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Results from the EC-project BRAHMATWINN

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Dedicated to the People of Brahmaputra River Basin

Preface

Alpine mountains are source areas of major rivers in the world like the Danube River in Europe and the Brahmaputra River in Asia both having glaciered headwaters in the Alps and the Himalayas, respectively. Within the 6th Framework Programme (FP6) of the European Commission (EC), research projects were funded to study Integrated Land and Water Resources Management (ILWRM) issues in 'twinning basins'. The latter have been selected according to common physiographic and socio-economic features that are related to water resources and most likely will be impacted by climate change (CC).

The EC-project BRAHMATWINN was carried out within this programme between June 2006 and December 2009 in the transboundary twinning Upper Danube River Basin (UDRB) in Europe and the Upper Brahmaputra River Basin (UBRB) in South Asia. Its overall goals were firstly to develop methods and tools to assess, model and analyse scenario based impacts of CC and secondly to develop harmonised ILWRM strategies to adapt to such impacts within the existing institutional and governance framework.

They were addressed by natural and social scientists in cooperation with water law experts and local stakeholders and yielded the following results:

1. Regional Climate Model (RCM) based modelling of IPCC SRES scenarios (IPCC 2000) to quantify CC and providing projected climate forcing as input for hydrological water balance modelling;
2. Comprehensive assessment and analysis of the Natural Environment (NE) and its Human Dimension (HD) of both twinning basins including LULC classification and change detection by means of remote sensing, GIS analysis and stakeholder participation.
3. Comparative assessment of glacier distribution and dynamics of glacier retreat complemented by modelling of permafrost distribution.
4. Assessment and classification of wetlands and their vulnerabilities with respect to hydrological ecosystems functions (ESF), ecosystem services (ESS).
5. Hydrological modelling of the water balance dynamics in the UDRB and the UBRB for historical and projected time periods and analysis of hydrological impacts generated by CC signals from IPCC SRES scenarios (IPCC 2000).
6. Regionalisation of the modelled water balance components with respect to flood generation applying the Response Unit (RU) concept and results from the hydrological model for the delineation of Water Resources Response Units (WRRU).

7. Regional vulnerability assessment and risk analysis against flooding applying the RU approach complemented by statistical indicator analysis.
8. Development of 'what-if?' scenario based adaptive ILWRM strategies from stakeholder and expert analysis applying the Delphi approach and selected decision support criteria.
9. Development of a prototype Integrated Land and Water Resources Management System (ILWRMS) to develop and analyse 'what-if?' scenario based adaptive ILWRM strategies.

This book will be useful to researchers, professionals, managers and decision makers associated with study and application of sustainable ILWRM strategies in the backdrop of climate change.

Roorkee, India Nayan Sharma
Jena, Germany Wolfgang-Albert Flügel

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Dr. Nayan Sharma is Professor in IIT Roorkee teaching river engineering and hydraulic structures. Earlier, he was professional engineer for flood control and irrigation in Brahmaputra basin. He supervised 160 M.Tech theses, 19 PhD with 132 publications, and is member of 62 national and international technical committees. He undertook 72 consulting and 9 National and International Research Projects. He edited Springer and INCID books. He received the Indo-Swiss Bilateral Research Award as Visiting Professor in Swiss Federal Institute of Technology Lausanne. He delivered talks in The Imperial College London, Southampton University, Edinburgh University, EPFL Lausanne, Iowa University, IST Lisbon, Dr. K. L. Rao Memorial Lecture in 26th National Convention of Civil Engineering, Institution of Engineers (India) and Engineers Conclave-2014. He researched on new Piano Key Weir technology for dam safety and in-stream storage as adaptation measure for climate change, and implementing RCC Jack Jetty for channelizing Ganga reach.

Introduction

1

Wolfgang-Albert Flügel and Nayan Sharma

In the past decades, climate change (CC) has become a consistent global threat and research challenge (IPCC 2007a, b, c), and there is rising concern that CC will alter a wide spectrum of drivers that are likely to impact our continental and global hydrological domains both in terms of natural and socioeconomic processes (IPCC 2000; IUCN 2000; MEA 2005). Responding to the challenge of global CC, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988 and in a special report published special emission scenarios (SRES), of which the A1B and B1 scenarios (IPCC 2000) are considered as the most likely ones. Therefore, they have been evaluated in the BRAHMATWINN project (Flügel 2011b).

It became obvious that even if greenhouse gas emissions will be reduced, CC will persist, and it is evident that flexible management strategies have to be developed to cope with environment systems that are adapting to related impacts. Integrated water resources management (IWRM) as defined by the Global Water Partnership (GWP) internationally is accepted to be a proper strategy to address these issues (GWP-TAC 2000). As water resources are regenerated in the landscape of a river basin and are controlled by processes that relate to LULC, the IWRM concept has been enhanced by Calder (2005) toward integrated land and water resources management (ILWRM) and both terms are used and addressed in this publication.

Alpine mountain massifs are a key factor for the hydrological regime of major rivers in the world, such as the Danube River in Europe and the Brahmaputra River in Asia, which have their headwaters in the Alps and the Himalayas, respectively. In humid parts of the world, Alpine mountains provide 30–60 % of downstream freshwater, and in semi-arid and arid environments, this figure adds up to 70–95 %. As mountains often have great spiritual, cultural, and historical value for people, they have been recognized in Chap. 13 of *Agenda 21*: “As a major ecosystem representing the complex and interrelated ecology of our planet, alpine mountain environments are essential to the survival of the global ecosystem” (EC 2003).

BRAHMATWINN in its overall objective addressed these issues by enhancing and improving capacity to support sustainable IWRM and ILWRM in river systems of alpine mountain massifs to cope with impacts from likely CC, and to apply and further develop professional geoinformatics tools in case studies carried out in two twinning European and Asian river basins: the Upper Danube River Basin (UDRB) in Europe and the Upper Brahmaputra River Basin (UBRB) in South Asia (Flügel 2011a).

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Although the research studies presented herein have been carried out in both twinning basins the focus will be given to the UBRB, which has not been assessed and studied in this comprehensive and integrated context before.

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2 Conceptual Background of Applied Geoinformatics

Wolfgang-Albert Flügel

2.1 Modelling Global Climate Change

Present global climate modelling state-of-the-art and results have been published by the 4th Assessment Reports of the IPCC (IPCC 2007a, b, c). They compile the results from 21 different atmosphere–ocean global circulation models (AOGCM) for the IPCC scenario A1B (IPCC 2000), evaluated as multimodel datasets (MMD-A1B) in the Program for Climate Model Diagnosis and Intercomparison (PCMDI). According to the 4th IPCC report the temperature projections based on the MMD-A1B models indicate a significant warming over the 21st century. Temperature rise greater than the global mean is projected for South Asia (3.3 °C) and East Asia (3.3 °C), and is significantly higher than the global mean in the continental interior of Asia, for example, 3.7 °C in central Asia, 3.8 °C in Tibet, and 4.3 °C in northern Asia.

