crop yield and variability, and soil water content and biomass, and may be in probabilistic terms if ensemble meteorological forecasts are used as inputs (particularly for seasonal forecasts).

As in many other hydrometeorological applications, a key consideration is obtaining sufficient field data for model calibration and operation, at an appropriate spatial and temporal scale. There can also be issues with scaling up results at the crop scale to the catchment or regional scale. As described in Chapter 3, if meteorological forecasts are used, then there is often also a need to post-process (downscale) forecasts to the appropriate scale, and to take account of the forecast performance to date (e.g. Challinor et al. 2003, Stone and Meinke 2005, Hansen et al., 2006). Some studies have also used stochastic weather generators to disaggregate long-range forecasts to a shorter timestep, and resampling of historical data to provide an indication of likely seasonal variations.

Some well-known crop simulation models include APSIM (and Whopper Cropper), DSSAT (CERES and CROPGRO), EPIC, GRASS, SIRIUS and WOFOST, and sometimes include decision support components (e.g. Stone and Meinke 2005, Thornley and France 2007, World Meteorological Organisation 2009). Applications have ranged from short-term tactical decision-making, such as on when to provide irrigation, or to apply fertilizers, through to longer-term strategic decisions on when to plant or harvest crops, and the mix of crop types to plant. There is also particular interest in the use of seasonal forecasts in agricultural applications, with research covering not only the technical aspects of generating forecasts, but also the socio-economic and other factors in decision-making. These can include consideration of the risk profiles of users (particularly subsistence farmers), the likely benefits in terms of greater yield, and the financial and other consequences if the forecast is poor; also, the use and communication of forecasts, particularly for probabilistic forecasts (e.g. Troccoli et al., 2008). Models of this type are also sometimes embedded in decision support systems, and the outputs are in some cases available to subscribers via the internet (see Chapter 8).

Dynamic vegetation models are also increasingly included in land-atmosphere simulators as part of climate change impact assessments (see Box 11.4 for an example). Studies of this type usually also need to consider factors such as population growth, economic growth (and the impacts on the types and quantities of food grown and used worldwide), soil condition (nutrients, leaching, salinity etc.), and adaptation strategies to changing climate (including within the agricultural sector).

Box 5.2 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 Water Development and Management Unit focuses 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 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 three FAO Land and Water Division Irrigation and Drainage Papers:

- Crop Water Requirements – which provides guidance on estimating effective rainfall, the irrigation requirements for different types of crop, and the design of irrigation schedules (FAO 1998)
- Yield Response to Water – which provides guidance on crop selection, the relationship between crop yield and water availability, and on water management for optimum crop production and water efficiency (FAO 1979)
- Crop Evapotranspiration – which provides an updated version of the evapotranspiration estimation method in 'Crop Water Requirements' using the Penman-Monteith approach (FAO 1998)

The main meteorological inputs which are required are 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 5,000 meteorological stations worldwide (FAO 1993). Measured values of evapotranspiration may also be used and, if only temperature data are available, the remaining parameters can be estimated based on the altitude and latitude of the location. 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. User supplied values are also required for the percentage of area planted, planting date, 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. 5.4). 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.

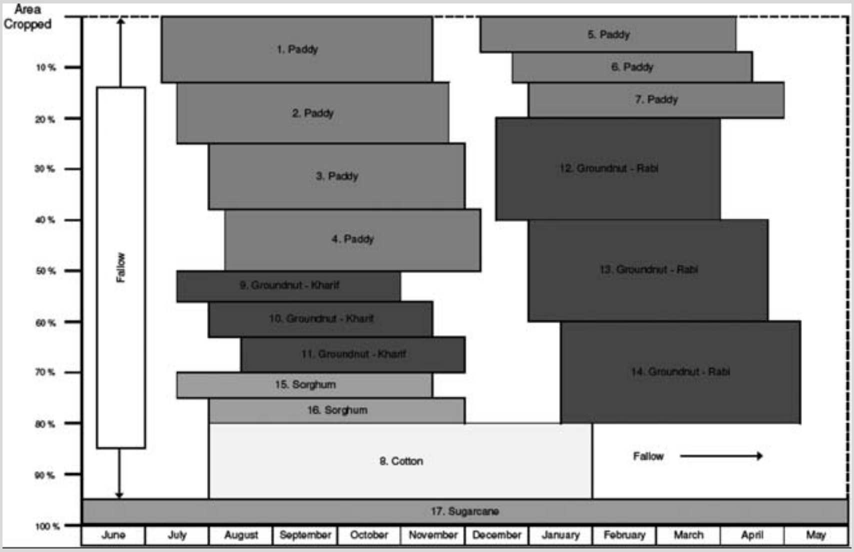

Fig. 5.4 Illustration of cropping pattern for Rajolibanda in Andhra Pradesh, India (Food and Agriculture Organization of the United Nations; FAO 2009)

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 percolation losses or groundwater contributions to irrigation (Clarke 1998). Indicative irrigation schedules can be developed using 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 program 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. 5.5 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).

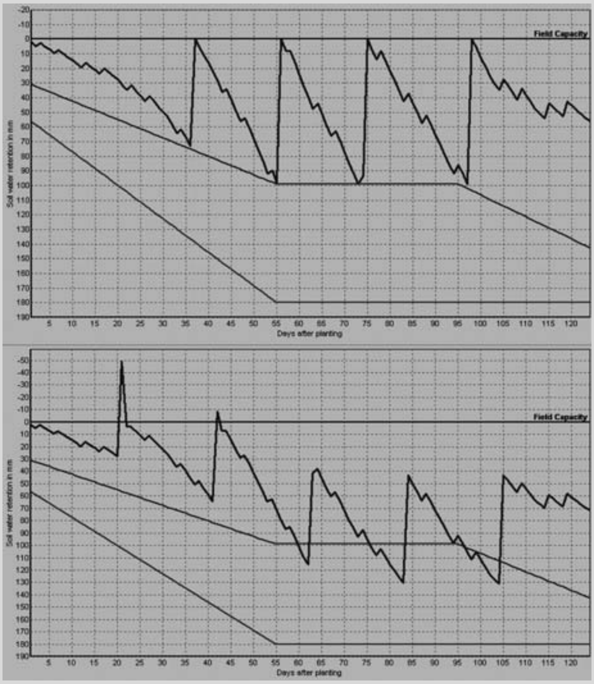

Fig. 5.5 Illustration of irrigation scheduling graph outputs from CROPWAT 8.0 for optimal and sub-optimal schedules, showing irrigation amount, RAM (*upper deficit line*) and TAM (*lower deficit line*) (Food and Agriculture Organization of the United Nations)

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 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 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 rice crops.

5.4 Power Generation

5.4.1 Thermoelectric Power Stations

Thermoelectric power stations typically use coal or natural gas to generate power from steam turbines. These can generate significant quantities of heat, and are usually cooled by passing river or sea water through heat exchangers, whilst the use of water for steam generation is relatively minor. 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 also used in some types of industrial and petrochemical plants, and nuclear power stations. Air-cooled (or dry cooling) systems are also used in some situations, but do not have any significant water requirements.

The water requirements for once-through systems are high and, if a river source is used, require a large river flow to support both the abstraction, and for dilution of the thermal plume which is caused when water is returned (to reduce environmental impacts). Such schemes therefore tend to be located in the lower reaches of major rivers or on the coast, if seawater is used. However, the net water use is generally low since cooling water is returned directly to the river or sea, although this may be some way downstream of the abstraction point when taken from a river. The main losses arise from leakage and evaporation.

By contrast, for closed loop systems, the recirculated water needs to be cooled before it is used again and this is usually achieved by spraying the water into cooling towers, with the cooling effect arising from evaporation. Both natural and forced convection may be used, 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 account for a much higher consumption of water than direct cooling systems, although avoid the thermal pollution caused by once-through systems. For example, in the USA, it is estimated that, in closed loop systems, more than 50% of the water which is abstracted is lost, although this type of system accounts for only about 10% of overall river abstractions for power generation (Hutson et al., 2004).

Demand forecasts for individual plants are probably best performed on a case by case basis, in collaboration with the plant owner or operator. For regional assessments, regression and other techniques similar to those described in Section 5.2 might be used; for example, in the United States, one approach to estimating water demand at a state level is multiple regression (National Academy of Sciences 2002), with predictors including information in the following general categories: generation method, installed generation capacity, availability of cooling towers, weather conditions (temperature, degree days etc.), state water law, and the number of generating units.

5.4.2 Hydropower Schemes

5.4.2.1 Introduction

Hydropower schemes use the flow of water through turbines to turn generators to produce electricity. The main types of scheme are:

- Reservoir Storage Schemes – water is stored in a reservoir for subsequent release to meet the required electricity demand (Fig. 5.6)
- Run-of-River Schemes – water passes through a small barrage or dam without any significant storage, providing a baseload supply of electricity (e.g. see Fig. 9.1)
- Pumped Storage Schemes – water is pumped from a lower reservoir to a higher reservoir during periods of low demand for electricity, then released to meet peak demands (Fig. 5.6)
- Diversion Schemes – water is diverted from the main river into a channel to pass through a penstock and turbine before being returned further downstream

Tidal barriers are also used in the tidal reaches of some rivers to generate power from the head differences caused by the rise and fall of the tides. Water wheels,

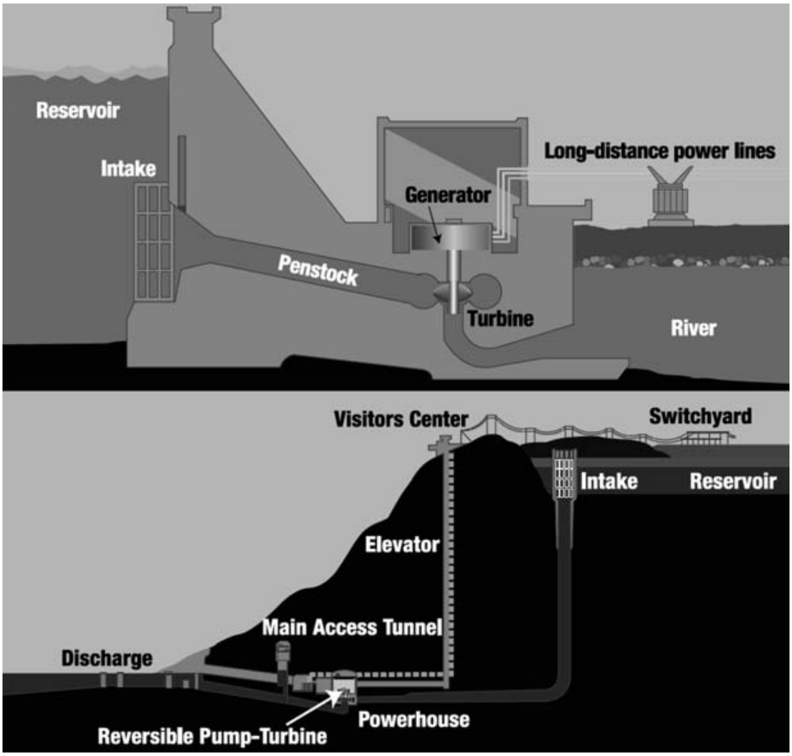

Fig. 5.6 Examples of reservoir storage and pumped storage schemes (Tennessee Valley Authority, TVA 2009)

diversion schemes and in-stream turbines are also used in some micro-hydropower and small-hydropower schemes.

For a hydropower plant, the power generated depends on the turbine efficiency, the flow rate and the net head (difference in levels). Hydropower is estimated to provide 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.

Depending on the mix of energy sources in a region, hydropower may be used as the primary supply for electricity, or for balancing short-term fluctuations in demand which cannot easily be supplied by thermal or nuclear power stations or other power sources. Hydropower has a significant advantage over some other forms of power generation due to the speed at which power can be supplied (sometimes within a few minutes), although has the disadvantage of being dependent on short-term and seasonal inflows (although large reservoir storage volumes can 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 volumes, and longer-term investment planning. The optimum operating strategy depends on a range of factors, including the forecast inflows, outflow capacity, reservoir capacity, the current storage, and forecasts for future electricity demand and energy prices. Other objectives may also need to be considered, including the requirements 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. In particular, the need for the greatest flood storage may coincide with the peak winter demand for electricity; however, where snowmelt dominates the water supply to reservoirs, the highest (spring) inflows may lag the peak (winter) demand by several weeks or months. Emergency releases may also occasionally be required for flood control during high flow periods.

Traditionally, hydropower operators have used historical climate and river flow records and energy price forecasts to define control or rule curves for reservoir releases. For medium to long-term planning, linear and dynamic programming techniques (including stochastic forms) are widely used, with both simulation and linear programming methods used at shorter timescales (e.g. Yeh 1985). The level of detail in models is generally less at longer timescales (e.g. hydraulic characteristics, load profiles), and the timestep used is longer (e.g. weekly or monthly). For forecasting hours to days ahead, semi-distributed integrated catchment models are also widely used, and combine rainfall-runoff, flow routing and reservoir components. Ensemble precipitation and temperature forecasts are also increasingly used to guide operations (see Chapter 9), particularly for medium to long-range planning, and several studies have shown that this can offer significant improvements in system performance and overall energy generation; for example, the use of long lead time streamflow forecasts to allow operating constraints to be relaxed in years when there is a high likelihood of ample streamflow (Hamlet et al., 2002). Chapters 6 and 9 describe examples of these techniques, together with decision support systems for optimizing the operation of multi-objective, multiple reservoir systems.

5.4.2.2 Hydro Scheduling

Hydro scheduling is the process of operating a hydropower scheme to meet the required objectives, subject to system constraints. Some meteorological factors which can influence operations include:

- Precipitation – which affects river flows, direct rainfall on reservoirs and, where relevant, snow cover and the rate of snowmelt (when rain falls on snow)
- Air Temperature – which affects electricity demand, electrical transmission and distribution losses, and snowmelt (where relevant)
- Solar Radiation (or Cloud Cover) – which affects electricity demand and reservoir evaporation

High wind speeds can also increase the need for heating, whilst high humidity can increase the demand for air conditioning. Both of these variables also influence reservoir evaporation losses.

Meteorological forecasts can be used to help to plan operations, and some terms which have evolved to describe hydropower generation include (e.g. Hamlet et al., 2002):

- 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 short-term contracts for interruptable power which are established when surplus water is available (e.g. in the spring months).

Many countries now operate a deregulated energy market in which suppliers can 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 are also used. 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 can vary by an order of magnitude over a period of a few hours, and can depend on 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 (e.g. from thermoelectric power stations). A price cap may be set to reduce system vulnerability and, to provide a baseload income, a proportion of capacity may be offered on long-term fixed price contracts. Forward and futures contracts are also used as a way of reducing risk, in which suppliers agree to provide energy at a given time from weeks to months or years ahead.

Long-term demand, or load, forecasts are typically derived from an understanding of the requirements of individual end-users, whilst trend-based, regression, time series analysis and artificial neural network techniques are widely used for short lead time operations (e.g. Box 5.3). For example, one widely used classification is into residential, commercial and industrial users (e.g. Mazer 2007). Residential demands can arise from many sources, such as for lighting, heating, cooking, refrigerators and air conditioning, together with more recent developments such as electric vehicles, computer equipment and other types of home electronics. One important consideration is the likely daily, weekend and seasonal pattern of electricity use, which is often called the load shape, and can be 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, and may require a detailed analysis of individual components (e.g. pumps, generators, cooling systems), although respond to many of the same drivers as residential demands. Some other major users of electrical power can include the transportation sector (e.g. mass transit systems) and the agricultural sector (e.g. irrigation schemes).

For long-term forecasts of demand, the factors which may need to be considered include changes in population, likely changes in gross domestic product, employment, the regulatory environment (particularly regarding energy efficiency, and other demand reduction measures), and the links between energy consumption and prices. Climatic variability also needs to be considered, and the impacts of climate change. The installed generation capacity needs to be sufficient to meet typical loads over a day, season, and year, and likely peak demands. Import and export of energy between suppliers and regions also needs to be considered, and mixing of supplies from alternative energy sources. An assessment of the robustness of forecasts is often important, typically using Monte Carlo sampling 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 (see Box 5.3).

Box 5.3 Load Forecasting in BC Hydro

BC Hydro supplies power to more than 1.7 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 modeling and statistical techniques, as described in Box 11.3, and form part of a decision making process (Fig. 5.7) 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

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).

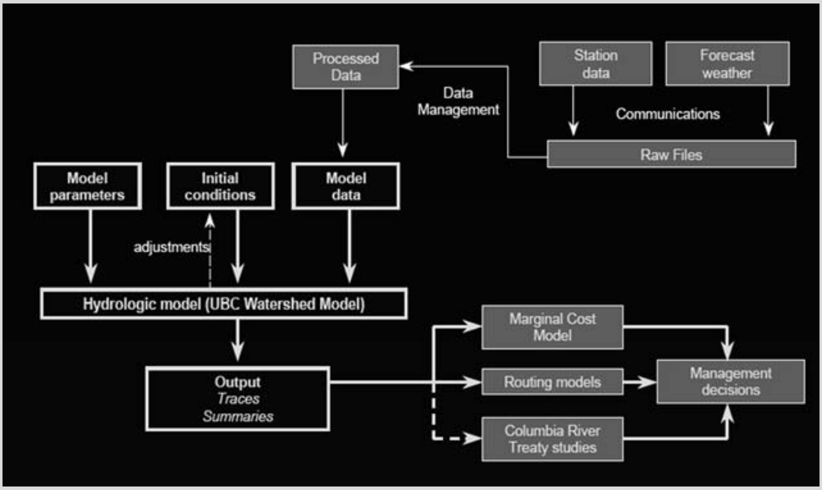

Fig. 5.7 BC Hydro Ensemble Streamflow Prediction Forecasting Process (Weiss 2004)

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 1–2 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 finalized, the optimized 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 4,000 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 characterized 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 7 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 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 7 days. This result is then scrutinized 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 understated 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 modeling 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 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 studies are also performed for major transmission, commercial and industrial end users. Peak demands are also forecasted for each individual electricity 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 the economic growth rate, electricity rates, the impacts of demand-side management measures, 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. Demand-side management measures can include energy efficiency programs and the installation of new on-site generation facilities by customers. 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. 5.8).

A review of demand forecasting accuracy (BC Hydro 2008) suggested that, over the period 1993–1997, the 10-years ahead demand forecasts, normalized for weather and labour disruptions, were within about 7% of the values which were subsequently measured in the years 2003–2007.

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.

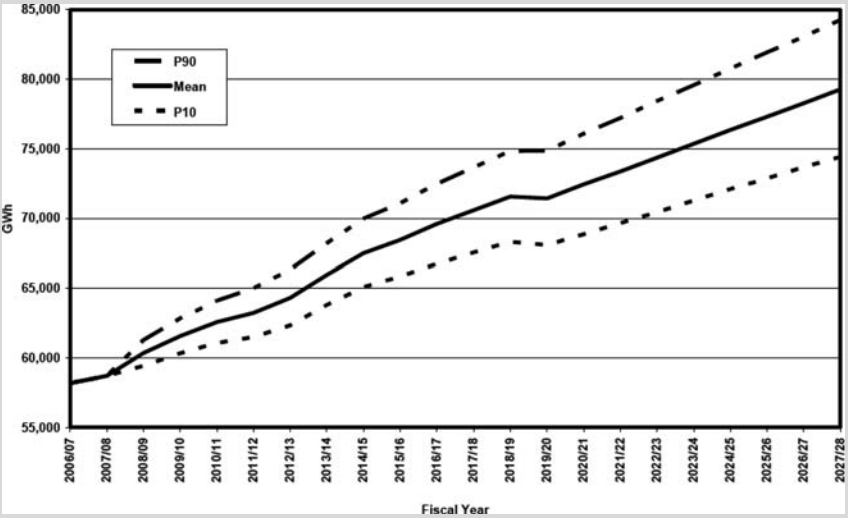

Fig. 5.8 High and low bands for total gross load requirements in Gigawatt-hours before Demand Side Management and Electricity Rate Impacts for the period 2007/08–2027/28 (BC Hydro 2008)

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Chapter 6
Decision Making

Abstract Hydrometeorological forecasts are used for many applications, including issuing alerts and warnings, strategic planning, and the real time control of reservoir and other systems. To support decision making, forecasts need to be interpreted in terms which are meaningful to the end user, and which provide sufficient lead time to take effective action. Perhaps the simplest approach, but one which can require considerable consultation and discussion, is to devise purpose-made forecast products appropriate to the recipient, and to decide how best to disseminate that information in time to be useful. This can include map-based and internet-based displays, and more traditional bulletins and situation reports. More automated techniques can also be used, and can include threshold criteria, decision support systems, and a range of probabilistic techniques. Also, a risk-based approach is increasingly used in decision-making, considering both the probability of an event occurring, and the likely consequences. This chapter provides an introduction to these topics, and to the decision-making techniques used in flood warning, drought early warning, pollution alert, reservoir control and other applications.

Keywords Decision-making · Forecast products · Thresholds · Risk management · Decision support · Ensemble · Probabilistic · Uncertainty

6.1 Introduction

Hydrometeorological forecasts typically provide future estimates of parameters of interest, such as river and reservoir levels, river flows, water quality and snowmelt, at a range of lead times from short- to medium- to long-term. Increasingly, information is provided in probabilistic terms, particularly for seasonal and longer lead times, but also at shorter lead times, where this has the potential to lead to better decisions.

One challenge in using forecasts operationally is to decide how best to communicate this information to decision makers, in time for that information to be useful. Examples of decision makers can include members of the public, local authorities, the emergency services, environmental regulators, water supply companies,

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and power station operators. There can therefore be a range of potential end users at local and national level, each with different requirements, responsibilities, resources, terminology (or ‘jargon’) and levels of technical understanding. For example, Chapter 1 summarises some typical lead times at which information can be useful in decision making for a range of applications, including irrigation scheduling, flood warning and water supply.

A community-based or people-centred approach is also widely advocated in the disaster warning literature (e.g. Basher 2006, UN/ISDR 2006), working with communities and other end users to develop the most effective and sustainable approach. For example, in flood warning applications (e.g. Andryszewski et al. 2005, Drabek 2000, Handmer 2001, Parker 2003), some typical communication activities can include:

- Public awareness campaigns (meetings, media, household visits etc)
- Developing automated dissemination systems (phone, email, the internet etc)
- Involving community representatives (flood wardens, observers etc)
- Improved ways of communicating forecasts (maps, visualization etc)
- Market research surveys (on success rates with issuing flood warnings etc)
- Rehearsals and exercises to test procedures (table-top, full scale etc)

Collier et al. (2005) also note that there is a need to keep a clear distinction between the needs of hydro-meteorological services and flood emergency operations. 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.

Similar considerations also apply in other areas, such as drought warning (e.g. Wilhite and Knuston 2008) and seasonal forecasting for agricultural applications (e.g. Troccoli et al. 2008). For organizations, roles and responsibilities are also important to consider and, in particular, the extent to which the forecasts issued 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 that ‘flows are expected to remain low for the next month’ compared to the instruction to ‘suspend pumping operations for spray irrigation for the next 10 days’.

Some traditional approaches to dissemination of information include indirect methods such as newspapers, radio, and television and – particularly for short lead-time applications – more direct approaches such as telephone calls, fax, sirens, and door-knocking. More recent approaches include the internet, mobile phones and email, and automated dialing and multimedia systems, sometimes including text to voice translation software. Satellite broadcast approaches, such as the internationally supported RANET radio system in Africa and Asia (http://www.ranetproject.net/), also allow information to be distributed to large numbers of people, and for the two-way communication of emergency information. Map based and visualization techniques are also increasingly used to help provide a spatial context to the information provided, and other chapters present a wide range of examples for specific applications, such as floods, droughts and pollution incidents.

The most appropriate methods also depend on the lead time available, with flash flooding being perhaps one of the most challenging types of hydrometeorological hazard for the issuing of warnings, due to the short times over which events develop, compared to the times needed for an effective response (see Chapter 7). As noted in Chapter 1, ideally all forecasts should be accompanied by information on when the forecast was made and the time of the next forecast. Also, for more specialist users (but possibly also for more general use), the uncertainty in the forecast, the spatial and temporal scale of the forecast, the time when the data used to initialize the forecast was observed, and recent information on forecast performance.

Perhaps the simplest quantitative approach to decision making is to use threshold values above (or below) which a decision is taken: for example, based on observations or forecasts of river levels, rainfall depth-duration values, and other criteria. Some alternative names for thresholds include triggers, alarm levels, alert levels, critical conditions, and criteria, and this approach is used in many flood warning, drought warning, pollution alert and other applications, as described in Section 6.2. The raw forecast outputs may also be passed to decision support systems, capable of combining forecasts with other types of information, such as on food prices and availability in famine early warning systems, and the properties at risk from flooding in a flood warning system. Section 6.3 discusses decision support systems for a range of applications.

Many organizations are also increasingly adopting a risk-based approach to decision-making, where risk is usually defined as the probability of an event occurring, and the likely consequences, perhaps also including measures of vulnerability and the level of preparedness (e.g. Haimes 2009; Rogers et al. 2007; World Health Organisation 2007). The consequences can include impacts on people, financial damages, business disruption, and other factors. Some typical options for managing risk include avoiding, reducing, transferring, sharing, controlling, or accepting the risk, and Table 6.1 summarises some examples of areas where a risk-based approach is used or advocated in hydrometeorological forecasting applications.

For example, in flood warning applications, provided that the warning provides sufficient lead time to take effective action, some risk management options during a flood event could include avoiding the risk (e.g. by operating a tidal barrier), reducing the consequences (e.g. by evacuating properties), transferring or sharing the risk (e.g. by flooding of farmland to prevent or reduce flooding of properties further downstream), controlling the risk (e.g. by the use of sandbags), and accepting the risk (e.g. by not providing door to door warnings if that would divert staff from other more urgent duties).

As noted, the vulnerability of the communities and people affected is also often considered, and this can include socio-economic factors (age, mobility, income, health etc), as well as factors related to the nature of the hazard. For example, one approach is to express vulnerability in terms of physical or material, constitutional or organizational, and motivational or attitudinal conditions (World Meteorological

Table 6.1 Examples of risk-based approaches which are used or have been considered in hydrometeorological forecasting applications

Sector	Location	Description	Examples
Agriculture	International	Short, medium and long range decisions on crop management, investment etc	Stone and Meinke (2005), Troccoli et al. (2008)
Drought warning	USA, international	Risk-based approach to disaster preparedness and mitigation	Wilhite and Knuston (2008), UN/ISDR (2007)
Flood warning	General	Risk-based criteria for flood-watches, flood warnings etc	Krzysztofowicz (2001), see Chapter 7 also
Food security	Africa, Haiti, Afghanistan	The FEWS NET famine early warning system	See Box 8.3
Water resources	International	Daily operation of multiple reservoirs systems through to long term planning and investment	Decision support systems and cost-loss approaches (see Chapters 9 and 11)

Organisation 2006a). These factors, together with the level of preparedness, all affect the extent to which people are affected by events such as floods and droughts, with vulnerable and less well-prepared communities less able to adapt and respond as events develop. The increasing use of ensemble and probabilistic techniques also provides the potential to make quantitative assessments of risk in real-time, based on probability and consequence, and this topic is discussed further in Section 6.4.

6.2 Thresholds

Thresholds are one of the simplest and most widely used approaches to operational decision-making, and are often linked to hazard or evacuation maps, showing areas at risk. Typically, decisions are taken on the basis of an observed or forecast variable exceeding or dropping below a critical value, triggering one or more response actions. Whilst most often associated with emergency situations, thresholds can also be used in more routine operations, such as triggering the operation of a flow control structure or pump.

Decisions may be based either on the parameter which causes the impact (e.g. river levels causing flooding), or a suitable surrogate (e.g. heavy rainfall as an indicator of potential flooding). Table 6.2 presents some examples of applications of threshold values, including references to examples presented in later chapters.

Thresholds can be defined in terms of observed values, forecast values, or both types of information, and can also include derived values, such as the Standardised Precipitation Index, which is widely used in drought forecasting (see Chapter 8). Combinations of parameters may also be used, such as Flash Flood Guidance thresholds (see Chapter 7) and the Palmer Drought Severity Index (see Chapter 8), which both combine rainfall and soil moisture information.

Table 6.2 Examples of applications of thresholds in hydrometeorological forecasting applications

Parameter	Application	Basis of method	Examples
River level	Flood warning	Exceedance of threshold value	See Section 7.1
	Drought watch	Level below threshold value	See Section 8.3.1
River flow	Water resources	Minimum flow in river	See Section 5.1
Rainfall	Flood warning	Exceedance of depth-duration value	See Section 7.1
	Bathing water quality	Exceedance of depth-duration value	See Box 10.4
	Drought watch	Depth-duration below critical value	See Section 8.2
Reservoir levels	Flood warning	Level and rate of rise above critical values	See Section 7.1
Water quality	Pollution incidents	Exceedance of value	See Box 10.2

In some applications, there may also be several thresholds at each location to escalate the warning as the severity of the event increases. For example, in water quality monitoring, the initial trigger for action can be a parameter passing an upper or lower limit, with a second critical limit, outside of which confidence in water safety would be lost (World Health Organisation 2008), whilst the following generic set of warnings is often used for natural hazards such as tropical cyclones, hurricanes and floods (World Meteorological Organisation 2006b):

- 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

To illustrate this approach, Fig. 6.1 shows an example of the flood and drought thresholds which might be established for a river gauging station. Four threshold values are illustrated, consisting of an initial flood watch and a flood warning threshold, based on observed levels, and a flooding threshold, at which property flooding begins, which might be a suitable trigger level for a forecasting model output. A threshold for triggering a drought watch is also shown, together with an indication of the cumulative deficit, which might also form the basis for another drought related trigger. Of course, the cumulative deficit would need converting to units of volume,

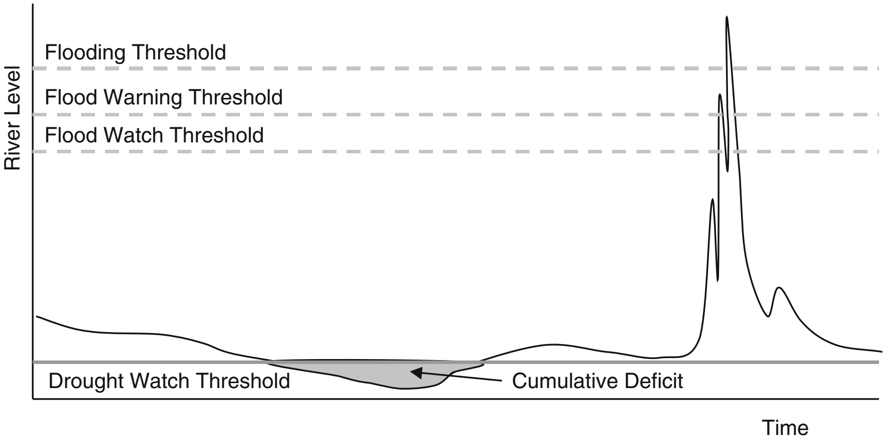


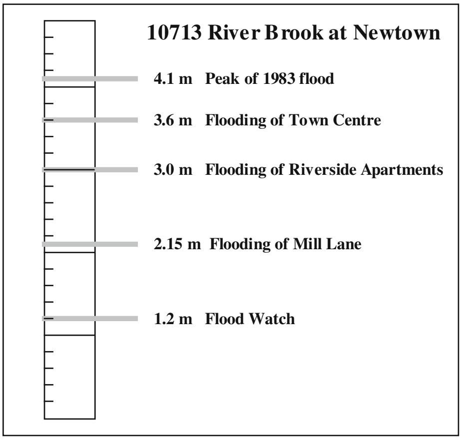
Fig. 6.1 Illustration of flood and drought thresholds for a river gauging station at or close to the location of interest (note that for illustration the time axis is not to scale)

and the horizontal scale on the graph is compressed to illustrate both a drought and a flood event on the same figure.

When observed values are used, there are usually in-built assumptions about the river or catchment response, providing a simple, empirical form of forecasting. For example, as shown in Fig. 6.1, when the gauge used is at or close to the location where a flood warning service is offered, flood warning thresholds are typically set at a level some way below the level at which flooding occurs, giving enough lead time to initiate operational actions, such as evacuating property, or operating a river flow control structure. The forecasting assumption is therefore that river levels will continue to rise at a similar rate to the values observed historically, or derived from a modeling exercise. An allowance or contingency for uncertainty may also be included in the estimate for the threshold.

To provide additional lead time and resilience, gauges further upstream are also often used, although often at the expense of a higher false alarm rate due to uncertainties in how flows will translate through the river system. More advanced forms of threshold are sometimes also used, such as variable rate of rise thresholds, which dynamically estimate the appropriate level for issuing warnings for the required lead time (Graham and Johnson 2007), and multi-criteria thresholds, which rely on levels observed at more than one location. Look-up charts and tables are also sometimes used, with multiple criteria to cover a wide range of conditions, such as for a range of tidal levels, in a tidally influenced river, or for different values of snow cover, or soil moisture conditions (e.g. World Meteorological Organisation 1994). The appropriate threshold is then identified from the chart and the forecast or observed values at a site.

Figure 6.2 illustrates how a system of threshold values might be implemented in an operational flood warning system. The threshold values are summarised in a flood intelligence or action table, which duty officers can refer to as river levels are received by telemetry to decide on the appropriate action(s) to take. To assist in interpreting the meaning of each value, a visual impression of the levels is shown against the backdrop of a staff gauge for the site in question (this form of presentation is sometimes called a thermometer plot). Procedures such as these may be implemented in an operational manual for use by duty officers and/or on-line as defined alert levels in a telemetry system, or within a decision support system. The threshold values are often associated with flood warning area or evacuation maps (off-line or on-line) showing the anticipated locations of flooding, and the properties at risk. Section 1.3 shows an example of an evacuation map.



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. 6.2 Illustration of a diagram showing the levels at which flooding is expected to occur, and a system of flood warning thresholds, summarized in an action table (illustrative example only)

When forecast values are available, there are a number of ways that these can be used, depending on confidence in the forecast and organizational policy. In some cases, the forecast alone may be relied upon before initiating the response, but often a mixture of observed and forecast values is used in decision-making, particularly for short lead-time applications. For example, Sene (2008) describes the following ways in which river level forecasts might be used operationally in triggering a flood warning:

1. Issue the warning either if the observed value is exceeded, or if the forecast value is exceeded
2. Issue the warning if both the observed and forecast values are exceeded
3. Consider issuing the warning if the observed value is exceeded, using the forecast outputs to take the final decision
4. Generate warnings to individual properties or groups of properties from real-time forecasts of the inundation extent

Each approach has its own advantages and limitations, and would provide different lead times and success and failure rates for issuing warnings. Also, as described in Sections 6.3 and 7.1, the forecast outputs could be used as input to a decision support system for reservoir operations, or for wider applications, such as evacuation management, or generating dynamic emergency response plans. Systems of this type sometimes also have the functionality to advise on optimum response strategies, although this approach is not yet widely used in flood emergency management.

Thresholds are normally defined off-line, based on experience, historical data, and – in some cases – river or catchment modeling studies. For example, rainfall depth duration thresholds might be estimated by feeding a range of design or historical storms with different profiles and durations into a catchment model to see which combinations lead to potential flooding. Other possibilities include Bayesian decision-making techniques based on historical rainfall data, soil moisture conditions, and stakeholder perceptions (Martina et al. 2006), and the use of probabilistic thresholds (see Section 6.4). Empirical, experience-based and modeling approaches are also used in defining values for drought triggers, with an emphasis on the use of drought indices (see Chapter 8). In some cases, such as pollution alerts, appropriate values may be available from national or industry-standard guidelines and standards.

Ideally, the performance of thresholds should be verified both when setting values, using long runs of historical data, and routinely in operational use. As described in Sections 3.3 and 4.3, some examples of performance measures include contingency measures, such as the Probability of Detection, and False Alarm Ratio, and the warning lead time provided. Often, when setting threshold values, there will be a trade-off between success rates, false alarm rates and lead times; for example, if a flood warning threshold is set too low, this will generally provide longer lead times, and a higher probability of detection, but a higher false alarm rate (e.g. USACE 1996). For a regional or national forecasting system, there may also be many sites to consider, in some cases with multiple threshold values for each location, in which case it is particularly important to fully document and test the values used.

Also, the more representative a threshold is of the problem being forecast, the more reliable it is likely to be; for example, due to the uncertainties in how rainfall translates into runoff, rainfall depth-duration thresholds are often used only for initial mobilization of staff, and for moving to an increased level of alert, rather than for issuing flood or drought warnings directly to the emergency services and the public. However, this approach can work well in some applications, such as providing warnings of poor water quality at beaches (see Chapter 10).

In some applications, such as flood or drought warnings, extensive discussions may also be required with stakeholders to agree on the values to use in future, particularly where these might affect emergency funding arrangements, evacuation of large groups of people, or restrictions on water use for water supply, irrigation or power generation. Indeed, one advantage of thresholds and associated hazard maps is that they can be set, verified and agreed in advance of an event, rather than interpreted during the pressures of an event; however, there are also many limitations arising from the use of a single pre-set value (or combination of values) since an event may unfold in different ways to that inherent in the historical data used for calibration. More sophisticated approaches, such as decision support systems, therefore also have an important role to play, and are described in the following section.

6.3 Decision Support Systems

Decision support systems can provide useful additional information to help with decision-making, and 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'. For a computer-based system, some key elements can include:

- User Interface – a user friendly interface for entering choices and viewing results, which is often map-based
- Simulation Models – models which use meteorological observations and forecasts as inputs, such as crop simulation and reservoir supply-demand models
- Optimisation Modules – to advise on the optimum strategy according to predefined criteria (e.g. for evacuation of properties, reservoir releases)

Some examples of decision support systems which are used operationally in hydrometeorological forecasting applications include:

- Agricultural Risk Management Systems – which use crop simulation models to provide information which can be used by farmers to decide on optimum planting, harvesting and storage strategies, and shorter-term scheduling for irrigation and fertilizer use etc (see Chapter 5 for examples)
- Drought Management Systems – which provide information which can be used by disaster managers to decide on optimum response strategies to food and water supply shortages (see Chapter 8 for examples)
- Flood Emergency Response Systems – which provide 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 Chapter 7 for examples)
- Reservoir Operation Systems – which provide information to assist reservoir operators to decide on optimum reservoir release strategies to meet a range of requirements (water supply, irrigation, hydropower etc), subject to regulatory, environmental, economic and other constraints (see Chapter 9 for examples)
- Urban Real Time Control Systems – which control gates, valves and other components in urban drainage systems to minimize sewer pollution incidents during heavy rainfall (see Chapter 9 for examples)

In systems of this type, the modelling component may be integrated into the system, or the outputs imported from a separate modeling environment. Note also that in most cases these types of system provide information to support decision making, rather than automatically triggering the response; however, in some cases, such as flow control for urban drainage systems, or tidal barriers, the software may also control the operation of gates and other structures via telemetry links and actuators.

Geographic Information Systems (GIS) are also often a key component of decision support systems, and usually include the options to overlay maps of different types (e.g. catchment boundaries, rivers, roads, aerial photographs, satellite images, evacuation routes), and to present forecast outputs in a map-based format (e.g. as inundation maps, maps of drought indices). Often, the options to search for information and to combine values spatially are also included. This approach is increasingly used in real time to assist with emergency management, and some general advantages of using GIS for an integrated emergency response 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

More generally, the extent to which decision support systems are used operationally will depend on a range of factors, including the reliability and useability of the software and associated systems, the degree to which the system is integrated into operational and planning procedures, and the confidence that users have in the outputs. Also, as with any computer-based approach, some other factors which are important in determining whether the system is sustainable and useful over the long term include the level of training and technical and financial support provided, and the extent to which users were involved in design of the system.

In particular, for safety critical applications, and where large investment or other decisions will be made, the system design needs to be extensively documented and tested, with backup procedures in place for system failures, loss of telemetry, and other problems. For example, for the Maeslant tidal barrier in the Netherlands, which protects Rotterdam and surrounding areas from tidal flood risk, the design documentation for the automated decision support system consisted of some 4,000 pages of natural text and operation schemas and formal descriptions (Tretmans et al. 2001; see Chapter 9). By contrast, for real-time control of urban drainage systems, one widely used design option is to ensure that, should the system fail, it falls back to a situation which is equivalent to, or better than, that before the system was installed (Schütze et al. 2004).

For use in emergency situations such as flood events, there is also the option of using stored (pre-defined) model outputs for key outputs such as flood inundation maps, rather than relying on real-time outputs, particularly where the simulations may require long computer run times (e.g. for probabilistic estimates). An advantage of this approach is that it allows scenarios to be discussed and validated before use, whilst a disadvantage is that during an event different factors may come into play which a suitably designed and calibrated forecasting model is more likely to predict. Data assimilation also has a key role to play in helping to adapt model outputs to cope with unforeseen circumstances.

Of the examples provided, decision support systems have been used for many years for water resources and reservoir operations (e.g. Loucks 1996), and probabilistic components are increasingly being included. Urban real time control systems are also widely used in some countries following pioneering work in the 1990s and before (see Chapter 9). Decision support systems have also been used for a number of years for large-scale commercial farming applications, and are increasingly starting to include crop simulation models, to make use of seasonal forecasts, and to be used in regional food security applications (e.g. World Meteorological Organisation 2009). By contrast, the use of decision support systems in flood emergency response applications is a developing area, with only a few examples of operational use worldwide. However, it is worth noting that systems with similar types of forecast inputs and objectives have been used operationally in the USA for many years for hurricane evacuation applications (e.g. Wolshon et al. 2005).

The inclusion of an optimization module is also less widespread than for the simple combination and presentation of information which many systems provide. Where optimization routines are used, these can take many forms, and the system may either provide a wide range of possibilities, from which the forecaster can select options, or may provide advice on a single or small range of optimum strategies. As noted earlier, in a few cases, due to the fast responding nature of the system, or the complexity of the situation, the decision making process may also be automated, if the required standards of safety and reliability can be achieved.

Some examples of approaches to optimization include:

- 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, and alternative options, leading to a range of outcomes from which one or more is selected
- Dynamic or Linear Programming – stochastic or deterministic techniques which use simplified system representations to iteratively arrive at an optimum solution
- Expert Systems – 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

For example, Harrison et al. (2008) provide a simplified illustration of how a decision tree approach might be used to guide key decisions on food security based on a seasonal climate forecast (Fig. 6.3). The square symbols here are decision nodes (yes/no), whilst the circle is a chance node (based on probability). The implications of each decision are shown in monetary terms, working leftwards from the known values on the right of the diagram, allowing the lowest expense or largest profit option to be identified. Here, some approaches to hedging the risk would be to purchase insurance or to buy part of the crop that might be needed. In practice, the actual decision making process would be considerably more complex, and could also consider uncertainty in the various estimates, and the attitudes to risk of decision makers; decisions may also be interdependent, and other tools, such as influence diagrams, may be more useful in that situation (Harrison et al. 2008).

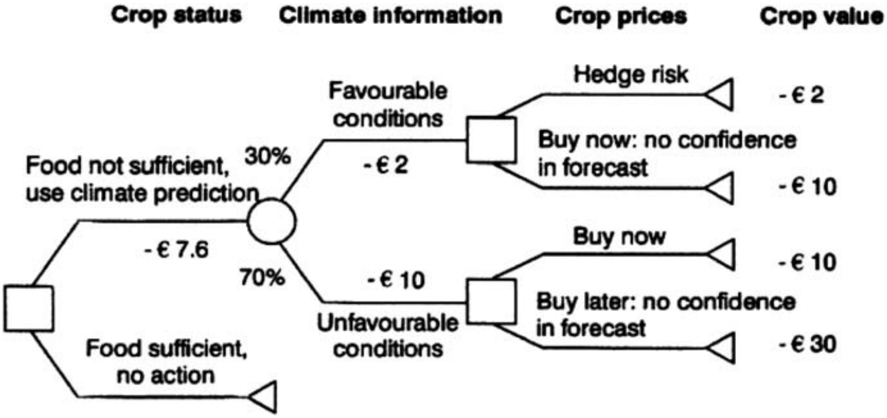


Fig. 6.3 Example of a highly simplified decision tree to illustrate a food security application, purposely constructed to focus on its mechanics, where the values shown are in million of euros. See text for details (Troccoli, in Harrison et al. 2008)

As illustrated by this example, options can often be formulated in financial terms to provide a common basis for making decisions across a range of possible alternatives. This approach can also work well in other situations where environmental and other gains and losses can be expressed financially; for example, the opportunity loss for hydropower generation by reducing reservoir levels to provide flood storage, or the damage to properties and businesses if flooding occurs. However, utility functions are also widely used where outcomes cannot easily be expressed in financial terms, 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). For example, in reservoir operations, overtopping of the dam wall is usually an unacceptable outcome, so a high value would be placed on this not occurring. To allow functions to be combined, values are normally expressed on a scale from 0 to 1 and, when there are several utility functions to consider, the optimum solution is often taken to be the outcome which provides the maximum combined utility (although other approaches are possible).

Also, in some cases, outcomes may not be so clear-cut and can vary between locations and applications, particular 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. Functions can also be interpreted in terms of the risk tolerance of the user (e.g. Murphy and Katz 1985). These concepts can also be used in probabilistic decision-making, and that topic is discussed in the next section.

Of these various decision making techniques, dynamic and linear programming techniques, utility functions and decision trees are widely used in reservoir management systems (see Chapter 9), whilst artificial intelligence techniques have been used or explored in a number of applications, including seasonal forecasting for drought and agricultural applications (see Chapter 8) and demand forecasting (see Chapter 5). Monte Carlo techniques are also widely used in probabilistic assessments of risk; for example, Box 6.1 describes a Monte Carlo approach for long-term assessments of flood risk in England and Wales. As discussed in Chapter 7, approaches of this type might also be used in real-time to assist with flood emergency management.

Box 6.1 Risk Assessment of Flood and Coastal Defence for Strategic Planning (RASP)

In England and Wales, recent estimates suggest that more than 5 million people in 2 million properties are at risk from flooding. The main risks arise from rivers, coastal flooding, and surface water flooding.

In recent years, the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency have increasingly adopted a risk-based approach to decision making in flood and coastal erosion management. This helps to identify the various components of the problem and associated consequences, and allows valid comparisons to be made with other investment decisions to protect and support society (Institution of Civil Engineers 2001, Defra 2005). For flood risk management, some typical choices at a catchment level can include balancing the requirements for new flood defence infrastructure against other options, such as improvements to flood warning systems, restricting property development in flood prone areas, and maintaining and improving existing infrastructure.

To assist in assessing options and prioritising future improvements, a decision support tool called RASP (Risk Assessment of Flood and Coastal Defence for Strategic Planning) has been developed (Sayers et al. 2002b; Gouldby et al. 2008). The method has recently been adapted to enable a forward uncertainty propagation approach to estimating the joint probability of flooding from a range of sources, using a ‘Source-Pathway-Receptor’ conceptual framework (Gouldby et al. 2009). For flooding applications, the main components to consider are:

- The characteristics of the source(s) of hazards (e.g. high river, estuary or coastal levels)

- The performance and response of pathways (e.g. flood defence failure or overtopping)
- The impact of flooding on receptors (e.g. properties, environmental impacts)

Generic risk characterisation curves, such as the examples shown in Fig. 6.4, are used to represent the probability distributions for different loading conditions on flood defences, the response of defences to those loads, the impacts from other sources of flooding, and the impacts on people and the environment. The types of socio-economic impacts which can potentially be considered include the numbers of properties affected (and associated economic damages), the flooding of critical infrastructure, and assessments of vulnerability to flooding, based on factors such as the age and economic status of those affected. A rapid flood-spreading model allows multiple scenarios to be investigated in a computationally efficient manner.

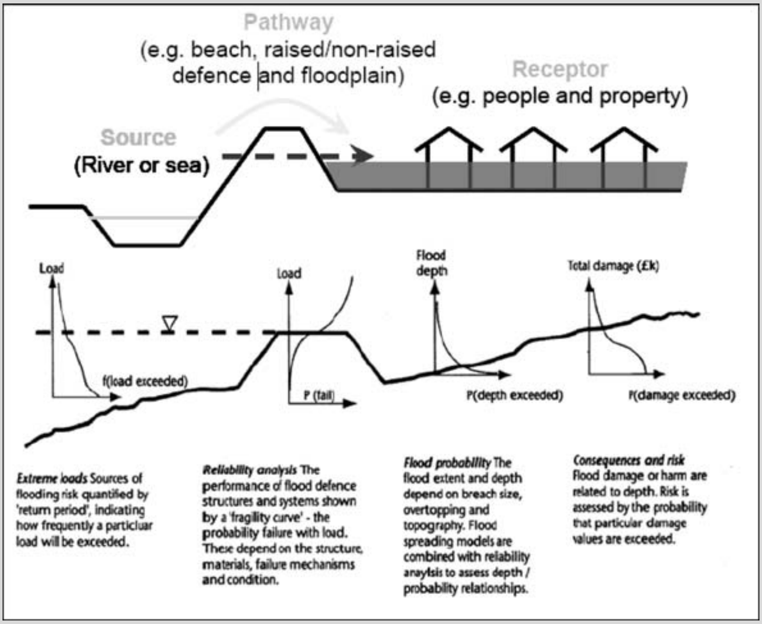


Fig. 6.4 Generic risk characteristic curves used in the first generation RASP methods (adapted from Sayers et al. 2002a)

In implementing the RASP methodology, a tiered or hierarchical approach is used, in which the spatial and temporal scale of the modelling is tailored to the application and the available data; for example, in moving from national to catchment to site-specific assessments, or from a high-level to an intermediate to a detailed analysis. For river flooding applications, some key inputs in applying the approach typically include the outputs from hydrological and hydraulic models, the characteristics of flood defences, digital terrain data, and information on property locations and depth-damage curves. Changes over time and dependencies can also be considered if required; for example, the impacts of climate change, and the probability of a defence failure at one location impacting on defence performance at another.

The first major application of the methodology was for the 2004 National Flood Risk Assessment (NaFRA) of assets at risk for the whole of England and Wales. This study, and subsequent annual updates, have provided estimates for the likelihood of flooding in areas at risk for a wide range of possible flooding scenarios, taking account of the locations and standards of protection of flood defences. The RASP approach has also been adopted in a number of more specialised tools for other applications; for example, for strategic asset management, catchment flood management planning, and site-specific flood risk assessments.

6.4 Dealing with Uncertainty

One characteristic of most types of forecast is that there is usually an element of uncertainty, particularly for medium- to long-range forecasts, and it is widely recommended that this uncertainty should both be taken into account in decision-making, and conveyed to decision makers (e.g. World Meteorological Organisation 1994; Krzysztofowicz 2001; Troccoli et al. 2008). In particular, for some types of forecast, such as seasonal forecasts, or rainfall intensity forecasts for thunderstorms, outputs may only be meaningful in probabilistic terms. As discussed in Chapter 1, the provision of information on uncertainty allows end users to make a better assessment of choices in taking decisions and also provides one way of assessing risk in real-time, and potentially providing better targeted forecasts. In flood warning applications for example, some examples of situations where targeted, risk-based warnings might be useful include (e.g. Environment Agency 2007):

- Local authorities who can close riverside and coastal footpaths to walkers
- Large businesses who can prevent customers parking in areas at risk
- Outdoor event organisers who can reschedule or relocate an event
- Farmers who can move livestock between fields
- Residents in frequent flooding locations who can install flood boards or sandbags
- Emergency managers who can plan staff rotas and check that equipment is ready
- Operators of temporary defences who can mobilise staff and equipment
- Hospitals who can reschedule operations and alert staff to the possibility of flooding
- Utility operators who can invoke contingency plans for flood events

When considering the use of probabilistic forecasts, a contrast also needs to be drawn 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. Some examples of the first situation might include a farmer taking day to day decisions on irrigation scheduling, or a hydropower operator deciding on the generation plan for the next few days, where typically the benefits arise from consistent application of risk-based decision making techniques over a number of events or years.

There is therefore a balance to strike between probability, risk and response, and probabilistic and ensemble forecasts can assist in that process (although ultimately the recipient of the forecast needs to make the decision). Of course, there are many issues surrounding the interpretation and communication of the uncertainty in forecasts, and in how best to make decisions based on that information (e.g. National Research Council 2006; Pappenberger and Beven 2006; Troccoli et al. 2008; Beven 2008).

Chapters 3 and 4, and later chapters, discuss approaches to the generation of ensemble and probabilistic forecasts, whilst some techniques for making use of this information can include:

- Visualisation – spaghetti plots, plumes, histograms, box plots, confidence limits, probabilistic maps, and other outputs which show different aspects of the forecast (the range, distribution, spatial variations etc)
- Thresholds – the definition of threshold values in probabilistic terms (e.g. to provide a warning if there is more than a 60% probability of rainfall exceeding 50 mm in 2 h)
- Decision Theory – for example, evaluation of the costs and losses (or utility) of different probabilistic or ensemble scenarios to help to identify optimum solutions
- Bayesian Techniques – formulation and solution of the problem using Bayesian statistical theory

Give the wealth of information available in probabilistic forecasts, visualization techniques have a powerful role to play, and forecasts may need to be presented in many forms, whilst also taking account of the potential for misinterpretation (e.g. National Research Council 2006, Troccoli et al. 2008). For example, one option is to deliver forecasts over the internet, and to provide users with a range of options for viewing information over different time periods, at different scales, and in different formats. Several examples of approaches to visualization are presented in other chapters, including spaghetti plots for air temperature (Chapter 3) and river flows (Chapters 7 and 11), plumes for river flows (Chapter 4), hydropower energy potential (Chapter 7), and groundwater levels (Chapter 7), box and whisker plots for snow water equivalent (Chapter 11), confidence limits for load forecasts (Chapter 5), and probability maps for rainfall intensity forecasts (Chapter 3). Figure 6.5 also shows two examples of experimental forecast products from the National Weather Service in the USA (Seo and Demargne 2008), consisting of a river level (stage)

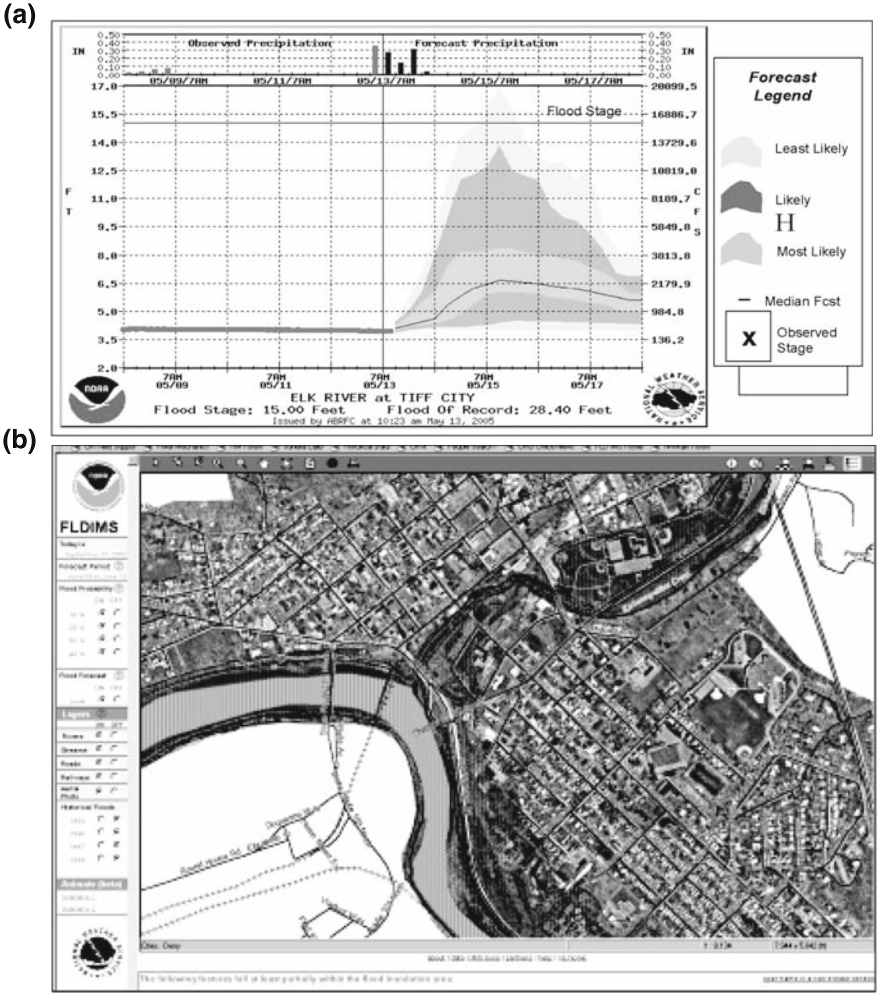


Fig. 6.5 Illustration of experimental ensemble river flow forecast products (**a**) 5-day river stage forecast (**b**) real-time flood inundation map (National Weather Service, Seo and Demargne 2008)

forecast where the probability ranges are expressed in descriptive terms, and a flood inundation map showing the probability of flooding.

To make quantitative use of probabilistic forecasts, probabilistic thresholds might also be defined, based on a given percentage of ensemble members exceeding the thresholds. Some studies have also shown that considering the persistence in consecutive forecasts can help to reduce false alarm rates (e.g. Bartholmes et al. 2009). Some approaches to setting probabilistic thresholds include trial and error, analyses of the historical forecast performance, use of frequency based estimates (e.g. flood return periods), and techniques from decision theory. For example, cost-loss approaches can be used for both deterministic and probabilistic forecasts, and consider the cost of acting upon a forecast compared to the losses which would occur if no action is taken. As illustrated in Table 6.3, these choices can be summarized in a contingency table (or expense table), similar to those described earlier in Sections 3 and 4 for performance monitoring of meteorological and hydrological forecasts.

Table 6.3 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

Over a number of events, it can be shown that mitigating action is cost effective if it is taken whenever the probability of the event occurring (p) exceeds the cost loss ratio C/L (e.g. Katz and Murphy 1997). To take a simple example, on the basis of a short-term forecast of river levels, temporary barriers might be installed at a riverside location incurring staff and other costs (C). If the levels subsequently exceed the original flooding threshold, 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 tolerance to false alarms (e.g. Roulston and Smith 2004). Some additional post-processing of ensembles may also be required to express values in an unbiased, statistically meaningful form (see Chapters 3 and 4). Utility functions, as described in the previous section, may also be used to consider factors which cannot be expressed in monetary terms, and to consider the risk tolerance of end users. A further extension (Richardson 2003) is to consider the economic value of the forecast to users, compared to the situation of only knowing the long term average conditions (or climatology) at the location, from which optimum probability thresholds can be estimated depending on the costs, losses and/or risk profile of the user.

This general approach to decision making is well established in some aspects of hydrometeorology, such as reservoir management (see Chapter 8), and has also been proposed for applications such as flood forecasting (e.g. Roulin 2007; McCollor and Stull 2008). However, for extreme events, there are some practical issues to consider regarding the small number of events which may be available for calibration of the approach, and relating to the response of organizations and individuals when faced with a forecast of a high impact or catastrophic events with a low probability, compared to high frequency/low consequence events (e.g. Haimes 2009).

There are also other areas in decision theory which are used by economists, and which have potential in climate forecasting applications (e.g. Rubas et al. 2006); for example, game theory (in which the actions of one group can affect another), general equilibrium modelling (which accounts for overall supply and demand), and mechanism design theory (which allows for adaptation of institutional and economic behaviour). Prospect theory is also a widely used alternative to utility theory, and considers the response of individuals to gains and losses, rather than to absolute values (Tversky and Kahneman 1992).

Bayesian theory provides another approach to decision making with uncertainty, and Bayesian Uncertainty Frameworks have been developed for flood forecasting and warning applications, for example (Krzysztofowicz et al. 1994; Reggiani and Weerts 2008). One option with this approach, which is potentially useful in decision-making, is to include the decision criteria in the overall framework, such as the economic damages arising from the event, or flood warning performance criteria.

Another Bayesian approach, perhaps best suited to long-term planning and sensitivity studies, is that of Bayesian Belief Networks. These are usually in the form of a network describing the inter-relationships between items, such as rainfall, runoff and erosion, and the conditional properties of outcomes depending on changes at any point in the network. Box 6.2 describes an application of this technique in ecosystem services, and also notes some real time applications which have been explored in flood forecasting, and flood emergency management.

Box 6.2 Bayesian Networks

Bayesian Networks – sometimes called Bayesian Belief Networks – provide one possible approach to combining observed data with less precise or uncertain information, combined with expert judgement. The earliest practical applications were in the 1980s in areas such as medicine and software fault diagnosis, but the method has since been used in a wide range of industrial, financial, transport and environmental applications, including agriculture, integrated water resources management and water quality prediction.

The relationship between inputs and outputs (or cause and effect) is typically 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, whilst the links represent causal or influential relationships (Jensen 1996; Fenton and Neil 2007). 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. Conditional probabilities can be estimated from data, expert judgement, subjective ideas on cause and effect, and other methods. Given observations (or evidence) of outcomes, it is possible to revise prior assumptions (distributions) using Bayes Theorem, to obtain the posterior distributions (or revised beliefs) for variables at other nodes at any point in the network. Bayesian networks therefore provide a framework for successively updating beliefs as new information becomes available, and computer algorithms and graphical tools have been developed to allow solutions to be obtained for networks with large numbers of nodes.

One potential application of Bayesian Networks is in exploring the role of ecosystems in protecting and enhancing the natural environment. This can be described using the concept of ecosystem services, which cover the products (e.g. food, fresh water), regulating services (e.g. flood mitigation), cultural services (e.g. tourism), and supporting services (e.g. soil formation, nutrient cycling) provided by the environment. For example, in a research study for Natural England, Haines-Young and Potschin (2009) explored a range of possible typologies for services such as carbon storage and sequestration, recreation, renewable energy, water provisioning and flood regulation in upland areas of England. For flood regulation, discharge volume, flood risk and water quality were assumed to be influenced by a range of factors, including rainfall amount and intensity, soil type and topography, together with ecological factors such as vegetation cover, grazing pressure and land drainage (Fig. 6.6)

The main ecological driver was assumed to be vegetation cover, with general categories including arable, woodland, heathland, hedgerows, upland fens and swamp, rivers, blanket bog, wet woodland, as well as bare ground. Some examples of applications which were considered included the influence of rainfall intensity on soil erosion for different types of vegetation, and the effects of the removal of surface drainage on water quality. One conclusion (Haines-Young and Potschin 2009) was that, whilst the network maps produced cannot yet be used directly for decision support for this particular application, they are valuable social learning devices, and can be actively used:

- As a device for taking stock of what is known about individual services and of organising it in relation to particular user needs
- As a communication tool that can facilitate discussion about how upland systems might react under different management, policy or environmental scenarios
- As a way of investigating the weights different users assign to various scenario or management outcomes, and hence the changes in marginal value brought about by different components of the network
- As a heuristic device to rapidly prototype ideas and allow users and experts to connect up topics that are not currently well integrated

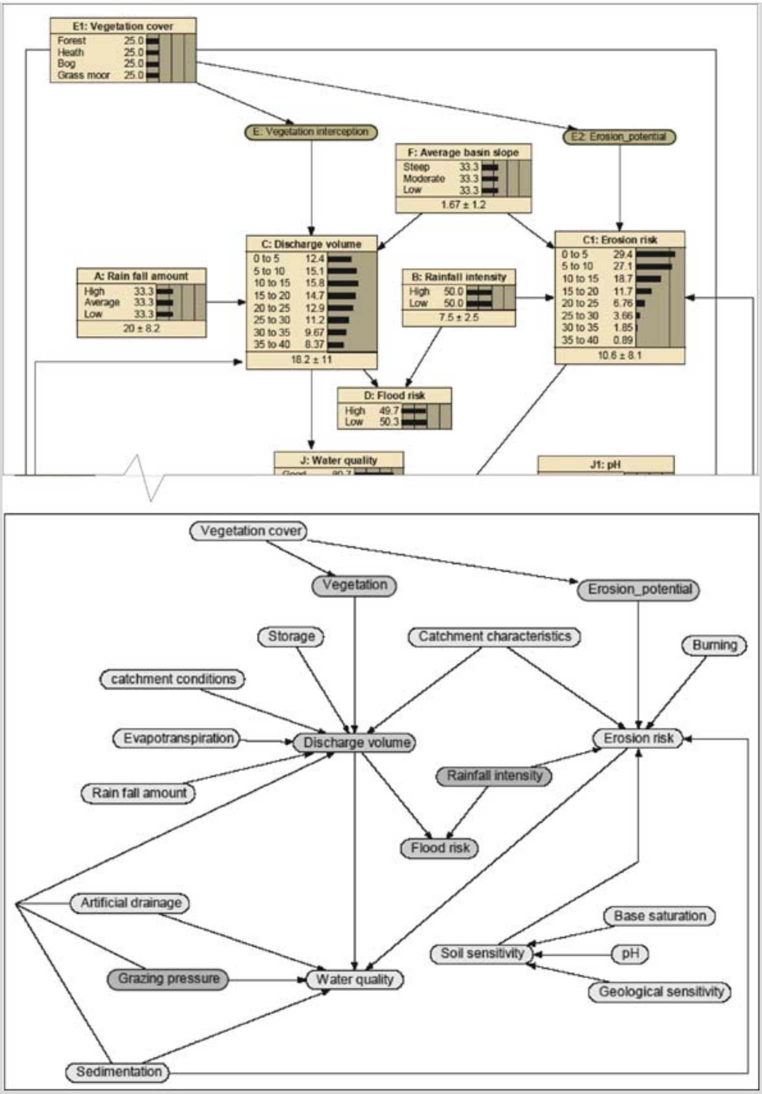


Fig. 6.6 Part of a Bayesian Belief Network for water provisioning and flood regulation developed for use during an initial consultation phase, and the modified influence diagram proposed following those consultations (adapted from Haines-Young et al. 2008 and Haines-Young and Potschin 2009)

Research has also been performed into dynamic networks which can use time varying inputs. Some options for reducing computational and storage overheads in a dynamic network of this type include object-oriented solutions, and the use of compact representations of the full network. For example, in a flood prediction system (Fenton and Neil 2007), the aim would be to estimate the probability of flooding based on information on rainfall, water levels and flood defence elevations. For the case of a static network, at each time step, each new rainfall observation would allow the probability distributions for the degree of flooding and future water levels to be updated. For real-time flood forecasting, the posterior distribution of water levels would then be used as the prior values at the next time step. Garrote et al. (2007) provide another example of the potential use of Bayesian Networks for a flood forecasting application, whilst Molina et al. (2005) present an application for a flood emergency response system. Some other current areas of research in Bayesian Networks include the use of continuous, rather than discrete, probability distributions, statistical learning for parameters, and network verification techniques (Fenton and Neil 2007).

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Part II
Selected Applications

Chapter 7
Floods

Abstract Flood warnings provide a well established way to help to reduce the risks to life and property during flood events. Hydrological forecasts are often used as a component of flood warning systems, and can improve the accuracy of warnings and the lead time available, giving more time to protect property and evacuate areas at risk. The lead time may also be extended by using Quantitative Precipitation Forecasts and other meteorological forecasts. The types of hydrological models which are used include rainfall-runoff, flow routing and hydrodynamic models, as well as more empirical approaches, such as peak to peak correlations. Models are usually operated within a forecasting system which gathers data, schedules model runs, and post-processes model outputs into map-based and other products. Data assimilation techniques are also widely used both to initialize model runs, and in the post-processing of model outputs. This chapter provides an introduction to these topics, and discusses developing areas such as decision support systems for flood event management, and the use of ensemble flood forecasts.

Keywords Flood warning · Thresholds · Rainfall-runoff · Flow routing · Hydrodynamic · Snowmelt · Flash flood · Data assimilation · Forecast verification · Ensemble · Probabilistic · Uncertainty · Decision support

7.1 Introduction

Flood events can cause widespread disruption and damage, and loss of life, particularly if flood waters are deep, fast flowing or have a high debris content, and when flooding occurs at night or at low temperatures. For example, during 2007, a year which saw extensive flooding in China and some 20 countries in Africa, and due to the Asian monsoon, more than 177 million people were affected by flooding, causing more than US$ 20 billion of damages (Scheuren et al. 2007).

To help to reduce the impact of flooding, many countries and organizations operate a flood warning service since, with sufficient warning, property and valuables can be moved or protected, and people and livestock evacuated from areas at risk from flooding. Also, it may be possible to operate river and reservoir control

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structures or install temporary defences in time to reduce or prevent flooding. For example, sandbags are widely used in some countries both to raise the levels of flood defences (levees or dikes), and to protect individual properties from flooding. Emergency maintenance and other flood fighting activities, such as clearing debris from watercourses, and reinforcing weak points in flood defences, can also help to reduce flooding when sufficient warning time is provided. The effectiveness of the warnings provided is of course dependent on a number of factors in addition to the lead time and accuracy of forecasts, including the approaches used to disseminate warnings, the wording of messages (where applicable), public awareness of the actions to take, confidence in the organization providing the warnings, and an individual's personal experience of flooding (e.g. Drabek 2000, Handmer 2002, Parker 2003, Martini and de Roo 2007).

Despite the increasing use of flood forecasting models, many flood warnings are still issued (or considered) when observed river levels cross pre-defined threshold values or alarm levels, selected so that sufficient warning time is provided to the people at risk. River levels may be observed at or near the location at risk from flooding, or at locations further upstream to provide additional lead time (although this is usually at the expense of some accuracy and reliability). As discussed in Chapter 6, warnings are often escalated as river levels rise; for example, from an initial advisory or alert through to a flood watch and a flood warning. The initial alert is often provided on the basis of rainfall observations and forecasts, as discussed in Section 7.3.1.

For each location at risk, typically there will be flood warning area or evacuation maps available of the properties and infrastructure at risk, such as the example shown in Fig. 1.10 in Chapter 1. Often, these are prepared on the basis of historical evidence or detailed flood hazard mapping studies based on statistical analyses of flood frequency (see Chapter 4), and hydrological and hydrodynamic modeling studies. Maps of this type typically show the boundaries of areas at risk, evacuation routes, and the locations of shelters and other features of interest, such as critical infrastructure (e.g. EXCIMAP 2007). Where a forecasting model is available, real-time inundation maps, generated at each time step in the model run, are also increasingly used, as discussed in Section 7.2.

The use of observed levels alone provides a robust approach which is widely used, but which does have some limitations. For example, Fig. 7.1 shows a flood warning threshold level which is set at a value based on a typical rate of rise for river levels. However, this response may not always occur, particularly if there are complicating factors such as tidal influences, backwater effects from tributary inflows, or spills onto the floodplain. There is also often a trade-off between setting threshold levels low, so as to increase the lead time available for flood warnings, but at the expense of an increase in false alarms, and the converse of setting thresholds too high, giving fewer false alarms, but a reduced lead time and success rate with warnings (e.g. USACE 1996).

There are also limitations to the lead time which can be provided with this approach, particularly on small fast responding catchments. The lead time requirement depends on the emergency response actions which are required, and the effectiveness of warning dissemination systems. Values might range from a few

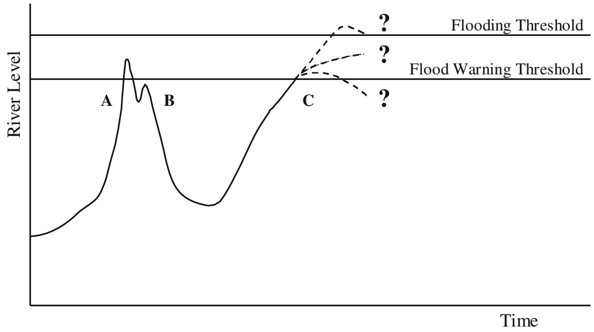

Fig. 7.1 Illustration of decision making when using observed levels alone for a telemetry site at or near the location at risk from flooding. At time *A* a flood warning is issued, but levels drop before flooding occurs, whilst at time *B* levels drop in time to avoid a second false alarm. At time *C*, the three scenarios shown by dotted lines have all occurred from this starting point in previous flood events, although the threshold level for issuing warnings assumes a typical average rate of rise across all flood events

minutes to provide warnings to road users or to people in a campsite of the risk from flash flooding, through to several hours or more to install temporary barriers to reduce the risk of flooding, to evacuate people from a large city, or to draw down a major reservoir to provide additional storage to mitigate flooding further downstream. The emergency services and utility operators can also use longer lead times (at the expense of more false alarms) to provide more time for mobilization of staff and deployment of equipment.

Thus, a flood forecasting model can assist both with understanding the complexities of the situation, and extending the lead time available for providing flood warnings (if there is confidence in the model outputs). Additional outputs can also be obtained, such as forecasts for the extent of inundation, and probabilistic outputs, to help to assess confidence in the forecast. Figure 7.2, which was originally developed to illustrate the range of issues to be considered in flood risk management in the UK (Office of Science and Technology 2003), also provides an excellent summary of the range of the factors which may need to be considered in the development of a flood forecasting model. This can include flooding from sewer systems, tidal influences, overtopping of river banks and flood defences, and other types of flooding.

When a forecasting model is available, the model outputs are often used directly when deciding whether to issue flood warnings, based on forecasts for the crossing of threshold levels, or inundation of property (if a real-time mapping option is available). Chapter 6 discusses some possible approaches to decision making when forecasts are used in this way. Alternatively, forecasts may used in a less formal way, as another piece of information to assist duty officers in deciding whether to issue a flood warning. The raw model outputs can also be used as inputs to a wider decision support system, which combines information on flooding extent, properties at risk, emergency response assets, traffic flow, and other factors, as described in Box 7.1. Decision support systems of this type are only used by a few organizations at present, but are increasingly being developed and evaluated for use in flood warning applications.

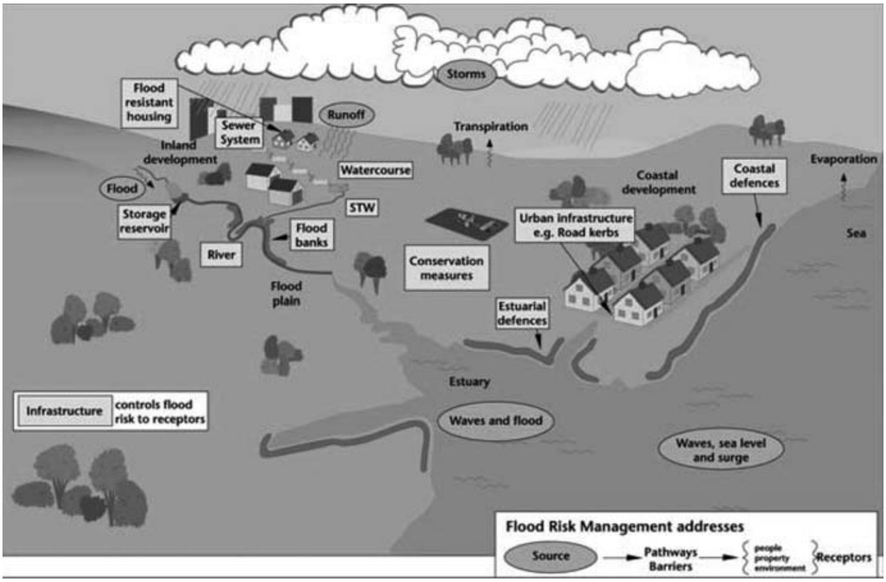

Fig. 7.2 A hydraulic perspective of the physical flooding system (Office of Science and Technology 2003). Note that a Source-Pathway-Receptor approach is also illustrated, as described briefly in Chapters 4 and 6

More generally, flood forecasting models are usually just one component in a wider decision making process, as illustrated by Fig. 7.3. In this example, observations and forecasts of river conditions are evaluated against threshold values (possibly within a decision support system), and a decision is then taken on whether to disseminate a flood warning. Approaches to dissemination can include direct and community-based methods such as door-knocking, sirens, telephone, fax, email, pager, and loud-hailers/megaphones, and indirect or broadcast approaches such as radio, television, telephone help lines and internet-based information systems (e.g. Emergency Management Australia 1999, Martini and De Roo 2007, NOAA/NWS 1997).

As noted in Chapter 6, multimedia systems are also increasingly used for automated telephone dialing and transmission of emails, faxes and other electronically based warnings, and may include text to speech conversion software (e.g. Andryszewski et al. 2005). Warnings are typically disseminated to the emergency services, civil protection authorities, local authorities, utility operators and – in some countries – directly to the public. In addition to responding to the emergency, there is typically also a recovery phase, as services and businesses are re-established, debris cleared, and damage repaired, followed by a post-event review, including evaluating the performance of any forecasting models which were used. Preparedness for future events is also an important function in any flood warning service, and activities can include raising public awareness of the risks from flooding, and the actions to take on receiving a flood warning, flood hazard mapping, improvements to instrumentation, and the development of new or improved flood forecasting models.

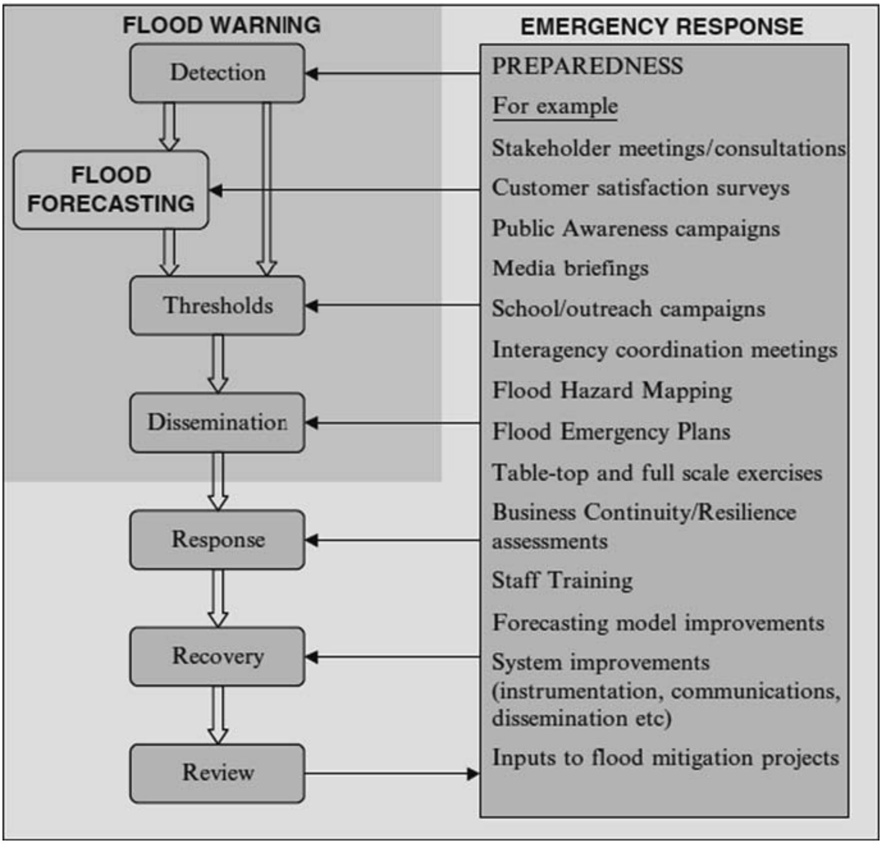

Fig. 7.3 Illustration of the components of a flood warning, forecasting and emergency response system (Sene 2008)

Flood forecasting models are often operated within an automated forecasting system, which can control the scheduling of model runs, post processing of model outputs, and collection and pre-processing of telemetry data and meteorological forecasts. Section 7.2 provides a brief introduction to this type of system, although it is worth noting that most organizations require forecasts to be assessed and/or approved by duty officers before being issued, rather than issued automatically. This can be for a range of reasons, including a recognition of the inherent uncertainty in forecasting outputs, and the need to avoid false alarms and their consequences, such as unnecessary evacuation of properties (including hospitals, nursing homes, prisons and businesses). False alarms can also cause a lowering in confidence in future warnings if warnings are often issued unecessarily (i.e. the ‘cry-wolf’ effect).

It is also worth noting that forecasts may be only one factor in the overall decision making process. For example, some other factors which may need to be considered include current river and reservoir levels, information sent by staff on site, and reports from the public and emergency services on flooding incidents. Other considerations can include traffic flows, the time of day (or night) and meteorological conditions (air temperature, wind chill etc). However, in some low-risk or flash flood applications, forecasting outputs are sometimes used to trigger actions directly, such as the closing of road barriers, or the activation of electronic signs and flashing lights along footpaths, roads and in car parks. As discussed in Chapter 9, forecasting model outputs are also sometimes used directly in high-risk flow control applications, provided that the required levels of reliability and resilience can be met for the system.

The remainder of this chapter discusses a range of issues relating to the operational implementation of flood forecasting models. In Section 7.2, the main techniques are summarized, including approaches to data assimilation, forecasting systems, forecast verification, and probabilistic forecasting, together with a brief introduction to the types of models which are used operationally (see Chapter 4 for more details). Section 7.3 then presents some examples of more specialized applications, including flash flood forecasting, forecasting for the effects of snow and ice, and long-term flood forecasting. Also, it is worth noting that, whilst some organizations operate forecasting systems whose main aim is to predict the onset of flooding, other applications may include water resources management, drought forecasting, and reservoir operations. Some examples of multi-purpose systems of this type are described in Chapters 1 and 11, and in Sections 7.2 and 7.3.

Box 7.1 Decision Support Systems for Flood Events

During a widespread flood event, the emergency services and other organizations can be faced with a wide range of information. This can include forecasts for the locations where flooding is likely to occur, the availability of emergency response staff and assets (vehicles, boats, helicopters etc), and individual emergencies which need addressing (people requiring rescue, dam-break risks, power failures, water supply issues, environmental hazards etc). Often this information will be incomplete, uncertain and – at times – contradictory so, to help overcome some of these problems, Geographic Information Systems (GIS) and Decision Support Systems are widely advocated as a useful tool for use in flood emergencies, and are used operationally in some countries. The types of information which may need to be included in systems of this type include:

- Basemaps – including maps for property locations, vulnerable people, streets and roads, railways, airports, tourist sites, flood defences (levees), together with aerial photographs, satellite images, digital terrain models etc

- Critical Infrastructure – the locations of critical assets such as power stations, pumping stations, telecommunication hubs, and water and sewage treatment works, and transmission and supply routes
- Emergency response assets – the locations of mobile and fixed assets, such as vehicles, helicopters, sandbags, temporary barriers, excavators, boats, medical centers, police stations, fire stations etc
- Environmental risks – potential sources of pollution, such as industrial sites, waste disposal sites, waste water treatment works etc
- Flood Forecasting model outputs – for river, reservoir and lake levels and (if the functionality is available) flood inundation extent
- Flood Hazard or Evacuation Maps – maps showing areas at risk from flooding under different scenarios, potential evacuation routes, and other features (sometimes known as Flood Warning Area maps)
- Hydrometeorological observations and forecasts – including river levels, rainfall, inundation extent, and Quantitative Precipitation Forecasts
- Shelters – the locations of emergency shelters for people evacuated from their homes, access routes, and the current occupancy rates
- Telemetry data – from raingauges, weather radar, river, reservoir, lake and tide gauges, and other instrumentation (e.g. control gate settings)
- Traffic flows – road capacities, roadworks, and information on current traffic conditions relayed by telemetry, perhaps coupled to traffic flow forecasting models

At the most basic level, a selection of this information can be collated and presented on maps in a Geographic Information System, with the option to show different layers against a backdrop of street maps, digital elevation data, and satellite imagery. Global Positioning System (GPS) devices can also be used to report via telemetry on the locations of vehicles, helicopters etc. A next stage is then to include tools to assist with decision making, such as the ability to run ‘what-if’ scenarios (for example, for future rainfall, or gate or flood defence failures), and to advise on optimum response strategies, perhaps using logical rules, cost-loss and utility function approaches of the types described in Chapter 6. Scenarios may be prepared in advance or calculated in real-time, with the advantage of stored scenarios being that they can be checked and audited in advance, and require minimal computing time to retrieve during an event, whilst dynamic scenarios are more likely to represent current conditions, including situations which were not considered in advance.