2.2 Hydrological Impacts of Climate Change

Glacier retreat and permafrost thaw in high mountains, for example, the Alps, Himalaya, and the Quinghai-Tibetan Plateau, have presently reached an extent and speed that is without historical precedence (Frauenfelder et al. 2009; Karma et al. 2003; Lang et al. 2011; Paul et al. 2004; Ren et al. 2004; Subba 2001). This is likely to have substantial impacts on the hydrological dynamics, resulting in a greater variability in precipitation and stream flows, and increasing the intensity of extreme events comprising water quantity and quality. Declining dry season discharge in rivers of such kind is expected to have major impacts on their ecological ecosystem services (ESS) and unforeseen socioeconomic consequences for rural and urban development (Kääb et al. 2005; Morrison and Gleick 2004). Changing discharge regimes of rivers fed by melting glaciers, snowfields, and permafrost, impact the design and implementation of sustainable integrated land and water resources management (ILWRM) both in the urban and rural domain and is likely to change vulnerabilities of sensitive management systems with respect to floods and erosion (Hutton et al. 2011; Nepal 2012; Nepal et al. 2013; Prasch et al. 2011).

Considering the geographic distribution of glaciers in alpine mountains, the global dimension of this phenomenon becomes obvious (IUCN 2003; Querner 2002), and today diminishing glacier resources have become an international affair as rivers such as the upper Danube and upper Brahmaputra provide the downstream countries with essential water resources to sustain food production, socioeconomic development, and the environment.

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2.3 Applied Geoinformatics in Hydrological Modelling and Integrated Land and Water Resources Management (ILWRM)

Geoinformatics is applied in various ways in hydrological water balance modelling ranging from integrating remote sensing and geographic information system (GIS) (Flügel 2011a; Flügel et al. 2000; Helmschrot and Flügel 2002) to sophisticated data management and software developments for process based, distributed river basin models (Fink et al. 2007; Kralisch et al. 2003, 2005a, 2007, 2009; Krause 2002; Mauser and Bach 2009). The latter either apply raster cells as distributed model entities (Mauser and Ludwig 2002) or hydrological response units (HRU) delineated by means of GIS analysis (Flügel 1995, 1996; Krause et al. 2006) and based on a thorough hydrological system analysis (Flügel 2000). Both techniques use topological models derived from GIS modelling (Pfennig et al. 2009) and respective landscape analysis (Wolf et al. 2009). Object oriented modelling has improved increasingly in recent years to develop process modules (Krause 2002; Krause and Flügel 2005) for model design in model framework systems (MFS). Examples are the Jena Adaptable Modelling System (JAMS) (Kralisch et al. 2005b, 2007; Kralisch and Krause 2007) and the Object Modelling System (OMS) developed by the United States Geological Survey (USGS) (David et al. 2013). The benefit of distributed hydrological river basin models for climate change impact analysis has been demonstrated by various modelling studies (Fink et al. 2007; Helmschrot 2006a, b; Krause and Hanisch 2009; Mauser and Bach 2009).

Applied Geoinformatics for ILWRM concerns the spatial assessment and analysis of landscape systems integrating their natural environment (NE) and its human dimension (HD) and applies innovative software and hardware technologies to provide the detailed information required to adapt toward sustainable ILWRM (Flügel 2009, 2011a; Kralisch et al. 2012). The potential of applied geoinformatics in ILWRM can be described with respect to the BRAHMATWINN project as follows:

1. Model results obtained from the different AOGCM deliver information for model grids cells that are by far too large for applied integrated water resources management (IWRM) and landscape management. They have to be downscaled by means of models and methods developed by means of geoinformatics (Dobler et al. 2011).
2. Changing land use and land cover (LULC), that is, by deforestation or retreating glaciers happens on a meso-scale level in remote areas with no or limited access. Remote sensing combined with GIS are geoinformatics technologies that provide the means for a multiscale comprehensive LULC classification and process oriented analysis. This in turn will allow the delineation of process based landscape model entities for water and solute transport modelling (Lang et al. 2011).
3. Efficient and sustainable IWRM depends on hydrological measurements of high quality from a sufficient dense hydrometric infrastructure. In alpine mountain massifs and particularly in the Himalaya, there is a considerable lack of both of these IWRM prerequisites. Geoinformatics provides the means, that is, geostatistic and process based modelling tools to regionalize the required input data (Prasch et al. 2011).
4. Adapting IWRM to changing environment conditions, that is, to ongoing climate change requires appropriate model tools that are able to represent the hydrological processes which control the river basin water balance and its water and solute transport dynamics. These models apply model entities derived by geoinformatics, that is, from the response units (RU) landscape model (Flügel 1995, 1996; Flügel and Märker 2003) and attribute the latter by means of remote sensing and GIS analysis.
5. Applied in "what-if?" scenario analysis these modelling tools permit predictions of changing water balances, discharge regimes and water resources regeneration, and support IWRM decision making by means of an IWRMS (Flügel and Busch 2011).

As sustainable ILWRM applies a holistic systems approach (Flügel 2000) that accounts for scale related system process dynamics, integrated geoinformatics toolsets are required that offer methods and technologies for multiscale system assessment, modelling, and analysis. The integrated land management system (ILMS) applied in the BRAHMATWINN project provided appropriate software components to carry out such integrated river basin analysis (Kralisch et al. 2012; Zander et al. 2012).

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The EC-Project BRAHMATWINN

3

Wolfgang-Albert Flügel and Nayan Sharma

The BRAHMATWINN project was funded by the European Community (EC contract no. 036952) and was carried out between June 2006 and December 2009. Its overall objective was to provide a comprehensive impact assessment of climate change to the hydrological dynamics and integrated land and water resources management (ILWRM) in alpine mountain massifs (Flügel 2011b). Two twinning basins (Figs. 3.1 and 3.2) from Europe and South Asia have been studied and comparatively analysed:

i. The *Danube river* basin ($A = 801.463$ km^2, $Q_{mouth} = 6.460$ m^3/s), shared by 18 countries, is the second largest river basin in Europe (ICPDR 2005). The upper Danube river basin (UDRB), is defined as the drainage area upstream of the gauging station "Achleiten", located just downstream of the mouth of the Inn river into the Danube river near Passau in Germany. It covers altogether 76.653 km^2 with the majority in Germany (73 % in Baden Württemberg and Bavaria) and Austria (24 %), and the remaining 3 % in Switzerland, Italy, and the Czech Republic.

ii. The Brahmaputra river basin, the mainstream of which originates as Yarlung Tsangpo from the Chema Yundung glacier on the Tibetan plateau, is the biggest trans-Himalayan river basin ($A = 938.000$ km2; $L = 2.880$ km), encompassing parts of the territory, ecosystems, people, economies and politics of China, Bhutan, Nepal, India, and Bangladesh. The upper Brahmaputra river basin (UBRB) shown in Fig. 3.2 in this project is defined upstream of the town Guwahati in Assam, of northeast India, and for the modelling exercises has been calculated to 514.717 km^2. The UBRB is shared mainly by China (282.950 km^2), Bhutan (43.546 km^2), and northeast India (188.111 km^2), where in the state of Assam the river flows in a broad flood plain in front of the Himalaya with a braided channel network and severe bank erosion.