The overall objective is to provide emergency response organisations and others with a detailed spatial overview of the current situation, forecasts for what will happen next, and information to assist with deciding on priorities for response, including updates to emergency response plans and situation reports (e.g. Macfarlane 2005). This approach also links into the concept of Virtual Emergency Operations Centres (e.g. Becerra-Fernandez et al. 2007), which are increasingly used by the emergency services in some countries as part of an all-hazards approach (e.g. the USA, the UK). Systems of this type typically link incident rooms, vehicles and staff on the ground using GPS, mobile phone, video, laptop, Personal Digital Assistant (PDA), and other technologies. Information is also increasingly made available over the internet both to the public, and in more detail (with appropriate security measures) to emergency response organizations.

For flood emergency response applications, there has been much research on this topic (e.g. Mens et al. 2008), and systems of this type are gradually being adopted for operational use (although sometimes using only a map-based display system, rather than offering decision support functionality); for example, Sene (2008) provides references to more than 10 research and operational systems, including examples in China (Huaimin 2005) and the Netherlands and Germany (http://www.noah-interreg.net/). Perhaps the longest established systems are those developed for hurricane warning and evacuation in the USA (e.g. Wolshon et al. 2005) which, although primarily to assist with managing the response to high winds and coastal flood risk, also need to allow for river flooding caused by the associated rainfall; for example, the Hurrevac (http://www.hurrevac.com) and Evacuation Traffic Information System (http://www.fhwaetis.com). Some studies (e.g. Simonovic and Ahmad 2005) have also considered systems which take account of the social, psychological, policy and other aspects of response to flooding.

For flood warning applications, the safety-critical nature of many systems also needs to be considered and, as discussed in Chapter 6, this can require a detailed investigation of the resilience of systems, with backups in place in case of failure of any one component. Alternatively, another approach is to use the system as an add-on to the existing service, and in the worst case to fall-back to that service in the event of failure of the decision support component.

7.2 Operational Flood Forecasting

7.2.1 Modelling Approach

Many different modeling approaches have been used in flood forecasting systems, and probably all of the types described in Chapter 4 have at least been 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 flash flooding, snowmelt, and reservoir, lake and urban drainage related flooding.

A distributed approach uses a grid-based representation of the catchment whilst a lumped approach considers the catchment as a single unit. If a semi-distributed approach is used, typically rainfall-runoff models are used in the upper reaches of the catchment and for significant tributary inflows further downstream. These then provide the inflows to flow routing models for the main river network, which might include hydrodynamic models for high-risk areas and locations where a hydrological flow routing approach is not sufficient; for example, in the lower reaches of the catchment, where river slopes are flatter, and tidal influences may be important. Figure 7.4 shows an example of this approach for a general simulation model for assessing long term flood risk in a catchment in England (Environment Agency 2003), and similar catchment conceptualization approaches are also used in flood forecasting applications. As illustrated in the figure (by subcatchments with the suffix ‘i’), when using this approach, it is also often necessary to represent the inflows from ungauged parts of the catchment, using scale and lag, parameter transfer and other approaches (see Chapter 4). There may also be a requirement to include observed or forecast tidal levels at the lower boundary of the model. Also, a hydrodynamic modeling approach is usually required for any locations where real-time inundation maps are required, together with a digital terrain model for use in estimating flows and levels on the floodplain.

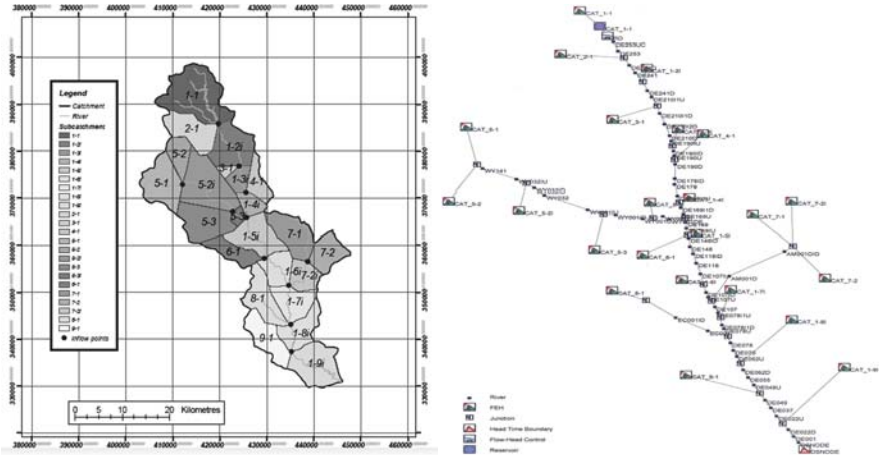

Fig. 7.4 Example of a semi-distributed catchment model, and a hydrodynamic model schematic for a pilot Catchment Flood Risk Management Plan study (**a**) Division of the River Derwent into sub-catchments and sub-areas (**b**) Model Schematic, shown at a larger scale (Environment Agency 2003, Copyright © Environment Agency 2009 all rights reserved)

Table 7.1 presents several examples of the types of rainfall-runoff models which have been evaluated or used operationally in flood forecasting applications. The examples shown are simply for illustration, and many other types of model could be cited, both for these countries, and for other countries.

Chapter 4 provides further background on these different modeling approaches, and discusses some of the advantages and limitations of each approach. Further examples can be found in the reviews by Singh 1995, Beven 2001, Moore 1999 and Todini 2007, in intercomparison studies by WMO (e.g. World Meteorological

Table 7.1 Some examples of operational and pre-operational applications of rainfall-runoff (hydrologic) forecasting models; note that many countries also use additional types of models to those shown in the table

Category	Location	References
Distributed (physically-based or physical-conceptual)	Brazil	Collischonn et al. (2007)
	Europe-wide	Thielen et al. (2009)
	Finland	Vehviläinen et al. (2005), see Box 7.3
	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	Lindstrom et al. (1997), see Box 7.2
	Western Canada	Quick (1995), see Box 11.3
	UK	Madsen (2000) and Moore (2007)
	USA	Burnash (1995), see Box 1.2
Data-driven	Scotland	Lees et al. (1994)
	UK	Yang and Han (2006)
	General	Dawson and Wilby (1999)

Organisation 1992), and in the proceedings of international conferences on flood forecasting, such as the following two examples:

- The ACTIF International Conference on Innovation, Advances and Implementation of Flood Forecasting Technology, which was held in Norway in 2005 (ACTIF 2005)
- The WMO International Workshop on Flash Flood Forecasting, which was held in Costa Rica in 2006 (World Meteorological Organisation 2006)

By contrast, for flow routing approaches – again as described in Chapter 4 – the choice is more often linked to specific solution schemes for the Navier Stokes and St Venant equations for fluid flow, and approximations such as the Muskingum Cunge and Kinematic Wave approaches Data-driven approaches such as artificial neural networks, and transfer function modeling approaches, are also sometimes used, together with simpler approaches such as peak to peak correlations.

In addition to the model type, and choice of a lumped, semi-distributed or distributed approach, some other factors which can influence the modeling approach include (e.g. Sene 2008):

- Artificial Influences – the need to represent reservoirs, flow control structures and other factors which may affect flooding
- Catchment Characteristics – the nature of the response to rainfall, and any tidal, backwater or other influences which may need to be considered
- 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 or resolution of data, and the data quality and reliability

- Flood Risk – the level of risk to people and property, based on the probability of flooding and consequences, perhaps also considering vulnerability
- Flood Warning Lead Time Requirements – the minimum lead time ideally required by end users for an effective emergency response
- 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 (sometimes called Flood Forecast Points)
- Forecasting System – the software, hardware and other constraints on the types of models which can be used in real-time
- Organisational Issues – expertise in particular types of models, availability of calibration and run-time software, organizational policy, budgets etc
- Operational Requirements – the types of forecast products and outputs required, such as flood inundation maps and probabilistic outputs
- Scenario Requirements – the requirements (if any) to include the option to assess scenarios during an event; for example, 'what-if' model runs to explore the impacts if a gate fails, or an embankment is breached, or if the rainfall from a previous major storm is repeated in the current event

Whilst organizational issues and budgets can be an over-riding factor, some other key issues include the availability of data, the level of flood risk, the flood warning lead time requirement, and the locations of forecasting points. For example, when using a semi-distributed modeling approach, as noted in Chapter 4, the sub-catchment boundaries are often defined to the available river telemetry gauges, rather than to the confluences with the main river network, and this may require some compromises in how models are configured and used. If possible, it is also desirable for there to be a telemetered river gauge at or near to each forecasting point, both for real-time verification of forecasts, and to allow forecasts to be updated in real-time.

Flood risk is typically defined as the combination of the probability and consequences of flooding, sometimes combined with vulnerability (see Chapter 6), and a more complicated (and, possibly, expensive) modeling 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. The choice of model type can also be influenced by the likely benefits from improvements to the flood warning service, and various cost-benefit techniques have been developed for flood warning applications. Typically, these methods compare the costs of implementing the system, and the damages which would be avoided for a given lead time and accuracy (e.g. World Meteorological Organisation 1973, USACE 1994, Carsell et al. 2004, Parker et al. 2005, Tilford et al. 2007).

The combination of the flood warning lead time requirement and the catchment response time to forecasting points is also often a key factor in deciding on the most appropriate modeling approach (e.g. Reed 1984, Lettenmaier and Wood 1993, Tilford et al. 2007). For example, for a forecasting point in the lower reaches of a large catchment, it may be possible to meet the required lead time and accuracy using a flow routing model operated using the observed inflows from an upstream gauging station. However, for locations higher up in the catchment, if the required lead time is close to or exceeds the catchment response time to the forecasting point, then a rainfall-runoff modeling approach, using rainfall forecasts as inputs, may be the only way to meet the requirement. There is also generally a trade-off between increasing lead time and reductions in forecast accuracy, although data assimilation can often considerably improve the forecast outputs (see Section 7.2.3).

The flood warning lead time is often defined as the time between the receipt of a warning, and the onset of flooding, and it is worth noting that this may be considerably less than the lead time which is theoretically possible from the forecasting model. For example, Fig. 7.5 shows a simplified illustration of the various time delays for a single rainfall-runoff model providing forecast outputs at a single forecasting point. The sequence starts from the initial rainfall on the catchment through to the receipt of a flood warning by all recipients, and shows the time which that then leaves before the onset of flooding. Although the time delays are exaggerated in places, the warning lead time can be considerably less than the catchment response time or forecast lead time, and these time delays all need to be factored into the model design. The polling interval for rainfall and river flow data also needs to be considered, and whether the resulting model run frequency is sufficient for the application. For example, if river levels tyically rise from low levels to a peak in 1–2 hours, then an hourly polling interval is unlikely to be sufficient to resolve the rising limb of the hydrograph. Also, if rainfall forecasts are used, then account needs to be taken of the time intervals at which forecasts are issued, which might be every 15 minutes or hour for short-range nowcasts through to every 6–12 h for medium- to long-range forecasts (see Chapter 3). Similar diagrams for different forecasting situations are also provided by USACE (1996), Nemec (1986), and Carsell et al. (2004), for example.

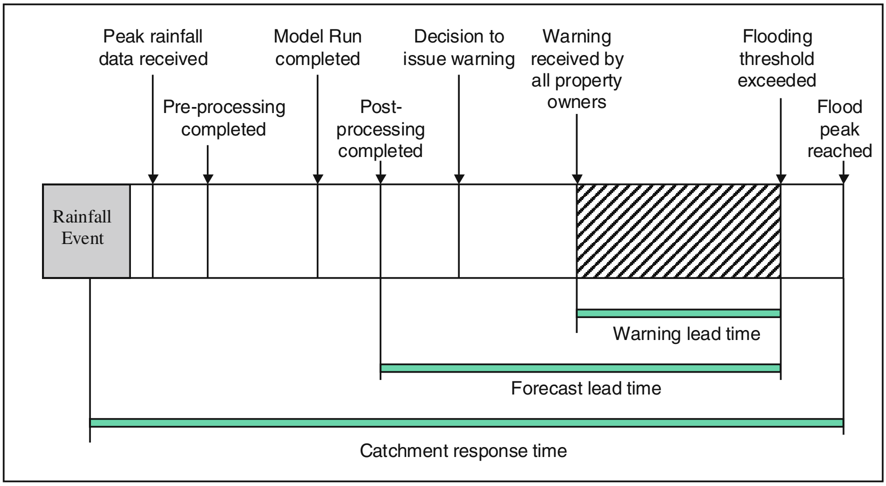

Fig. 7.5 Illustration of the time delays in issuing a warning for a single rainfall-runoff model (Sene 2008)

Another consideration is that it may also be possible to reduce some of the time delays in the system. For example, the polling interval for telemetry data could possibly be reduced (e.g. from hourly to 15 min), the approach to issuing warnings improved (e.g. using automated phone dialing rather than manual approaches), and the model run times reduced. New instrumentation could also be installed to provide longer lead times and/or additional opportunities for data assimilation.

Regarding model run times, this can be a significant factor for more complex types of models and for probabilistic forecasting approaches. For example, for hydrodynamic models, for flood forecasting applications the usual approach to improving run times is to identify computationally intensive aspects of the model which can be improved, and parts of the model which are not essential (e.g. Chen et al. 2005). Some steps which can then be taken to reduce run times include improving the stability and convergence of the model, thereby reducing the number of iterations required, removing bottlenecks to data transfer, and simplifying models at locations away from the main forecasting points; for example, by removing unnecessary detail at structures and in river reaches. More generally, increases in computing power and parallel processing are other options for making models run faster, and emulators also show potential for this application (Young et al. 2009).

Box 7.2 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. 7.6). The river enters the Netherlands at the village of Lobith, where the mean discharge is approximately 2,300 m^{3}s^{-1}. The average annual rainfall for the whole of the Rhine basin is approximately 910 mm/year, and reaches more than 1,400 mm in the Alps, with 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 Rijkwaterstaat 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

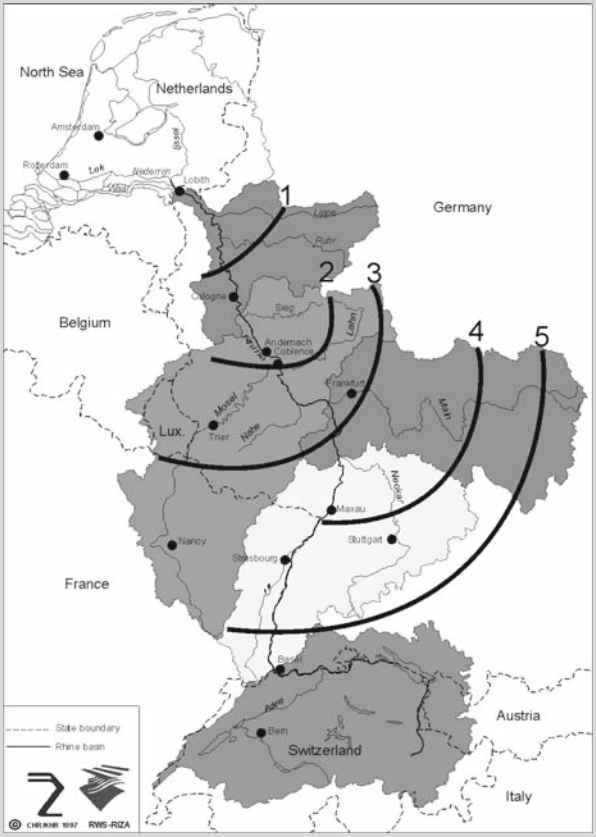

Fig. 7.6 The River Rhine basin with travel time isochrones (in days) (Parmet and Sprokkereef, 1997)

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 600 meteorological stations, and water level observations at some 60 gauging stations. Weather forecasts are obtained from the German Weather Service (DWD), at a resolution of 7 km with a 3-day lead time, and at 50 km with a 7-day lead time, and from the Royal Netherlands Meteorological Institute (KNMI), again at a resolution of 7 km and a 3-day lead time. Deterministic forecasts and 50-member ensemble forecasts are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), with lead times of 10 days and 15 days respectively, and 16-member ensembles from the higher resolution COSMO-LEPS system managed by ARPA-SIM. 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 latest version of the forecasting system for the Rhine and Meuse catchments 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 are also being 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).

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 warning pre-alerts at lead times of up to 14 days (e.g. Fig. 7.7).

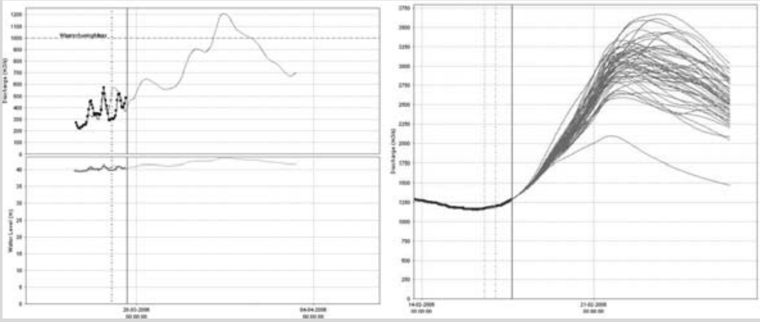

Fig. 7.7 Example of a deterministic forecast for Borgharen-Dorp on the Meuse and an ensemble forecast for Lobith on the Rhine (Beckers et al. 2008)

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 also 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 Chapter 10, and which provides early warnings of pollution incidents which might affect water supply, agriculture and recreation on the Rhine.

7.2.2 Forecasting Systems

In the run up to a flood event, and as flooding occurs, the situation can change rapidly, and hourly or more frequent timesteps are often used for model runs in order to capture these effects. In addition to other tasks, a forecasting duty officer may also need to consider information from a wide range of sources, including raingauges, weather radar, satellite observations, meteorological forecasts, river gauging stations, media reports, situation reports, and information on reservoir, lake and tidal levels. This complexity means that a forecasting system is often the best way to routinely generate forecasts, particularly if (as is usual), forecasts are initialized or post-processed using data assimilation techniques.

Chapter 4 provides an introduction to the main functionality of a forecasting system, which can include data gathering, pre-processing of data and meteorological forecasts, model run control, data assimilation, post-processing of model outputs, and overall management of data and forecasts. Some examples of operational forecasting systems include the national systems for Bangladesh (Paudyal 2002), China (Huaimin 2005), England, Wales and Scotland (Werner et al. 2009), Finland (see Box 7.3), the Netherlands (see Box 7.2) and the USA (see Box 1.2 in Chapter 1). However, whilst the modern focus is on automated systems, it is also worth noting that manually-based systems still have a valuable role to play in some countries and, as described in Chapter 4, much can be achieved with simplified approaches, particularly for slower responding catchments.

As an example of a more automated approach, Fig. 7.8 illustrates a typical system configuration whilst Table 7.2 summarises the options which are often available in many national and commercially available systems. Note that, in the example shown in the figure, 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. Also, the forecasting system is operated on two server systems running in parallel, and the standby system can take over with minimal time delay if the duty system fails. Indeed, system resilience is often a key design criterion for forecasting systems, particularly when the flood forecasting outputs are an integral part of the flood warning process. Some other approaches to improving resilience include:

- 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

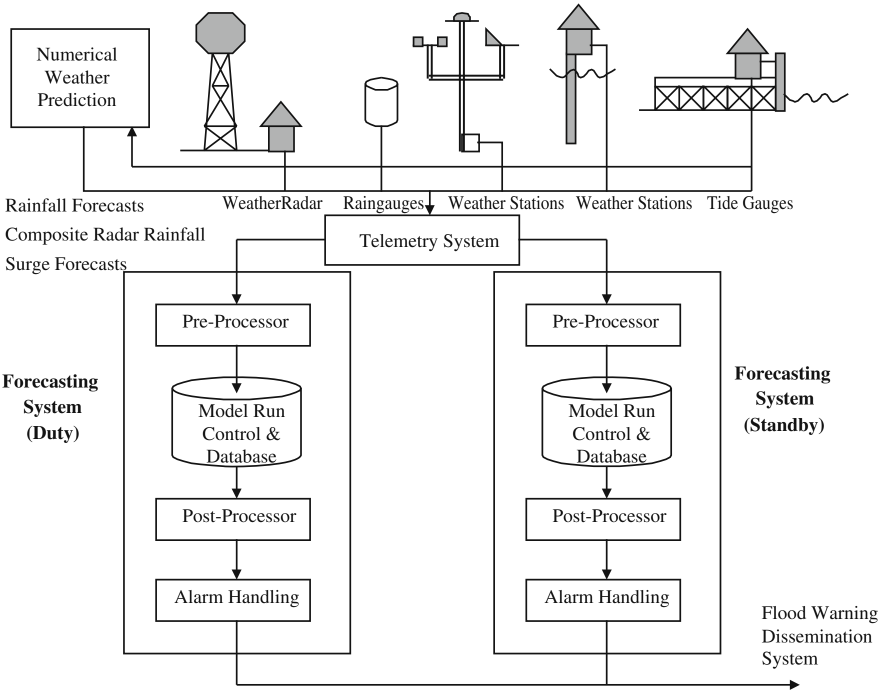

Fig. 7.8 Illustration of a possible configuration for a flood forecasting system (Sene 2008)

- Backup Forecasting Procedures – simpler graphical, chart-based or tabulated procedures which can be used in case of a major failure of the forecasting or telemetry system; for example, by using data received from observers on site by telephone or radio
- Contingency Planning – systematic risk-based assessments of all aspects of the system, including telemetry links, power supplies, access to the site under flood conditions, the flood risk at the site itself (if any), and other factors, with alternates available where required, such as a backup control room
- Data Hierarchies – fallback positions if a key instrument fails, such as the widely used approach in raingauge-based systems of designating alternative raingauges, and using weather radar or satellite inputs in case the raingauge telemetry network fails
- Duplicate Systems – in addition to operating parallel server systems, backups can also be located at other sites, many kilometers from the main site, to reduce the risk of both systems being affected by the same event (e.g. flooding, fire, earthquake, power failures)
- Telemetry Resilience – studies to assess the risk of instrumentation and telemetry equipment being flooded, and then either relocating sites at risk, installing flood barriers, or raising key electrical and other equipment above likely flood levels

Table 7.2 – Some typical functionality in modern flood forecasting systems (Sene 2008)

Item	Function	Description
Pre-processing	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, spatial and other validation methods
	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 methods
Model runs	Model run control	Scheduling and control of model runs, and error handling
	Data assimilation	Application of real time updating and data assimilation algorithms
	Data hierarchy	Automatic fall-back 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 etc to generate information on areas at risk at each time step
	Alarm handling	Raising alarms when thresholds are forecast to be exceeded, using map based displays, email, pager, 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, defence breaches, gate operations etc)
	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

7.2.3 Data Assimilation

Compared to off-line, simulation modeling, one advantage in real time forecasting is that comparisons can be made between the forecast outputs and recent observations at the locations of interest. However, due to the basic assumptions in any model, it is unlikely that the forecast values will match the observed values, which has led to the widespread use of data assimilation techniques in operational flood forecasting. Some sources of uncertainty can include model structural issues, and uncertainties in the model parameters, initial conditions and boundary conditions.

The basic approaches to data assimilation are described in Chapter 4, and include input updating (or pre-processing), state updating (i.e. of model initial conditions), parameter updating and output updating (or post-processing). For flood forecasting applications, output updating and state updating are probably the most widely used approaches, and then the other two approaches. Typically, any adjustments which are applied aim to achieve a good match with recent observations, and/or the observations which are available for the current time ('time now'), and the effectiveness of the adjustments will tend to decrease with increasing lead time, as the information content of the observed values decreases. For example, one commonly used technique (see below) is to fit an autoregressive moving average model to the time series of model errors (residuals) and then to use that model to estimate how the sequence of errors might evolve over the forecasting horizon.

For flood forecasting applications, one particular consideration is that, at high flows, the measurement uncertainty is often higher, and in some cases updating may degrade the forecast accuracy, rather than improve it. In this situation, some possible options are not to apply updating above a given flow value, or to truncate the model output at that point, or to acknowledge the uncertainty and use a probabilistic approach (see Section 7.2.4). Generally, if possible, before approving a forecast, it is good practice to compare the model outputs with and without updating to check for any problems with data and other issues; for example, some output updating approaches can be very sensitive to timing errors, leading to rapid changes in the sequence of model errors.

Many approaches have been developed for data assimilation in flood forecasting, and Table 7.3 summarises a selection of those which have been used operationally. Note that there is no entry for parameter updating since approaches tend to be specific to the specific type or brand of model, although more general techniques, such as the Kalman Filter (and extended and ensemble forms), can also be used. Some examples of parameter updating techniques include adjusting the roughness coefficient in a hydrodynamic model, or the parameter values in a transfer function model.

In flood forecasting applications, output updating is often called error correction or error prediction, or real time adaptation, and is analogous to the use of real-time observations in statistical post-processing techniques for meteorological forecasts (see Chapter 3). Also, as described in Chapter 4, some pre-processing of meteorological forecasts may also be performed before use within a hydrological forecasting model (see Box 7.3 for example). Several intercomparisons of techniques have also been performed, including evaluation of wide range of methods during a World Meteorological Organisation intercomparison study (World Meteorological Organisation 1992, Refsgaard 1997), and of a range of approaches to output updating by Goswami et al. (2005).

In some cases, flood forecasting models have also been developed specifically for use within a data assimilation framework. For example, in data-driven modeling, the

Table 7.3 Examples of data assimilation techniques which have been used operationally in flood forecasting models (note that the references shown in italics are general review articles, which also provide information on some of the other techniques noted in the table)

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 Forecasts	Kalman filter, other approaches	See Chapters 3 and 4
	Soil moisture, snow cover	General	*Alavi et al. 2009)*
State updating	Distributed rainfall-runoff	Variational, distributed Kalman filter, others	*Le Dimet et al. (2009)*, Seo et al. (2009)
	Conceptual rainfall-runoff	Gain updating, model specific (e.g. model stores)	Moore (2007), Wöhling et al. (2006)
	Data-driven	Stochastic transfer function, others	*Young and Ratto (2009)*
	Conceptual rainfall-runoff, data-driven, hydrodynamic	Kalman filter (including extended and ensemble versions)	*Beven (2008)*, Butts et al. (2005), Weerts and El Serafy (2006)
	Conceptual rainfall-runoff	Particle filter	Weerts and El Serafy (2006)
	Snow water equivalent and snow cover	Model specific	Bell et al. (2000), see also Boxes 7.3 and 11.3
Output updating	Can be used to post-process the outputs from most types of model	Autoregressive Moving Average (ARMA), Gain Updating, manual adjustments, several other approaches	*Reed (1984), Serban and Askew (1991), Moore (1999), Goswami et al. (2005)*

aim is often to estimate future river levels or flows on the basis of the information available at the time of the forecast, at the lead time(s) of interest. The model identification and calibration is typically performed using advanced time series analysis techniques including estimates for the predictive uncertainty. Some examples of this approach include stochastic transfer function methods (e.g. Young 2002, Young and Ratto 2009), and machine learning and artificial intelligence techniques (Shrestha and Solomatine 2008).

7.2.4 Forecast Uncertainty

As noted in the previous section, uncertainties in forecast outputs can arise from a wide range of sources. This has led to the search for methods to quantify the uncertainty in model outputs, and research into the best ways to use and communicate this information to end-users, including flood forecasting duty officers. Probabilistic flood forecasting is an active area for research within national hydrological services in the USA, Europe and elsewhere, and is one of the key areas of interest within the Hydrological Ensemble Prediction Experiment (HEPEX). This international project involves researchers from the National Weather Service in the USA, the European Centre for Medium-Range Weather Forecasts (ECMWF) and the European Joint Research Centre, and from Canada, Italy, Brazil, and elsewhere (Schaake et al. 2007).

Chapter 6 discusses some of the potential advantages of having information on forecast uncertainty available (e.g. Krzysztofowicz 2001, Schaake et al. 2007), which can include an increased awareness of the confidence (or otherwise) to attach to forecasts, and the use of outputs in decision support systems for reservoir operations, flood event management and other applications. The additional information on forecast performance can also be a valuable guide to priority areas for improvements to models and instrumentation. The availability of quantitative estimates of probability also raises the possibility of using a risk-based approach to the issuing of flood warnings, in which warnings can be tailored to the risk, defined as the combination of probability and consequence, perhaps also taking account of the risk profiles and vulnerability of recipients (e.g. risk taking, risk adverse). For example, a local authority might wish to receive low probability warnings well in advance of any possible event in order to plan staff rotas and to check equipment and known flooding locations (e.g. for a build up of debris), By contrast, some other organizations might only wish to receive a warning when there is high confidence that flooding is going to occur.

Chapter 4 describes a range of approaches to estimating uncertainty which, in general terms (e.g. Beven 2008), can be described under the following categories:

- Forward Uncertainty Analysis – methods in which the uncertainty is defined in advance on the basis of historical performance, and propagated through the forecasting model. Common approaches include 'what if' and sensitivity studies, ensemble forecasts, and Monte Carlo sampling
- Data Assimilation – the use of techniques which not only constrain uncertainty, but also provide an estimate of that uncertainty, such as Kalman Filtering (including extended and ensemble versions), Particle Filtering, and some types of transfer function model.

These techniques can be complementary; for example, ensemble forecasts can be updated, although with some care needed regarding the statistical interpretation of the outputs.

Perhaps the first technique to be used operationally was the Ensemble Streamflow Prediction approach in the USA, which has been used since the 1980s (e.g. Day 1985). The basis of the method is to draw samples of meteorological data from the historical record for input to the hydrological modeling component, assuming current conditions as a starting point. Section 4.3.3 describes this approach in more detail including an example of the types of outputs obtained. Also, during the 1980s and 1990s, there were rapid developments in the use of techniques which, as well as improving the forecast, could also provide a measure of uncertainty, such as Kalman Filtering and transfer function approaches (e.g. Lees et al. 1994, Young 2002).

The introduction of ensemble meteorological forecasting techniques in the early 1990s (see Chapter 3) also quickly led to investigations into the use of these outputs in hydrological forecasting models, and much of the research in recent years has focused on rainfall forecast uncertainty. However, some pre-processing of ensemble meteorological forecasts is often required to translate them to the space and time scales of interest for hydrological forecasting, at the required lead times (see Chapter 4). A typical configuration is to consider between about 10 and 50 ensemble members, and operational implementations are becoming increasingly widespread, with one review (Cloke and Pappenberger 2009) noting operational and pre-operational applications in more than 10 countries. Examples include the European Flood Alert System (Thielen et al. 2009), and the systems in the Netherlands and Finland which are described in Boxes 7.2 and 7.3. Other studies have also considered the uncertainty arising from other sources, such as weather radar inputs, raingauge-based estimates of catchment average rainfall, model parameters, and stage-discharge relationships.

Having obtained an initial estimate of the hydrological forecast uncertainty, an additional calibration or conditioning step may be applied based on analysis of the statistical aspects of the model performance over the long-term (e.g. Schaake et al. 2007, Wood and Schaake 2008). As discussed in Chapter 4, when meteorological forecasts are used, this also requires keeping up to date with any improvements to the underlying nowcasting or Numerical Weather Prediction (NWP) techniques since these may impact on the calibration of the hydrological component. Bayesian Model Averaging (Beckers et al. 2008, Todini 2008) might also be used for real-time evaluation of the performance of each ensemble member, particularly for multi-model ensembles, and for combining outputs using weights based on the recent performance. There is also a case for formulating the overall forecasting and data assimilation problem within a Bayesian Uncertainty Framework expressed in terms of the overall predictive uncertainty (e.g. Krzysztofowicz and Maranzano 2004, Todini 2009).

The emphasis on short to medium-term lead times in flood forecasting applications, and the short time intervals between model runs, has also led to an interest in approaches to improving the computational or modeling efficiency, so as to be able to complete ensemble or probabilistic analyses within the time available. Some approaches which have been considered include:

- Computational Efficiency – increased processor speeds, parallel processing, nested models, improved data transfer rates
- Emulators – simpler models (e.g. transfer functions) which can emulate the behaviour of more complicated models, such as hydrodynamic models (e.g. Young et al. 2009)

- 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)

7.2.5 Forecast Verification

Forecast verification and performance monitoring is also an important component in most operational flood forecasting systems, and a general introduction to this topic is provided in Chapter 4, together with several key references. Typically, measures of the whole hydrograph (e.g. the root mean square error), and key aspects of the hydrograph (e.g. the peak, the time of the peak), are evaluated over a number of events in simulation mode, and for different forecasting lead times (i.e. the N-step ahead forecast, where N = 1, 2, 3 . . . etc time steps). Values may also be normalized by factors linked to catchment characteristics (e.g. the Mean Annual Flood) to allow forecast performance to be compared between catchments. Given the flood forecasting application, some statistics may only be calculated above a given threshold level or flow.

To illustrate the derivation of some of these types of performance measures, Fig. 7.9 considers an example of a river level (stage) forecast generated at hourly intervals over a 50-h period. The figure shows every tenth forecast which was generated, and the flows which were subsequently observed. In this case, 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 the forecasts typically increasingly overestimated the observed values as the forecast lead-time increased.

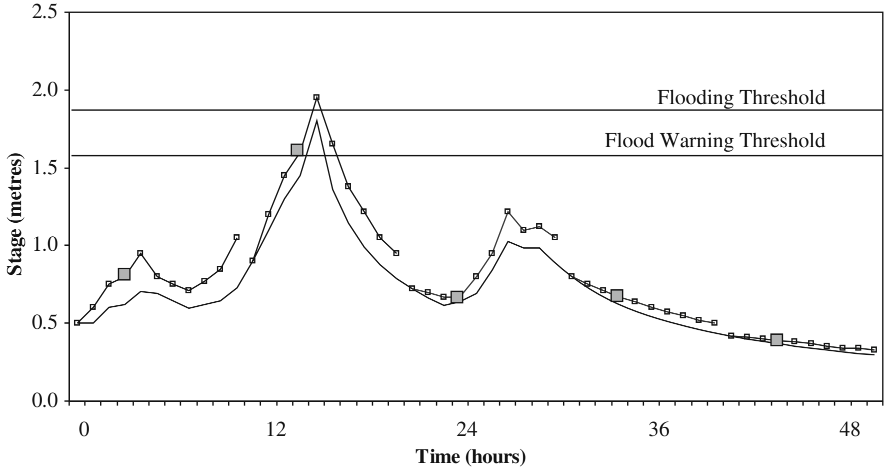

Fig. 7.9 Illustration of the construction of a fixed-lead time hydrograph and threshold crossing measures. See text for description of symbols

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. Performance statistics such as the root mean square error could then be estimated for this pseudo-hydrograph, and the analyses then repeated for other lead times of interest. The resulting measures could also be plotted or analysed as a function of lead time, to give an indication of the maximum lead time at which the forecast contains useful information or skill. In this example, the forecast is truncated at a forecast horizon or window of 10 h for illustration although, if meteorological forecasts are used, the forecast could be extended for much longer periods, although the forecast accuracy would of course continue to decrease with increasing lead times. Comparisons are sometimes also made between the values obtained using the actual rainfall forecasts, and assuming ‘perfect foresight’ of future rainfall; for example, using observed raingauge or weather radar data (with the assumption that this has no errors).

The figure also shows a flooding threshold and a flood warning threshold and, over the long term, as described in Chapter 4, additional statistics could also be accumulated for measures such as the Probability of Detection and the False Alarm Ratio, perhaps linked to specific lead times. For example, for the second forecast, issued after 10 h, the forecast 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 also be exceeded. This would therefore have resulted in a false alarm if a warning had been issued based on the forecast. Statistics could also be produced on the lead times provided and the associated timing errors in the crossing of thresholds, both with and without the use of data assimilation, and for continuous measures produced by integrating or accumulating values throughout the flow range. Of course, in post event analyses of this type, there is the luxury of knowing how the observed river levels subsequently evolved, whereas in real-time a forecaster would only have access to the observed values up to the time at which the forecast was issued.

The increasing use of ensemble and probabilistic forecasts has also raised the need to define appropriate forecast verification and performance measures, with a wealth of potential measures which could be used already available from meteorological and other applications (e.g. Jolliffe and Stephenson 2003, Laio and Tamea 2007). Some examples of measures which are used include the Brier Skill Score (including continuous versions), Ranked Probability Score, Relative Operating Characteristic, Reliability and Sharpness. As discussed in Chapter 3, these measures typically assess the skill of the ensemble, compared to the climatological equivalent, the closeness of the distribution to the historical values, when evaluated in hindcasting mode, and success at forecasting other features, such as the probability of occurence at different threshold levels, and the sharpness, which is a measure of how closely grouped the ensemble members are to a definite outcome (i.e. a 0 or 100% probability of occurence). There is, however, the difficulty that flood events tend to be rare, whilst many meteorological verification measures are tailored towards events which occur more frequently; some possible solutions include the pooling of results across many catchments, and the development of long-term hindcasts or reforecasts for both meteorological and hydrological forecasting models which include a number of extreme events (e.g. Jolliffe and Stephenson 2003, Schaake et al. 2007, Cloke and Pappenberger 2009).

7.3 Selected Applications

Whilst the general techniques described in Section 7.2 can be applied to many flood forecasting situations, adaptations or extensions of these methods are sometimes required for specific forecasting problems. The following sections describe forecasting techniques for flash floods and snowmelt and ice-related flooding issues, and forecasting for seasonal and longer timescales. Some additional information on techniques which are relevant to flood forecasting can be found in Chapters 4 and 10, which provide a brief introduction to forecasting techniques for surge and waves on large lakes, and at the lower (tidal) boundary of rivers, and Chapter 9, which discusses a range of techniques for flow forecasting for reservoirs and urban drainage systems (including flood forecasting applications). Chapter 11 also discusses the wider issue of forecasting for water resources applications, including floods, droughts, and the overall water supply and demand.

7.3.1 Flash Floods

Flash floods are generally characterized by the rapid onset of flooding, which is often exacerbated by a high debris content (mud, trees etc), which can cause blockages at culverts, bridges and other structures. Flow velocities may also be high presenting a risk to life, particularly for vehicle drivers. Flash floods are normally considered to be floods which arise from heavy rainfall, although some other types of flood event are sometimes described as flash floods, such as floods due to the break up of ice-jams, debris flows, and dam breaches.

The definition of a flash flood varies between countries, and in some places is defined as a flood on a catchment with a response time of 4–6 h or less (e.g. World Meteorological Organisation 1982, 2008), whilst in other locations a flood is only called a flash flood when the response time is much faster than this. Another approach to defining flash floods is to consider the catchment response time in relation to the effectiveness of emergency response procedures. Flash floods are then defined as those events for which current forecasting, warning and response procedures are not able to provide people at risk with an effective warning; for example (ACTIF 2004):

> 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).

As discussed earlier, there can be benefits in a review of all of the time delays in the chain from monitoring through to forecasting and the dissemination of warnings, since improvements in any area can provide more time for an effective response.

Some common features which appear in many definitions of flash floods include the following items (e.g. World Meteorological Organisation 1982, Meon 2006, Sene 2008) although, in many cases, only some of these factors may apply:

- Tend to be caused by short duration, localised, intense storms (e.g. thunderstorms)
- Develop rapidly in response to rainfall
- May have significant mud/debris content
- Tend to occur on small, steep and/or urban catchments
- May be strongly influenced by catchment antecedent conditions
- Tend to occur in locations with no recent experience of such events

Note that, where there is no recent experience of flash flooding, this often means that there may have been no need in the past to install telemetered flow instrumentation for use in flood warning, which can present a particular challenge for developing rainfall-runoff and other forecasting models (i.e. the catchment is ungauged). However, where river levels are monitored by telemetry, perhaps the simplest and most reliable way of detecting flash floods is to compare observed levels with pre-defined threshold values, if this provides sufficient lead time.

To provide additional lead time, similar forecasting techniques can be used for flash flooding to those described in Chapter 4 and Section 7.2. However, the focus tends to be on the rainfall-runoff modeling component and, due to the rapid response, there may be no flow routing component. Data assimilation is particularly important due to the likelihood that rainfall will be caused by convective rainfall events, with many uncertainties in both the timing and spatial distribution of rainfall. Quantitative Precipitation Forecasts are also often used, although are not always necessary, if observed rainfall values from raingauges, satellite and/or weather radar observations would provide sufficient lead time when used as inputs to the model. As described in Chapters 3 and 4, where forecasts are used, these may be in ensemble or stochastic form, perhaps with some additional pre-processing using statistical or weather matching/analogue techniques (e.g. Obled et al. 2002, Rebora et al. 2006). In urban areas, additional factors may also need to be considered, such as influence of the drainage system and flood storage areas (see Chapter 9).

For ungauged catchments, it is more challenging to provide useful flood forecasts, and views differ on whether flood warnings should be issued on the basis of the outputs from uncalibrated rainfall-runoff models. Rather than developing a catchment-specific forecasting model, one widely used approach is to use off-line simulation modeling to estimate the combinations of rainfall depth-duration values and catchment state (e.g. Soil Moisture Deficit, Antecedent Precipitation Index) likely to cause flooding. One problem which can arise is a lack of knowledge of flooding thresholds, so some typical criteria which are used can include the flows which would cause bankfull values, or which exceed a given return period. Bank full flows can be estimated from river channel survey data, and off-line hydraulic modeling or, for a more indicative approach, are often linked to a given return period, such as 1–2 years (e.g. Leopold et al. 1995).

Typically, these types of simulation are performed using inflows derived from unit hydrograph or conceptual rainfall-runoff models (see Chapter 4). In real time use, the catchment state can then be estimated from a region-wide soil moisture accounting procedure, such as a water balance or distributed modeling approach (see Chapters 2 and 4), or from the soil states within operational forecasting models. This approach forms the basis of the Flash Flood Guidance method which has been used operationally in the USA since the 1970s (e.g. NOAA/NWS 2003, Georgakakos 2006), and more recently in Central America (http://www.hrc-lab.org/), and which has been evaluated for use in some European countries (e.g. Norbiato et al. 2009).

Several studies have also considered the estimation of soil moisture from satellite observations (e.g. Alavi et al. 2009, Weerts et al. 2008). Physical conceptual distributed models also show promise for providing improved estimates for ungauged catchments (e.g. Seo et al. 2009, Cole and Moore 2009, Younis et al. 2008), often combined with threshold-frequency values derived from long-term model simulations (e.g. Reed et al. 2007). The use of Bayesian approaches to defining thresholds has also been considered, using utility function approaches to allow for the risk profiles of end users (Martina et al. 2006). Indicators of flash flood potential, such as soil moisture, channel constriction/debris risk, and storm characteristics, might also be incorporated into the decision making process to assess the areas most at risk (e.g. Collier 2007).

A simpler yet widely used approach for both flash flooding and other types of flooding is to use rainfall depth-duration values alone to provide initial alerts (or pre-warnings) of flooding and/or for landslides and debris flows (e.g. NOAA-USGS 2005). Threshold values can be estimated from historical data and observations (or anecdotal evidence) of flooding, catchment modeling studies, and other approaches. However, except for situations where the catchment state is relatively unimportant, such as for some desert mountains, there can be considerable uncertainty in when, where and whether flooding will occur. For this reason, depth-duration approaches alone, which do not take account of catchment state, are more often used for providing an initial 'heads-up' or alert for the possibility of flooding, such as for mobilizing staff and initiating more frequent forecasting model runs, rather than for issuing warnings to the public. Also, if warnings are issued, these tend to be general in terms of timing and location, and may have a quantitative or descriptive measure of uncertainty attached (e.g. 'a 30% chance' or 'localized flooding is possible').

Another possibility for providing early warnings of rainfall which might cause flash flooding is to use diagnostics derived from post-processing of the outputs from Numerical Weather Prediction model runs and/or observations by radiosondes and satellite. The predictors or indices which could be used are similar to those used for thunderstorm prediction and can include the precipitable water, which is the available moisture in a column of air from the ground up to a specified geopotential height, the Convective Available Potential Energy (CAPE), and the potential vorticity, which is an indicator of atmospheric stability (e.g. Wilks 2006, Environment Agency 2007). Lightning activity can also provide an indication of the potential for heavy rainfall and flash flooding, and is often used as one of the inputs to rainfall nowcasting systems, as described in Chapter 3. These methods all provide additional lead time, although with greater uncertainty in the precise locations and severity of any rainfall and related flooding which may occur.

7.3.2 Snow and Ice

In some countries, particularly at higher latitudes and in mountainous areas, snowmelt and ice jams and breakups present a significant flood risk, and need to be considered in flood forecasting models. Snowmelt can arise from a number of mechanisms, including solar radiation, rising air temperatures, and rainfall falling on snow, or a combination of these factors. Runoff can also be enhanced when rainfall falls on frozen snow, and river baseflows can also be raised due to snowmelt, making some locations more vulnerable to flooding during rainfall events that would normally not present any significant risk.

For the spring snowmelt, one widely used empirical approach to estimating the rate of snowmelt is to assume that this is proportional to the difference between mean air temperature values and a threshold value (i.e. the ‘degree-days’) as a measure of the energy input to the snowpack. Additional factors such as wind speed and radiation can also be brought into this type of temperature index relationship (e.g. Hock 2003). Linear and non-linear regressions are also used to relate snowmelt to factors such as air temperature, water equivalent depth of the snow layer, soil moisture, rainfall and the depth of frozen soil (e.g. World Meteorological Organisation 1994).

As discussed in Chapter 4, a more detailed approach is to use a conceptual model, or a physical-conceptual or physically-based model, in which precipitation is partitioned into rainfall or snowfall according to air temperature, and possibly other criteria. For example, Essery et al. (2009) compare the performance of 33 models of this type in forested areas for 11 countries in the northern hemisphere. Conceptual models are typically used on a lumped or semi-distributed basis, although may include areal zones to represent elevation and other effects, such as partial snow cover in a catchment, whilst the other model types are typically applied on a gridded basis. Conceptual and physical-conceptual models normally consider just the water balance, whilst physically-based models may also consider the energy balance, relating the net radiation to sensible, latent and soil heat fluxes, and energy stored in the snow layer, also allowing for factors such as forest cover. Meteorological inputs may be obtained from weather stations and/or meteorological forecasts. Ensemble Streamflow Prediction techniques are also widely used for longer term forecasting of snowmelt, and are based on sampling of historical meteorological data as described in Chapter 4 and Section 7.3.3. This approach is used in the Watershed Simulation and Forecasting System (WSFS) in Finland, for example, together with medium-range ensemble forecasts from a Numerical Weather Prediction model (see Box 7.3)

For operational use, one requirement for both conceptual and distributed models is to obtain up to date and spatially representative estimates of snow depth, snow condition, and snow cover. Values can vary widely with topography, aspect (e.g. south or north facing slopes), forest types and other types of land cover, and other factors. As described in Chapter 2, both manual observations and automated approaches are used to provide local ground-based estimates, often supplemented by satellite observations of the extent of snow cover and snow water equivalent. Data assimilation techniques may also be used to initialize the model runs (e.g. Bell et al. 2000; see Boxes 7.3 and 11.3 also).

Compared to snowmelt forecasting, similar problems apply to forecasting for the flooding caused by river ice, with the added difficulty that flooding problems can be very site specific. The main mechanisms which can occur include:

- Ice formation – a build up of ice on a river surface impeding flows at bridges and other structures, and reducing the flow capacity of river channels, or even forming a barrier to flow (an ice dam)
- Ice break-up – break up of the ice layer on a river, or of ice jams and ice dams, causing a sudden increase in flows and levels further downstream
- Ice jams – partial or complete blockages at bridges and other structures caused by an accumulation of floating ice

Ice tends to form slowly over a period of days or weeks, but ice jams can form rapidly, and break ups can also be rapid (and if flooding occurs, this is sometimes viewed as a type of ‘flash flooding’). Ice melt occurs for similar reasons to snowmelt, with the temperature of the river (or reservoir) water as another factor, and also with the more unpredictable mechanical effects from floating ice colliding with ice jams or ice layers.

Again, degree-day and correlation approaches are widely used where temperature and/or energy are the dominant mechanisms, and there has also been much research into more physically-based methods, using hydrodynamic models for the flow component, with an energy component to represent the formation and melting of ice (e.g. World Meteorological Organisation 1994, Kubat et al. 2005). Some other areas for research include multivariate statistical methods, the use of ice break-up databases, artificial intelligence (e.g. neural networks), and Kalman filtering, in some cases combined with a hydraulic modelling approach (e.g. Daly 2003, White 2003, Morse and Hicks 2005, Mahabir et al. 2006). The presence of ice can also affect the stage-discharge relationships used to estimate flows at river gauging stations, which is another factor which needs to be represented in forecasting models where ice may be an issue.

Box 7.3 Watershed Simulation and Forecasting System (WSFS)

In some countries, river flow forecasting systems also need to include particular consideration of the influences from snow and ice and other effects, such as lake storage. For example, since the 1980s, the Finnish Environment Institute has operated a national flow forecasting system called the Watershed Simulation and Forecasting System (WSFS) (Vehviläinen et al. 2005). The system represents approximately 6,200 river basins and 2,400 lakes (area $>$ 1 km^2) in an area of 390,000 km^2, and provides forecasts for more than 1300 forecasting points with updates every 3–5 h. The system is also used off-line for planning of lake regulation policies, estimation of flood damages, water resources studies, and estimating design floods for dams (http://www.environmet.fi/waterforecast).

A semi-distributed approach is used, covering the whole of the land surface of Finland, in which rainfall-runoff, flow routing and lake water balance models are combined within a Geographical Information System (GIS) framework, with an allowance for ice formation and break-up in the flow routing and lake components. The rainfall-runoff modelling component is a development of the HBV model (Bergström 1995), which includes snowmelt, soil moisture, subsurface and groundwater storage components. Rainfall and air temperature observations and forecasts are obtained from the Finnish Meteorological Institute (0–3 days) and the European Centre for Medium-Range Weather Forecasts (ECMWF; 0–10 days EPS forecast), together with weather radar data at a 1 km grid resolution from the Finnish Meteorological Institute. Precipitation and temperature values are interpolated to each grid square to account for differences in elevation and air temperatures using correction factors derived from historical data. For longer-term forecasts, an ensemble streamflow prediction approach is also used based on sampling from 50 years of historical meteorological data or monthly and seasonal EPS forecasts from ECMWF for input to the watershed model.

The data assimilation techniques which are used make use of water level and discharge observations, satellite observations of snow cover, ground-based snow-line measurements of snow water equivalent, and satellite measurements of snow water equivalent. In the forecasting models, snow water equivalent and snow cover area values are updated at a sub-catchment scale, based on both the ground-based and satellite data. Snow cover is estimated from the polar-orbiting Moderate Resolution Imaging Spectroradiometer (Terra/MODIS) and RADARSAT Synthetic Aperture Radar (SAR) observations, using a reflectance model at a 5 × 5 km scale which allows for reflectance from wet snow and snow-free ground, and forest transmissivities. Trials have also been performed of data assimilation based on satellite observations of flood extent and soil moisture content.

Forecast outputs include values for river levels, river flows, snow cover, soil moisture, groundwater levels, evaporation, areal rainfall, and for lake levels, water temperatures and storage. Some other forecast products which are particularly relevant to high-latitude locations include snow load warnings for building roofs, probabilistic estimates for the dates of ice break-up, a national summary of inflow energy for hydropower generation, and the outputs from a phosphorus load simulation model (which is described in Chapter 10). Figure 7.10 presents a selection of these outputs.

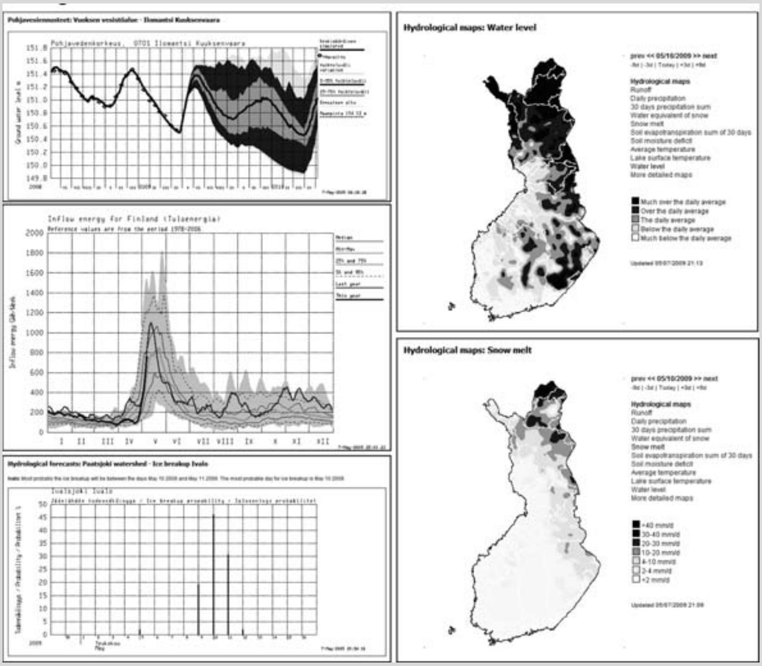

Fig. 7.10 A selection of outputs available from the Watershed Simulation and Forecasting System (WSFS) of the Finnish Environment Institute. From the top left clockwise (**a**) 12-month probabilistic ground water level forecast (**b**) 9-day lake water level forecast in 5 probability bands relative to long term average values (**c**) 3-day deterministic snowmelt forecast map in mm/day (**d**) 9-day ice break up forecast for a river station (**e**) probabilistic national inflow energy forecast for Finland in 2009 in GWh/week compared to the 1978–2006 range (http://www.ymparisto.fi/ Accessed 7 May 2009)

7.3.3 Seasonal and Longer Term Forecasts

The provision of flood forecasts for medium- to longer-term lead times is a key challenge in hydrology, since flood events may only last a few hours, and the magnitude can be strongly dependent on the location, timing and spatial extent of rainfall. In general, for forecasting at these lead times, it is easier to predict mean flows, or flow volumes, than it is to estimate flood peaks. Also, for many catchments, it may not be possible to provide information other than in very general terms (e.g. that 'There is likely to be more frequent flooding than average this summer').

However, there are some situations in which the natural or artificial storage in a catchment can be sufficiently slowly responding that useful information can be provided at longer lead times. Some examples include:

- Snowmelt – catchments which are covered by snow for part of the year, with spring floods due to melting snow
- Lakes and reservoirs – catchments with large lakes and/or multiple reservoirs whose volumes respond slowly to variations in rainfall or inflows, and whose outflows dominate flows further downstream
- Groundwater – catchments with flooding issues whose response is dominated by groundwater storage and outflows
- Large (macroscale) catchments – major river catchments where it can take several weeks or more for water to flow from the headwaters to the sea; particularly catchments in which snowmelt or storage effects are also significant

For these types of situation, some forecasting techniques which are used include:

- Numerical Weather Prediction (NWP) – using the probabilistic long-range outputs from coupled ocean-atmospheric models operated to lead times of several months, with appropriate post processing, and possibly combining the outputs from several models in a multi-model approach (see Chapter 3)
- Ensemble Streamflow Prediction – in which historical meteorological records are sampled, but starting the model runs from current catchment conditions, and sometimes using long-range NWP forecasts to guide the generation of the ensembles (see Chapter 4)
- Statistical Techniques – development of regressions and other data-based relationships linking flow-related parameters such as flow volumes and reservoir storage to seasonal or longer term indicators, such as monthly rainfall, seasonal rainfall to date, snow water equivalent, and El Niño-Southern Oscillation (ENSO) indices (see Chapters 3 and 4)
- Groundwater Models – where groundwater storage is the dominant factor, then numerical models of the type described in Chapter 4 might be operated on a daily or longer basis to assess the risk from groundwater flooding

For example, in the northwestern parts of the USA and western Canada, there is significant snowfall every winter in mountain areas, and the magnitude and timing of floods can to some extent be estimated using techniques such as Ensemble Streamflow Prediction, statistical relationships between flow volumes and snow cover or snow water equivalent, and by using long-range forecasts for rainfall and air temperature as inputs to distributed hydrological models (e.g. Day 1985, Wood and Lettenmaier 2006; see also Boxes 1.2 and 11.3). Another example, for a large catchment with a well-defined flood season, is the medium to long-range ensemble flow forecasting system for the Ganges and Brahmaputra rivers in Bangladesh (Webster and Hoyos, 2004, Hopson and Webster 2008).

For longer term forecasting (or prediction), the main area of interest has been in assessing the likely impacts of climate change on flood magnitudes and the frequency of occurrence, based on the latest projections from the Intergovernmental Panel on Climate Change http://www.ipcc.ch/ (e.g. Bates et al. 2008). A typical approach is to take existing simulation or forecasting models, and to perturb the meteorological inputs (rainfall, air temperature etc) to assess the impacts on river flows, snowmelt and other factors. Multi-model ensembles from General Circulation Models are increasingly used in this approach (e.g. Palmer and Räisänen 2002) Typically, statistical, weather matching or dynamic downscaling techniques are used, and stochastic weather generators, to translate the outputs to the spatial and temporal scales of interest, including representation of the spatial correlations inherent in many forecasting problems (see Chapters 3 and 4).

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Chapter 8
Droughts

Abstract Droughts usually arise from a shortfall in precipitation, and can be exacerbated by increases in demand for water supply, agriculture and other applications. The onset of a drought is often recognised through the impacts on key water users, and may include meteorological, hydrological, groundwater, agricultural and socioeconomic droughts. Some difficulties in forecasting the onset and progression of droughts include factors such as their slowly developing nature, the large spatial extent, and the spatial and temporal variations in impacts which often occur. This has led to the development of a wide range of possible indices and indicators, of which several may be used operationally to identify different stages in the progression of a drought. For short-term forecasts, forecasting techniques range from simple regression techniques through to integrated catchment models driven by rainfall observations and forecasts. At longer time scales, ensemble forecasting techniques are widely used, together with statistical techniques relating conditions to oceanic and atmospheric phenomena such as the El Niño-Southern Oscillation. These methods may also be combined with forecasting techniques for individual applications, such as supply-demand models for water resources operations, and crop simulation models for irrigation scheduling. This chapter presents an introduction to these topics, and includes several examples of operational drought warning systems.

Keywords Drought · Forecasting · Meteorological drought · Hydrological drought · Groundwater drought · Agricultural drought · Drought indices · Low flows · Ensemble forecasting · El Niño-Southern Oscillation · Teleconnections · Water resources · Famine early warning

8.1 Introduction

Drought is often referred to as a creeping phenomenon, which develops slowly and has a prolonged existence, sometimes over a period of several years (e.g. Tannehill 1947, Wilhite 2005, World Meteorological Organisation 2006).

Recent estimates suggest that, in the period 1900–2004, more than ten million people died and almost two billion were affected by droughts (Below et al. 2007).

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Table 8.1 Some examples of significant drought events in the past century (Tallaksen and Van Lanen 2004, Guha-Sapir et al. 2004, Wilhite 2005, World Meteorological Organisation 2006, Smith 2007)

Region/Country	Years	Examples of impacts
Australia	1982–1983	Spatially extensive drought with major economic losses; other drought events include 1895–1902, 1937–45, 1965–68, 1991–95
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	More than 100 million 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, also prompting widespread migration between states
	1988, 2002	Severe impacts on hydropower generation, river navigation and crop yields

The impacts can spread across entire regions and continents, as illustrated by the droughts which resulted from the 1982/83 and 1997/98 El Niño events, which affected the United States, and countries in Africa, Asia and South America (e.g. Hoerling and Kumar 2003, Smith 2007). Table 8.1 summarises some features of other major drought events world-wide.

Droughts are usually considered to arise from a cumulative shortfall in precipitation, and can be defined either in meteorological terms, or in terms of the impacts on people, agriculture, water supply or the environment. Droughts can occur in almost any climatic region (tropical, temperate, arid, semi-arid etc) and can vary widely in duration, severity, time of occurrence and spatial extent (Tallaksen and van Lanen 2004). A broad definition 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 (UN/ISDR 2007). 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 hydrometeorological forecasting applications, one convenient way to consider drought is through the impacts on the hydrological cycle, since typically a meteorological drought leads initially to a soil moisture drought, and then to a hydrological drought. These terms can be defined as follows (e.g. Tallaksen and Van Lanen 2004):

- 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, coupled with high evaporation rates
- 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 drought persists – a slower-onset groundwater drought. Following a return to normal rainfall, the recovery from a drought typically occurs in this sequence also, with soil moisture being replenished first, streamflows recovering next, before finally, possibly months or even years later, groundwater levels return to normal values. In the absence of sufficient irrigation, a soil moisture drought can lead to reductions in crop yield and a so-called agricultural drought (Fig. 8.1). Similarly, in the absence of alternative sources of water, such as groundwater sources and water transfer schemes, a hydrological drought can lead to a shortage of water for public water supply, irrigation, and hydropower generation. There may also be other impacts on the environment and ecosystems, such as the appearance of toxic algal blooms, and decreases in water quality. A drought which causes major social, economic or political disruption is often called a socioeconomic drought.

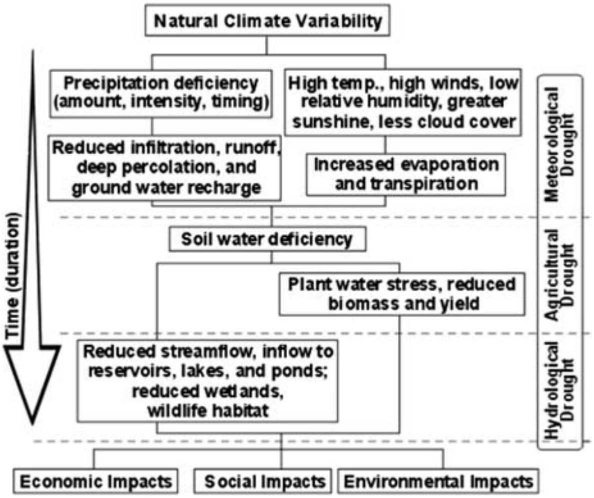


Fig. 8.1 Sequence of drought occurrence and impacts for commonly accepted drought types (National Drought Mitigation Center, University of Nebraska–Lincoln, USA; http://drought.unl.edu/whatis/concept.htm)

In a drought forecasting system, as with many types of early warning system, the forecasting component is typically just one aspect of a wider system which covers preparedness and mitigation measures, and response and recovery components (see Chapter 1). The effectiveness of dissemination procedures, and drought management and response plans, also needs to be considered, accounting for the physical, social, economic and environmental vulnerability of communities and end-users (e.g. Wilhite 2000, UN/ISDR 2007). A distinction is sometimes also made between the different requirements for strategic, tactical and emergency response measures (USACE 1994), where:

- Strategic measures are long term physical and institutional responses such as water supply structures, water law, and plumbing codes
- Tactical measures, like 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

Response measures can cover both water supply and demand. For example, if water supply shortfalls seem likely, demand might be reduced by voluntary or compulsory restrictions on water use, such as for spray irrigation and by the use of standpipes for drinking water. Alternatively, the available water could be increased by imports from other sources using water tankers, emergency pipelines and other methods. Existing adaptation strategies and economic development also need to be considered; for example, the use of livestock by subsistence farmers as a buffer to supplement shortages from rain-fed farming systems, and the use of grain stores and imported food to supplement local sources. As with many types of natural and technological hazard, the impact of a drought can depend strongly on the social, economic and environmental vulnerability and resilience of those affected, with poorer regions being affected more than those with the resources to adapt to a developing drought.

A risk-based approach is also increasingly being adopted to the management of droughts, where risk depends on the probability of an event occurring, and the economic or other consequences. For example, Wilhite and Knutson (2008) note that the principles of 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 programmes
- creating a safety net of emergency response programmes that ensure timely and targeted relief
- providing an organizational structure that enhances coordination within and between levels of government and with stakeholders

Table 8.2 Examples of recent or current drought early warning systems

Name	Location	Main objectives	References
Drought Watch Service, Bureau of Meteorology	Australia	Consistent starting point for national drought alerts and drought-related products	http://www.bom.gov.au/
Beijing Climate Center (BCC) of the China Meteorological Administration (CMA)	China	Monitoring of drought development including a range of bulletins and web-based products	http://www.bcc.cma.gov.cn/en
IGAD Climate Prediction and Applications Centre, Nairobi (ICPAC)	Eastern Africa	Climate outlooks and early warnings to national meteorological and hydrological services	http://www.icpac.net
Crop Weather Watch Group	India	Agricultural impacts of drought	Samra (2004)
National Integrated Drought Information System (NIDIS)	USA	Interagency approach to drought monitoring, forecasting and early warning	Wilhite (2005), NIDIS (2007)

Many countries operate drought forecasting and early warning systems and Table 8.2 summarises several examples. Section 8.3 also provides examples of approaches specifically for hydrological and agricultural droughts.

In Australia, for example, publications from the Bureau of Meteorology include a Monthly Weather Review and a Drought Statement, with information on 4-month and 10-month rainfall deficiencies, in terms of percentile values. The National Agricultural Monitoring System in Australia (http://www.nams.gov.au) also provides information relevant to agricultural production across Australia and is described in Section 8.3.

A similar multi-agency approach is also used in the USA, where the National Integrated Drought Information System (NIDIS) provides a focus for drought monitoring, forecasting and early warning. The Implementation Plan for this programme (NIDIS 2007) notes that this approach is being developed 'through the consolidation of physical/hydrological and socio-economic impacts data, engaging those affected by drought, the integration of observing networks, the development of a suite of drought decision support and simulation tools, and the interactive delivery of standardized products through an internet portal'. The portal (http://www.drought.gov), has been developed with the following objectives, and provides links to a wide range of experimental and operational forecast products, including outputs from the National Drought Mitigation Centre (see Box 8.1):

- 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

For ICPAC (see Table 8.2), in addition to producing a wide range of forecast products, another key activity is to organize (with others) the Climate Outlook Forum for the Greater Horn of Africa which is held before the start of each rainfall season. This is one of more than ten Regional Climate Outlook Forums established by the World Meteorological Organisation since 1996 in South and Central America, Africa, southeastern Europe, South East Asia, the Caribbean and the Pacific. Typically, these provide advice on seasonal climate outlooks and impacts, using information from national and international experts in meteorology, health, disaster risk management, agriculture and food security, water resources, and the media (http://www.wmo.int/).

Box 8.1 National Drought Mitigation Centre, USA

Recent estimates suggest that, over the past century, approximately 14% of the United States has been affected by severe or extreme climatological drought in an average year, reaching 65% during the Dust Bowl drought of the 1930s, and this has recently been about 35% for some regions (NIDIS 2007). To help to improve the information available on drought at a national level, the National Drought Mitigation Centre at the University of Nebraska-Lincoln was established in 1995 and issues a number of key products for drought monitoring in the USA (http://drought.unl.edu/), which include:

- Standardised Precipitation Index Maps – for durations of 1, 2, 3, 6 and 12 months, and the year to date, based on data from the National Climatic Data Centre, updated daily
- Drought Impact Reporter – a database of drought-related impacts (agricultural, water/energy, environment, fire, social etc) based on validated information from a number of sources, including government agencies, news reports, and members of the public, and accessible via a map-based interface at state or county level, which is updated on a daily basis (Fig. 8.2)
- US Rain Days and Dry Days – maps showing the number of dry days in the past 7 days, past 30 days and since the last rainfall (a USGS-EROS product)

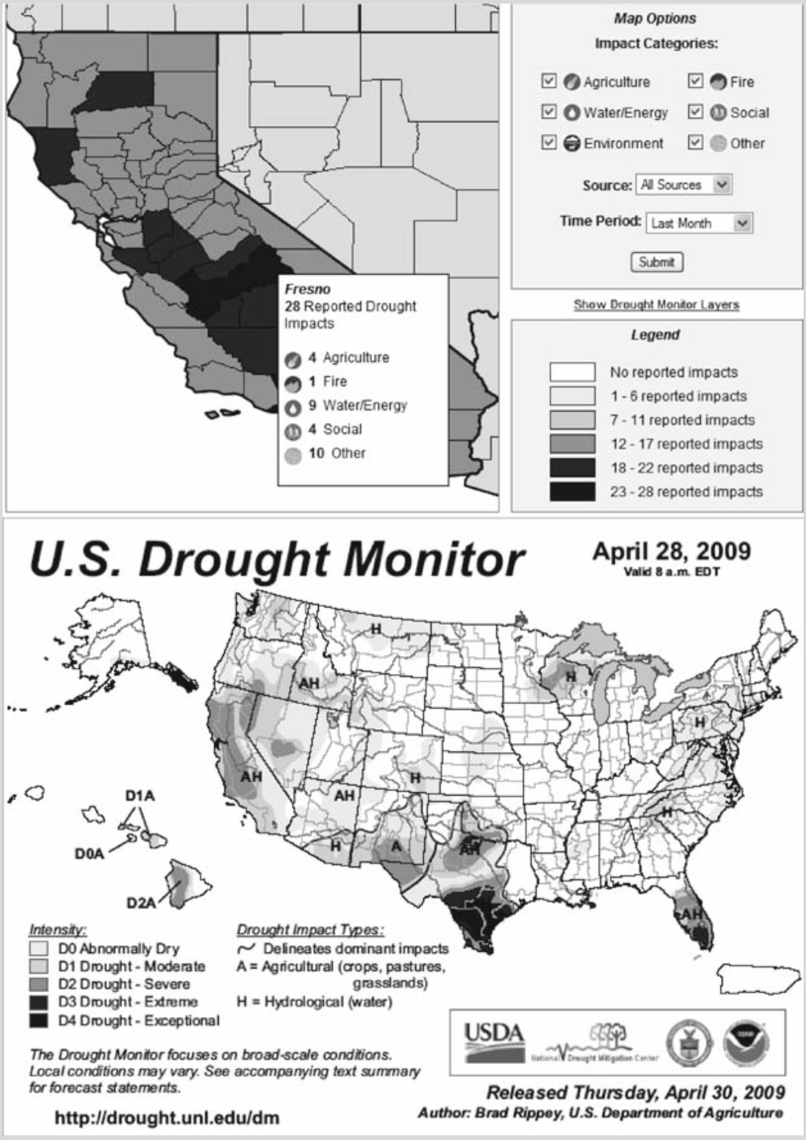


Fig. 8.2 Example of a Drought Impact Reporter map for California for April 2009 and of the US Drought Monitor output released on 28 April 2009 (http://drought.unl.edu/dm)

- Vegetation Drought Response Index – nation-wide maps at a 1 km resolution of drought-related vegetation stress based on the Palmer Drought Severity Index, Standardised Precipitation Index (12 month duration), satellite observations of Percent Annual Seasonal Greenness and Start of Season Anomaly, and biophysical characteristics (soils, land cover, land use, ecological setting), combined using a regression tree model (VegDri), and updated every 2 weeks
- US Drought Monitor – a map and associated text summary describing areas experiencing drought, the current severity of that drought, and trends in recent months, for the whole of the USA (and individual regions) which is updated weekly (Fig. 8.2)

The US Drought Monitor (Svoboda et al. 2002) is based on a number of climatic, hydrological and soil moisture indices, combined with expert opinion, and is produced in collaboration with the US Departments of Agriculture and Commerce, and a number of other agencies. Five stages of increasing dryness and drought intensity are identified which are related to the probability of a given drought magnitude occurring in any given year in a 100 year period. These stages are abnormally dry, for areas showing dryness but not yet in drought, or for areas recovering from drought (21–30%), and moderate (11–20%), severe (6–10%), extreme (3–5%) and exceptional (≤2%) drought conditions. A distinction is also made between agricultural and hydrological droughts. For example, Table 8.3 shows the impacts associated with each drought category for hydrological droughts.

Table 8.3 Drought intensities used for hydrological droughts

Intensity		Impacts
D0	Abnormally Dry	Streamflow below average
D1	Drought Moderate	Streamflow, reservoir and well levels are low; some water shortages develop
D2	Drought Severe	Water shortages common; water restrictions imposed
D3	Drought Extreme	Widespread water shortages and restrictions
D4	Drought Exceptional	Shortages of water in stream, reservoirs and wells; creating emergencies

Before being published, the draft outlook is circulated to a review group consisting of more than 100 experts, including weather forecasters, climatologists, hydrologists and agricultural specialists. The resulting product has been produced since 1999 and is widely used by government and federal agencies, the media and the general public. Since 2002, a North American Drought Monitor has also been issued based on collaboration between drought experts in the USA, Canada and Mexico.

8.2 Forecasting Techniques

Hydrological and meteorological services and other organizations use a range of techniques for monitoring and forecasting the onset of droughts. Typically, water availability is established from observations of rainfall, river flows, and reservoir and groundwater levels, and identification of departures from the mean, such as cumulative deficits in river flows (run-sums) and precipitation anomalies (e.g. percentages of long term averages). Satellite monitoring of vegetation, soil moisture and other parameters is also widely used to assist with assessing the regional progression of a drought.

Where appropriate, other parameters may also be monitored using ground-based observations, such as soil moisture, water abstractions and pumping operations, and water quality indicators. Different parameters may also be suitable in different climatic regions; for example, in arid and semi-arid zones, rivers sometimes only flow occasionally, and other types of data, such as reservoir and groundwater levels, are likely to provide more information about the drought situation (Gustard et al. 2004). Other less quantitative indicators may also provide useful information on the onset of drought conditions, such as an increase in enquiries and complaints from the public, requests to increase abstractions from rivers (and an increase in unlawful abstractions), and damage to environmentally sensitive sites.

Rainfall and air temperature forecasts are also widely used as part of the drought prediction process, with an emphasis on medium- and long-range forecasts both of meteorological parameters (e.g. rainfall), and drought indices (e.g. the Standardised Precipitation Index). The typical approaches used in forecasting (see Chapter 3) are to operate Numerical Weather Prediction (NWP) models at a relatively coarse scale over periods of several months, and/or to use regressions and other types of statistical methods which relate future rainfall to indicators such as sea surface temperatures and surface pressure differences (e.g. Ropelewski and Folland 2000, Palmer and Hagedorn 2006, Troccoli et al. 2008).

For example, droughts have been associated with a number of regional and global-scale features of the atmospheric and ocean circulation, and several of these so-called teleconnections are illustrated in Table 8.4. Chapter 1 provides background information on the driving mechanisms for these phenomena, and Chapter 3 describes the forecasting techniques which are used in more detail. The influence of the El Niño-Southern Oscillation can be particularly widespread, causing both reductions in rainfall, affecting the availability of water, and increases in air temperature, increasing evaporation and water demand (e.g. Ropelewski and Halpert 1987, Chiew and McMahon 2002). Forecasting techniques include the use of NWP model outputs at seasonal timescales, and correlations linked to indicators and predictors such as Sea Surface Temperatures (SST) and the Southern Oscillation Index (SOI) (e.g. Chiew et al. 1998).

Local influences can also cause additional complications even during a drought; for example, the warmer conditions may lead to more frequent thunderstorms,

Table 8.4 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)	Sub-Saharan Africa, South Asia	Twice yearly	Reductions in rainfall extent and intensity and/or the northwards or southwards progression of the zone
El Niño-Southern Oscillation (ENSO)	Australia, South East Asia, north eastern 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
North Atlantic Oscillation	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

locally providing some recharge of surface and groundwater supplies. Small variations in regional scale phenomena can also have major impacts; for example, for the Sahel, small changes in the northernmost locations reached by the Inter Tropical Convergence Zone can cause major differences in rainfall in that region. Feedback influences between the land surface and atmosphere have also been suggested as a mechanism for changing the progression of prolonged droughts and causing desertification; for example, the changes in albedo as vegetation cover decreases, and reductions in water vapour transfer associated with decreases in soil moisture and surface water volumes.

For deciding whether to issue warnings of potential drought, thresholds and drought indices are two of the key tools used in decision making. Decision support systems are also used in some water resources and agricultural applications, as discussed in Chapter 6 and Section 8.3. For threshold values (e.g. Knutson et al. 2005), the approach used is to compare the monitored or forecast values to critical values, which are sometimes called drought triggers (see Chapter 6). Drought indices are also widely used, and are usually defined in a way which is appropriate to the type of drought and the spatial scale at which it is being monitored, such as at a farm, catchment, county, regional or national scale. Table 8.5 shows some examples of the types of parameters which are used.

Values are often compared to long-term estimates calculated using the World Meteorological Organisation's climatological standard periods, which include the years 1901–1930, 1931–1960, and 1961–1990. However other more locally relevant or extensive periods may be selected. For example, many meteorological services also update statistics at the end of each decade (e.g. 1971–2000) whilst, in arid or

Table 8.5 Examples of drought monitoring indicators and indices (Wilhite 2005, World Meteorological Organisation 2000, 2006)

Type	Name	Countries (examples)	Basis of method
Meteorological	Rainfall percentiles	Australia	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)	USA, China	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 (McKee et al. 1995), expressed in terms of the number of standard deviations from a mean of zero
	Palmer Drought Severity Index (and Palmer Hydrological Drought Severity Index)	USA	Conceptual water balance approach which compares the available water to the climatological normal, considering rainfall, evapotranspiration, soil recharge and runoff (Palmer 1965)
	Water Requirements Satisfaction Index	FEWS NET	The ratio of actual to potential cumulative crop evapotranspiration (Senay and Verdin 2003; see Box 8.3)
Soil moisture	Crop Moisture Index	USA	A component of the Palmer Drought Severity Index calculation focusing on short-term changes in soil moisture (Palmer 1968)
Hydrological	Low flow statistics	Widely used	Flow duration (e.g. Q_{95}), run-sum and other statistical measures of flow in terms of duration, values relative to a threshold etc
	Surface Water Supply Index	Western USA	Weighted sum of snowpack, streamflow, precipitation, and reservoir storage values normalized by non-exceedance frequencies (Shafer and Dezman 1982)
Agricultural	Aridity Index	India	Difference between actual and potential evaporation as a fraction of potential evaporation (World Meteorological Organisation 2009)
	Normalised Difference Vegetation Index (NDVI)	Widely used	Normalised difference between near-infrared and infrared reflectance values, giving a measure of vegetative cover

semi-arid regions, much longer periods are often used since, as shown in Table 8.1, droughts can persist for many years and may span the boundaries of these thirty-year periods. Considerable effort may also be required to ensure that records are homogeneous; for example, to allow for changes in the types and locations of instruments, and changes in recording procedures over time.

Hayes (2006) provides a useful comparison of the applications and strengths and limitations of some of these approaches. Due to the range of potential impacts of droughts, and the uncertainties over when a drought begins and ends, it is often recommended that multiple indices are used (see Box 8.1 for example). The slow onset of droughts also means that it can be difficult to recognize 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 in future forecasts. In the USA, for example, some key research needs which have been identified to improve the forecasting of droughts include (Western Governor's 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.

Some other key research needs, summarised from a publication by The Geological Society of America (2007) include: more accurate predictions of soil moisture, improved understanding of the El Niño-Southern Oscillation (ENSO), accurate predictions of ocean temperatures throughout its depth, better model representation of air-sea interactions particularly at timescales of 40–70 days, a better understanding of the 'weather-climate connection', and improvements in connecting global and regional climate models with basin-scale and watershed-scale hydrologic models. Similar requirements also exist for many other countries which experience droughts (e.g. Tallaksen and van Lanen 2004).

Internationally, some of the most prominent challenges with developing drought monitoring and early warning systems which have been noted include (World Meteorological Organisation 2000, 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.

8.3 Selected Applications

8.3.1 Hydrological Drought

A hydrological drought typically occurs when streamflows, reservoir levels and/or groundwater levels drop well below normal 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, power station cooling water, and hydropower generation. The period over which a drought develops can be strongly influenced by the amount of storage available; for example, groundwater dominated systems and catchments with large reservoirs or lakes may only be sensitive to shortfalls in rainfall over a period of months or years, whilst surface water flows in small catchments respond over much shorter periods (and recover quickly as well).

During drought conditions, a range of measures may need to be introduced to limit abstractions and water use to maintain river flows further downstream and/or to augment river flows by controlled releases from reservoirs or groundwater sources (Box 8.2). Some examples of the actions which may be taken can include banning non-essential uses, such as watering of gardens, or the filling of swimming pools, rationing water via standpipes and rota cuts, temporarily modifying abstraction licence conditions, installing temporary dams and pipelines, and issuing of special permits to allow abstractions from other sources.

Various techniques are used for forecasting the onset of hydrological drought. For short time scales, up to a few days ahead, sometimes a regression or recession forecasting approach can work well. For example, in recession forecasting techniques it is typically assumed that river flows will decrease following an exponential relationship, where the parameters of the expression are estimated from a number of previous low flow recession periods (e.g. World Meteorological Organisation 1994). Estimates for travel times, obtained from historical data, or from controlled releases, and typical transmission losses per river reach, can also assist with assessing likely flows further downstream. For longer term forecasting of hydrological conditions, supply demand models are widely used, of the types described in Chapter 11 and Box 8.2. These may include linear or dynamic programming components to help with the management of complex, multiple source (reservoir, groundwater etc) conjunctive use water supply systems, and a detailed representation of all significant abstractions, discharges and water transfers in the system (see Chapter 9).

Real-time forecasting models similar to those used for flood forecasting (see Chapter 7) are also increasingly used provide an indication of future river levels and flows at key locations (forecasting points) in the catchment; for example, to assist with water supply, irrigation, hydropower and navigation operations, and to avoid unnecessary releases of water for flood control or other purposes during any rainfall events that occur. Typically, an integrated catchment modeling approach is used, consisting of a semi-distributed network of rainfall-runoff models, providing inflows to one or more flow routing or hydrodynamic model reaches, and possibly also including a groundwater component. Distributed (grid-based) models may also be used. Real-time inputs can include raingauge or weather radar rainfall data, short-, medium- and long-range meteorological forecasts, and information on river levels, reservoir levels, and other parameters. Some examples of models of this type include:

- River Thames, England – a risk-based technique for tactical drought decision making, using categorical monthly rainfall forecasts, and sampling historical sequences of daily rainfall for input to conceptual rainfall-runoff and water resources system models, with state updating of model initial conditions (Moore et al. 1989)
- Lake Powell, Colorado River Basin, USA – a combination of multiple regression techniques and rainfall-runoff forecasting models using Ensemble Streamflow Predictions as inputs, with outputs adjusted based on climate forecasts and indices, to provide seasonal outlooks of flow volumes into Lake Powell (Brandon 2005)
- National Hydrological Instrument, the Netherlands – a national drought forecasting system, operating at a daily timestep, providing estimates of actual and forecast surface, ground and soil water conditions to support decisions on allocation of water to different users (agriculture, navigation, industry etc) in the near future (i.e. 10 days ahead). 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 of the Netherlands (Weerts et al. 2009)
- Welland and Glen catchment, England – a real-time flow forecasting model developed for a range of applications including flood forecasting and the management of raw water transfers, river support, drought and licence control, pollution incidents, and navigation, with many complicating influences on flows, including pumped and gravity fed discharges and abstractions, offline storage reservoirs (‘washlands’), tidal influences, and manual and automatic flow control structures. The model included 55 lumped conceptual rainfall-runoff models, more than 400 km of hydrodynamic model network, with almost 500 structures including flood storage reservoirs, siphons, pumps and complex gates, bridges, weirs and culverts (Huband and Sene 2005)
- Orange River, South Africa – use of a real-time hydrodynamic model to provide operators of Vanderkloof Dam, which is the lowermost dam on the Orange River, with information to help to determine releases to meet the water demands of users further downstream in the 1400 km reach down to the Atlantic Ocean, particularly during low flow conditions, and with a particular focus in the model development on losses due to evaporation (Fair et al. 2003)

Compared to flood forecasting applications, naturally a greater focus is needed on the low flow response, including any significant abstractions or discharges related to water supply, irrigation, power generation or other purposes. The hydrodynamic component (if used) may also require adapting so that the model remains stable and convergent at low flows, and a water quality component may also be required (see Chapter 10).