Because of the macroscale size of both basins, two reference catchments of the Lech river in Germany and Salzach river in Austria are shown in Fig. 3.1 and three reference catchments of the Lhasa river in Tibet, China, Wang Chu river in Bhutan, and the Brahmaputra flood plan in Assam, India are shown in Fig. 3.2 and have been selected for detailed studies in both twinning basins.

The overall objective of the project was realized by applying concepts, methods, and software technologies of geoinformatics and other

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Fig. 3.1 Upper Danube river basin (UDRB), selected test catchments, and tributary countries in Europe

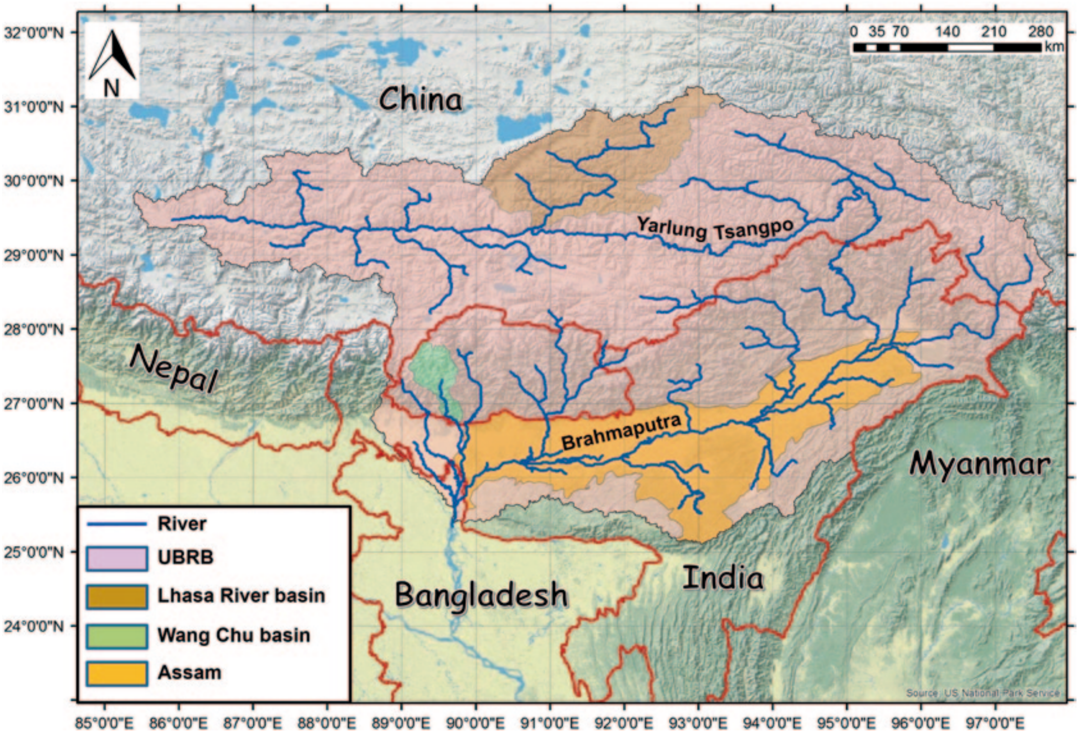

Fig. 3.2 Upper Brahmaputra river basin (UBRB), selected test basins, and tributary countries in South Asia

science disciplines when elaborating on the following project objectives:

i. Downscaling of atmosphere–ocean general circulation model (AOGCM) results modelled for historical and selected climate change scenarios by means of a regional climate model and analysis of the model results.
ii. Comprehensive assessment and analysis of the natural environment (NE) and its human dimension (HD) of the two twinning basins with special focus on land use and land cover (LULC), glacier retreat and wetlands.
iii. Hydrological modelling of the river basin water balances for the time series provided by the climate modelling exercises.
iv. Delineation of water resources response units (WRRU) and analysis of model results with respect to ILWRM.
v. Flood related spatial vulnerability assessment in representative test basins and their comparative analysis.
vi. Development of adaptive ILWRM options to mitigate obvious impacts of climate change taking into account the preferences of stakeholders interviewed.
vii. Implementation of the Integrated Land Management System (ILMS) component River BAsin Information System (RBIS) and enhancement of the system toward a comprehensive ILWRMS.

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4 Regional Climate Projections

Bodo Ahrens and Andreas Dobler

Regional climate projections are required to further downscale the results provided by Atmosphere-Ocean Global Circulation Models (AOGCM) from the global scale grid size to the mesoscale grid size used in ILWRM application for mesoscale and macroscale river basins. The results provided from this climate modelling study were inputs into the hydrological modelling exercises done by the means of DANUBIA hydrological river basin model.

4.1 Objectives

Global climate models (GCMs) are applied to project the climate dynamics into the future under various scenarios (future greenhouse gas concentrations, land use, etc.). The scenarios used in recently performed projections are defined in the Intergovernmental Panel on Climate Change (IPCC) special report on emission scenarios (SRES) (IPCC 2000). The global projections of about 20 models compiled for the IPCC Fourth Assessment Report (4th AR), which are considered here, have a horizontal grid resolution of about 2°. Here, we discuss how a selected set of global projections is dynamically downscaled to regional projections with a horizontal resolution of 0.5°. The purpose of this exercise is to bridge the scale gap between global climate-change projections and impact modelling in the spatially heterogeneous Upper Danube river basin (UDRB) and Upper Brahmaputra river basin (UBRB), respectively. Additionally, this section provides first indications on the expected climate change in these river basins.

4.2 State-of-the-Art

In Europe, regional climate projections were performed with several regional climate models (RCMs) driven by an ensemble of global projections and a variety of scenarios (available, e.g., through http://www.ensembles-eu.org/, Hewitt and Griggs 2004). Only recently, transient regional projections are possible because of the increase in computational power. They project future climate based on continuous simulations with dynamical models initialized with the present climate state. Transient simulations are necessary when natural processes with long memory like glacier and permafrost melting shall be investigated and when the respective impact models shall be driven by the regional climate projections.

Kripalani et al. (2007) evaluated 22 GCMs on the ability to simulate the South Asian summer monsoon precipitation and its variability. The

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study revealed that most of the models are able to reproduce the observed annual cycle (with some difference in amplitude), but also showed that the simulation of precipitation at regional scales is very difficult. Moreover, Kumar et al. (2006) stated that GCM applications in the Indian region are limited by an insufficient orographic representation of, for instance, the Western Ghats or the Himalayan foothills due to their coarse grid resolution. Therefore, the use of a RCM helps to add regional details to the GCM simulations, especially for precipitation. There has been a lack of transient RCM projections in South Asia. For example, the RCM simulations discussed in Kumar et al. (2006) are based on time slice experiments, which are of limited value in the present context.

Empirical/statistical downscaling (see Benestad et al. 2008) of GCM projections are also of limited value in the present context for similar arguments as time slice experiments with RCMs. Additionally, it is difficult to provide a consistent dataset of the necessary input parameters (atmospheric and skin temperature, precipitation, humidity, etc.) for the different impact models applied here. Furthermore, the application of empirical methods is limited in the monsoon climate because of data availability restrictions and event representativeness (the number of precipitation events in the training period of the empirical downscaling method is small in the monsoon off-season).

4.3 Methods Applied

In consequence of the discussion above GCM projections for different SRES scenarios were selected. These global projections were consistently downscaled by transient projections with an RCM, and the regional projections were bias corrected, if justified by observational data. While most GCMs showed agreement in the projected global and continental temperature trends during the twenty-first century, there is much more disagreement in the projections of precipitation, especially at the regional scale. For instance in the Upper Brahmaputa river basin (UBRB), the well-known HADCM3 model is projecting an increase of annual precipitation of about 14% comparing the period 1971–2000 with the period 2071–2100 while the MPI-ECHAM5 model shows an increase of 3% only (data not shown). Kripalani et al. (2007) have tested 22 GCMs used in the fourth IPCC assessment report for their performance in the South Asian region. Amongst these models, they identified no best model within a group of better models, which includes both the HADCM3 and the ECHAM5 models.

The selected RCM is the COSMO model in CLimate Mode (CCLM) version 3.1 (Dobler and Ahrens 2008; Kothe et al. 2011) with a horizontal grid-spacing of 0.44°. Since there is a substantial amount of experience in driving the CCLM with ECHAM5, this GCM is chosen as a driver. The spread in the projection using different driving GCMs is smaller than using different scenarios. The scenarios applied were A1B, B1, A2, and Commitment.

Figure 4.1 shows the applied simulation domain for the European and South-Asian target areas. In both domains, an identical model setup was applied. The time resolution of the provided projection data was 3 h.

Before the projection data were delivered to BRAHMATWINN researchers for the modelling and evaluating of climate impacts on ILWRM, a bias correction was applied for the parameters temperature and precipitation. The temperature was linearly corrected by fitting the monthly annual cycle in the baseline period 1971–2000. Precipitation was corrected using daily precipitation datasets with a grid spacing of 0.5° as described in Dobler and Ahrens (2008) and Dobler et al. (2011). This correction fits the seasonal frequency of wet days and the mean wet day precipitation in the baseline period. Since this correction method relies on a sufficient number of precipitation days in the training period, it was only applied in the monsoon season in the UBRB.

4.4 Results

As shown in Fig. 4.2, the CCLM and the bias correction perform well in the baseline period 1971–2000. Obviously, the CCLM performs better in the European domain than in the Asian domain.

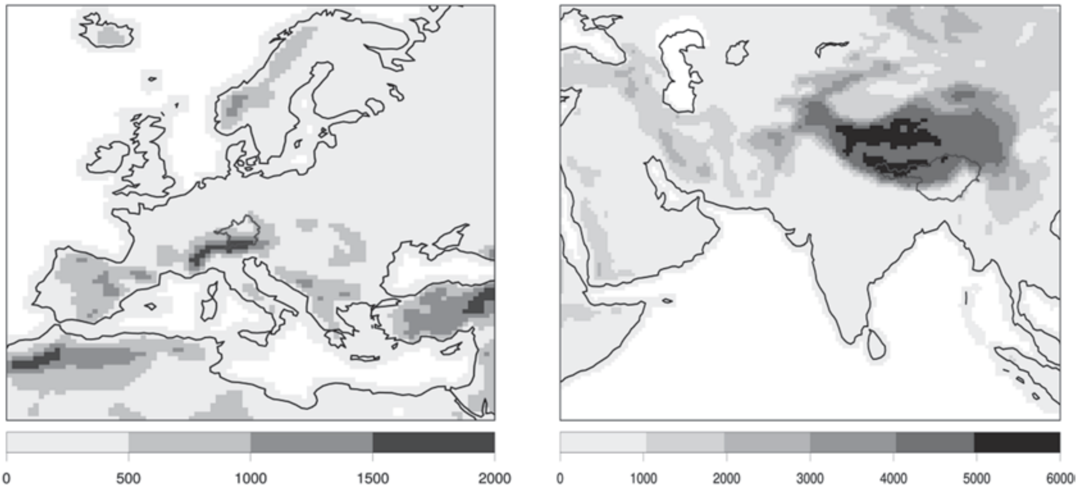

Fig. 4.1 Simulation domains and orography (m) applied for the regional climate modelling with the CCLM in the UDRB (*left*) and the UBRB (*right*) which are marked in *gray*. (Dobler et al. 2011; CC by 3.0 license)

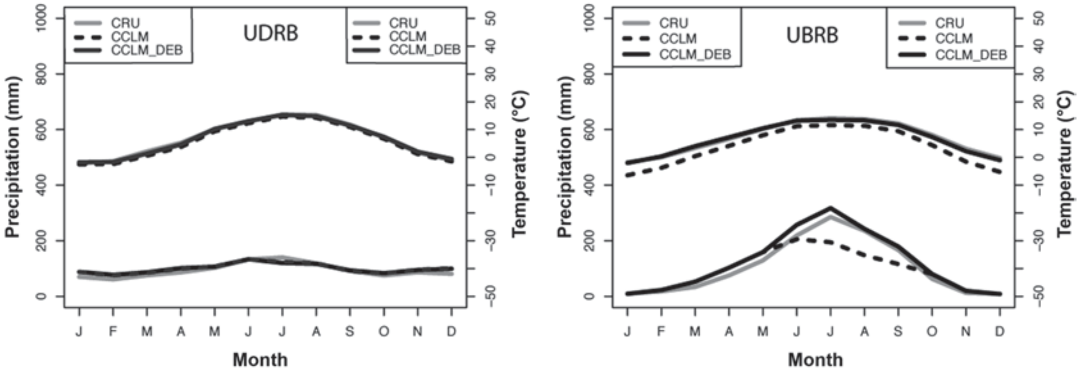

Fig. 4.2 Mean monthly temperature (*upper lines*) and precipitation from CCLM projections (*CCLM*) and bias corrected projections (*CCLM_DEB*) are compared to the observed data (*CRU*; Mitchell and Jones 2005) for the period (1971–2000). (Adapted from Dobler et al. 2011)

The reasons are (a) the longer experience in application of CCLM in Europe and (b) the less complex European climate regime.

Figure 4.3 shows the annual temperature and summer/monsoon precipitation trends in the UDRB and UBRB, respectively. Average temperature increase is projected up to 5 °C in 2100 in the UBRB and up to 4 °C in the UDRB. The annual precipitation shows no significant trend because of compensating trends in different seasons. But the summer precipitation amount in UDRB is decreasing with about 20 %/100 years (see Table 4.1). The negative trends in the UBRB are less significant. Here, the large interannual variability of precipitation amounts has to be kept in mind as indicated in Fig. 4.3.