For these more complex approaches, demand estimates or forecasts are also often required so that model runs can be performed to assess the impacts of abstractions, and ‘what-if’ scenarios investigated, perhaps leading to the decision to impose restrictions on making abstractions to maintain river flows at key locations. Chapter 5 describes approaches to demand forecasting for a range of applications, and some examples of the types of abstractions and discharges which may need to be considered include:

- Boreholes – the potential influences of groundwater abstractions on aquifer levels and river flows
- Canals – diversions for maintaining levels in canal systems
- Hydropower – diversions 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
- Irrigation – pumped or gravity fed abstractions for surface irrigation, spray irrigation and other uses

- Mining – abstractions for cooling, washing, conveyance, and other purposes, possibly with return flows
- Reservoirs – minimum (compensation) flow releases required for environmental and ecological purposes and/or for water supply
- Thermoelectric Power Stations – abstractions for cooling water, and sometimes also return flows (for direct cooling systems), which may be limited by water temperature considerations
- Waste Water Treatment Works – discharges of treated effluent, often limited by river water quality requirements
- Water Supply – pumped or gravity fed abstractions to water treatment works and storage reservoirs

The influences of non-consumptive uses on flows may also need to be considered such as for navigation or run-of-river hydropower schemes. For the benefit of users further downstream, or ecological and other reasons, abstractions may also be subject to the requirement not to allow river levels or flows to drop below a specified value, variously called the residual, prescribed or hands-off flow.

Usually, real-time information is only available for the largest flows, such as discharges from major waste water treatment works, or abstractions to power stations or water treatment works. Approximations may therefore need to be made for smaller abstractions and discharges, assuming typical seasonal profiles, or values linked to current river levels or flows. Estimates also need to take account of any abstraction licences or discharge consents which the operator has agreed to respect in day to day operations. For example, for some types of abstraction, it may be possible to assume a value which is constant, or proportional to river levels, provided that river flows remain above a threshold, then to assume that abstractions would stop once flows drop below that threshold. Typical uptake factors may also need to be assumed, since users may not necessarily abstract the full amount to which they are entitled, or may take that amount, but only at certain times of the day or year. Return flows may also need to be considered in some applications.

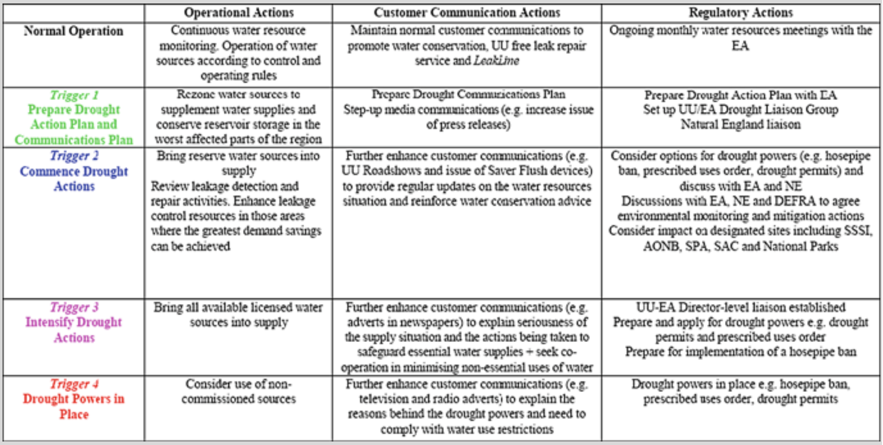
As indicated in some of the examples above, probabilistic and ensemble forecasting techniques are also increasingly used in drought forecasting applications, using ensembles generated by Numerical Weather Prediction models (see Chapter 3) and stochastic or other sampling techniques. For example, as described in Chapter 4, the Ensemble Streamflow Prediction approach used by the National Weather Service in the USA provides forecasts several months ahead which are derived by sampling historical rainfall and air temperature records, sometimes taking account of medium- to long-range meteorological forecasts in the sampling procedure, and using the resulting ensembles as inputs to catchment models. Each model run uses the current state variables for soil moisture and snow cover as a starting point. Outputs available to forecasters to indicate low flow conditions include non-exceedance histogram and probability plots (e.g. Mullusky et al. 2003). As in flood forecasting research (see Chapter 7), some active areas of investigation for drought and water resources forecasting include the use of grid-based distributed hydrological models, multi-model ensemble approaches, data assimilation techniques, and techniques for combining model outputs (e.g. Wood and Lettenmaier 2006). Chapter 9 also provides some additional examples of forecasting approaches to assist with the management of reservoir systems.

Box 8.2 Drought Management, North West England

The North West of England experiences a temperate climate, with the highest monthly rainfall typically between the months of September and March, although with significant rainfall throughout the year. The region covers an area of 14,000 km^2 and extends from Crewe in the south, to the Lake District and the Scottish border in the north, incorporating major towns and cities including Liverpool, Manchester, Bolton, Lancaster, Preston, Penrith and Carlisle. Water supply is managed primarily by a single water company (United Utilities), which owns and operates 152 water supply reservoirs, 59 river and stream intakes, 5 lake abstractions, and 170 groundwater sources (boreholes, springs, mine and adit sources) (United Utilities 2008). Some 65% of the supply is obtained from upland reservoir sources, 25% from river intakes, and 10% from groundwater sources.

United Utilities' Drought Plan is reviewed every three years in line with the statutory requirements set out in the Water Act 2003, including the need for public consultation. The Drought Plan builds upon the experience gained from maintaining essential water supplies during the 1995/1996 drought and the more recent drought of 2003 (United Utilities 2008). The plan specifies the procedures for identifying the onset of drought, communications with the media, the public and other organisations, and actions to be taken, such as measures to reduce water demand (e.g. leak repairs, hosepipe bans) and to increase water supply, such as increasing borehole production, transfer of water around the region, and reducing releases from reservoirs under drought permit powers. The plan also specifies a priority order for environmental studies which are required in support of applications for drought permits, and United Utilities plans to complete initial environmental studies for all potential drought permit sites. To maintain water quality, sources of supply may also be changed; for example, from reservoir to groundwater sources.

Four triggers for drought actions are identified in the plan which, following discussions with the Environment Agency and other organisations, may initiate a range of operational, communication and regulatory actions at regional, resource zone or local level, as appropriate (Fig. 8.3).



	Operational Actions	**Customer Communication Actions**	**Regulatory Actions**
Normal Operation	Continuous water resource monitoring. Operation of water sources according to control and operating rules	Maintain normal customer communications to promote water conservation, UU free leak repair service and *LeakLine*	Ongoing monthly water resources meetings with the EA
Trigger 1 **Prepare Drought Action Plan and Communications Plan**	Rezone water sources to supplement water supplies and conserve reservoir storage in the worst affected parts of the region	Prepare Drought Communications Plan Step-up media communications (e.g. increase issue of press releases)	Prepare Drought Action Plan with EA Set up UU/EA Drought Liaison Group Natural England liaison
Trigger 2 **Commence Drought Actions**	Bring reserve water sources into supply Review leakage detection and repair activities. Enhance leakage control resources in those areas where the greatest demand savings can be achieved	Further enhance customer communications (e.g. UU Roadshows and issue of Saver Flush devices) to provide regular updates on the water resources situation and reinforce water conservation advice	Consider options for drought powers (e.g. hosepipe ban, prescribed uses order, drought permits) and discuss with EA and NE Discussions with EA, NE and DEFRA to agree environmental monitoring and mitigation actions Consider impact on designated sites including SSSI, AONB, SPA, SAC and National Parks
Trigger 3 **Intensify Drought Actions**	Bring all available licensed water sources into supply	Further enhance customer communications (e.g. adverts in newspapers) to explain seriousness of the supply situation and the actions being taken to safeguard essential water supplies + seek co-operation in minimising non-essential uses of water	UU-EA Director-level liaison established Prepare and apply for drought powers e.g. drought permits and prescribed uses order Prepare for implementation of a hosepipe ban
Trigger 4 **Drought Powers in Place**	Consider use of non-commissioned sources	Further enhance customer communications (e.g. television and radio adverts) to explain the reasons behind the drought powers and need to comply with water use restrictions	Drought powers in place e.g. hosepipe ban, prescribed uses order, drought permits

Fig. 8.3 UU Generic Drought Triggers and Associated Actions (United Utilities 2008)

Drought Permits are dealt with by the Environment Agency whereas Drought Orders are dealt with by the Secretary of State. The legislation covering drought permits and ordinary drought orders requires that the Environment Agency and Secretary of State respectively must be satisfied that a serious deficiency of water supplies exists or is threatened because of an exceptional shortage of rain. In exceptional circumstances, an emergency drought order may be requested, in which case the Secretary of State also needs to be satisfied that the deficiency will impair the economic/social well-being of persons in the area. The legislation governing hosepipe bans was first drafted in 1945, and states that, in order to prohibit or restrict the use of water under legislation (the Water Industry Act of 1991) companies need to be '. . . of the opinion that a serious deficiency of water available for distribution by that undertaker exists or is threatened. . .'. Hosepipe bans can be enforced by a water company without recourse to the Environment Agency or the Secretary of State. The legislation covering hosepipe bans is currently being reviewed by the Government.

Droughts in the northwest of England usually develop over periods of several months of below average rainfall, with the initial impacts typically being on public water supply, followed by environmental impacts if the drought persists over many months or across seasons. In collaboration with the Environment Agency, as part of normal operations, United Utilities monitors a range of hydrological and hydrogeological variables, including reservoir levels, groundwater levels, abstraction rates, reservoir compensation flows, rainfall, river flows, and water demand. Some factors which can provide the basis for recognising drought at an early stage include (United Utilities 2008):

- A high probability of sources failing to meet demand or failing to refill sufficiently
- Storage in reservoirs below control curve levels
- Rapid weekly decline in stocks (or slow rise in stocks during winter) of key reservoirs
- Low, and declining, river flows at river sources resulting in abstraction being limited
- Significant reductions in the output from spring and groundwater sources
- Significant declines in groundwater levels as measured at key observation boreholes in major aquifers
- Magnitude and duration of peak demands significantly higher than normal for the time of year
- Rainfall significantly below average for periods of 2 months and longer

For example, Fig. 8.4 shows an example of the triggering of drought actions based on remaining net reservoir storage.

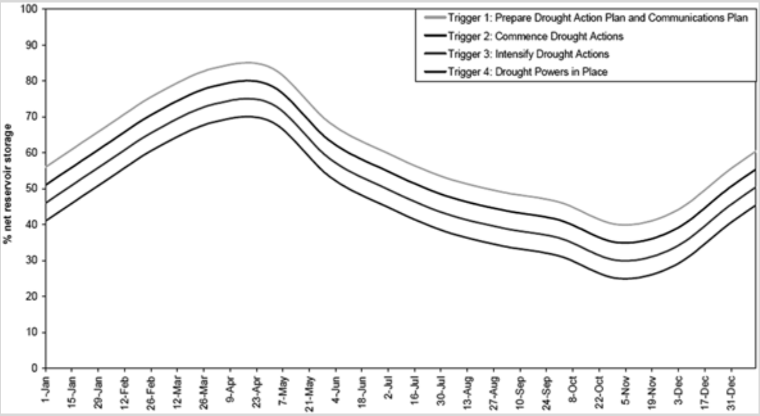


Fig. 8.4 Example drought trigger curve (United Utilities 2008)

The probability of sources failing is assessed from water resource simulation models, which include a tool called Droughwatch, which assesses reservoir storage probabilities for the next 36 months based on current levels, abstraction rates and compensation flows, and inflow series at different probabilities, based on analysis of historical data. During periods of reducing flows, river recession curves are also used to forecast future flows.

These and other models are operated year-round to assess the security of supplies, and in developing regular Production Plans which indicate the required abstractions from each water source, production from water treatment works, and transfers of treated water to meet the forecast demand. Weekly situation reports are also provided to the Environment Agency (e.g. Fig. 8.5) and joint meetings are held monthly to assess current conditions, with a Drought Liaison Group meeting more frequently once drought triggers are passed.

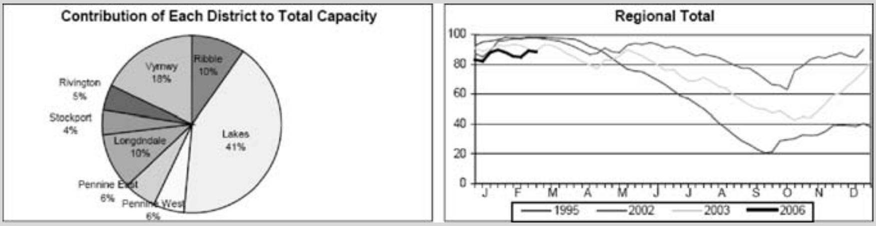


Fig. 8.5 Example of reservoir storage (stocks) as a percentage of maximum values from a weekly Hydrofax drought report (Environment Agency 2006, Copyright © Environment Agency 2009 all rights reserved)

8.3.2 Agricultural Drought

Agricultural droughts typically arise from shortfalls in precipitation, reducing the amount of soil moisture available to crops and pasture and – where irrigation is used – may be exacerbated by the effects of hydrological drought, such as reductions in the amount of water available from rivers, reservoirs and groundwater sources. Increases in air temperature, wind speed and solar radiation, and changes in humidity, may also affect crop growth, crop condition (e.g. diseases, pests), and water demand. The impacts of drought conditions can depend on the types of crop, the timing of water shortages relative to the crop growing season and growth cycle, the soil type and water holding capacity, the drought resistance of individual crops, and other factors, such as temporary restrictions on water supply to protect other water users.

Some responses to forecasts of potential drought can include identifying supplementary sources of irrigation, changes in the use of fungicides and pesticides, use of crop protection and soil water conservation measures (e.g. weeding, mulching), deciding to plant more drought resistant crops, and changing sowing/planting and harvest dates and the mixture/spacing of crops. At a regional or national scale, other measures can include the rationing, stockpiling and importing of food (e.g. UN/ISDR 2007, World Meteorological Organisation 2009). The lead times required for these decisions can vary from short–term and intraseasonal, for tactical decisions such as when to plant crops, and to apply fertilizer and pesticides, through to seasonal and inter-annual decisions on crop type and sequence, and longer-term strategic financial and production decision making (e.g. Meinke and Stone 2005).

One widely used approach for forecasting the impacts of drought on crops is to use ground-based surveys of current crop conditions combined with trend and/or multiple regression analyses to link crop yield or development to selected climatic and other indicators and forecasts (e.g. Boken et al. 2005, Funk and Brown 2006). Some examples of the types of information required from surveys can include estimates for plant growth, leaf area index, soil moisture profile, and crop rooting depth. River flow and supply-demand forecasts, of the type described in the previous section, can also provide estimates of the likely availability of water for irrigation schemes, and of the impacts of abstractions on water users further downstream.

Crop simulation models of the types described in Chapter 5 are also increasingly used. Models can be operated at a range of scales, from field scale through to catchment, regional or national level, with different types of model, model parameter values, and data and forecast inputs appropriate at each scale. One key issue is often the requirement to downscale meteorological forecasts to the scales required by farmers and other decision makers (see Chapter 3), with another being the interpretation of probabilistic forecasts at longer timescales (e.g. Stone and Meinke 2005, Hansen et al. 2006).

Decision support services of this type are increasingly offered to farmers by agrometeorological services, research organisations and the private sector for a range of weather related hazards, including web-based services (see Chapter 6 also). Although the focus tends to be on large-scale mechanised production and high value crops, there is increasing research into the use of seasonal forecasts for smallholder farmers (Sivakumar 2006).

Increasingly, a risk-based approach or framework is also being adopted for assessing the risks to production, and to take advantage of opportunities to increase production in average to good years, and take precautionary measures in drier years (e.g. Laughlin and Clark 2000, World Meteorological Organisation 2009). This is only possible, of course, if the forecasts are credible, and appropriate methods are in place for the dissemination and uptake of forecasts to potential users (Vogel and O'Brien 2006).

At a national or regional scale, remote sensing of crop development is also widely used (area planted, condition etc), sometimes combined with estimates for soil moisture, evapotranspiration and irrigated and waterlogged/flooded areas (see Chapter 2). Some typical approaches to monitoring crop areas and condition include the Normalised Difference Vegetation Index (NDVI), based on the difference in reflectance in the infrared and near infrared channels, and Leaf Area Index (LAI).

In Europe, for example, the MARS (Monitoring Agricultural ResourceS) programme of the Joint Research Centre in Europe provides crop yield forecasts at a European scale and internationally (http://mars.jrc.it/). Regular bulletins are issued 6–8 times per year providing an agrometeorological overview (temperature, evapotranspiration, rainfall, climatic water balance), map-based summaries (e.g. Fig. 8.6), and anticipated crop yields and analyses at a country or regional level. Special bulletins are also issued for different locations and situations, 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 generic crop simulation models, with statistical post-processing of model outputs.

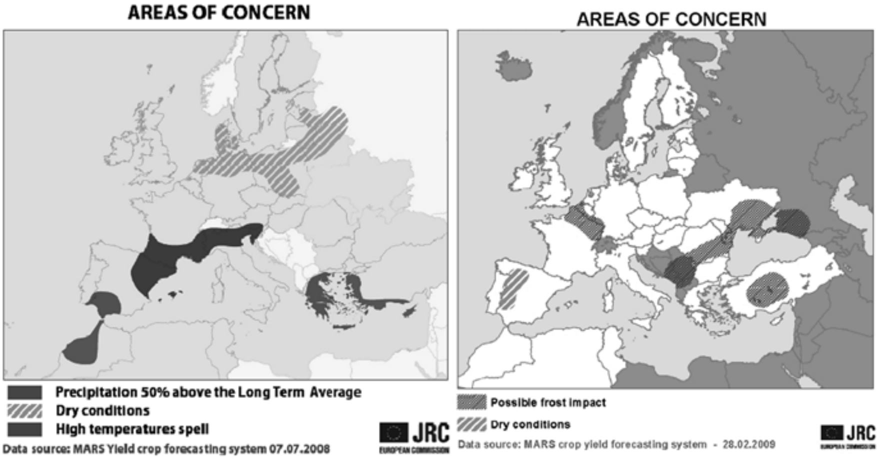


Fig. 8.6 Examples of Areas of Concern Maps from MARS Agrometeorological Crop Monitoring in Europe Bulletins for 1–30 June 2008 (*left*) and 21 November 2008–28 February 2009 (*right*) (© European Communities 2008, © European Communities 2009; http://mars.jrc.it)

Two other examples of operational agrometeorological forecasting systems at a national or international scale include:

- China Crop Watch System (CCWS), which monitors crop growing condition, crop production, drought, crop plantation structure and cropping index using a combination of ground-based surveys 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 throughout the year providing information on crop conditions throughout China and a number of other countries (http://www.cropwatch.com.cn/en/index.html)
- The National Agricultural Monitoring System in Australia, which provides information on historical, current and emerging climatic and agricultural conditions across Australia (http://www.nams.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 information on the current availability of irrigation water, and on market feed prices.

Drought forecasting techniques are usually also a key component of famine early warning systems, often with a focus on meteorological drought, since many subsistence economies rely mainly on rainfed agriculture. Systems of this type typically include satellite monitoring of rainfall and vegetation cover, use of short- to medium-range and seasonal Quantitative Precipitation Forecasts from meteorological services, and monitoring of a wide range of indicators from surveys and routine reports in the region likely to be affected. Indicators can include crop yields, food and livestock prices, the incidence of health-related and nutritional problems, and other local factors which may increase risk, such as war and border closures (e.g. UN/ISDR 2007, Brown 2008). Crop simulation and water supply-demand models are also sometimes used to better assess the likely impacts at a more local scale. Some notable examples of famine early warning systems include:

- FEWS NET – which operates in Africa, Central America, Haiti and Afghanistan (see Box 8.3)
- GIEWS – The Global Information and Early Warning System on Food and Agriculture, which is operated by the United Nations Food and Agriculture Organization, and which 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)

Projects such as the WMO Global Earth Observation System of Systems (GEOSS) are also seeking to harmonize and combine information from different national and international systems through adoption of common definitions, the generation and verification of products, and approaches to data processing and sharing; for example, the Agricultural Component of GEOSS calls for an operational system for monitoring global agriculture that includes the following three main functional components (Justice and Becker-Reshef 2007):

- Global mapping and monitoring of changes in distribution of cropland area and the associated cropping systems
- Global monitoring of agricultural production leading to accurate and timely reporting of national agricultural statistics and accurate forecasting of shortfalls in crop production and food supply and facilitating reduction of risk and increased productivity at a range of scales
- Effective early warning of famine, enabling the timely mobilization of an international response in food aid

Box 8.3 FEWS NET Famine Early Warning System

The Famine Early Warning System (http://www.fews.net) was established in 1986, partly in response to the severe drought which affected West Africa in 1984 and 1985. 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). Funding is provided by the United States Agency for International Development (USAID) and a range of regional and national organisations. The focus of FEWS NET is primarily on Africa, but also extends to Central America, Haiti, and Afghanistan.

Forecasts and early warnings are issued from a network of regional and national field offices in more than 30 countries 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

Some key products from FEWS NET include monthly food security updates, executive alert briefs and 1 page alert statements, with alert levels of No Alert, Watch, Warning and Emergency. 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 also made on topics such as livelihoods and markets to provide additional information to support the analyses as well as program 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 8.6), 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 8.6 Description of a few main rural livelihoods (adapted from FEWS NET livelihood profiles) (Brown 2008)

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

Historically, the main type of remotely sensed information used by FEWS NET has been vegetation data derived from NOAA polar-orbiting environmental satellites (TIROS-N, NOAA-N series) carrying the Advanced Very High Resolution Radiometer (AVHRR). The version of AVHRR launched in 2005 has 6 channels with sensors in the visible, near-infrared and thermal infrared bands, with typical uses including daytime cloud and surface mapping, detection of land-water boundaries, snow and ice detection, night cloud mapping and estimation of sea surface temperatures (http://www.noaa.gov). More recently, other sources of information which have been incorporated into FEWS NET include high resolution vegetation data from the 36-channel Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on NASA's Terra (EOS AM) and Aqua (EOS PM) satellites, and the VEGETATION products derived from the European SPOT series of satellites (Verdin et al. 2005, Brown 2008).

Since 2001, the NOAA Climate Prediction Center Rainfall Estimation (RFE 2.0) outputs have also been used (see Chapter 2), which provide daily estimates of rainfall at a grid scale of approximately 10 km based on raingauge data obtained from the WMO Global Telecommunication System, 6-hourly microwave precipitation estimates from two polar orbiting satellite systems, and half-hourly GOES Precipitation Index (GPI) rainfall amounts derived from geostationary satellite observations. Typically, for Africa, recent rainfall values are available for up to 1000 raingauge stations on any one day (NOAA 2009). The RFE algorithm combines satellite data from different sources using a maximum likelihood estimation method, and then the raingauge data are used to remove bias. Products include daily, 10-day and monthly values relative to 10-year means, and cumulative totals and anomalies for seasonal values.

The rainfall estimates, together with Penman Monteith estimates for actual evapotranspiration, are also 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).

Forecasts for future rainfall over the next 7 days are also obtained from the Numerical Weather Prediction model outputs from the NCEP Global Forecast System (GFS). Longer-range forecasts (to several months ahead) are derived using a technique called Canonical Correlation Analysis, which relates the probability of above, near or below average rainfall to variations in sea surface temperatures (Barnett and Preisendorfer 1987, Barnston et al. 1996). Seasonal forecasts are also used from a number of other organisations, together with Monte Carlo resampling techniques for post-processing of the regional seasonal forecasts from the Regional Climate Outlook Forums in Africa (Husak 2005, in Brown 2008). Forecasts for rainfall and NDVI projections (Normalised Difference Vegetation Index) are also combined with other information (for example, on food prices, commodity trading, crop production, health and nutrition, water and sanitation) to provide a Food Security Outlook for the next six months ahead.

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Chapter 9
Flow Control

Abstract The runoff response of a catchment is often modified by the influence of river control structures, reservoirs and other factors, such as urban drainage systems. In hydrometeorological forecasting applications, these artificial influences can cause flows to be delayed, attenuated, and otherwise modified from the natural response. The extent to which these effects need to be considered varies with the application; for example, in flood forecasting applications, the flow releases from a reservoir for ecological purposes might be relatively insignificant, although would probably be relevant in a drought forecasting application. The influence also varies with scale so that, for example, urban influences might sometimes be relatively minor at a catchment scale, but important at a local level in terms of the impacts on river flows and water quality. This chapter discusses a range of techniques for forecasting the impacts of flow control structures on river flows, under the main headings of river structures, reservoirs, and urban drainage. In many cases, the operating strategy will be governed by a set of control rules, based either on off-line studies, or optimised in real-time, and sometimes implemented using a decision support system. A brief introduction is also provided to decision support and real-time control systems of this type.

Keywords River structure · Tidal barrier · Reservoir · Urban drainage · Decision support · Flow control · Real-time control · Artificial influences

9.1 River Structures

Many rivers contain structures which can influence flows and levels, particularly in or near to urban areas. Examples include weirs, sluices, tilting gates, radial gates, flap gates, canal gates, siphons and tidal barriers. Several examples are shown in Fig. 9.1, and some typical applications include (e.g. Chanson 2004, Chow 1959, Novak et al. 2006):

K. Sene, *Hydrometeorology*, DOI 10.1007/978-90-481-3403-8_9,

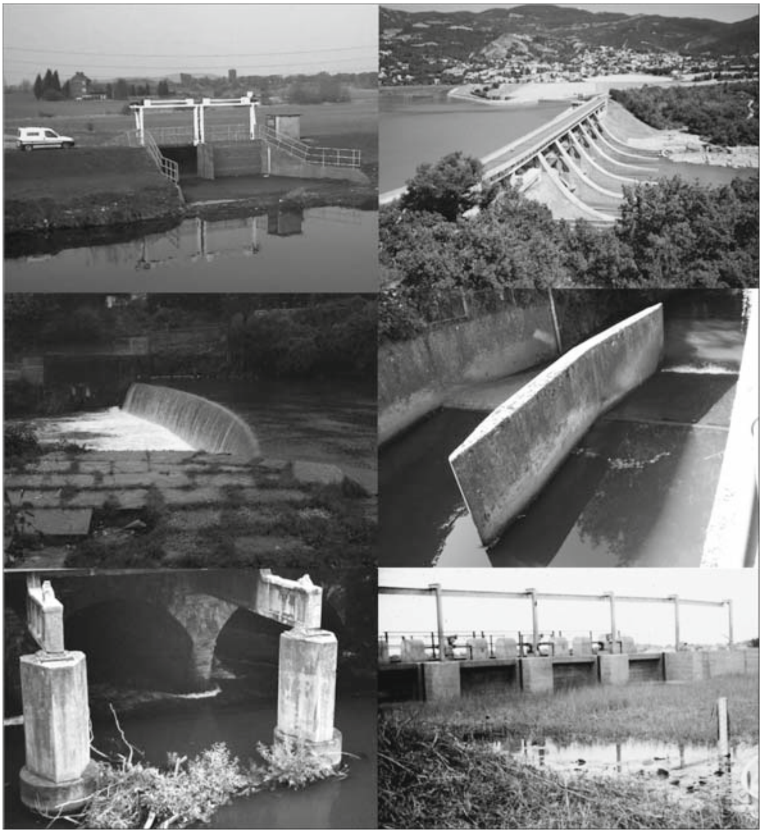


Fig. 9.1 Illustration of some types of river structures, clockwise from *top left* (**a**) sluice gates at off-line storage area (England) (**b**) hydropower scheme (France) (**c**) compound Crump Weir gauging structure (England) (**d**) irrigation canal sluice gates (Somalia) (**e**) arched culverts (England) (**f**) weir (Wales). Credits: (**a**) Sene (2008); (**c**) Copyright © Environment Agency 2009, all rights reserved

- Raising upstream water levels to allow flows to be abstracted for irrigation, or diverted for other purposes, such as to canal systems
- Control of river levels and/or flows and/or velocities for navigation, recreation, environmental or ecological purposes
- Protecting upstream areas from tidal flooding and/or downstream areas from river flooding
- Run of river hydropower generation, and tidal barriers with a generating capacity (see Chapter 5)
- Flow transfer using pipes, canals and aqueducts etc to reduce flood risk downstream or augment flows in another river
- Monitoring river levels and flows, including weirs, flumes, and other configurations (see Chapter 2)

Some structures may also be actively controlled, with approaches including manual operations by staff on site, automated operations based solely on local monitoring of levels or flows, and remote operation based on commands sent over a telemetry system, typically taking account of catchment-wide flows. Under high flow conditions, additional effects may also arise from structures which are normally above water levels, such as bridge decks, culvert inverts, and pipeline crossings. Also, flood defences (levees or dikes) and natural embankments may be overtopped, resulting in a reduction in levels, or a 'flat-top' to river level hydrographs further downstream.

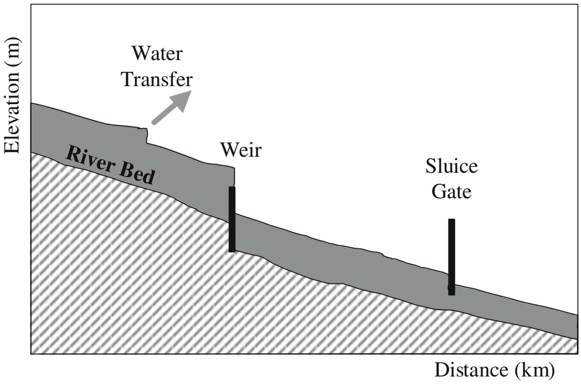
As discussed in Chapter 4, in river flow forecasting applications, the impacts from flow control structures can vary widely, particularly for controlled structures. However, Table 9.1 summarises some typical characteristics for a selection of types of structure and Fig. 9.2 shows schematically some examples of how these can influence the water level profile of a river reach.

Table 9.1 Examples of the impacts of river control structures on river levels when in operation

Structure	Upstream influences	Downstream influences
Irrigation offtake	Usually only minor local influences	Increases and decreases in levels linked to abstractions for irrigation, which are linked to levels if gravity fed, or to pumping operations if pumped. Sometimes leads to the appearance of quasi-sinusoidal variations in levels
Sluice	Raised levels upstream and reduced flow velocities locally	Reduced levels downstream and increased flow velocities locally
Tidal Barrier Tidal Flap Gate	Levels increase during high tide periods, then decrease as flows are released at low tides	Not applicable; note that a typical tidal cycle is a twice daily peak, with monthly and annual maximum ranges
Transfer pipe, canal or aqueduct	Usually no significant influence except locally on levels	Reductions in levels and flows further downstream, often linked to river levels if gravity fed, or pumping operations if pumped
Weir	Raised levels upstream; ponding at very low flows (compared to the situation before the weir was constructed)	Lowered levels downstream although some weirs can 'drown' at high flows due to 'non-modular' flows

The need to include structures in a forecasting model depends on the application, and in some cases the influence can be neglected, or represented approximately. If the impacts need to be represented in terms of flows alone, then simple water balance or hydrological flow routing approaches can often represent the changes in flow which may occur; for example, as water is abstracted for irrigation. However, hydrodynamic models are often required for a more detailed investigation of the changes in river flows and depths, and these influences can sometimes be important in a range of applications; for example, in forecasting effects such as:

Fig. 9.2 Illustration of the influence of structures on the long profile for a river reach (note the exaggerated vertical scale typical of many diagrams of this type)



- The risk of flooding to properties immediately upstream of a river flow control structure, and further downstream
- Whether river levels will be high enough to allow water to be abstracted at a gravity fed or pumped off-take for irrigation, water transfer or flood relief
- The levels reached in environmentally sensitive areas such as wetlands and marshes due to the automatic and manual operation of structures
- The variations in river levels over each tidal cycle upstream of a tidal barrier or flap gate, and possible influences on flooding
- The influence of structures on the dilution and concentration of thermal plumes and contaminants within a river, including saline intrusion from tidal waters (if relevant)
- Ecological applications such as modeling the spread of harmful algal blooms, and impacts on fish and other species

Modelling may be performed off-line, to develop charts or look up tables to assist with real-time decision making or, as discussed in Chapter 4, performed in real-time. Some software packages also include modelling components for water quality, sediment transport and ecological applications.

For controllable structures, various techniques can be used to guide operations. Where the risks and/or investment are small, structures are often operated using simple control rules based on charts or look up tables linked to observed levels, or possibly even to the time of day or tide tables (e.g. for tidally influenced rivers). Where the risks are higher, then a decision support system may be justified to either guide operators on the most appropriate strategy, or to automatically control the structure according to the current and/or forecast conditions. Systems of this type may also incorporate a real-time hydrodynamic modeling component including logical rules linked to observed or forecast river levels or other parameters; for example, to lift a sluice gate by 0.2 m, or to rotate a radial gate by 10°, above a certain river level, and then to repeat those operations at the next critical level (or combination of levels), and so on. Where (as is often the case) real-time values are not available for structure operations, or are less extensive than ideally required, then considerable investigation may be required to decide how best to parameterize the control rules, particularly for manually operated structures, since operators often depart from the design rules for a range of reasons, which can include practical, technical, political and other factors.

Tidal barriers can present a particular challenge for real-time control, since both coastal and river conditions need to be considered. In deciding how best to operate a barrier, some considerations include the time required before high tide to close the barrier, the river flows which will be accumulated whilst the barrier is closed, and backup procedures if there is a problem with gate operations, or conditions suddenly change. To obtain additional lead time, river and/or coastal forecasting model outputs may also be used in the decision making process. Box 9.1 describes examples for three systems of this type: the Maeslant Barrier in the Netherlands, the Thames Barrier in England, and Cardiff Bay Barrage in Wales. Other systems include those for the Venice Tidal Barrier scheme in Italy, and the St Petersburg Flood Protection Barrier project in Russia. Chapter 6 also includes some further discussion of the Maeslant Barrier, and of decision support systems in general.

Box 9.1 Tidal Barriers

Tidal barriers typically provide protection from the sea to inland areas, and may also be used for other purposes, such as hydropower generation. When used to protect major cities, a high standard of reliability is required, with detailed investigations of performance based on historical data and hydrodynamic modeling. If forecasts are used in the decision making process, then the likely accuracy at the relevant lead times also needs to be factored into the decision making process.

The operating rules and procedures which are used depend on a range of factors, including the time needed to operate the barrier, the impacts (if any) of closing the barrier, and the volume of river water likely to accumulate whilst the gates are closed. Some examples of impacts can include interruptions to shipping, raised water levels upstream of the barrier causing minor flooding, possible environmental and ecological considerations, and other factors. The costs of operation may also need to be considered, both in terms of each individual operation (e.g. staff costs, power), and the impact on the long-term maintenance of the structure.

Some examples of major barrier schemes include the Maeslant Barrier in the Netherlands, the Thames Barrier in England, and Cardiff Bay Barrage in Wales. The Maeslant Barrier was constructed between 1991 and 1997 in a 360 metre wide section of the New Waterway ship canal to Rotterdam Harbour.

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, which are normally stored in dry docks on the river banks, and which are moved into the river when the barrier is required. In the closed position, the gates are filled with water and sink to the river bed, and this water is then pumped out again before the gates are moved back to the open position (Fig. 9.3).

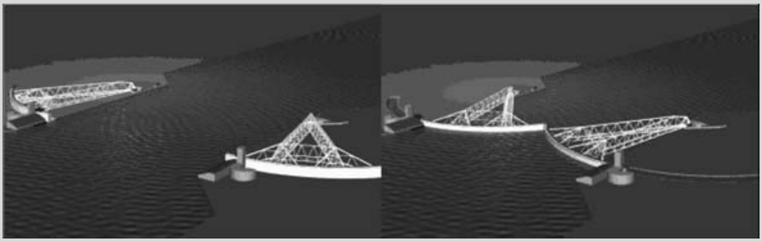


Fig. 9.3 Illustration of the Maeslant Barrier gates in the open and closed positions (Rijkswaterstaat, part of the Dutch Ministry of Transport and Public Works http://www.keringhuis.nl/)

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 one-dimensional 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 Chapter 6 (Tretmans et al. 2001).

The Thames barrier was constructed between 1974 and 1982 to protect London from coastal flooding. Control is provided by six rising sector gates, and four simple radial gates, and the rising sector gates lie in sills flat against the river bed when not in use (Horner 1985). 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 modeling 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. 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 constructed to create a freshwater lake as a focus for urban renewal, and for flood control, and is approximately 1,100 metres 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 modeling. 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 an extensive network of sensors on the upstream and downstream sides of the barrage.

9.2 Reservoirs

Reservoirs are an important component in many water supply, irrigation and hydropower schemes, and can also influence river flows at a catchment scale, particularly when (as is often the case) there are multiple reservoirs, operated as a system. The main types of reservoir are:

- In-stream, on-stream or in-line reservoirs, formed at a dam or other barrier placed across a river (or sometimes at the location of a naturally occurring lake outfall)
- Off-stream or off-line storage areas, which are typically used for flood mitigation for areas further downstream, and are sometimes called washlands, retarding basins or polders (although note that a polder is normally considered to be a protected area of land, defended from rivers or the sea by embankments)

For in-line reservoirs, various approaches may be used to discharging flood flows, including overflow, tunnel or bellmouth spillways, as illustrated in Figs. 9.4 and 9.6.

More generally, reservoirs can be regulated, with flows controlled using gates, sluices and other structures, or unregulated, so that flows occur automatically as key water levels are exceeded; for example, water spilling over a spillway, or self-priming siphons flowing for emergency flood releases. Figure 9.5 illustrates the types of changes which can occur to river inflows when routed through an in-line reservoir with a spillway, or removed above a certain threshold level at an offtake to an off-line reservoir. For the in-line reservoir, spillway flows do not start until reservoir levels exceed the spillway crest level, and so are delayed and attenuated compared to the inflows whilst, for the off-line reservoir, the peak of the hydrograph is diverted into storage. Note that, for an in-line reservoir, the timing and magnitude of the downstream flows is often strongly influenced by the initial reservoir level at the start of the event; also, many in-line reservoirs will have a small regulated outflow component, although this is not considered here.

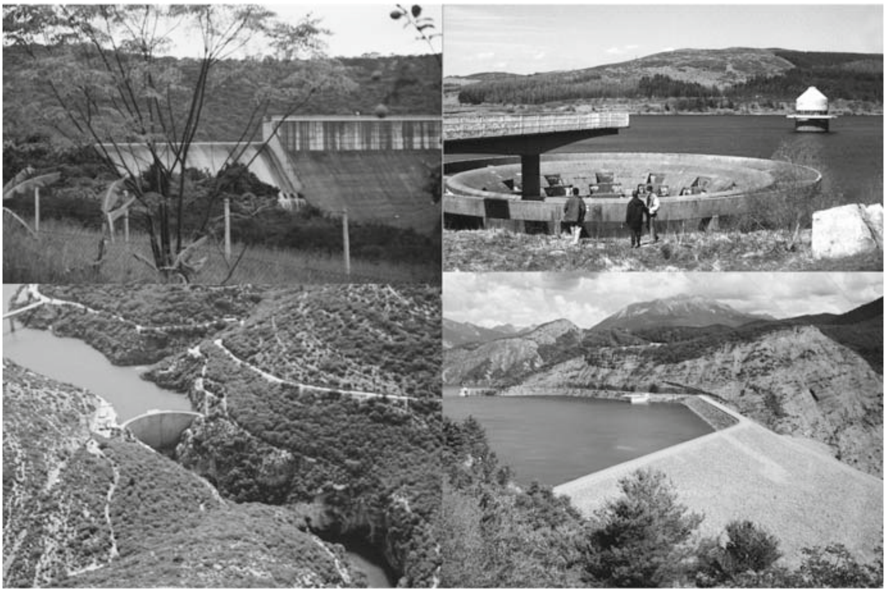


Fig. 9.4 Illustration of different types of dam and spillway. From *top left* clockwise (**a**) gravity dam with overflow spillway (**b**) bellmouth spillway (**c**) earth-fill dam with side tunnel inlets for hydropower generation and flood-relief and (**d**) arch dam (Photographs (**a**) and (**b**) from Sene 2008)

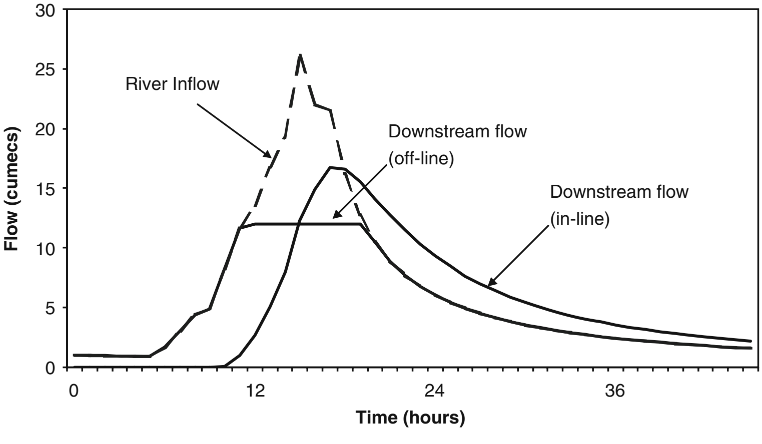


Fig. 9.5 Illustration of the impacts of an in-line and off-stream reservoir on river flows

As for river flow control structures, reservoirs are often operated according to control rules or rule curves, which are sometimes called steering rules. These may be based on the experience gained from historical operations and/or from simulation modeling or linear or dynamic programming, based on analyses of long term time series of historical river flow and other data. Typically, the more detailed types of analysis seek to find an optimum control strategy considering operating costs and system constraints, and the required levels of service and reliability.