Table 4.1 illustrates trends of a sample of precipitation-based indicators. The given statistics

Table 4.1 Projected indicators and their linear change (% per 100 years) in the UDRB and in the UBRB for the IPCC SRES emission scenarios A1B and B1 (IPCC 2000). Only the trends for the summer season (JJA) for the UDRB and the monsoon season (JJAS) for the UBRB, respectively, are given. Significant trends at the 5 % level are marked in italics. (Adapted from Flügel 2011a)

Abbreviation	Parameter for climate projections in IPCC scenario A1B and B2	UDRB		UBRB	
		A1B	B1	A1B	B1
PFRE	Fraction of wet days	*−27*	*−19*	*−19*	*−11*
PRECIP	Mean annual precipitation (mm)	*−22*	*−16*	*−11*	−6
PX5D	Max. 5-day precipitation (mm)	0	−5	6	6
PCDD	Longest period of consecutive dry days	*34*	*22*	*24*	*16*

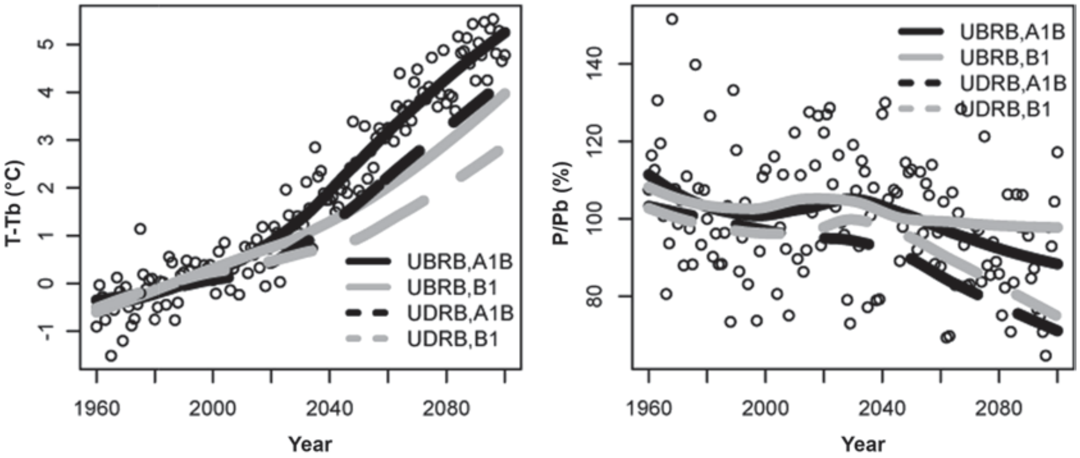

Fig. 4.3 Projections of the annual-mean temperature (*left*) and the summer/monsoonal precipitation (*right*) trends in the UDRB and the UBRB for the IPCC SRES scenarios A1B and B1, respectively (IPCC 2000). Temperature trend is given as an increment against the mean baseline temperature and precipitation is shown as the percentage of the baseline precipitation both for the period 1971–2000. The circles are the projected annual increments for scenario A1B in the UBRB, and the lines are smoothed projections

indicate that the number of precipitation days decreases in both twinning basins in summer/monsoon yielding an increase of the length of consecutive dry days. Concurrently, the projected maximum precipitation in 5-day periods increases in the UBRB, but not significantly if the large interannual variability is taken into account. At sub-basin scales, the trends are diverse. For example, the monsoonal maximum 5-day precipitation shows no trend in Assam but an increasing trend of 11 % in the Lhasa River basin, the length of the longest period of consecutive dry days increases by 28 % in Assam and by 40 % in the Lhasa River basin, respectively (not shown).

4.5 Impact of Global Climate Change

The temperature is projected to increase in both basins and for all seasons in the coming decades with higher values in the UBRB and especially in the regions of the Tibetan Plateau (Dobler et al. 2011). In consequence, parameters directly dependent on temperature like potential evapotranspiration show clear trends, too. Precipitation trends are less unanimous. Annual precipitation is projected not to change substantially, but seasonal amounts change. Also, the derived statistical parameters indicating dry spells, like the length of longest dry periods, are projected to increase. Since this is not correlated with a decrease in the values of the parameters indicating wet spells, there is a tendency to more frequent droughts but not less flooding events are to be expected. The increasing amount of spring precipitation in the UDRB in combination with the spring snowmelt in the Alps might even yield more intense and frequent flooding events.

4.6 Conclusions for Adaptive ILWRM

Using the CCLM regional climate projections driven by the global climate model ECHAM5 with different SRES forcing as defined by the IPCC (e.g., A1B, B1) as input for the hydrological model PROMET (Mauser and Bach 2009) for the period from 1960 to 2100 will allow the analysis of impacts from the climate-change signal on the regional water balance. Thus, it provides the basis for the integrated land and water resources management system (ILWRMS) comprising the hydrological model system DANUBIA, the river basin information system RBIS, and the network analysis, creative modelling decision support system NetSyMoD applied in the EC project BRAHMATWINN. A specific model chain applying an alternative GCM projection for driving the RCM will result in slightly changed regional projections. For example, since the GCM HadCM3 projects a larger increase of precipitation in South-Asia than ECHAM5, it is expected that CCLM would project slightly different trends if driven by HadCM3. This uncertainty has to be taken into account, but is expected to be smaller than the uncertainty because of different SRES scenarios.

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Land Use/Land Cover Classification of the Natural Environment

5

Rajesh Thapa, Stefan Lang, Elisabeth Schöepfer,
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Land use/land cover (LULC) information is one of the most important spatial input for environmental modelling and a crucial indicator to identify and quantify natural and socioeconomic impacts triggered by LULC changes. Such impacts are related to glacier, snow cover, and permafrost melting, the forming of GLOFs (Subba 2001), erosion by land slides, discharge and sediment transport dynamics of alpine rivers, and the socioeconomic regional urban and rural development to name some of them.

5.1 Objectives

Up-to-date LULC information in alpine mountains is not available globally, as the means and capacities to make use of innovative satellite remote sensing techniques is lacking in many countries located in or sharing mountainous regions. Consequently the BRAHMATWINN project objectives in this respect were:

i. Development and application of a comprehensive LULC classification for the alpine Upper Danube River Basin (UDRB) and Upper Brahmaputra River Basin (UBRB) which will serve as a basis for subsequent mapping and modelling tasks.
ii. Improvement of existing remote sensing techniques for satellite image interpretation by means of topography-based corrections.
iii. Capacity development at BRAHMATWINN partner sites to implement and establish state-of-the-art of innovative remote sensing methods.

5.2 State of the Art

The term ‘land cover’ comprises the biophysical properties of the Earth’s surface (e.g. forest, water bodies, glaciers, etc.). ‘Land use’ complementary addresses functional attributions of a

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particular subset of the Earth's surface by human management (e.g. productive timber forestry, agriculture, settlements, and the like). Despite the significance of LULC as an ecological variable, our understanding of LULC dynamic is still poor. For large areas, satellite remote-sensing techniques have now become the single most effective method for LULC data acquisition (Thompson 1996) and are currently in the process of being made operational through global monitoring endeavours like GlobCover (Bicheron et al. 2011).