Control rules usually define operating zones based on reservoir volumes or depths, which can vary throughout the year as inflows and demands change, and may also be used for initiating a drought or flood response. For example, Box 8.2 in Chapter 8 shows a set of curves for the triggering of drought actions based on remaining net reservoir storage. Typically, operating zones are defined for spills, unrestricted releases, releases restricted to the design yield, and dead or inactive storage. Provision may also be made for departing from the long-term policy to respond to emergency situations, such as droughts or flood events. For example, if a reservoir is required to provide flood storage to mitigate flooding further downstream and/or to reduce the risk of overtopping, then the rules would specify the flood buffer which needs to be maintained at given times during the flood season. Alternatively, a more dynamic approach can be used, taking account of current reservoir volumes and river flows, and forecast inflows, and the uncertainty in these values. Many studies have shown that this should in principle allow for more efficient operation of the system by being more adaptable to event-specific factors (e.g. Yeh 1985, Lobbrecht et al. 2005, Todini 2005, Georgakakos et al. 2007).

At a catchment scale, the extent to which reservoir influences are included in a flow forecasting model will depend on the influences on the natural flow regime, and the application. For example, for a flood forecasting application, in some cases the influence may be relatively small compared to typical flood flows at the forecasting points of interest, and can be neglected. However, if an in-line reservoir might overtop, or breach, or has siphons, or has a significant influence on downstream flows, then representation of these effects could be important. Similarly, off-line storage areas can sometimes have major influences on flows further downstream. The importance of reservoir influences is best determined from long term records of reservoir inflows, releases, outflows, and river flows, if these are available, combined with hydrological analyses to assess the magnitude of flows and storage volumes under the conditions of interest. For water resources forecasting, such as during droughts, a more detailed model may be required, and factors which may need to be represented include the evaporation from the reservoir surface, transfers between reservoirs (e.g. by pipes, canals, or by regulation of river flows), and abstractions directly from each reservoir (e.g. for water supply or irrigation).

Often, there is also 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, irrigation, recreational, environmental and hydropower requirements at key times of the year. The longer term operating plan then provides overall constraints on short- to medium-term operations, such as minimum allowed reservoir levels. For large reservoirs, or multiple reservoir systems, the reservoir capacity may be of comparable magnitude to, or greater than, mean annual runoff volumes, so strategic objectives may extend over periods of years, rather than months. This is particularly the case in arid and semi-arid regions, where a large reservoir capacity is needed to compensate for interannual variations in rainfall and inflows, and high evaporation losses.

For reservoir forecasting at short time scales, up to a few days ahead, integrated catchment models of the type described in Chapters 4, 7, 8 and 11 are widely used. Typically, these combine rainfall-runoff, flow routing and reservoir models, and may include snowmelt models, where this is relevant (see Boxes 1.2, 7.3, 9.2 and 11.3 for example). For the reservoir component, water balance or hydrological flow routing approaches are typically used, with a real-time hydrodynamic component for higher risk applications, or where the outflows are particularly sensitive to reservoir levels. Rainfall inputs may be obtained from raingauges or weather radar or satellite observations, and forecasts from Numerical Weather Prediction model outputs and nowcasts, with appropriate downscaling if required (see Chapter 3). Some major sources of uncertainty can include the actual releases at the reservoir, particularly if these are controlled manually, and the initial starting level for each reservoir, which can have a major influence on subsequent forecasts for outflows. Ideally telemetered values would be available for each of these parameters, although are often not available, and real-time updating (data-assimilation) would be used for reservoir levels and other parameters. For many reservoirs, the inflow term is also another source of uncertainty, and often may not be monitored in real-time, requiring the use of ungauged catchment runoff estimation techniques. As with river control structures, it is quite common for operating rules to differ from the design values, for a range of technical, operational and other reasons.

At longer lead times, probabilistic or statistical techniques are normally used, and are also increasingly used at shorter lead times, due to the inherent uncertainties in model performance. Ensemble Streamflow Prediction techniques are perhaps the most widely used approach, based on sampling from long term historical records for rainfall and possibly air temperature, as described in Chapter 4. The resulting values are then used as inputs to rainfall-runoff models and routed through the river and reservoir system to derive probabilistic estimates for the likely range of future volumes, using current reservoir levels and catchment states as a starting point. A snowmelt component is usually also included in locations where this is relevant. Ensemble rainfall forecasts from Numerical Weather Prediction models are also used in some systems, including multi-model values, and long-range, seasonal predictions (e.g. Wood and Lettenmaier 2006; see Box 9.2 also).

At longer time scales, simpler statistical techniques are also sometimes used, relating flow volumes to factors such as cumulative precipitation, snow water equivalent, monthly flow volumes, and indices related to the El Niño-Southern Oscillation and other oceanic or atmospheric phenomena, as described in Chapter 4 and Boxes 1.2 and 11.2. Linear, non-linear or dynamic programming techniques (including stochastic versions) are also sometimes used in real-time operation; for example, for updating reservoir release plans every day, week or month (e.g. Loucks 1989, Yeh 1985, Wurbs 1992, McMahon and Adeloye 2005). 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 optimization criteria and subject to the physical constraints of the system (volumes, flow rates etc) and desired short-term and longer term control objectives. For forecasting applications, some examples of optimization criteria can include:

- Minimise opportunity losses for water supply, irrigation or hydropower generation due to reservoir spills
- Maximise the storage available for flood control based on a forecast for high reservoir inflows, and minimize flood damages further downstream
- Maximise revenue from individual or multi-purpose operations (water supply, irrigation, hydropower etc)
- Minimise costs for pumping and water treatment, and maximise yield and reliability for water supply
- Minimize fluctuations in reservoir levels and maintain reservoir levels for recreation, navigation and water abstractions
- Control outflows and water temperatures for ecological and environmental objectives relating to fisheries, in-stream ecology and other factors

Optimisation criteria are usually expressed either in financial terms, or in terms of utility or penalty functions (see Chapter 6). Models typically operate on a daily, weekly, monthly or annual timestep, depending on the time horizon of interest, with models nested at different timescales. For longer timescales, typically a simple water balance approach is used to estimate reservoir storage, and hence levels, for a given set of inflows, control rules, and other terms in the water balance. The amount of detail included and the objective function(s) used typically vary with the timestep chosen, with some factors being more relevant at different timescales. The initial estimate for the optimum approach is then sometimes fine-tuned using a more detailed simulation model; for example using a supply-demand approach at longer timescales (see Chapter 11), and perhaps an integrated catchment model at short timescales.

Given the complexities even for a single reservoir, but particularly for multi-reservoir systems, these techniques are often incorporated into a real-time decision support system. Table 9.2 presents some examples of research and operational applications of systems of this type, whilst Section 5.3 discusses some examples for hydropower operation, Section 6.2 provides some further discussion of decision support systems, and Chapter 11 discusses regional water resources systems combining reservoirs and other sources of water.

In reservoir forecasting, perhaps one of the greatest technical challenges is to provide forecasts for the locations and impacts of dam breaches. The main hydrometeorological risks which might lead to a breach are from flood waters overtopping the crest, or exceeding the spillway capacity, or from landslides into a reservoir or lake following heavy rainfall. Wave erosion can also sometimes be a factor on large reservoirs. However, such occurences are fortunately rare, and dam failures are more often due to geotechnical or structural reasons, such as earthquakes or design or construction defects (e.g. Graham 2000).

The two main aspects to forecasting a dam breach are to predict the location, timing and extent of the failure, and the inundation likely to be caused by the resulting flood wave. However, except when there is some obvious structural problem,

Table 9.2 Examples of real-time decision support systems for reservoir control (adapted from Sene 2008)

Location	Reservoir uses	Model inputs and structure	Example of optimisation problem	References
China	Reservoir flood forecasting and control system	Deterministic	Flood control	Guo et al. 2004
Ebro river basin, Spain	Multi reservoir systems (41 reservoirs)	Deterministic	Flood Control, Water Management	Garcia et al. 2005
Feitsui Reservoir, Taiwan	Water supply, hydropower	Deterministic	Flood control in typhoons	Nandalal and Bogardi 2007
Folsom Dam and Reservoir, California, USA	Flood protection to Sacramento, hydropower, water supply, recreation	Deterministic, ensemble	Flood control, emergency response, multi-objective	See Box 9.2
Lake Como, Italy	Irrigation, hydropower	Stochastic	Opportunity losses from drawdown versus flood damage downstream	Todini 2005
Lake Okeechobee, Florida	Lake regulation	Decision tree	Flood control, water supply, environmental objectives, accounting for seasonal forecasts	http://www.sfwmd.gov/
Netherlands	Polder systems	Artificial Intelligence techniques	Optimisation of water level management	Lobbrecht et al. 2005
Northern California, USA	Multi-purpose, multiple reservoir systems	Ensemble, statistical	Dynamic reservoir regulation. Multi-objective trade offs	Georgakakos et al. 2007
Paranaiba river basin, Brazil	Hydropower, flood control	Deterministic	Hydropower operation and flood control	Collischonn et al. 2007
Powell and Lois rivers, Canada	Hydropower	Ensemble, statistical	Hydropower generation	Howard 2007
Portugal	Dam Break	Decision Support	General application	Rodrigues et al. 2006
Sanaga River, Cameroon	Hydropower	Probabilistic adjusted by ITCZ forecast	Flow regulation for hydropower generation	Wyatt et al. 1992

it is difficult to predict with any certainty when and where a breach will occur, although process-based and other approaches show promise for predicting the rate of failure, once the problem has been identified (e.g. Wahl et al. 2008, Morris et al. 2008). Monitoring techniques such as laser survey equipment, piezometers and accelerometers can also provide useful information for input to models.

For the flood inundation component, similar techniques can be used as for river modelling, taking account of the much greater depths and velocities, and the need to represent flows through areas which are not normally under water. This can include the choice of an appropriate set of parameters, such as roughness coefficients, and the representation of likely flow paths. Inundation models of this type could be included in flood forecasting models, although the more usual approach is to calculate flood inundation extents off-line as part of contingency planning arrangements. Also, if time permits, modelling studies are sometimes performed on an ad-hoc basis as an event develops to identify likely areas of inundation.

Box 9.2 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 2015.

The reservoir catchment rises in the Sierra Nevada mountains and the area to the spillway is approximately 4,800 km^2 (Fig. 9.6). Snowmelt forms a significant input to the reservoir during the winter and spring months, although 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. Forecasts are based upon a network of approximately 20 raingauges and 3 river gauges, and from Quantitative Precipitation Forecasts (QPF) and forecast air temperatures provided by the CNRFC HAS (Hydrometeorological Analysis and Support) Unit with support from National Centers for Environmental Protection (NCEP) and the local National Weather Service Office (WFO) in Sacramento.

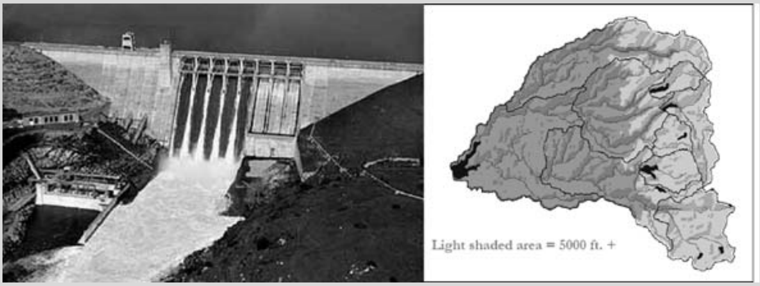


Fig. 9.6 Folsom Dam and sub-catchments used in the inflow forecasting model (Fickenscher 2005)

In the forecasting model, the reservoir catchment is represented by nine 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. 9.7). Long term (90-day ahead) ensemble forecasts are also produced twice per week by sampling historical rainfall and air temperature records using an Ensemble Streamflow Prediction approach (Day 1985).

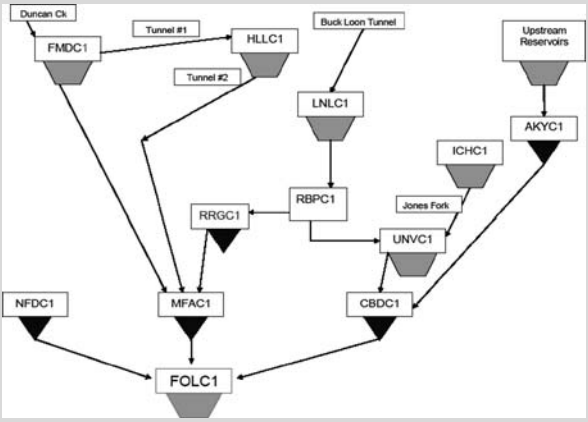


Fig. 9.7 Schematic of the ‘simplified’ watershed model (Fickenscher 2005)

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. An uncertainty mode is also available 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 the uncertainty component 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 decision making methodologies to make use of ensemble forecasts, including extending the lead time available for pre-releases for flood control (Yao and Georgakakos 2001, Carpenter et al. 2003), the development of seasonal release rules to regulate downstream temperatures for fishery habitats (Field and Lund 2006), and extension of the existing Decision Support System to more than one reservoir (i.e. for multi-reservoir operation).

9.3 Urban Drainage

Urban drainage systems typically consist of a surface network of culverts and open drains, and a subsurface network of pipes, which collect domestic and other waste water for treatment and discharge to rivers or the sea. Other components may include flood detention areas, control structures (e.g. diversion weirs), and control equipment, such as gates, pumps, and pressure relief valves. The subsurface network is usually designed to be able to be able to convey runoff from heavy rainfall events up to a certain return period or probability; for example, this value is notionally 1 in 30 years in England and Wales for open spaces (i.e. excluding properties). For more severe rainfall events, water flows across the surface, and may collect in low-lying areas, causing localized flooding.

Systems which combine waste (or foul) water and surface runoff are usually called combined sewer systems and, during high flow periods, flows which exceed the system capacity are typically discharged into the river network through Combined Sewer Overflows (CSOs). A more recent development is to use separate systems for the waste and storm runoff components so that, except in extreme conditions, all of the sewerage component is treated before being discharged. Figure 9.8 shows an illustration of these types of systems. Surface runoff, or wet weather runoff, may also be contaminated by material collected from roads, pavements and gardens, such as oil residue, pesticides, and animal waste. Also, for a combined sewer system, the discharge to rivers may be combined with untreated effluent, causing a serious pollution risk. Undertaking capital works to reduce the frequency and magnitude of CSO discharges is a major activity for many water companies and local authorities.

At a catchment scale, urban drainage usually modifies the overall response to an extent which depends on the urbanized area within the catchment. Some typical changes include enhanced runoff and a more rapid response from impermeable areas such as roads and car parks. The main discharge points from the subsurface network

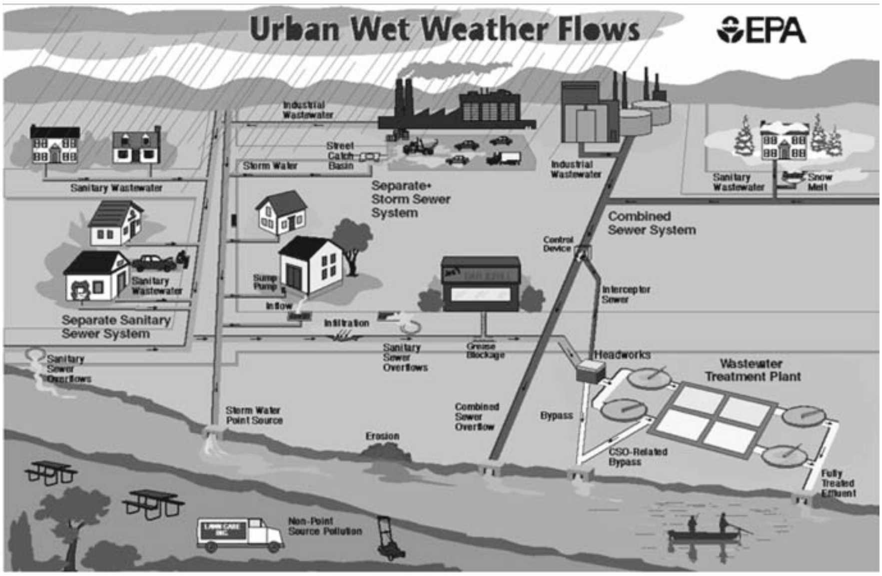


Fig. 9.8 An illustration of the three types of systems that are used for sewage and stormwater disposal (United States Environmental Protection Agency; http://www.epa.gov/reg3wapd/cso/index.htm)

may also be some distance from where water enters the systems, and can sometimes be into a river in another catchment, complicating the hydrological analysis of runoff response. Snow cover can also influence the response; for example, in cities such as Milwaukee, Chicago, Boston, and New York, the largest overflow events are created when intense rain falls upon an existing snow cover (EPA 2006).

In catchment-scale flood forecasting models, the influences of urban drainage and water supply systems are often small compared to flood flows, so are not included. However, at low to medium flows, urban influences become more significant, and are often represented in greater detail, at the level of individual abstractions for water supply, and discharges of treated effluent, using typical daily and seasonal profiles, or real-time data from telemetry. Chapter 5 discusses techniques for demand forecasting, whilst Chapters 4, 8 and 11 discuss techniques for real-time forecasting at this level of detail. Chapter 10 also discusses forecasting techniques for bathing water quality pollution incidents, which are often caused by CSO discharges, whilst Chapter 11 discusses a range of supply-demand techniques for longer term forecasting of catchment response.

Forecasting techniques are also increasingly used at the scale of the urban area covered by the drainage system, with applications including the scheduling of operations at water treatment works, real-time flow control, and providing early warning of urban flooding incidents. Table 9.3 summarises some examples of operational systems of this type.

Table 9.3 Some examples of operational flood forecasting and real time control systems in urban drainage networks (adapted from Sene 2008)

Location	Key features	References
Haute-Sûre Reservoir, Luxembourg	Raingauge and radar inputs to sewer model	Henry et al. 2005
Quebec urban community RTC, Canada	Multi-objective optimisation to minimise overflows, maximise treatment plant use, minimise accumulated volumes etc	Schütze et al. 2004
Brays Bayou, Houston, USA	Weather radar inputs to a fine mesh distributed physically-based rainfall runoff model	Vieux et al. 2005

The forecasting models which are used typically include a rainfall-runoff component, adapted for urban areas, possibly also linked to a hydraulic model for the urban drainage system, representing all key subsurface and surface flow routes, where known. The river network may also be represented, and possibly coupled to the drainage model, to allow interactions between the two systems to be included, such as high river levels impeding drainage, or river water entering the drainage network. Information on rainfall can be derived from raingauges, weather radar, and rainfall forecasts, although the accuracy of the results is often hampered by the sparse resolution of the information available, compared to typical scales of interest. However, for high-risk areas, installation of a dense raingauge network may be justified, or a local weather radar (e.g. Tilford et al. 2001). The resolution of nowcasts and short term Numerical Weather Prediction model outputs is also improving, with typical grid resolutions of 1 km now achievable at a city scale or larger for short- to medium-range forecasts (see Chapter 3).

In scheduling applications, some typical uses of forecasting models include reducing system operating costs and better planning of maintenance-related operations, such as dewatering of culverts and storage areas, and other activities. There may also be a safety related dimension; for example, in not allowing staff to work in subsurface parts of the network when heavy rainfall is forecast. By contrast, real-time control systems aim to make better use of existing storage capacity in an urban drainage system to reduce operating costs and pollution incidents, and to defer the requirement for capital expenditure (e.g. Schilling 1989, Cluckie et al. 1998, Colas et al. 2004, Shütze et al. 2004).

The first opportunities for real-time control were identified in the late 1960s and early 1970s, with an early example being a system to control CSO discharges in Seattle, which was initially implemented in 1971, with a rainfall-runoff modeling component introduced in 1992 (EPA 2004). More than 20 cities in the USA, Canada, Europe and Japan now operate this type of system and 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

A real-time control system typically uses remotely or automatically controlled devices, such as pumps, valves, sluice gates and inflatable dams, to divert flows in the drainage network away from areas which are operating at full capacity, or overflowing (e.g. surcharging at street level), towards areas with capacity remaining, and off-line areas such as flood storage ponds. For example, during a storm event, without any control, water may flow into the system at one location in a town, overloading the drainage system locally, whilst spare capacity remains elsewhere.

Control rules are typically derived off-line using detailed urban drainage hydraulic models, of the types normally used for design. The rules can then be implemented in a specialized decision support system for use in real-time, and may include an optimization component; for example, using expert system, artificial intelligence, or linear or dynamic programming techniques (see Chapter 6 and Section 9.2). Some commercially available forecasting systems also have the capability to include urban drainage hydraulic models for real-time use within the overall control system, taking account of system constraints, such as pipe capacities, flow routes, and the volumes of offline storage areas. Rules may be implemented at local level (e.g. using Programmable Logic Controllers), with either automated or remote control, or at system wide (or 'global') level, and may need to switch automatically from dry to wet weather objectives.

For example, some typical control objectives are to reduce overall operating costs during dry weather (e.g. for pumping operations, and at water treatment works), and to reduce surface flooding and the frequency and severity of CSO events during heavy rainfall. Safety considerations can be addressed by ensuring that the worst-case scenario should be to fall back on a system behavior equivalent or better than the situation before the introduction of real time control (Schütze et al. 2004).

For example, the system in Quebec City which is shown in Table 9.3 started as a demonstration study for the western part of the city's sewer network (Field et al. 2000, Pleau et al. 2001) which, at that time, served approximately 230,000 residents in an area of more than 300 km^2. At the time of the study, the system included 66 km of interceptor pipes, with three main branches and two tunnels providing some 13,000 m^3 of in-line storage, and a waste water treatment works. There were also 22 CSO outfalls of which 9 had significant overflows into the St Charles and St Lawrence Rivers. The operational system used data from flow and weather station sites, radar rainfall images, and rainfall forecasts with a two-hour lead time (Schütze et al 2004). The optimization criteria which were used whilst developing the system were to minimize the volumes discharged at CSOs, the number of CSO events, and the surcharge flows from private connections, and to maximize the treatment plant utilization (subject to tidal variations in the St Lawrence River) and use of existing in-line storage capacity (but without causing any local overflows).

Some current research themes for real time forecasting for urban drainage systems include improved monitoring techniques, the use of higher resolution weather radar data and meteorological forecasts, the development of distributed rainfall-runoff modeling techniques, including automated generation of flow paths from digital terrain and land use data, probabilistic approaches, and improved techniques for developing and optimizing control rules.

As already noted, another use of hydrometeorological forecasting techniques is in providing early warnings for flooding linked to urban drainage problems. In many towns and cities, this can be a nuisance where water collects due to insufficient local capacity in the drainage network, or blockages to flow paths, such as at road or rail embankments. However, more serious flooding can occur; for example, during a widespread flood event in England during the summer of 2007, approximately 10,000 homes and businesses were flooded in the city of Hull, due primarily to the drainage network being overwhelmed.

The techniques used for forecasting urban flooding are similar to those already described in Chapter 4, but some challenges can include the interactions between the river and drainage networks, and surface and subsurface flows, and the fine scale of the runoff response, compared to the resolution of rainfall observations and forecasts. For example, at street level, the land cover may consist of a mosaic of gardens, roads, pavements, industrial areas and other features, which need to be modeled in aggregate, in some approximate way, or in detail, with the individual responses combined in some plausible way. Also, small-scale local features, such as pavements (sidewalks) may have a significant influence on flood flow paths. Information on rainfall would ideally also be available at scales comparable to urban catchment areas although, even for radar rainfall data, and high resolution Numerical Weather Prediction models, this is often not the case. The performance of the drainage network can also depend on the direction of travel of a storm relative to the direction of drainage; for example, storm events traveling downstream will tend to add more water to flows draining from further upstream, adding to the load on the network.

If a real-time forecasting approach is considered unfeasible, then one approach is to perform detailed hydrological and hydraulic modeling beforehand, to prepare maps of areas at risk under different rainfall and antecedent conditions, perhaps also developing scenarios for known problem areas, such as culverts which may be blocked by debris. Also, for major rainfall events, one simplification which may be possible is to assume that the subsurface drainage network is overwhelmed, so that the total rainfall, or some fraction of it (e.g. allowing for what has already drained) can be distributed across the topography using simple volumetric calculations within a digital terrain model. Results may also be refined for plausible flow paths, and flow routing, based on site visits and ground-survey (e.g. Defra 2009). As already noted, a more sophisticated approach is to operate a distributed hydrological model in real-time, perhaps also coupled to hydraulic models for the drainage and river networks, although this remains a developing area for flood warning applications.

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Chapter 10
Environmental Impacts

Abstract Hydrometeorological forecasting techniques can play a role in estimating future changes to the water quality and ecology of rivers, lakes and reservoirs. Forecasting models typically combine meteorological measurements and forecasts with catchment models for flows and the water quality and/or ecological components. River models may include rainfall-runoff and flow routing components, whilst hydrodynamic models are widely used for modeling reservoirs and lakes. Distributed rainfall-runoff models are also increasingly used, particularly for considering the impacts of diffuse (non-point) sources of pollution, such as from farmland and urbanized areas. Some examples of applications include forecasting the development of river pollution incidents, providing warnings for poor bathing water quality, and predicting longer term changes to the environment. Water quality and ecosystem forecasting techniques are also increasingly being combined with more traditional flow forecasting approaches. This chapter provides a general introduction to these topics, and presents several examples of operational real-time forecasting systems.

Keywords Water quality · Pollution incidents · Ecosystem forecasting · Harmful algal blooms · Bathing water quality · Real-time

10.1 Introduction

Pollution incidents, and longer-term problems arising from diffuse (non-point) and point sources of contaminants, can affect the ecology of rivers, reservoirs and lakes, and the quality of water abstracted for public water supply, irrigation and other uses. National and international legislation, such as the European Water Framework Directive, is also increasingly requiring a higher level of water quality and environmental protection and control.

Perhaps the earliest and most widely used application of water quality monitoring was in public water supply. In some countries, this has also included the development of river flow and water quality forecasting models to predict the spread of

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pollutants from accidental spills so that, if pre-defined thresholds are exceeded, mitigating action can be taken, such as aeration, temporary suspension of abstractions, and the use of other sources. There can also be financial and operational benefits from the real-time management and control of river flows, abstractions and effluent releases to maintain water quality, rather than constructing additional facilities to store and treat water following abstraction (e.g. Whitehead 1980).

More recent developments have included steps towards improving bathing water quality standards at beaches and lakeside resorts, and to reduce the pollution arising from uncontrolled releases of contaminated surface runoff from Combined Sewer Overflows (CSOs) in urban areas. For example, in Europe, from 2012 the European Bathing Water Directive requires all bathers at lake and coastal resorts to be provided with information on potential risks to their health whilst, internationally, the need to reduce CSO incidents has resulted in massive investments by many water supply organisations in recent years. Section 10.3.2 describes some approaches to forecasting bathing water quality incidents, whilst forecasting and real time control techniques for CSO's are discussed in Section 9.3 as an application of urban drainage modeling.

Alongside the need to protect people, there is an increasing requirement to understand and reduce the adverse effects of water quality changes on ecosystems, such as the spread of toxic algal blooms and invasive or 'alien' species, and deteriorations in in-stream habitat, affecting fish and other wildlife. Modelling of this type has traditionally considered long term changes, using off-line simulations, but shorter-term ecosystem forecasting approaches, using real-time data and meteorological forecasts, are increasingly becoming a practical proposition, and Section 10.2 describes some of these techniques. Reservoir operators also often need to factor in the need to maintain environmental or ecological releases during normal operations, as discussed in Section 9.2.

The range of potential contaminants is vast, and includes chemicals, heavy metals, organic pollutants, and other sources, such as the thermal pollution from power station outfalls. Table 10.1 lists some common types of contaminant and the types of activity and industry from which they are generated.

As noted in the table, a distinction is usually made between pollution from individual (point) sources, and diffuse (non-point) pollution from surface runoff. Diffuse sources often show an initial rapid response following rainfall (the 'first flush') followed by a more gradual decline as runoff continues whilst, for point sources, pollution may arise as a pulse generated by a single incident, or accumulate incrementally over time. Note also that, in water quality modeling, the term constituents is often used to describe both contaminants and physical characteristics, such as water temperature or dissolved oxygen.

The techniques used for forecasting these types of impact are similar to those used in many other applications, such as flood forecasting and water resource forecasting (see Chapters 4, 7 and 11), with the addition of a water quality and – possibly – an ecological modeling component. For example, one widely used approach is to combine rainfall-runoff and flow routing models, driven by observed or forecast rainfall, with models for the transport of contaminants, sometimes allowing for

Table 10.1 Some examples of sources and types of contaminant

Type	Examples	Point sources	Diffuse sources
Fuels/hydrocarbons	Oil, petrol, gasoline	Transport (road/rail) accidents, incidents at refineries	Urban and industrial areas
Heated water		Power station cooling systems	
Heavy metals	Cadmium, mercury, lead	Industry, Mining	Mining, contaminated land
Nutrients	Nitrogen, phosphorus	Sewage/Waste Water Treatment Works	Arable farming, horticulture etc
Pathogens	Bacteria, protozoa, viruses	Waste Water Treatment Works, CSO’s	Arable farming, livestock, urban areas
Pesticides			Arable farming, horticulture
Solvents		Paper, food, textile industries	Industrial areas
Suspended solids		Waste water treatment works	Farming, forestry, construction etc

dilution, chemical reactions, and other factors. Box 10.1 describes an example of this approach for the real-time simulation of point and diffuse pollution from phosphorus at a national scale. Other meteorological inputs may also be used, such as air temperature, for example affecting water temperatures directly and indirectly (e.g. via snowmelt), and wind speeds and directions, affecting currents and wind waves in reservoirs and lakes.

Box 10.1 Real-time phosphorus load simulation

In Finland, the national river flow forecasting system, which is described in Chapter 7, includes a real-time phosphorus load simulation model (Huttunen et al. 2008). The forecasting system is called the Watershed Simulation and Forecasting System (WSFS) and is operated by the Finnish Environment Institute (Vehviläinen et al. 2005). The outputs are used for a range of purposes, including flood warning, lake regulation, hydropower generation and water resources management. The system represents approximately 6200 river basins and 2400 lakes in an area of 390,000 km^2, and provides forecasts for more than 1300 forecasting points. Forecasts for river flows and a range of other parameters are displayed as graphs, maps and tables on a website (http://www.environmet.fi/waterforecast) and, for selected sites, forecasts are also presented for real time nutrient (phosphorus) load, as shown by the example in Fig. 10.1.

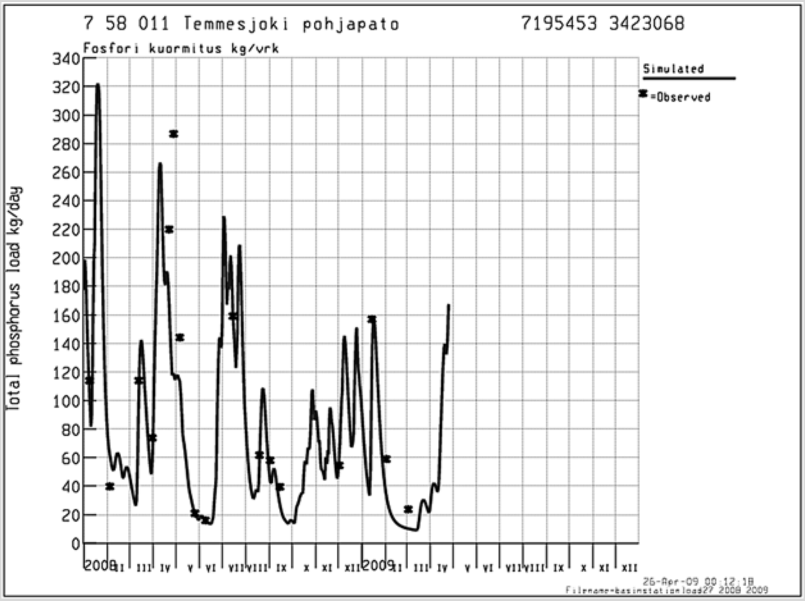

Fig. 10.1 Example of a total phosphorus load simulation for the Temmesjoki river in Finland (http://www.environmet.fi/waterforecast. Accessed 26 April 2009)

The water quality component simulates erosion and the leaching of phosphorus from land areas and concentrations in rivers and lakes, and allows for agricultural, non-agricultural and point sources of pollution. Models are calibrated at a regional level so as to achieve a good fit based on a weighted sum of the mean square errors for concentration and load for all of the monitoring points. Phosphorus concentrations are estimated from runoff values, with 5 separate coefficients to represent response over the full flow range from baseflows to flood flows. Values are then routed through the river and lake network using a flow routing and mass balance approach, with an allowance for deposition within lakes.

The modelling is performed at a fine level of detail within a Geographical Information System which includes 36,000 wetlands, information on slope, soil texture and plant types at a field scale, and the drainage basins for 58,000 lakes with an area greater than 0.01 km^2 (1 hectare). Generally good agreement is obtained between modeled and observed values both at individual sites, and for annual total phosphorus loads entering the Baltic and Barents Seas. Models for nitrogen and suspended solids are also under development together with the introduction of automated monitoring equipment to increase the availability of data for model calibration and performance monitoring.

The real-time observations required to support the operation of forecasting models can include values for river, reservoir and lake levels, river flows, rainfall (from raingauge, weather radar or satellite observations), and water quality parameters. As described in Chapter 2, a wide range of continuous monitoring instrumentation is now available for water quality applications, including devices for measuring standard variables such as water temperature, dissolved oxygen, turbidity, conductivity/total dissolved solids, and pH. Ultrasonic and other devices can also be used to measure vertical profiles in rivers, lakes and reservoirs, and sampling techniques using micro-organisms, such as algae and daphnids, can detect the presence of toxins which are difficult to measure, such as herbicides and pesticides, or for which no other instrumentation is in place. For example, Box 10.2 describes an operational early warning system for pollution incidents on the River Rhine which uses many of these monitoring techniques, combined with river flow and water quality forecasting models.

At longer lead times, hydrodynamic models continue to be useful for systems with a slow response, such as large lakes, whilst, at the catchment scale, supply-demand models are often used, combining detailed water balance models with a water quality modeling component, and possibly an ecological component, as discussed in Chapter 11. For climate change impact assessments, and other long-term studies, it can also be important to consider the feedback between atmospheric chemistry and the land surface, as illustrated in Fig. 10.2, which was prepared as part of a major UK-based research programme (QUEST), for which one key objective is to better understand the earth climate system and to reduce uncertainties in climate prediction (http://quest.bris.ac.uk/). Some interactions to consider include the influence on climate and radiative energy transfer from aerosols and other atmospheric pollutants, and the impact of changes in the rates of deposition from pollutants, radiation inputs, and other factors, on vegetation and other ecosystems, and feedback effects on climate, including the influence of forest fires.

In all types of forecasting applications, another key consideration is how to make best use of the outputs which are provided. For example, at short- to medium- time

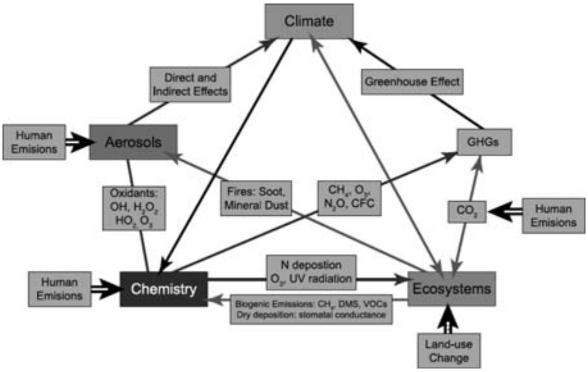

Fig. 10.2 A schematic of the Earth System Model being developed both within the NERC QUEST (Quantifying and Understanding the Earth System) programme and at the Met Office Hadley Centre; CFC = Chlorofluorocarbon, VOC = Volatile Organic Compound; DMS = dimethylsulfide; UV = ultraviolet, GHG = greenhouse gas (Blyth et al. 2006; http://quest.bris.ac.uk/)

scales, decisions on whether to respond to unusually high or low values of contaminants are often taken on the basis of threshold values, which are sometimes called operational or critical limits (World Health Organisation 2006), and are discussed in more detail in Chapter 6. For drinking water supply, typically these consist of maximum or minimum values across a wide range of chemical, organic, microbial and pesticide compounds. The response to the crossing of threshold values can include decisions to restrict abstractions of water for irrigation, water supply or other purposes and/or to select other sources of water either to replace the shortfall, or the dilution of the contaminated supply to bring values back within acceptable limits. Waste water treatment works and industrial users are also often required to meet prescribed standards for the Biochemical Oxygen Demand (BOD) and/or Chemical Oxygen Demand (COD) of the effluent that it is discharged, which are measures of the demand for dissolved oxygen from micro-organisms and contaminants.

Some other approaches to decision-making, which are again described in Chapter 6, include the use of decision trees, and decision support systems. Risk-based techniques are also increasingly used; for example, in deciding whether to close a beach due to the risk of pollution following heavy rainfall, or to suspend water abstractions due to the likelihood of harmful algal blooms or other types of contamination. There is also a long tradition of accounting for uncertainties in water quality measurements and model outputs (e.g. Loucks and Lynn 1966, Beck and van Straten 1983), which fits well with the more recent interest in using ensemble meteorological forecasts as inputs to flow forecasting models (see Chapter 4). Decision-making techniques which can make use of information on uncertainty, such as Bayesian Networks and fuzzy logic, have also been evaluated for use in environmental applications, and are described in Section 6.3.

Box 10.2 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 also 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 Transport, Public Works and Water Management. Since 1974, the Rijkswaterstaat Centre for Water Management has operated a system called AQUALARM (http://www.aqualarm.nl/) 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. 10.3), 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).

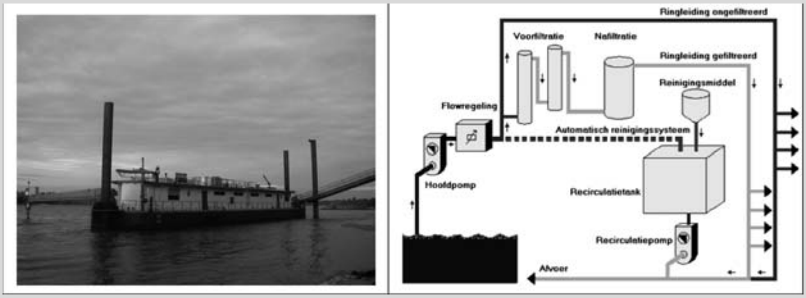

Fig. 10.3 Illustration of the sampling system and monitoring station at Lobith on the River Rhine (Rijkswaterstaat – Centre for Water Management; http://www.aqualarm.nl/)

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 pre-defined thresholds are crossed, warnings are provided to the appropriate authorities, including the main water supply company in the Netherlands; the Water Transport Company Rhine-Kennemerland. 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, Mazijk et al. 1999, Diehl et al. 2005). River flow forecasts are also available from a network of rainfall runoff and hydrodynamic models, as described in Chapter 7.

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 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 (http://khr-chr.org/en/projects/rhine-alarm-model).

10.2 Forecasting Techniques

For real-time forecasting applications, some factors which may need to be considered include current and future flows, the transport of contaminants within those flows, and any biological, chemical, ecological or other changes which may occur due to dilution, chemical reaction, and the life cycle of organisms. Physical characteristics such as dissolved oxygen, temperature and pH may also need to be considered, whose monitoring and control are often important to maintaining river ecosystems, and for which small changes can affect more sensitive species.

Typically, different forecasting approaches are used for rivers and for reservoirs and lakes and, to some extent, the approach which is used depends on the forecast lead times which are required. For rivers, the flow velocity is often the dominant factor on the transport of constituents, and a one-dimensional model can be used, neglecting vertical and lateral motion. For the flow component, steady-state or water balance techniques may be sufficient at long timescales whilst, at shorter timescales, a hydrological or hydrodynamic flow routing approach may be required. By contrast, for large reservoirs and lakes, currents are often driven mainly by wind and temperature effects, so the hydrodynamic aspects are more complicated, and often require a two- or three-dimensional modeling approach.

The following sections discuss the general approaches which are used, although it is worth noting that there can also be intermediate situations; for example, for smaller reservoirs and lakes, the mixing from river inflows may also be a significant factor both for water quality and the lake circulation. Section 10.3 also describes two forecasting applications which are currently of interest in a number of countries; for the growth of harmful algal blooms, and for pollution incidents in public bathing areas at lakes and coastlines.