Traditional, image analysis methods include supervised and unsupervised classification, but results of these have proved to be unsatisfactory due to their dependence on spectral values (Ji et al. 2005). Since the 1980s, improvement of land cover interpretation has been an important research topic (Campbell 1981) and to improve the reliability of LULC classifications, scientists developed a wide range of classification methods, including artificial neural network (ANN) classifiers, expert-system or knowledge-based classifiers, GIS/RS integrated classification, and fuzzy-set techniques.

Since, the 1990s knowledge-based methods were integrated in order to take advantages of the expert knowledge derived from image interpreters into image classification. The knowledge-based expert system provides the interface for an expert with first-hand knowledge of the data and the application to identify the variables, rules, and output classes of interest and create the hierarchical decision tree.

In recent years, a new methodology and concept known as object based image analysis (OBIA) was introduced into remote sensing sciences (Lang and Blaschke 2006) and are implemented either in a commercial or open source software environment (Benz et al. 2004; Kralisch et al. 2012). Satellite images are partitioned into image segments which can be modelled to meaningful objects. Their attributes can be used for advanced, knowledge-based classifications. The generated image objects have spatial properties such as size and form, neighbourhood relations, hierarchical relationships between different levels of aggregation, etc. In addition to the spectral properties of the objects, all these additional information can be used in the classification process.

5.3 Methods Applied

With the objective to enhance the classification results combined approaches have been applied to the LULC classification process. For example, we applied an ecologically driven spectral decision tree approach in combination with Cognition Network Language (CNL) comprising image segmentation and object-based feature extraction. Administrative and topographic map layers have been integrated together with field data collected by means of GPS. Depending on the scale domain of the application Landsat ETM + satellite data (~ the year 2000) have been used on basin-scale and recent Quickbird satellite data for fine-scale studies (Lang et al. 2011).

To ascertain comparative studies between river basins, a harmonized classification scheme was developed which relates to the IPCC guideline (IPCC 2003) based on six LULC classes. The classification scheme used is shown in Fig. 5.1 and applies an adaptive and hierarchical approach, where different levels are defined by the underlying data type, the availability of external knowledge and ground truthing:

- Level 1 comprises eight main classes which are differentiated from spectral signal processing.
- Level 2 further differentiates level 1 in 22 subclasses and applies the spectral signal processing together with auxiliary data like classifications from a digital elevation model (DEM).
- Level 3 contains structurally defined subclasses like vegetation density, e.g. dense vs. sparse forest obtained from expert knowledge or ground truthing field surveys.
- Level 4 requires additional external knowledge, either from experts or from field surveys, regarding the land use management, e.g. irrigation vs. dryland agriculture.
- Level 5, finally, the 'species level' requires very high spatial resolution data and detailed field verifications mapping different LULC features, e.g. wheat or paddy, and thus are applied

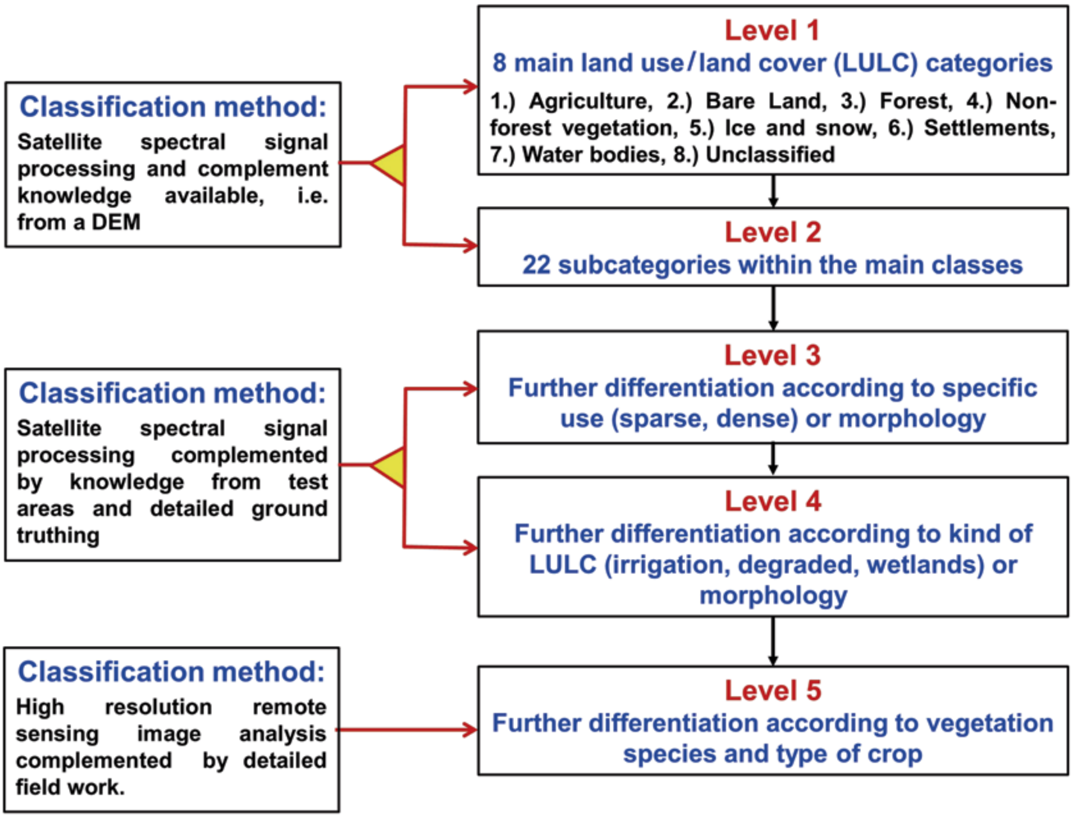

Fig. 5.1 BRAHMATWINN land use/land cover (LULC) classification scheme

on representative micro-scale test areas. As an input to subsequent modelling tasks, Level 1 and Level 2 listed in Table 5.1 have been applied to the reference test catchments within the twinning UDRB and UBRB respectively.

Automated LULC classification is often hampered in areas of high topographic relief due to shadowing effects, which results in different values for one and the same land cover class (Füreder 2010). Topographic normalization as a pre-processing step aims to compensate for the topographically induced illumination variation by means of a digital elevation model (DEM). Within the catchments of either high altitudes or very rugged terrain, Landsat TM satellite data as well as a SRTM-DEM that was re-sampled to 30 m spatial resolution were used as input data to calculate different methods of topographic normalization (cosine correction, Minnaert correction, *C*-correction, and statistic-empirical correction). The results were evaluated and compared visually and statistically regarding quality and usability in order to improve the consequent LULC classification. Minnaert correction, *C*-correction, and statistic–empirical correction proved to successfully reduce topographically induced illumination variations. Overcorrection, however, also occurs in areas of low illumination due to the inadequate estimation of the diffuse irradiance as well as the insufficient resolution of the DEM, which normally should be at least as fine as the satellite image (Civco 1989) pixel resolution.