10.2.1 Rivers

For river forecasting applications, the aim is often to predict the changes in concentration at one or more locations (e.g. at one or more water abstraction points) as a contaminant travels downstream. There may also be a more general requirement to assess the status of the river for ecological purposes, and to assist with overall river management; for example deciding on whether to place restrictions on water abstractions and discharges, and to augment flows from reservoir or groundwater sources.

Contaminants may enter river flows from point or diffuse sources, and point discharges may consist of a single short-lived pulse (relative to typical travel times), or occur over longer timescales. For example, Fig. 10.4 shows conceptually how a pulse of a contaminant might travel downstream in a river reach.

Quantifying the impact of point sources is usually simpler than for diffuse sources, since the time of occurrence, type of contaminant, and indicative volume or concentration, will often be known, or can be estimated. Diffuse sources are more difficult to represent, and the modelling approach which is used needs to be able to represent the build-up of contaminants in dry weather, and then the runoff following rainfall, typically also allowing for the influence of catchment drainage networks and the main types of land use. A grid-based distributed modeling approach is typically used, as illustrated in Box 10.1. For off-line, simulation studies, models of this type are sometimes also coupled to a three dimensional groundwater model to allow for the transport of contaminants by subsurface flows, and this type of

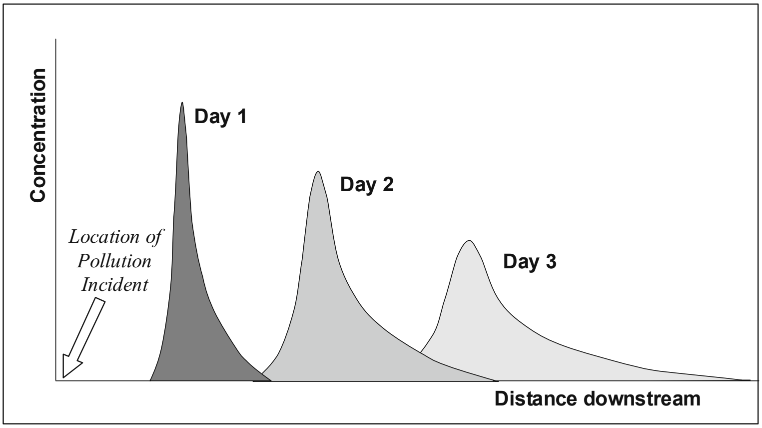

Fig. 10.4 Idealised example of the transport of a pulse of pollution down a river channel

integrated model is becoming feasible to operate in real-time for water resources applications (see Section 8.3, for example), and might also be extended to include a water quality component. Simpler regression based techniques, and methods using export coefficients, are also sometimes used to estimate contaminant loads from catchment characteristics such as land use, topography and geology.

For short- to medium-term forecasts, some techniques for real-time forecasting include multiple regression approaches, relating travel times and other parameters to flows and catchment characteristics (e.g. Wilson et al. 1997), and models which assume either a mean or typical flow velocity, or which use approximations to the full dynamic equations for fluid flow. Data-driven or black box approaches can also be used, in which time series analysis methods are used to relate downstream conditions to conditions further upstream (e.g. Young 1998). When flows are only slowly varying, as may occur under low flow conditions, for example, a steady state approach can work well, with the focus of the modelling on the water quality and ecological aspects. Models of this type might operate at a daily or longer timestep, rather than the sub-daily timesteps which are typically used for flood forecasting applications (see Chapter 7). Estimates for the inflows to the model may be obtained from long term averages, or rainfall-runoff modeling components. For example, Whitehead et al. (1984) describe a forecasting model for real-time control of water quality on the Bedford Ouse river in eastern England. The model included components for key variables such as dissolved oxygen and ammonia, and also included the option to consider algal growth and decay.

Where unsteady flow influences are important, the usual approach is to use a hydrodynamic or flow routing model, of the types described in Chapters 4 and 7, to estimate transient flow velocities, coupled to an advection-diffusion model for the transport of constituents (e.g. Chapra 1997, Huber 1993, Ji 2008). For the flow component, typically rainfall observations and forecasts are used as inputs to rainfall-runoff models, which provide inflows to a flow routing component to translate flows through the river network. A range of hydrodynamic, conceptual and data-driven modeling techniques can be used for the routing component of the model. For the water quality component, an advection diffusion approach is often used, in which the rate of change of the concentration over time is related to partial derivatives for the changes in concentration along the direction of flow, and a diffusion or dispersion coefficient. Variations in other parameters, such as water temperature and radiation load, can also be represented using this approach.

Estimates for the model coefficients are typically derived from field observations and, due to the wide range of values which are found in practice, should ideally be measured for each river reach under consideration; for example, using tracer experiments, or from monitoring the transport of background pollution in the river. For a medium to large river, there is often the difficulty of obtaining a representative value, requiring traverses across the river section by boat or cableway (see Chapter 2). Models must typically be calibrated over the full flow range, and in particular for low flows, and other effects may also need to be considered, such as reverse flows and saline intrusion in the tidal reaches of rivers.

In water quality applications, the underlying equations are often referred to as an advection-dispersion model to highlight that the application is to a constituent, rather than for other types of diffusive process, such as turbulent diffusion. The resulting non-linear partial differential equations are usually solved using finite difference or finite element solution schemes in which the river system is divided into a number of discrete reaches, within which conditions are assumed to be constant (see Box 9.2 for example). Inflows from features such as waste water treatment works, irrigation scheme return flows, tributaries, and diffuse pollution sources, and outflows from abstractions, can also be included in the reach mass balance if appropriate.

In many practical applications, in addition to dilution of a contaminant, another complication can be reaction or decay (or conversion) of the contaminant, requiring additional terms in the governing equations. Some examples of kinetic processes which may need to be represented include sorption (e.g. adsorption onto sediment), volatilization, sedimentation, biodegradation, photolysis, and hydrolysis (e.g. Huber 1993). Another important consideration is the availability of dissolved oxygen; for example, sewage effluents typically absorb dissolved oxygen for the decomposition of organic waste, whilst processes such as natural re-aeration (e.g. at weirs), forced aeration (e.g. from in-stream bubbler systems), and plant algal growth and photosynthesis help to raise the oxygen content of river water. The nitrogen and phosphorus cycles may also need to be considered, and the interactions with dissolved oxygen.

A typical approach is to use reaction or rate coefficients to parameterize the rate of creation or decay of each constituent, with a separate equation to be solved for each type. A first order approximation is to assume that the rate of decay or production is proportional to the concentration of the constituent, whilst higher order schemes can be considerably more complex, and may include terms which depend on the values for other constituents (e.g. water temperature). An allowance for solar or net radiation may also need to be included for processes involving photosynthesis.

A number of other complicating factors might also be considered, including flows around structures (underflow, leakage), saline intrusion, dead zones etc. Ecological components might also be included; for example, for algal growth, invertebrates, plants and fish, linking in to variables such as depth, velocity, water quality, substrate, shade and other factors which determine suitable habitats for each species at each stage in its life cycle. Factors of this type are commonly used in off-line (simulation) modeling, but could also be considered in forecasting systems, particularly if only used in occasional model runs during a flow season.

For point sources of pollution, another factor which may need to be considered is the near-field mixing close to the point at which contaminants enter the river system, such as outfalls, since this can have a strong influence both locally, and on the concentration profile further downstream. One common example of the use of near-field studies is two-dimensional or three-dimensional hydrodynamic modeling of the dilution and spread of thermal plumes from power station cooling water systems, although this type of study is normally performed off-line, rather than as part of a forecasting system.

One area that has perhaps received less attention than in other forecasting applications (see Chapter 4) is that of data assimilation; that is, using real-time observations of constituents to update the forecast outputs to help to account for the differences between observations and the forecast values. This approach is widely used in water resources and flood forecasting applications, and methods include autoregressive moving average, state updating, Kalman Filter, and other approaches. For water quality forecasting, these techniques are intrinsic to some data-driven approaches, such as stochastic transfer function models, but are rarely applied to update the outputs from physically-based models (other than for the flow component). However, there is considerable research underway into data assimilation for water quality and ecological variables in ocean, coastal water and groundwater models (particularly for the use of satellite observations in ocean models). Often, one particular consideration for water quality applications is the relative lack of real-time observations and the large number of constituents to consider, compared to flow forecasting applications.

10.2.2 Reservoirs and Lakes

As noted earlier, for modeling in reservoirs and lakes, the vertical transport of constituents may need to be considered, and the influence of thermal (convective) flow mechanisms, and thermal stratification. River flow inputs may also need to be considered where rivers enter the reservoir or lake. To represent these effects, typically this requires the use of either a three-dimensional hydrodynamic model, including thermal influences, or two-dimensional approximations, such as for shallow lakes or reservoirs (see Chapter 4). However, simpler water balance models can also provide useful results for some constituents.

For large lakes and reservoirs, wind effects may also need to be considered, both for the influence on waves and currents, and for the potential to drive surface contaminants, such as algal blooms, towards the shoreline. Waves are typically generated by the wind field at the water surface, and surge effects may also be a factor on very large lakes. For wave models, a phase-averaging approach is normally used, describing the wind energy inputs across the spectrum of wave frequencies, and the energy dissipation due to mechanisms such as wave breaking, wave interactions, and wave-current interactions. The wind field is normally derived from the outputs from a Numerical Weather Prediction model (see Chapter 4).

The interactions between water quality and ecology are also of increasing importance in many lakes, with runoff from rivers, sewage and the land surface raising nutrient levels, and also increasing turbidity and sediment loads. These, and related factors, such a algal growth, can cause major deteriorations to water quality and plant and fish life, in the most extreme cases leading to eutrophication and hypoxia, where the dissolved oxygen content drops below critical levels.

For real time use, the run times required for a typical hydrodynamic model for a lake or reservoir can be considerably longer than for river models. However, the timescales over which effects occur are also typically longer, making it a practical proposition to operate models daily (and possibly more frequently), or on demand as required. Also, whilst ecological modeling has traditionally been performed mainly off-line, there is increasing interest in developing ecosystem forecasting models for rivers and lakes for a range of timescales, and Box 10.3 describes a major research programme on this topic for the Great Lakes in the USA and Canada.

Box 10.3 Ecosystem Forecasting, Great Lakes

Lakes Erie, Huron, Michigan, Ontario and Superior are collectively known as the Laurentian Great Lakes and, with the exception of Lake Michigan, lie along the border between the USA and Canada. The lakes hold approximately 18% of the world's freshwater supply and have a combined surface area of about 245,000 km^2, with average surface water elevations between 74m and 182m above sea level (http://www.glerl.noaa.gov/pr/ourlakes/). The main outfall from the lake system is the St Lawrence River, which flows from Lake Ontario to the coast via a series of canals and locks.

Real time forecasts of water levels, temperatures and currents, ice cover, winds, waves and other parameters are provided by the Great Lakes Operational Forecasting System operated by NOAA, and the Great Lakes Coastal Forecasting System operated by the Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, Michigan. These systems combine data from meteorological, river and lake telemetry sites, weather radar and satellite observations, and forecasts from Numerical Weather Prediction models, to provide inputs to three-dimensional lake hydrodynamic and wave models. The forecasts are used for a range of applications, including water level management, shipping, recreation, and power and water utility operations. Longer term probabilistic forecasts of water levels are also provided based on the seasonal outlooks produced by NOAA and Environment Canada (Fig. 10.5).

Current research into forecasting techniques (e.g. Brandt 2003, NOAA 2006) is focussing on development of an ecosystem forecasting capability for a range of timescales from hours ahead through to seasonal and longer term forecasts. The overall aim is to estimate the impacts of physical, chemical and biological changes on lake ecosystems and components using statistical, process-based and other approaches (Table 10.2).

An integrated real-time modelling system is under development which includes hydrological, hydrodynamic, ecological, water quality, sediment transport, and other components. Some key issues include providing advanced warning of water quality degradation for public water supply and beach closings, the development of hypoxic (oxygen depletion) episodes and algal blooms, and the spread of aquatic invasive species. Some examples of ongoing research studies include the development of a hypoxia forecasting framework (DePinto et al. 2008), the development of a distributed watershed model for point and non-point sources of pollution (Croley and He 2005), and studies into the spread of Harmful Algal Blooms.

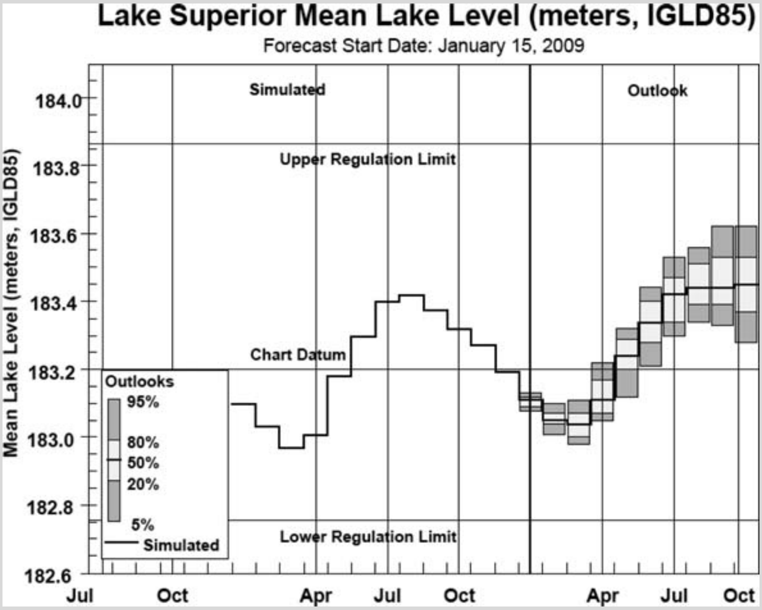

Fig. 10.5 Example of a seasonal water level outlook for Lake Superior (NOAA 2009, courtesy of NOAA, Great Lakes Environmental Research Laboratory)

Table 10.2 GLERL science issue areas and major forecasts of concern for the Great Lakes and marine coastal environments (NOAA 2006)

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 Quantity Water Levels
	Tributary Flows
Water Quality	Water Quality Turbidity/Clarity
	Taste and Odor
	Bacteria Concentration

Table 10.2 (Continued)

Issue Area	Forecasts
Human Health	Human Health Beach Closings (Bacteria/Pathogens)
	Fish Contamination
	Harmful Algal Blooms
Fish Recruitment and Productivity	Fish Recruitment and Productivity Numbers of Fish by Species
	Size of Fish
	Fish Condition
	Fish Distribution
Invasive Species	Invasive Species New Non-Native Species Introductions
	Spread of Introduced Species
	Impact on Ecosystem

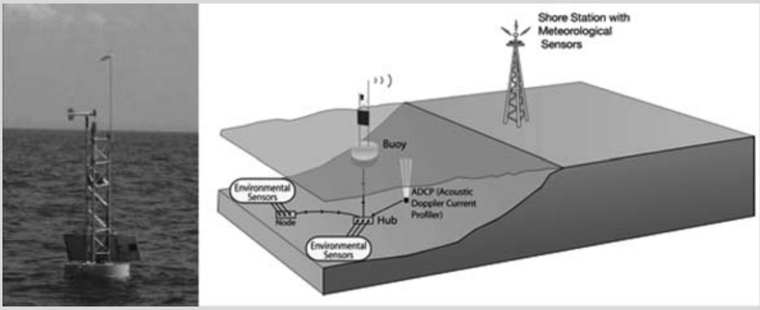

Fig. 10.6 Example of an observation buoy, and principles of operation (image and figure courtesy of NOAA, Great Lakes Environmental Research Laboratory http://www.glerl.noaa.gov/res/recon/)

An integrated Great Lakes Observing System is also being developed to support the operation of ecosystem forecasting models. For example, during the 2008 field season, the Real-time Environmental Coastal Observations Network (RECON) deployed six multi-sensor observatories in Lakes Erie, Huron and Michigan (Fig. 10.6). 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

10.3 Selected Applications

10.3.1 Harmful Algal Blooms

Algal growths are found in many streams, rivers, lakes and reservoirs, and are a major source of food for fish and invertebrates. There are many different species, although most types grow through a combination of photosynthesis and absorption of nutrients such as nitrogen and phosphorus from the surrounding water.

When nutrient levels and/or solar radiation are high, this can cause extensive growths of the harmful Cyanobacteria (Blue-Green Algae), which infact is a type of bacterium, although similar in appearance to many forms of algae. The growths typically become a problem when they appear as a dense layer on the water surface, which can form ‘mats’, commonly known as blooms, many centimeters thick, and are often blue/green in colour, although other colours also occur (e.g. red, brown). The growths can exist in freshwater, brackish water and seawater in both still and slowly moving water. Some species release toxins when the organisms die, whose effects on people can include vomiting, diarrhea, rashes, and respiratory problems, with a risk of death to animals and fish (and a lesser risk to people). The mass of blooms can also cause problems with water abstraction intakes and filters and affect dissolved oxygen content and drinking water quality.

One simple approach to forecasting the growth of algal blooms is to use a regression or decision tree approach, and fuzzy logic methods have also been considered (e.g. Blauw et al. 2006). Hydrodynamic forecasting models are also used operationally to assist in forecasting the motion of algal blooms at coastal locations, usually representing the motion as passive tracers. For example, the National Oceanic and Atmospheric Administration (NOAA) Harmful Algal Bloom Forecasting System provides forecasts for the Gulf of Mexico, and these are based

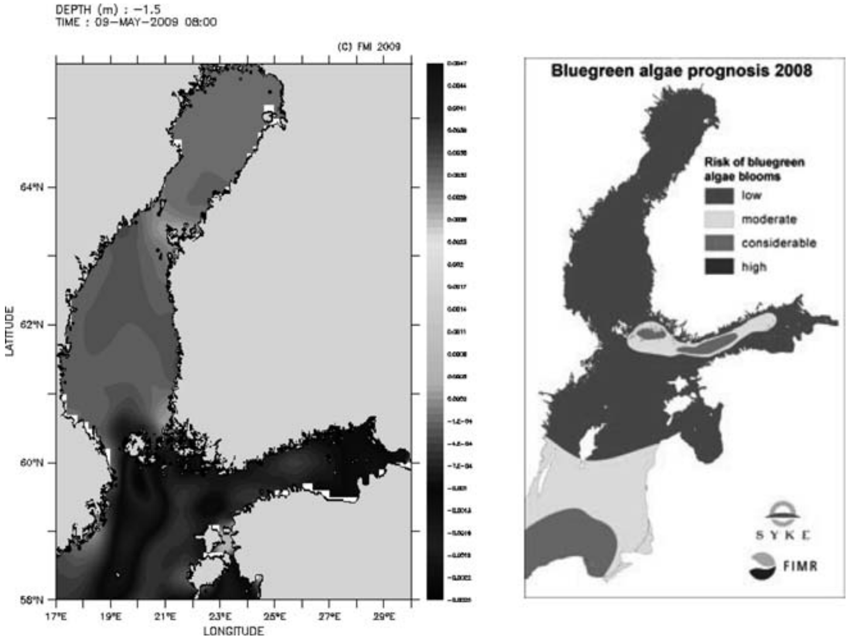

Fig. 10.7 3-day Cyanobacterial biomass forecast issued on 9 May 2008 and Bluegreen algae prognosis for 2008 for the Baltic Sea (http://www.fimr.fi/ and http://www.environment.fi/)

on expert assessment of meteorological and coastal forecasts, and satellite and ground based observations (http://tidesandcurrents.noaa.gov/hab/).

Blue green algae can also be a significant problem around the coast of Finland and in inland waters and, during the period from July to mid-September, are monitored jointly by the Finnish Institute of Marine Research and Finnish Environment Institute (and other groups) by satellite, ships and at more than 300 permanent monitoring locations at lakes and in the Baltic Sea. Algal bloom forecasts are issued weekly from 4 June to 27 August based on monitoring, ocean modeling and expert opinion, and are issued for three days ahead, and seasonally, as illustrated by the example in Fig. 10.7. The estimates of phosphorus load provided by the WSFS forecasting system (see earlier) provide useful information to assist in preparing these forecasts.

Research is also underway in several countries to develop operational models which can predict the occurrence, toxicity, transport and fate of toxins for harmful algal blooms (Lopez et al. 2008; see Box 10.3 also). Some key components include the need to forecast the main sources of nutrients from both point and diffuse sources of pollution, and the transport and life cycle of algal blooms within the receiving waters. This requires the use of catchment-scale models to forecast the influx of pollutants, and hydrodynamic or other simpler models which can take account of a wide range of factors which may influence the spread of algal blooms, including flow directions, surface water temperatures, wind speed and direction, and nutrient concentrations.

10.3.2 Bathing Water Quality

Pollution incidents at lakeside and coastal locations can cause a range of health problems to holidaymakers and other water users. Typically, the main problem is from bacterial and other infections arising from diffuse pollution from farmland and urban areas, and point source pollution from urban drainage systems; particularly Combined Sewer Overflows (CSOs; see Section 9.2). Accidental (episodic) spills may also occur from waste water treatment works, industrial plant and other sources. The introduction of accreditation schemes for bathing waters (e.g. Blue Flag beaches), combined with national and international legislation (e.g. the European Bathing Water Directive), is also leading to an increasing interest in approaches to forecasting the likely severity and frequency of incidents, and warning users when they are likely to occur, or closing beaches until the threat has passed.

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 widely used. There have also 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 Weisburg 2005).

For diffuse sources of pollution, and Combined Sewer Overflows, the trigger for a pollution incident is typically heavy rainfall, increasing urban runoff, and causing an initial ‘first flush’ pulse of pollution from the land surface. Several studies (e.g. EPA 1999) have shown that rainfall depth duration thresholds can provide a good indicator of the potential for problems, and these are implemented in several organizations and countries (see Box 10.4 for example). Rainfall values can be obtained from raingauges, weather radar, satellite observations and/or rainfall forecasts. Where other factors have an effect, multiple regressions can be derived to allow for those influences, with examples including the use of wind speed and direction, tidal conditions (for coastal sites), wave height, the season, water temperature, and the number of dry days since rainfall last occurred. Where there are many factors to consider, decision support tools, such as decision trees, may be useful in deciding on the warnings to provide, and whether to close beaches (see Chapter 6 for an example of a decision tree).

If the risks are primarily from a particular river, or known source(s), and impact upon a specific high-risk location, such as a harbour or a bay, rather than covering an extensive shoreline, then the potential also exists to develop a more process-based approach; for example, including a water quality component in an existing flow forecasting model as discussed in Section 10.2. The surface runoff component, including a water quality component, could possibly also be combined with a hydrodynamic lake or coastal model, operated in near real-time, to assess the likely timing and concentrations of pollution along reaches of interest. More detailed models could also be included; for example, for the hydrodynamic mixing and diffusion of the plume of pollution from discharge outfalls.

Models of this type are often used off-line for a range of applications, such as setting discharge consents, and studying the impacts of pollution on fisheries, but can also be used in real-time to assess bathing water quality. For example, for Copenhagen Harbour in Denmark, a real-time two-dimensional hydrodynamic model is operated to estimate E.coli concentrations at several beach locations accounting for CSO discharges (e.g. Mark and Erichson 2007).

Models of this type can also be used on demand for specific pollution incidents (e.g. treatment works failures), or used off-line to derive look up tables or graphs; for example, for the New York-New Jersey-Connecticut Metropolitan Area, a three-dimensional model was used to run multiple scenarios for 29 discharge locations and 53 beaches/shellfish areas, from which a quick reference tool was developed to allow estimates of total colliform concentration as a result of a spill at any one of the discharge locations (EPA 1999). The following parameters were required as input: discharge location, receptor site location, water temperature, volume of discharges, discharge concentration, and bacteria type to analyze (total coliform is the default). After several years of operation, the initial version was subsquently improved to include multiple discharge sites, for a wider geographical area, and to also consider enterococci bacteria and conservative tracers such as metals (Dujardin et al. 2008). However, in any given situation, the choice of approach will depend upon a number of factors, including the level of risk, the budget available, understanding of the sources of pollution, data availability (both historical, and in real-time), the time available for decision making, and the transport and mixing processes which need to be considered.

Box 10.4 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 requires 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 approximately 60 identified bathing water sites, and provides daily predictions at more than 10 of these sites. Information can be obtained from a recorded phone line and text messaging service (Beachline), and is displayed on electronic signs (e.g. Fig. 10.8) and the SEPA website (http://www.sepa.org).

Within the directive, Excellent, Good, Sufficient and Poor conditions are specified based on bacterial sampling over a period of 3–4 years, and SEPA uses the following messages to describe the meaning of these standards:

- Excellent = Excellent water quality is predicted today
- Good = Good water quality is predicted 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 et al. 2001). The main risks are of elevated levels of microbiological pollution from Combined Sewer Overflows 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. To help to identify potential problems, water quality is sampled every two weeks throughout the main bathing season (1 June to 15 September) for indicators of faecal pollution (total and faecal coliforms, along with faecal streptococci), and checks are also made of transparency, colour, mineral oil, surface-active substances reacting with methylene blue, and phenols. Checks for salmonella, enteroviruses and pH are also made if required and more frequent monitoring is performed during periods when water quality has deteriorated. Some sites are also eligible for reduced sampling due to sustained improvements in water quality. The full implementation of the 2006 directive by 2012 will replace these current water quality parameters with two microbiological parameters: Escherichia coli and Intestinal enterococci.

Predictions of water quality are currently based on historical correlations between faecal coliform concentrations and rainfall measured by raingauges

Fig. 10.8 Electronic bathing water quality sign at Prestwick (McPhail 2007)

(SEPA 2007). Rainfall depth-duration thresholds for issuing warnings are defined in terms of rainfall for the previous 24, 48 and 72 hours, together with rainfall forecasts for the current day to midday. 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.

Recent research has investigated the use of radar rainfall data as an alternative or complement to raingauge data, which also 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, and tide, solar radiation and wind speed/direction information, and the development of decision trees and separate models for faecal streptococci (McPhail 2007).

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Chapter 11
Water Resources

Abstract When forecasting the availability of water in a catchment or region, many factors may need to be considered, such as the influence of reservoirs, lakes, inter-basin transfer schemes, groundwater storage, and urban drainage, together with water demands from a range of users. Whilst in some applications, such as flood forecasting, smaller influences can sometimes be ignored, for water resources applications they may need to be considered in some detail. Forecasting techniques include integrated catchment modelling approaches which combine rainfall-runoff and flow routing models, supply-demand models which consider the balance between water supply and demand from a range of users, and regional, continental or global scale distributed models (which are sometimes called macroscale models). Increasingly water quality and ecological components are also included, and the role of atmospheric chemistry is also considered in climate change impact studies. Given this complexity, a toolkit approach is often used for model development, building models from the components which are required to represent the key features of the systems under consideration. For longer timescales, but increasingly also for medium- and short-term forecasting, probabilistic techniques are also used to estimate the sensitivity of results to the assumptions which are made. Data assimilation is also important in many applications, particularly for shorter lead times. This chapter presents an introduction to these various topics, and also briefly discusses some of the forecasting requirements for river basin management, integrated water resources management, and water resources planning and management.

Keywords Water resources planning and management · River basin management · Integrated water resources management · Supply demand · Forecasting · Data assimilation · Macroscale · Regional · Global · Climate change

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11.1 Introduction

Water resources forecasts can be required at a range of timescales, ranging from operational (day to day) management of supply and demand, through to seasonal water supply forecasting, and longer term investment planning. Some key applications include:

- Water Resources Planning and Management – the operation and design of networks of sources (rivers, reservoirs, lakes, boreholes etc) in an integrated way to meet demands for water supply, irrigation, hydropower generation etc, often also taking account of flood risk and water quality and ecological issues, and possibly spanning multiple river catchments
- Integrated Water Resources Management – long term planning studies into approaches to managing a catchment or river basin in a holistic way to meet water demand, socioeconomic, environmental and other objectives
- Climate Change Impact Assessments – assessing the impacts of climate change on water supply and the environment at a range of spatial scales, from local to global, also accounting for land-atmosphere interactions through changes in vegetation, land-use, and influences on water demand etc

There are considerable overlaps between these different types of study, and some applications may consider all three aspects, including factors which cut across individual catchments, such as inter-basin transfer schemes, and water supplies from regional aquifers. The terms river basin, catchment, watershed and drainage basin are also often used interchangeably.

For Water Resources Planning and Management, the focus of forecasting techniques is often on the operation of complex water supply systems from short term to seasonal time scales, and for investment and other planning at longer timescales. Probabilistic techniques are widely used at longer timescales, and increasingly at shorter timescales, to assess the sensitivity of results to uncertainties in meteorological conditions, demand forecasts, and other variables, and to allow a more risk-based approach to decision making (see Chapter 6). Schemes are often operated to meet multiple criteria, and may need to consider factors such as the level of service provided, system reliability, and revenue and operating costs.

The basic principles of what is now understood by Integrated Water Resources Management (IWRM) were established at international conferences on water and the environment in Dublin and Rio de Janeiro in 1992, with one widely used definition (Global Water Partnership 2000) being that 'IWRM is a process which promotes the co-ordinated 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.' In Europe for example, the Water Framework Directive is a key driver for this kind of study, whilst internationally this approach is adopted by the main international funding institutions. The term Integrated River Basin Management is also widely used, particularly in the development of River Basin Management Plans. In these types of study, in addition to planning future development, models are often used as tools for information exchange and negotiations amongst key stakeholders, such as governmental organizations, local authorities, industry, businesses and residents. Again, a key interest is often in the sensitivity to assumptions, through 'what-if', scenario and probabilistic modeling, whilst recognizing that, many years into the future, the actual conditions can never be known with great precision.

For both of these types of study, an allowance for climate change is often included using factors representing how rainfall or inflows may vary in the future, typically for conditions representative of periods of a decade or 30-years. For a more detailed assessment, the interactions between the land and atmosphere also need to be considered, such as the influence of atmospheric pollution on radiation exchange, the effects of changes in land use and vegetation cover on water and heat fluxes into the atmosphere, and surface albedo, and a range of other potential interactions. The outputs from General Circulation Models (GCMs) may also need to be downscaled to the spatial and temporal scales of interest for hydrological modeling. The Intergovernmental Panel on Climate Change (IPCC) assessments (e.g. Bates et al. 2008) are updated every few years, and include probabilistic estimates for future conditions under a range of emission scenarios (see Chapter 3).

The forecasting approaches, and forecast verification techniques, which are used in water resources applications have many similarities to the methods described in previous chapters for flood, drought, flow control, and other applications. However, there is often a greater focus on accounting for the overall water balance, considering both supply and demand, and for the cumulative flows across the full flow range, from low flows to high flows. Also, whereas in some applications, such as flood forecasting, some items can often be neglected, such as abstractions and return flows, these are central to many water resources applications.

As discussed in Chapters 5, 8 and 9, some factors which may need to be considered can include groundwater abstractions at boreholes, inter-basin transfers, the influences of hydropower regulation, abstractions for industry, irrigation, mining and power generation (and associated return flows, where relevant), and the operation of water and waste water treatment works. Chapter 5 provides an introduction to demand forecasting techniques for a range of applications, including water supply, irrigation, and thermoelectric and hydropower generation. At longer timescales, the distinction between forecasting (estimating values for a given date or time period) and simulation modeling or prediction (estimating values for representative conditions in the past, present or future) can also become blurred, although the underlying modeling techniques are similar, or the same, in both applications.

Another distinguishing feature between approaches is the way that the catchment, scheme or region is conceptualized, and the following classification is used in this chapter:

- Supply-Demand Models – representation of a water resources scheme using a water balance approach, including all key inflows, transfers, abstractions and discharges, together with the main constraints on flows, such as pipeline and water treatment works capacities, and sometimes including optimisation routines for water allocation based on multiple objectives, and models for water quality (e.g. Box 11.1)
- Integrated Catchment Models – representation of the hydrological features of a catchment, typically using a semi-distributed or distributed network of rainfall-runoff, flow routing and/or hydrodynamic models, and additional modeling components for reservoirs, lakes, river control structures, groundwater sources, and key abstractions and demands etc (as required)
- Land-Atmosphere Models – representation of the catchment or region using a distributed, grid-based approach, using physically-based or physical-conceptual models for a wide range of processes, including runoff production and flow routing between grid cells, vegetation growth, land-atmosphere interactions, and groundwater flows, and sometimes the mass balance (cycles) of constituents such as carbon, nitrogen and phosphorus.

These general approaches are described in Chapters 3 and 4, together with examples of simpler statistical approaches using regression relationships between flow volumes, rainfall and other indicators of flows. Water quality and/or ecological components may also be included in all three types of model, as described in Chapter 10. The choice of approach will depend on a number of factors, including the application, the lead time which is required, the performance measures which are specified (and forecast verification techniques to be used), the main processes which are to be represented, data availability and reliability, the software and forecasting systems which are available, and the level of risk.

Another consideration is the extent to which use is made of data assimilation; that is, the use of real-time and recent observations from ground-based, satellite or other sources to improve the accuracy of forecast outputs (e.g. Serban and Askew 1991, Refsgaard 1997). Data assimilation techniques are widely used in integrated catchment models, particularly for short- to medium-term forecasts and – as described in Chapters 4 and 7 – include autoregressive moving average, Kalman Filter, state updating, and other approaches. Typically, the main inputs to the data assimilation routines are river level or flow observations, although satellite observations are increasingly used for distributed parameters such as snow cover and soil moisture.

By contrast, for supply-demand models, often the only use of data assimilation is to define the initial conditions for components such as reservoirs, lakes, and river flows. Similarly, for land-atmosphere models, the focus is also usually on state updating, and the grid-based approach lends itself naturally to the assimilation of weather radar data and satellite observations of snow cover, soil moisture, and vegetation cover, and weather radar observations of precipitation, together with the outputs from Numerical Weather Prediction models.

Box 11.1 Olifants River Catchment, South Africa

The Olifants river rises at an altitude of 2300 m to the east of Johannesburg and passes through Kruger National Park to meet the Limpopo river at the border with Mozambique. The average annual rainfall is typically 500–800 mm, but ranges from 400 mm in the north to more than 1000 mm in the middle reaches of the catchment, with the main rainfall season from October to April. The catchment area is approximately 54,000 km^2 and the main land use types are grassveld, bushveld, forest and cultivation. Approximately 3 million people live within the catchment boundaries, with the main economic activities including agriculture, industry, tourism and mining.

The average annual runoff exceeds 2000 Mm^3, but the catchment experiences a variable climate, with frequent floods and droughts. The available water resources are also heavily used for public water supply, irrigation, commercial forestry and the mining industry. There are more than 3,000 dams in the catchment, including 37 major dams, which together generate more than half of South Africa's electricity. As in all catchments in South Africa, the National Water Act (1998) specifies a flow requirement ('the Reserve') which must be left in the river to meet basic human needs and ecological requirements.

Many studies have been performed into water supply, demand and allocation in the catchment by the Department of Water Affairs and Forestry, universities, and other organisations. For example, one investigation (McCartney and Arranz 2007) considered low, medium and high demand scenarios for public water supply and mining for the year 2025 compared to a baseline scenario for 1995, and a historic scenario for the period 1920–1989 (Fig. 11.1).

The estimated demands from irrigation (the largest water user), mining activities, rural and urban water supply, and commercial forestry were all considered. The 70-year period was also used to test the demand component of the model. For all scenarios it was assumed that the Reserve would be fully implemented by 2025, with no further increases in commercial irrigation, and no significant land use changes or increases in livestock. Likely future dam schemes were also included. Results were obtained for the water that can be supplied at different levels of assurance (reliability) for each type of demand, and for the total demand, and for the indicative costs of shortfalls in demand at each assurance level.

The modelling studies were performed using a water allocation (supply-demand) model called the Water Evaluation And Planning (WEAP) System, which was developed by the Stockholm Environment Institute (Raskin et al. 1992, Yates et al. 2005). The system calculates water demand, supply, runoff, infiltration, crop requirements, flows, and storage, and pollution generation, treatment, discharge and in-stream water quality, taking account of multiple

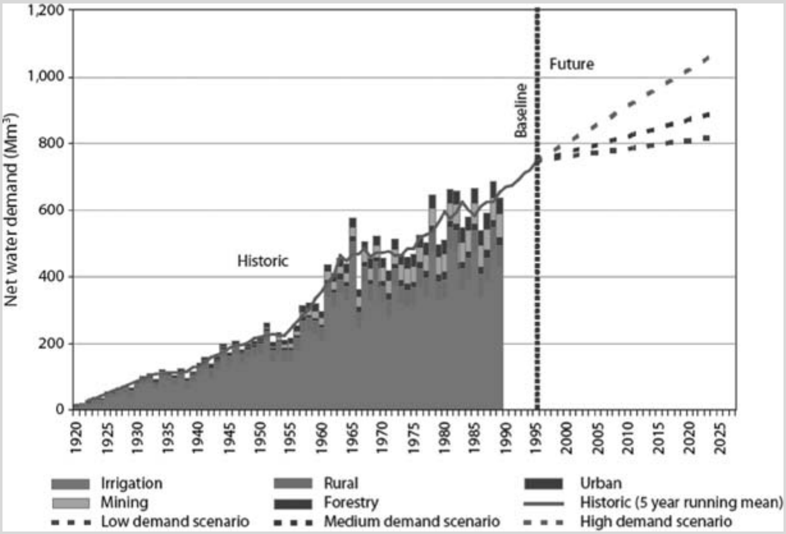

Fig. 11.1 Comparison of water demand in the Olifants River Catchment for the past, baseline and future scenarios (McCartney and Arranz 2007, reproduced with permission)

and competing uses of water and alternative policy options (http://www.weap21.com). The hydrological component uses a semi-distributed lumped rainfall-runoff modelling approach, which includes surface runoff, reservoir, snowmelt, groundwater, irrigated agriculture and surface water quality components (Yates 1996, Yates et al. 2005). Water allocation problems can be addressed using an iterative linear programming approach, and cost benefit analyses can also be performed to compare different options. A wide range of scenarios can be examined, including population growth, changes in reservoir operating rules, introduction of water conservation, inclusion of ecosystem requirements, changes in irrigation practices, and climate change impacts.

For application to the Olifants Basin, eight subcatchments were defined, together with the nine largest reservoirs in the catchment, representing some 68% of the total storage volume. Estimates were also derived for the total sustainable groundwater yield in each subcatchment from the ~10,000 boreholes in the basin. Much of the base data required to configure the model was obtained from the Department of Water Affairs and Forestry, and the model was calibrated using flow data for 5 key gauging stations along the Olifants River.

The modelling results provided a useful basis for discussions with stakeholders, giving an indication of the likely shortfalls in water, and associated economic losses, for a range of scenarios. For example, for the high demand scenario in exceptionally dry years, it was estimated that total annual economic losses could in some circumstances exceed US$300 million, even with the likely future storage being constructed. Several recommendations were made on possible future developments to the model, including a better assessment of model uncertainties, allowing for groundwater development and climate change impacts, and evaluation of the possible impacts of a range of social, political and economic factors.

11.2 Forecasting Techniques

11.2.1 Supply-Demand Models

Supply-demand models are widely used for assessing the availability and reliability of water resources in a catchment or region (e.g. Loucks et al. 1981, Loucks 1996, Wurbs and Wurbs 1995, McKinney et al. 1999, Millington et al. 2006). Some alternative names for supply-demand models, reflecting the wide range of approaches and applications for this type of model, include Decision Support Systems, Integrated Simulation and Optimization Models, River Basin Simulation Models, and Water Allocation Models. Box 11.1 provides an example of the application of supply-demand modeling techniques to river basin management for a catchment in South Africa, whilst Box 11.2 describes the use of this type of model in development of a Water Resources Management Plan in the United Kingdom.

Typically, a mass balance approach is used at a daily or longer timestep, for which dynamical effects can usually be neglected, although time delays in river reaches are often included. For longer term forecasting, such as in some types of reservoir operation (see Chapter 9), models might only be operated on a weekly or monthly timestep, considering primarily the supply component, and over forecasting horizons of several years. Models also increasingly include the option to model water quality and other constituents. To represent meteorological influences, many models also include the option to include a rainfall-runoff modeling component, and may also allow for other meteorological influences, such as reservoir evaporation, or the links between water demand and air temperature.

For water resources applications, the sources which are represented might include reservoirs, lakes, storage tanks and boreholes, whilst demands might be included for water supply, irrigation, industry, and other uses. Additional modules may also be used to keep account of water quality, operating cost, leakage, and other factors. This type of model is often used off-line, in planning mode and, as noted earlier, when used in forecasting applications, usually the only use of data assimilation is to define the initial conditions for components such as reservoirs, lakes, wetlands, and river flows.