5.4 Results

The LULC classifications in the UBRB, and here especially those areas heavily influenced by shadow effects, mainly occurring in the Wang Chu

Table 5.1 BRAHMATWINN classification scheme with main classes for level 1 and sub-classes for level 2. (Adapted from Lang et al. 2011)

BRAHMATWINN classification scheme for LULC			
Level 1 comprising 8 main classes		Level 2 comprising 22 subclasses	
No.	LULC	No.	LULC
10,000	Agriculture	1201	Arable land
		1202	Pasture and/or meadow
		1203	Plantation
20,000	Bare ground	2201	Soil
		2202	Rock and debris
30,000	Forest	3201	Coniferous
		3202	Deciduous
		3203	Evergreen
		3204	Mixed
		3205	Plantation
40,000	Non forest vegetation	4201	Bushland
		4202	Alpine grassland
		4203	Grassland
		4204	Shrubland
50,000	Ice and snow	5201	Glacier
		5202	Snow
60,000	Built up areas	6201	Urban
		6202	Rural
70,000	Open water	7201	Water courses
		7202	Water bodies
80,000	Unclassified	8201	Clouds
		8202	Shadow

catchment in Bhutan and the Lhasa catchment in Tibet/China have been improved by ground-truthing field campaigns carried out in Oct/Nov 2007. Verification has been based on a collection of 285 GPS measured ground reference points in the Lhasa catchment and 112 reference points in the Wang Chu catchment, respectively.

Change detection analysis has been carried out in the Guwahati floodplain test area based on a comparison between the Landsat ETM mosaic of 2000 and the Landsat TM mosaic of 1990. With a focus on bank erosion, the change of the river bed, along with increase or decrease of agricultural fields were investigated.

LULC classifications have been generated for the two UDBR reference catchments shown in Fig. 3.1 and for the three UBRB reference catchments shown in Fig. 3.2 respectively. Figure 5.2 is showing exemplarily the result of the Wang Chu catchment classification located at the southwards facing rim of the alpine Himalaya of Bhutan and Fig. 5.3 presents the flat floodplain of the Brahmaputra in Assam, India respectively.

5.5 Impact of Global Climate Change on LULC

It is likely that Global Climate Change will trigger changes in LULC which in turn will likely have numerous impacts on environment, landscapes, and rural livelihoods largely unknown at present. Hence, there is a strong need for further research on exploring LULC changes and consequent changes in landscape process dynamics. Scenario development has become a popular and important tool for the evaluation of the potential shifts. However, results from such exercises must not only be seen as a potential LULC forecast, but they also provide as a knowledge based methodology to reveal impacts of potential LULC changes on economy and society in general.

Changes in LULC are triggered by many factors like the enormous increase in world population over the last three centuries and closely linked with this fact the change of society's requirement on landscape resources to live. As

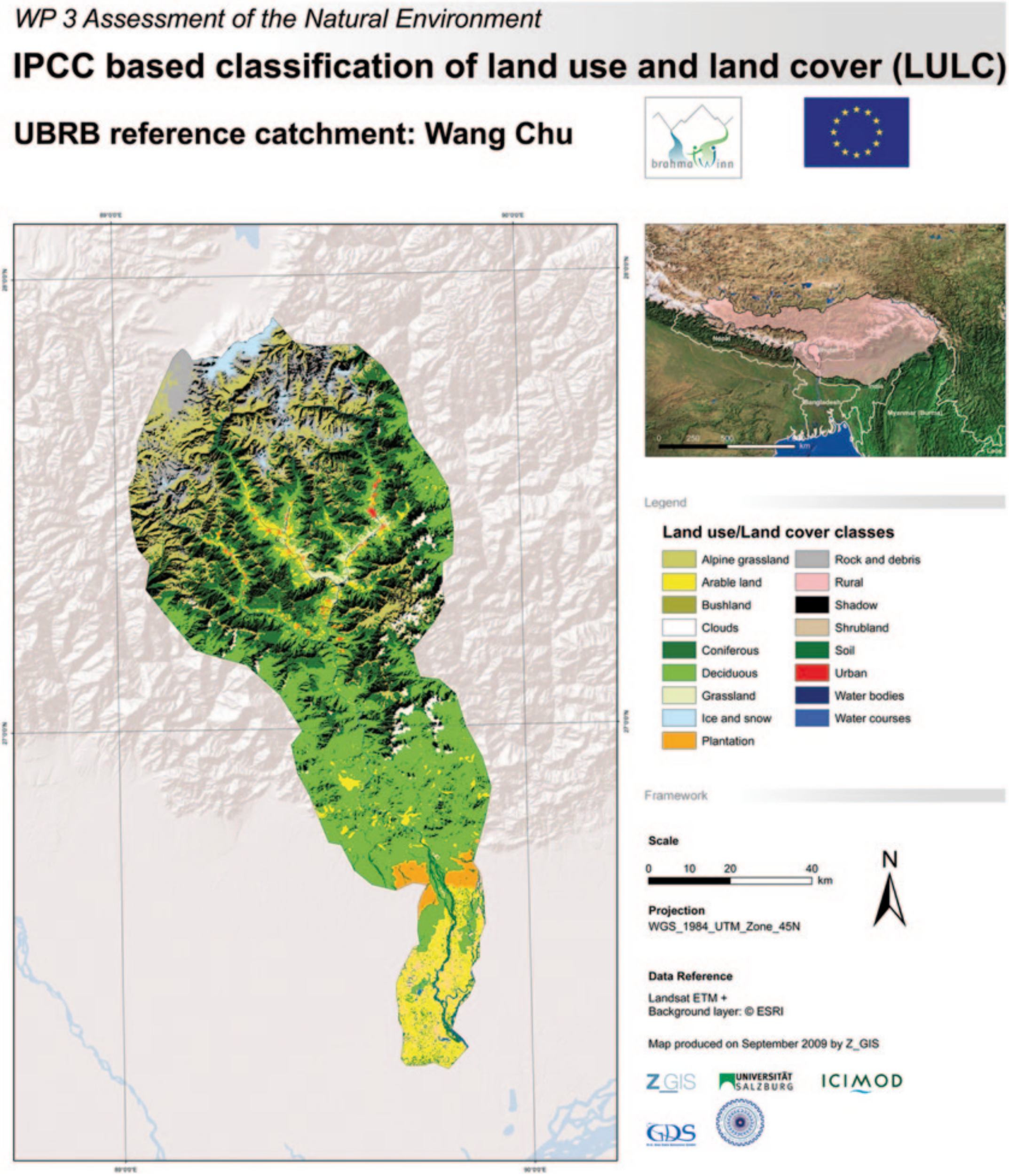

Fig. 5.2 LULC classification for the alpine Wan Chu river basin in the Himalaya of Bhutan. (Lang et al. 2011; CC by 3.0 license)

a result, people have been altering the global landscape for a long time. Deforestation can be taken as an example from the past to the present contributing to the cumulative carbon dioxide in the atmosphere. Albedo or evapotranspiration are hydro-meteorological factors that are impacted by changing LULC.