Many modeling systems are available and typically the key water sources and demands in the catchment are represented using a node and link approach, connecting the main water sources and demand centers, also allowing for river regulation. Fig. 11.2 shows an example of this type of approach for a coastal region in which two rivers provide water to several towns, two irrigation schemes and a major coastal city. There are also three reservoirs on the upper reaches of the rivers, which provide direct supplies to two of the towns. Two villages and a town also receive

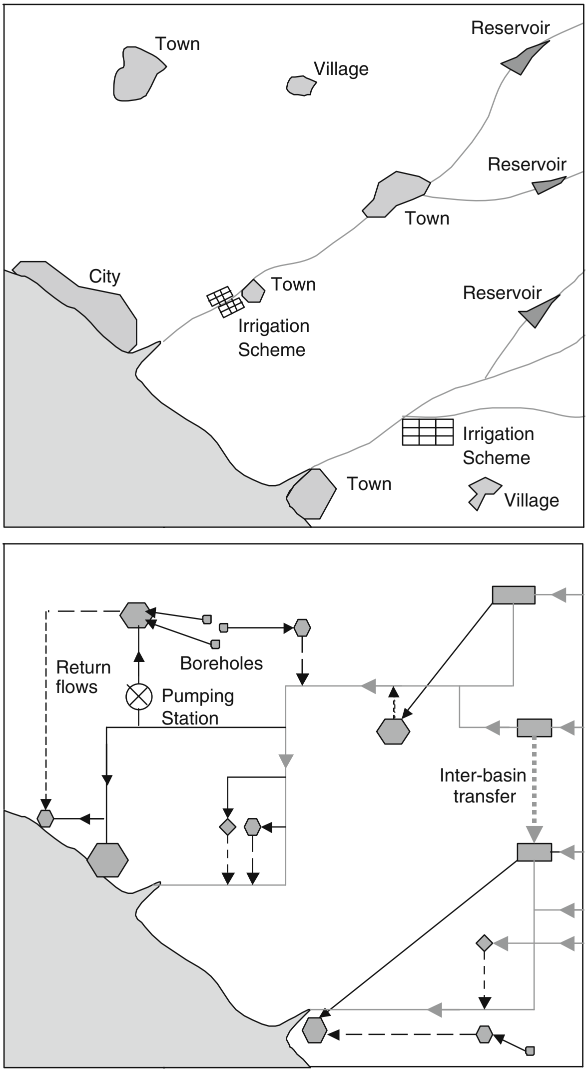

Fig. 11.2 Illustration of a supply-demand model for a coastal region (this is a hypothetical example omitting water and wastewater treatment works for simplicity)

water from groundwater sources, with water typically abstracted using diesel or electric pumps (not shown). The return flows are shown as dashed lines and, for the effluent returns from urban areas, would typically pass through a waste water treatment works (not shown) before being discharged at river or coastal outfalls. There is also an inter-basin transfer scheme between two of the reservoirs. Often, the network is configured using a graphical user interface and, as shown in the figure, does not need to correspond to the geographical layout of sources, demands and water transfer routes.

Modern software packages usually provide a wide range of functionality, including a Geographic Information System (GIS) component. Individual sources such as reservoirs can often be modeled to a high level of detail, including representation of control rules and operating constraints, such as the requirement for releases for environmental purposes. Similarly, it may also be possible to model irrigation, urban water supply, hydropower, and other demands (e.g. electricity demand) to a similar level of detail, including representation of irrigation scheduling, treatment works operations, and pump operating rules.

Usually, the main constraints on the system can also be defined, in terms of maximum flow and volume capacities, requirements for flow releases, abstraction and discharge licences, and other factors, such as minimum allowed flows in rivers, and institutional constraints. Also it is usual to be able to place a priority order on demands, or to specify other criteria, such as to equally share any shortfalls in supply (e.g. with the same percentage reductions). Individual costs can also often be assigned to different sources of water (pumped, gravity fed), and treatment costs, and for different modes of operation (if applicable).

Supply demand models can be used both for long term planning, and operationally to assist with water allocation over timescales of days to months ahead. For operational applications, typically a set of scenarios is run through the system, using a worst case period from the historical record, or sampling complete years from the record. Alternatively, a stochastic modeling approach may be used. Rainfall forecasts might also be included if a rainfall-runoff model is available to estimate flows, sometimes also using ensemble meteorological inputs (see Chapter 4). The reliability of supplies and yield can then be estimated for different scenarios, or in probabilistic terms, often with animations available showing how the water availability in different sources varies over time.

The scenario approach can require multiple runs using trial and error, so the next step beyond this is to optimize the system response based on one or more objective functions. Some approaches to optimization which have been used include linear, non-linear and dynamic programming, in deterministic and stochastic forms (e.g. McKinney et al. 1999, Walker et al. 1989, Walker 1998), and genetic algorithm and other data-driven or artificial intelligence techniques. Chapter 9 describes some of these techniques in more detail. Typically, given the complexity of a typical network, the optimization is often performed on a simpler version of the network, which captures the key features of interest, or performed on the full version using simpler approaches such as linear programming or data driven techniques (although inevitably with additional assumptions about the actual system response). Often, the results will then be fine-tuned using a more detailed simulation model, including the main factors which were excluded in the optimization (e.g. Yeh 1985).

The optimization may be performed in terms of water-related criteria, such as system reliability, or reservoir yield, or in terms of other factors, such as overall operating costs, environmental costs, or energy use. Multi-objective criteria are also often used. For example, in economic assessments, it may be possible to explore the various trade-offs between the use of pumped supplies, and (usually) cheaper gravity fed water sources, including the requirements to maintain water quality. Outputs can also include advice on optimum reservoir operating strategies.

Box 11.2 Integrated Resource Zone, North West England

United Utilities supplies water to some 6.8 million people and over 200,000 businesses and organisations in North West England. Water is supplied via four discrete water resource zones, of which the largest, supplying more than 95% of customers, is called the Integrated Resource Zone (United Utilities 2009). This is a conjunctive use system of reservoir, lake, river and groundwater sources consisting of pipelines, aqueducts and river transfer schemes (Fig. 11.3), for which the main sources are as follows:

- Haweswater and Thirlmere reservoirs in the Lake District
- Stocks reservoir near Clitheroe
- Rivington and Longendale reservoirs near Manchester
- Vyrnwy reservoir in Wales
- Abstractions from the River Lune near Lancaster
- Abstractions from the River Dee in Wales

For example, the Haweswater reservoir provides much of the water supply to Greater Manchester, which is some 160 km to the south.

Under the Water Resources Act of 2003, water companies produce Water Resources Management Plans every five years describing plans for maintaining the balance between water supply and demand over the next 25 years. The latest plan for northwest England (United Utilities 2009) covers the period 2010–2035 and has the following main objectives:

- To identify the best possible water resources and demand strategy
- To adapt to meet the challenge of climate change
- To ensure that abstraction from water resources is sustainable
- To ensure that plans deliver the needs and priorities of customers and other stakeholders

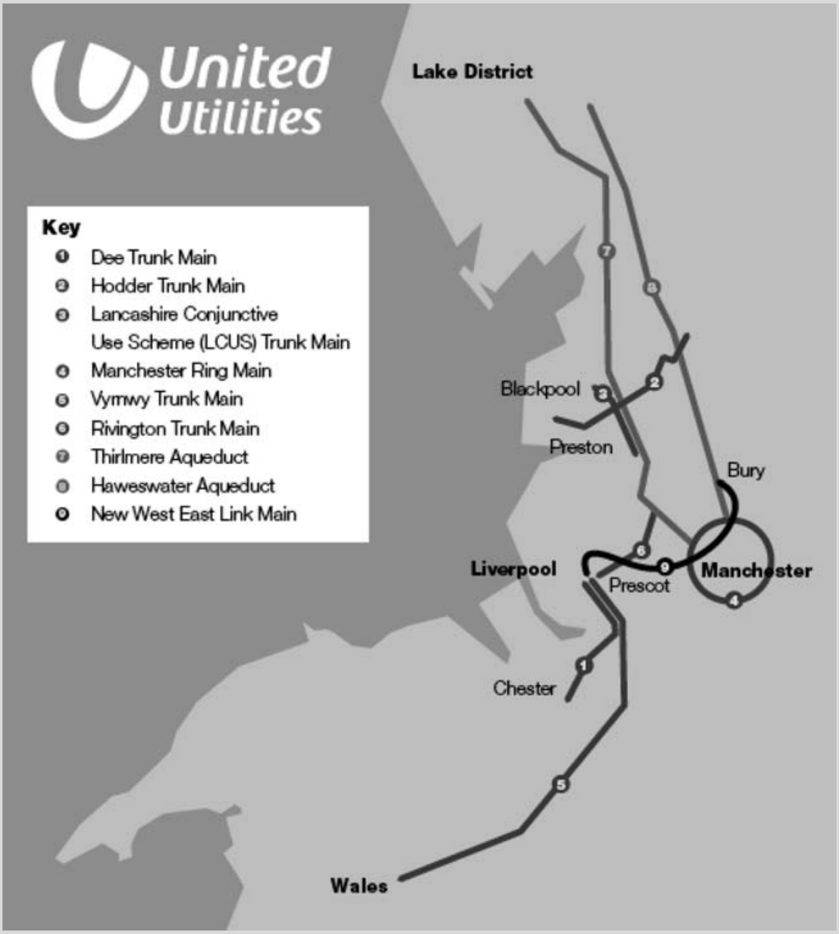

Fig. 11.3 Schematic of the Integrated Resource Zone (United Utilities 2009)

For water supply, some known and likely influences over the period covered by the plan include the requirement to restore sustainable abstractions at several nature conservation sites, the possible impacts of climate change, extra demands from new housing developments, and reductions in industrial demand for water. There may also be some (as yet unknown) sustainability reductions to meet the requirements of the European Union Water Framework Directive. Approaches to managing demand over this period will include leakage reductions, water efficiency initiatives (e.g. low flush volume cisterns), and increased use of metering of water supplies.

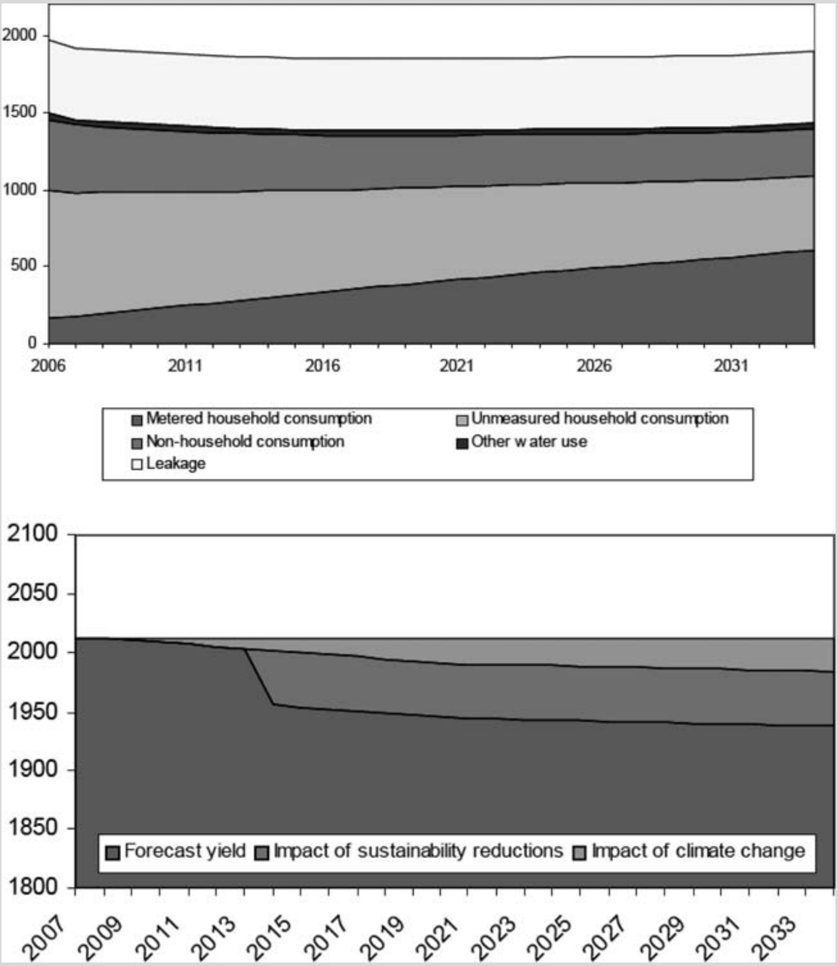

Fig. 11.4 Estimated baseline dry weather demand for all United Utilities zones before taking account of enhanced demand management actions, and trends in dry year water source yields (United Utilities 2009). All values in Ml/day

To assess the combined deployable output from the Integrated Resource Zone, a supply-demand model is used which represents all significant reservoirs, boreholes, river abstractions, aquifers, pumping stations, water treatment works and demand zones, key constraints such as abstraction licences and reservoir control curves, as well as the costs associated with water treatment and electricity usage in different parts of the system. Here, the deployable output is the maximum quantity of water output from a water source, or group of sources, or of a bulk supply, that can be sustained during a dry year (United Utilities 2009). Outage allowances are also included for borehole pump failures, short-term water quality problems, seasonal effects on surface water sources (e.g. algae problems, turbidity), plant breakdown at water sources and treatment works, and reservoir safety works. An emergency storage allowance of 20 days of supply is also included for the Integrated Resource Zone. The optimisation approach seeks to achieve (or improve upon) the following preferred levels of service:

- Hosepipe ban and drought permits to augment supply should not occur more frequently than once in 20 years
- Drought orders to ban non-essential water use and to further augment supply should not occur more frequently than once in 35 years
- No demand reductions achieved through rota cuts or standpipes, even during extreme drought conditions

Using a baseline period of 1927–2005, the model has been used to explore the influences of climate change, changes to abstraction licence conditions, and assumptions regarding demand forecasts and other factors. Investigations have also been performed into the effectiveness of alternative options for investment, such as leakage reduction, water efficiency measures, compulsory metering, enhancement of existing resources, and development of new water sources (e.g. Fig. 11.4).

Stochastic dynamic programming is also used to assist with the optimisation of control rules and operating policies, such as the trade-off between using gravity supply rather than more expensive pumped sources. This approach has also been used in research studies into the likely impacts of climate change on the yield of individual sources and the overall system (Fowler et al. 2007a).

11.2.2 Integrated Catchment Models

In an integrated catchment modeling approach, the river network is typically represented by hydrological or hydrodynamic flow routing models, with distributed or semi-distributed rainfall-runoff models to represent the inflows from tributaries, which may be both gauged and ungauged. Additional modeling components may also be included for river abstractions, reservoirs, lakes, and other features of the catchment, such as reservoirs and other flow control structures. The overall model may be coupled to a groundwater modeling component. The general modelling principles are similar to those for supply-demand models, and there may be many features in common, but typically hydrological and hydrodynamic processes are better represented, and greater use is made of real-time data and data assimilation techniques, such as input, state, parameter or output updating. Distributed, grid-based approaches are also sometimes used, although in a much less complex form than the land-atmosphere models which are described later.

Models of this type are widely used in flood forecasting, drought forecasting and water resources applications, typically for lead times of a few hours ahead through to seasonal forecasting of water supply. Some examples of this general approach are provided in Chapters 1, 4, 7, 8, and 9 including examples of coupled surface water and groundwater models, and techniques for estimation of seasonal snowmelt and other parameters. The rainfall inputs are typically obtained from raingauge, satellite and/or weather radar data, and Quantitative Precipitation Forecasts from nowcasting and Numerical Weather Prediction model outputs (see Chapters 2 and 3). For some applications, other meteorological parameters may also be required, such as air temperature (e.g. for snowmelt modeling), and the parameters required to estimate evapotranspiration using the Penman-Monteith approach (e.g. air temperature, humidity, wind speed and solar radiation; see Chapter 5). Ensemble meteorological inputs are widely used with this type of approach (see Chapters 3, 4 and 7, and Box 11.3).

For short lead time applications, the time available for model runs may be limited, so some simplification and other improvements to model convergence and stability may be required. For example, if a hydrodynamic model is used, some rationalisation may be needed for the model to run sufficiently quickly and reliably for real time use (e.g. Chen et al. 2005). However, in water resources applications, simpler hydrological flow routing approaches, such as Muskingum Cunge or Kinematic Wave models, are often sufficient to meet the requirement, except where particular hydraulic features need to be modeled, such as tidal influences (e.g. saline intrusion), the operation of gates and sluices (e.g. in wetlands), and the details of reservoir operations.

Figure 11.5, which is also shown in Chapter 7, shows an example of this approach for a general simulation model for assessing the long-term flood risk in a catchment in England (Environment Agency 2003). The catchment is represented by more than 20 subcatchments, with the ungauged sub-catchments (i.e those in which flows are not monitored) represented by the suffix ‘i’. As discussed in Chapter 4, some approaches to estimating the ungauged contributions can include scale and lag methods, the use of rainfall-runoff models with the same parameter values as a similar nearby gauged catchment, regionalisation of model parameters (if suitable regression or other relationships can be found), and other techniques. In this example, a significant proportion of the river network is represented by a hydrodynamic model, including all of the main tributaries.

For real-time applications, models are often configured to make best use of the available telemetry data, which may mean omitting some potentially useful gauges due to a lack of real-time data. Some practical difficulties can sometimes include the need to share information between organizations (e.g. on water transfers, or effluent discharges), and that smaller abstractions and discharges are often

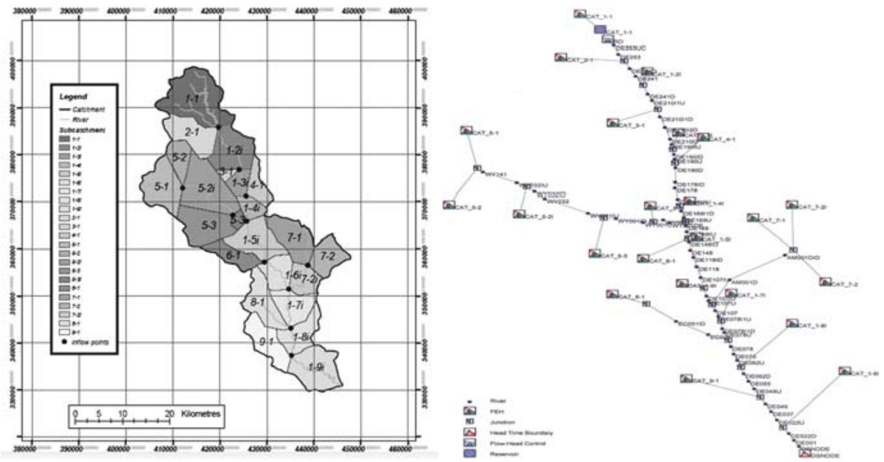

Fig. 11.5 Example of a semi-distributed catchment model, and a hydrodynamic model schematic for a pilot Catchment Flood Risk Management Plan study (**a**) Division of the River Derwent into sub-catchments and sub-areas (**b**) Model Schematic, shown at a larger scale (Environment Agency 2003, Copyright © Environment Agency 2009 all rights reserved)

not monitored in real-time (or at all). In many cases, water balance and other off-line analyses may show that these factors are not significant at the forecasting points of interest, and so need not be included in the model, or only need to be included in an approximate way. In the latter case, some methods for estimating values include scaling values on a similar known measured record, using typical daily, weekly, monthly or seasonal profiles, grouping similar types of abstraction and discharge together, and using sub-models which attempt to mimic the operating rules which are used; for example, based on observed values for river or reservoir levels.

Box 11.3 Inflow Forecasting at BC Hydro

BC Hydro is the third largest electric utility in Canada and supplies power to more than 1.7 million customers in British Columbia (BC) from 30 hydro-electric 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. Models are operated on an in-house forecasting system called the River Forecast System (RFS), whose main components are illustrated in Fig. 11.6 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.

Deterministic five-day inflow forecasts for 20 reservoirs are issued in the morning of every workday (e.g. Fig. 11.7), 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. 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, whilst forecasts for daily precipitation and maximum and minimum air temperatures are obtained from the

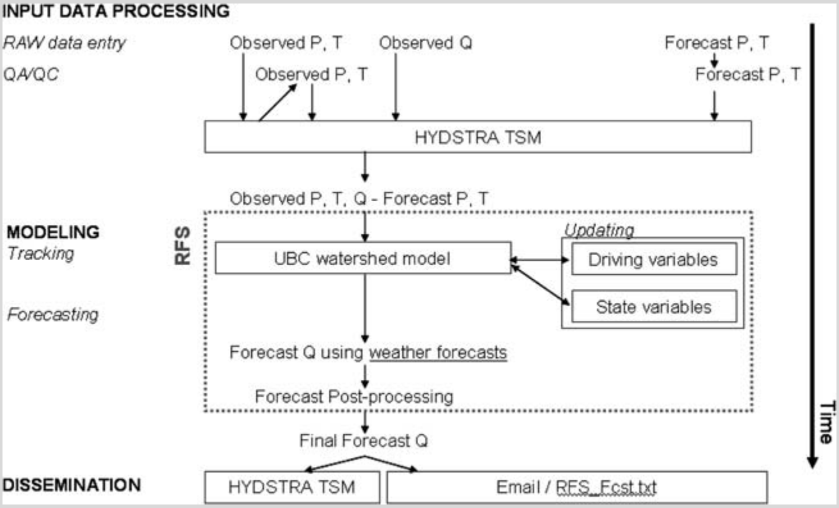

Fig. 11.6 River Forecast System – data flow for short-term forecasts and links to the operational database (HYDSTRA TSM). P = Precipitation, T = Air Temperature, Q = Inflow (BC Hydro)

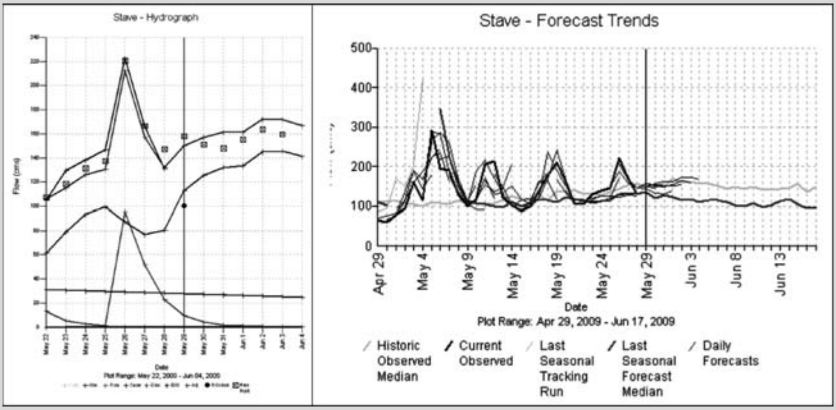

Fig. 11.7 River Forecast System:(**a**) short-term forecast hydrograph with runoff components for a forecast issued on May 29 and (**b**) 30-day record of historical forecasts for Stave Reservoir (BC Hydro)

Canadian Meteorological Center's (CMC) Global Environmental Multiscale model (GEM) operating at a resolution of 15 km to 48 hours ahead and ~33 km from 48 to 204 hours ahead. To be used as input to the UBC Watershed Model, gridded forecasts from the CMC models are downscaled to forecast locations using a spline function, and are subsequently re-calibrated (bias corrected) using the bias calculated from comparisons of observed and forecast values. For air temperature, these corrections are for a moving 21-day window that generally ends 2 days before the forecast date whilst, for precipitation, 60-day totals are used (Bourdin 2009). 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. The uncertainties arising from model parameters will be incorporated into the forecast system shortly, while 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 11.8 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.

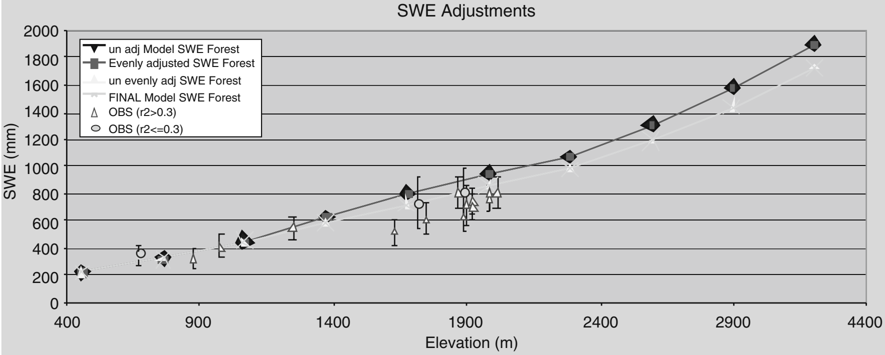

Fig. 11.8 Snow water equivalent data assimilation by elevation band, showing the unadjusted simulated, adjusted simulated and observed snow water equivalent (BC Hydro)

Driving variables and other basin states are also adjusted in the long-term forecast mode but only infrequently. 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.

As a complement to the ESP approach, a statistical approach, called the Volume and Distribution Calculator (VoDCa), 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 analyses 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.

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

11.2.3 Land-Atmosphere Models

For long-term water resources studies, distributed regional, continental or global scale distributed models are increasingly used, particularly for climate change impact assessments (e.g. Bates et al. 2008, Le Dimet et al. 2009). This type of model is sometimes called a macroscale model. A grid-based representation is typically used in this approach, which also facilitates linking of the meteorological and hydrological components of the model. Models may use the outputs from atmospheric models as provided, or a coupled land-atmosphere modeling approach may be used in which changes in land surface conditions can influence atmospheric conditions.

When integrated into General Circulation Models, and operational weather forecasting models, a particular focus in models of this type is often on the vertical exchange of water and energy, rather than parameters such as soil surface runoff (e.g. Shuttleworth 1988, Garratt 1993). However, the horizontal component is increasingly considered, particularly for modeling over longer timescales, when it becomes a more significant component of the soil water balance. The need to consider diurnal variations can also mean that the model time step is short; perhaps only 10–30 min. This general approach differs from the distributed hydrological modeling approach described in Chapters 4, 7, 8 and 10, in which the focus is on forecasting river flows for a range of applications, including water resources (e.g. Collischonn et al. 2007, Wood and Lettenmaier 2006).

Some key issues which are normally considered in developing land-atmosphere models include:

- Surface Energy Balance – representation of all significant terms in the energy balance, including sensible and latent heat fluxes and short and long wave radiation, often using SVAT (Soil Vegetation Atmosphere Transfer) models for soil/plant evapotranspiration, and requiring a detailed representation of the soil water balance (see Chapter 5)
- Data Assimilation – particularly for short lead times, initialization of model runs based on ground-based, weather radar and/or satellite observations of river flows, precipitation, snow cover, soil moisture and other parameters, possibly also with post-processing/real time updating of model outputs (see Chapters 4 and 7)
- Meteorological Post-Processing/Hydrological Pre-Processing – dynamic downscaling, weather matching or statistical processing of meteorological forecasts to better match the spatial and temporal resolution of the hydrological modeling component (see Chapters 3 and 4)
- Spatial Heterogeneity – approaches to representing the combined influence of small-scale variations in soil moisture, vegetation cover, evaporation, heat fluxes etc at the model sub-grid scale (see Chapter 3)
- Storage Influences – representation of the influences from reservoirs, lakes and groundwater flows, particularly artificial influences from irrigation, hydropower, water supply and other operations (see Chapters 5 and 9)

For water resources forecasting, the factors which need to be considered depend on the application, but might include all key abstractions and discharges for water supply, irrigation and/or energy generation, the influence of major reservoirs and lakes, and other key features. For demand forecasting, many techniques have been developed and tend to be specific to the application. Chapter 5 describes a variety of approaches, ranging from detailed consideration of the types and water requirements of individual ‘micro-components’ (drinking water, showers, baths etc) through to regression, artificial intelligence and other approaches.

Perhaps the most complex application of this general approach to date has been in regional and global scale water resources and climate change impact assessments. The range of factors which may need to be considered is large, and can include the mass balances for carbon, phosphorus, nitrogen and other constituents, and other factors such as the impacts of forest fires, atmospheric pollution/aerosols, and changes in vegetation cover. Dynamic vegetation models (or crop simulation models) of the type described in Chapter 5 are usually also included. The influences of feedback effects between climate, the oceans, land use and vegetation cover also need to be considered, together with social and economic factors, and downscaling of outputs to the spatial and temporal scales of interest (e.g. Wilby and Wigley 1997, Xu 1999, Fowler et al. 2007b). Increasingly, this requires a collaborative approach between researchers within an overall modeling framework, as illustrated in Box 11.4.

There is also considerable research underway on developing models of this type to provide early warnings of high-impact weather and climate across a range of timescales, from short-term (e.g. for emergency response) to decadal (e.g. for long-term planning). This would take advantage of recent improvements in weather forecasting and remote sensing techniques, and in hydrological and ocean modeling. However, development of such a system, covering the full range of timescales, has been likened to an endeavour which “will be comparable in scale to the Apollo Moon Project, Genome Project, International Space Station, and Hubble Telescope, with socioeconomic and an environmental benefits-to-cost ratio that is much higher” (Shapiro et al. 2007).

Box 11.4 Joint UK Land Environment Simulator

The Joint UK Land Environment Simulator (JULES) is an open-source (community) model, which is being developed primarily for studying the water and environmental impacts of climate change in an integrated way http://www.jchmr.org/jules (Fig. 11.9). The original version of the model, which was launched in 2006, was derived from the land surface model used in the operational weather forecasting models operated by the UK Met Office (the Met Office Surface Exchange Scheme; MOSES). The development of JULES is a joint initiative by the Natural Environment Research Council (NERC), through the Centre for Ecology and Hydrology (CEH), and the UK Met Office (Blyth et al. 2006).

The individual models within JULES are driven by values for wind speed, air temperature, humidity, incoming radiation and rainfall, either from

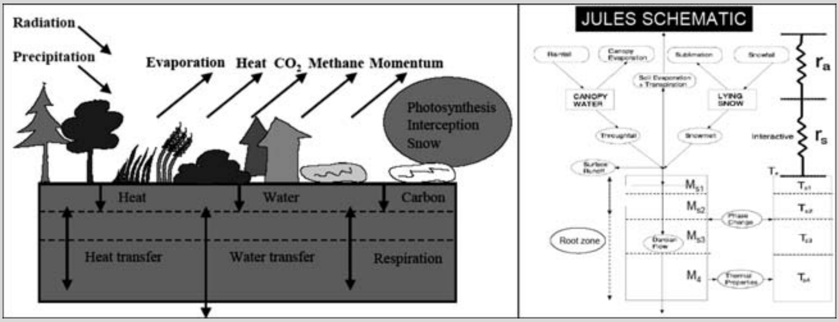

Fig. 11.9 Schematic diagram of the new Land Surface Model JULES (Blyth et al. 2006)

observations or from regional and general circulation models of the atmosphere. The main modelling components include multi-layer soil moisture and snowmelt models, a dynamic vegetation model, and sub-models for other factors such as photosynthesis and carbon fluxes. Components for the influence of reservoirs for irrigation and a simple irrigation scheme are being developed for the model, in which water can be supplied from river, rain-fed or groundwater sources.

To represent the land surface, a grid-based approach is used, calculating the energy, water and carbon balance for each grid. Within each grid cell, a number of surface tiles can be defined, with the land surface types selected from a default set of nine surface types, consisting of broad leaf trees, needle leaf trees, temperate grass, tropical grass, shrubs, urban, inland water, bare soil and ice. Other types can also be added to this list where appropriate. Typical values of albedo, leaf area index and other parameters are defined for each type, and the overall grid energy balance is found by weighting the value from each tile (Clark and Harris 2007).

Several research programmes have either contributed to, or are contributing to, the development of components within JULES, including those summarised in Table 11.1

Some key scientific questions which are being addressed within JULES and other similar programmes include (Cox 2008):

- How large is the climate–land carbon cycle feedback ?
- How will nitrogen cycling influence the land carbon sink ?
- How does biodiversity affect the resilience of ecosystems to climate change ?
- How important is land-management for carbon and water cycling ?
- Where does knowing the state of the land-surface improve the forecasting of rainfall ?
- How should we use observational data to constrain predictions ?

Table 11.1 Examples of research programmes which have contributed to the development of JULES

Programme	Name	Contributions	References
CLASSIC	Climate and Land-Surface Systems Interactions Centre	Improved understanding of land surface characteristics, radiation transfer, drought-deciduous leaf phenology, surface albedo, snow and frozen soil modeling, soil water stress and plant-water status	Cox (2006)
QUERCC	Quantifying and Understanding Ecosystems Role in the Carbon Cycle	A new dynamic vegetation model with improved representation of the nitrogen cycle, a wider range of functional types and more ecologically realistic sub-grid scale dynamics (a sub project of QUEST)	http://researchpages.net/QUERCC/ Blyth et al. 2006
QUEST	Quantifying and Understanding the Earth System	JULES is one component of the earth system models being developed in this major research programme	http://www.questesm.ac.uk/
WATCH	Water and Global Change	Improvements in land atmosphere parameterisations as part of a wider study into the global water cycle and past and future water resources	http://www.euwatch.org/

Some other topics under investigation include approaches to maintaining consistency between model scales (field, local, regional, global), defining standard procedures for the development of scenarios, allowing for interactions between meteorological variables and other parameters when applying scenarios, and benchmarking of model performance. The benchmarking studies are considering water, energy and carbon fluxes, and the model results are being compared with historical data from satellite observations, atmospheric carbon dioxide concentration, snow cover derived from satellite, river flow data and the results from previous field campaigns to measure land-atmosphere interactions, covering 10 locations world-wide.

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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 2001)

Antecedent Precipitation Index the weighted summation of past daily precipitation amounts, used as an index of soil moisture. The weight given each day's precipitation is usually assumed to be an exponential or reciprocal function of time, with the most recent precipitation receiving the greatest weight (UNESCO/WMO 2007)

Automatic Weather Station (AWS) an instrument for automatically measuring climate data in real time including (typically) wind speed and direction, solar radiation, air temperature, humidity, and rainfall, and possibly other parameters, such as soil temperature

B

Baseflow part of the discharge which enters a stream channel mainly from groundwater, but also from lakes and glaciers during long periods when no precipitation or snowmelt occurs (UNESCO/WMO 2007)

Basin see *Catchment*

Black Box Model a model that relates only an input to a predicted output by a mathematical function or functions without any attempt to describe the processes controlling the response of the system (Beven 2001)

Boundary Conditions constraints and values of variables required to run a model for a particular flow domain and time period (Beven 2001)

K. Sene, *Hydrometeorology*, DOI 10.1007/978-90-481-3403-8,

C

Calibration adjustment of the parameters of a model, either on the basis of physical considerations or by mathematical optimization, so that the agreement between the observed data and estimated output of the model is as good as possible (see *Model Calibration*, UNESCO/WMO 2007)

Catchment drainage area of a stream, river or lake, or area having a common outlet for its surface runoff (see *Basin or Catchment*, UNESCO/WMO 2007)

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 Hydrological Model simplified mathematical representation of some or all of the processes in the hydrological cycle by a set of hydrological concepts expressed in mathematical notations and linked together in a time and space sequence corresponding to that occurring in nature (UNESCO/WMO 2007)

Contingency Table a table usually summarizing the relationship between the frequencies of occurrence of two or more variables, at the simplest level consisting of a 2×2 matrix

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, which can include dependence on lead time, the influence of only partial protection against losses, and other factors

D

Data Assimilation the use of current and recent real-time observations of meteorological, river and/or coastal conditions to improve a forecast, and possibly to provide an estimate for the uncertainty in the forecast

Data Collection Platform automatic measuring device with a radio transmitter to provide contact via a satellite with a reception station (UNESCO/WMO 2007)

Debris Flow/Mud Flow flow of water so heavily charged with earth and debris that the flowing mass is thick or viscous (UNESCO/WMO 2007). A high-density mud flow with abundant coarse-grained materials such as rocks, tree trunks, etc (IDNDR 1992)

Decision Support System Decision Support Systems are a general type of computerized information system that supports business and organizational decision-making activities (NASA 2009)

Degree-Day algebraic difference, expressed in degrees C, between the mean temperature of a given day and a reference temperature (usually 0°C). For a given period (months, years) algebraic sum of the degree-days of the different days of the period (UNESCO/WMO 2007)

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 2001)

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 2001)

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 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 (UN/ISDR 2007).

E

Effective Rainfall that part of rainfall which contributes to runoff. In some procedures the prompt subsurface runoff is entirely excluded from direct runoff and then effective rainfall is equal to rainfall excess (UNESCO/WMO 2007)

El Niño-Southern Oscillation (ENSO) a complex system of interaction 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 Forecast a number of realisations of future meteorological, river or coastal conditions based on alternative values for initial conditions, model parameter values etc, which reflect the inherent uncertainties in observations and forecasting models

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 sea water mix. Sometimes called a Delta or River Delta (although this term describes the sediment deposited by some rivers within the tidal zone)

Evapotranspiration quantity of water transferred from the soil to the atmosphere by evaporation and plant transpiration (UNESCO/WMO 2007) . The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation that make up the earth's surface (AMS 2009)

F

False Alarm a warning which is issued but for which no subsequent event occurs. Can also include 'near misses'

Finite Difference the approximate representation of a time or space differential in terms of variables separated by discrete increments in time or space (Beven 2001)

Finite Element the approximate representation of time or space differentials in terms of integrals of simple interpolation functions involving variables defined at nodes of an irregular discretization of the flow domain into elements (Beven 2001)

Flash Flood flood of short duration with a relatively high peak discharge (UNESCO/WMO 2007). Alternatively, 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) (ACTIF 2004)

Flood Defence, Dike or Levee water-retaining earthwork used to confine streamflow within a specified area along the stream or to prevent flooding due to waves or tides (UNESCO/WMO 2007). Can be constructed from a range of materials, including concrete, steel and rockfill

Flood Fighting emergency response operations to reduce or prevent flooding, including reinforcing flood defences, sandbagging, installation of temporary defences, clearing water courses of debris, and other measures

Forecasting System a computer system for managing the operation of one or more forecasting models, include automated collection and validation of real-time data, post processing of model outputs, and possibly automated alerting facilities if thresholds are exceeded

Flow Routing (or Flood Routing) a technique used to compute the movement and change of shape of a flood wave moving through a river reach or a reservoir (UNESCO/WMO 2007)

Forecasting Point a location at which it is useful to have a forecast of future river or coastal conditions (e.g. a Flood Warning Area, a river or coastal monitoring site, a control structure). Sometimes called a Flood Forecast Point, or Water Supply Point.

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 graphical presentation and analysis of spatial datasets, and the associated hardware, procedures, equipment etc

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 in a river, estuary or coastal reach

Hydrograph graph showing the variation in time of some hydrological data such as stage, discharge, velocity, sediment load, etc (UNESCO/WMO 2007)

I

Ice Jam accumulation of ice at a given location which, in a river, restricts the flow of water (UNESCO/WMO 2007)

Initial Conditions values of storage or pressure variables required to initialize a model at the start of a simulation period (Beven 2001)

Integrated Water Resources Management IWRM is a process which promotes the co-ordinated 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 (Global Water Partnership 2000)

Inter Tropical 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 (World Meteorological Organisation 1992)

Lead Time the warning lead time is the time between receipt of a warning and the time of the start of an event; the maximum forecast lead time is the longest lead time at which forecasts can be provided to an acceptable accuracy

Levee see *Flood Defence*

M

Medium-range weather forecast in meteorology, a forecast from 72 to 240 h ahead (World Meteorological Organisation 1992)

Mesoscale Model 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 (AMS 2009)

Monte Carlo Simulation simulation involving multiple runs of a model using different randomly chosen sets of parameter values or boundary conditions (Beven 2001)

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 extrapolation modeling technique which combines the outputs from weather radar observations and possibly Numerical Weather Prediction model outputs and raingauge, satellite and lightning observations to produce short term (typically 0–6 h ahead) forecasts of rainfall and other parameters. Also used at longer lead times for tropical cyclones.

Numerical Weather Prediction (NWP) computer models in which the atmosphere, oceans and land surface are modelled on a three dimensional grid to produce forecasts of future conditions based on initial conditions observed from a wide range of sources (ground-based observations, satellite, ships, aircraft etc)

O

Objective Function a measure of how well a simulation fits the available observations (Beven 2001)

Orographic Precipitation precipitation caused by the ascent of moist air over orographic barriers (UNESCO/WMO 2007)

P

Parameter a constant that must be defined before running a simulation (Beven 2001)

Physically-Based Model a model which to varying degrees solves the partial differential equations representing catchment processes, typically on a gridded basis, perhaps including empirical or conceptual representations for some components of the model (in which case it may be called a physical-conceptual model)

Polder a mostly low-lying area artificially protected from surrounding water and within which the water table can be controlled (UNESCO/WMO 2007)

Public Switched Telephone Network (PSTN) the telecommunications equipment and infrastructure which connects land line telephones

Q

Quantitative Precipitation Forecasts precipitation (rainfall, snow, hail etc) forecasts typically based on nowcasting or Numerical Weather Prediction techniques

R

Rainfall-Runoff Model a model which converts observed or forecast rainfall into estimated river flows

Rating Curve see *Stage Discharge relationship*

Real Time Updating see *Data Assimilation*

Resilience the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures (UN/ISDR 2004)

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 (World Meteorological Organisation 1992)

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 (UNESCO/WMO 2007)

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 2001)

Stage Discharge Relationship or Stage Discharge Relation - relation between stage and discharge at a river cross section and which may be expressed as a curve, table or equation(s) (UNESCO/WMO 2007)

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 2001)

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 the meteorological, river or coastal conditions which initiate (or escalate) a warning dissemination process. Sometimes called triggers, criteria, warning levels, alert levels or alarms

Trigger see *Threshold*

Tropical Cyclone a synoptic-scale to mesoscale low pressure system which derives its energy primarily from evaporation from the sea in the presence of high winds and low surface pressure and condensation in convective clouds concentrated near its center (Holland 2007), usually for maximum sustained surface winds of 64 knots (33 ms^{-1}) or more (although sometimes defined for winds of 34 knots or more). The term tropical cyclone is used in the Indian Ocean, hurricane in the Atlantic and Eastern Pacific Oceans, and typhoon in the Western Pacific

U

Ungauged Catchment a catchment or subcatchment in which flows are not recorded to the extent required for the application (e.g. in real-time for many flood forecasting applications)

V

Vulnerability the conditions determined by physical, social, economic, political and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR 2004)

W

Wadi or Ouedd - channel which is dry except in the rainy season (UNESCO/WMO 2007)

Watershed see *Catchment*

Wave disturbance in a body of water propagated at a constant or varying speed (celerity), often of an oscillatory nature, accompanied by the alternate rise and fall of surface fluid particles (UNESCO/WMO 2007)

Weather Radar an instrument for detecting cloud and precipitation using microwaves typically with wavelengths in the range 3–10 cm

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