LULC scenarios and respective data have been collected in the Land Use and Land Cover Change Programme (LUCC) of the International Geosphere Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP). The Integrated Model to Assess the Global Environment

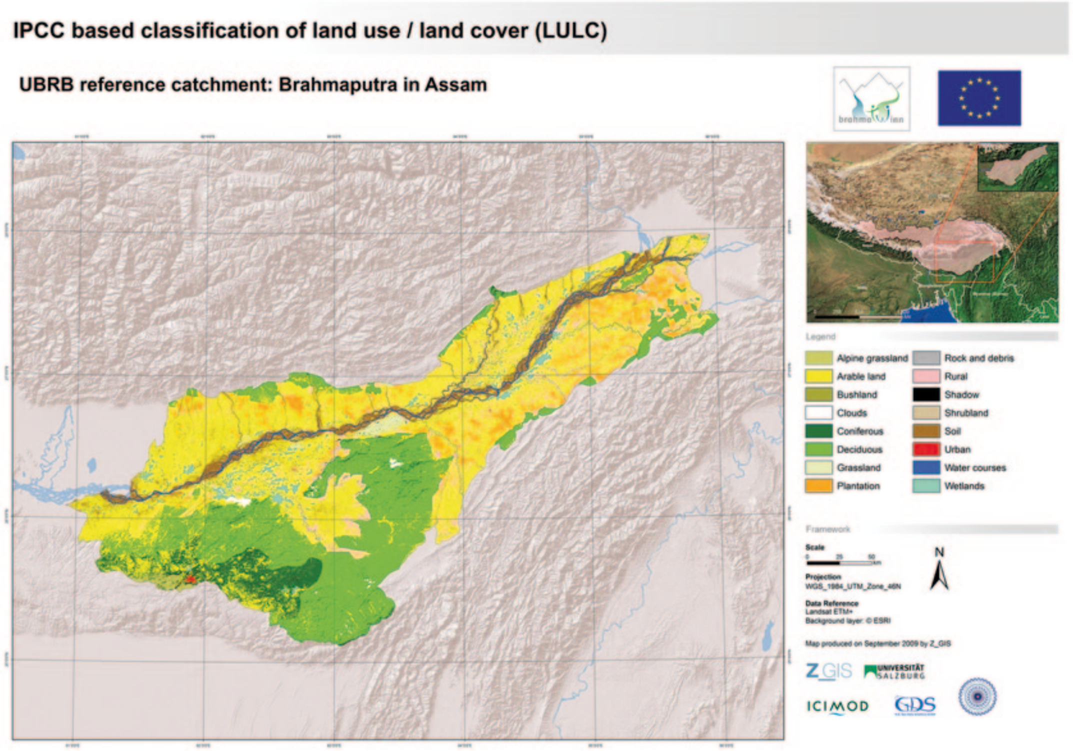

Fig. 5.3 LULC classification for the lower Brahmaputra River floodplains and wetlands in Assam. (Lang et al. 2011; CC by 3.0 license)

(IMAGE) provided by the Netherlands Environmental Assessment Agency, models future changes of LULC under the SRES scenarios (Srengers et al. 2004). In all these scenarios, the extent of land used for cropping, animal husbandry, the production of bio-fuels increases for several decades. Only the A2 scenario (IPCC 2000; Benestad et al. 2008) shows an increasing total crop area until the end of the century, where the total crop area in the other scenarios declines and even reaches lower levels.

If crop area is expanded into forests, the forest products are used until the demand for wood and pulp is met, and the remainder will be burnt. If there is no expansion of agricultural land, the demand for timber and pulp is taken from mature woods which afterwards recover again. All scenarios further show a significant increase in biomass crops to satisfy part of the energy demand. Land use change in industrialized regions shows that the total area of cropland in these regions increases significantly in all scenarios excluding B2.

The reason behind this is an increasing demand for food by Asian countries like India or China. Both of them are showing rapid economic development and an increase of population, and although self-sufficient in food productions at present this development will cause pressure on present LULC and will induce future extension of agricultural land. Consequently all scenarios except in B1 indicate continuing deforestation during the first half of this century and in the A2 scenario the total forested area will decrease rapidly. In other scenarios deforestation stops and is even reversed (Verburg et al. 2006; Tötzer et al. 2007).

5.6 Conclusions for Adaptive ILWRM

ILWRM is strongly related to updated information of distributed LULC and the latter has been identified as a crucial input element for the identification of adaptive ILWRM scenario options

(IPCC 2003). LULC is controlling landscape inherent process dynamics related to ecosystems functions (ESF), ecosystem services (ESS) generated by the water cycle and land degradation by erosion. Therefore, LULC can be transferred into model parameterisation and thereby becomes directly quantifiable with respect to its impact on these process dynamics. Remote sensing is the best way to classify LULC in meso- and macroscale river basins, and is of high priority when distributing the basin in process based model entities applied in hydrological models. LULC, in addition, is of high importance for the socioeconomic domain to model additional proxies.

Currently, data access is a less crucial point as the opening of the Landsat archive has shown, and efforts are currently ongoing to provide regular global monitoring services. Progress still has to be made in regard to future scenario models which allow a solid modelling of LULC predictions. The latter is an important component for scenario based IWRM assessment and the development of "what-if?" scenarios applied in the development of adaptive response options for sustainable ILWRM.

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Glacier Changes and Permafrost Distribution

6

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Glaciers, snow cover and permafrost are important storages of terrestrial fresh water and are released from the storage by melting processes having a seasonal dynamics. Their changes over time can have significant impact on the water cycle controlling the discharge behaviour of alpine rivers and on natural disasters relating to thawing of glaciers, snow and permafrost. These effects often include downstream areas outside of the direct glacial and periglacial zone.

6.1 Objectives

The overall objective of the glacier and permafrost assessment was to assess and evaluate existing know-how about their dynamics and to merge them into a comprehensive assessment of the glacier and permafrost situation in the Upper Danube River Basin (UDRB) and the Upper Brahmaputra River basin (UBRB). This was realized by means of the following scientific and technical objectives:

i. Compile the past and present glacier distribution in the UBRB and the UDRB for suitable points in time in order to detect and analyse recent changes in glacier cover in the basins by means of remote sensing (Paul et al. 2004; Kääb 2005).
ii. Estimate the alpine mountain permafrost distribution in the UBRB and the UDRB by means of topographic modelling, and validate the model results in particular for the UBRB where such model was developed for the first time.
iii. Evaluate the results obtained to better understand the glacial and periglacial character of the two basins, and to assess potential impacts from climate change related to glaciers and permafrost and their relevance for ILWRM.

6.2 State of the Art

Glacier inventories provide a map of glacier outlines and glacier-covered areas for a certain time step, defined by the base data used. A glacier inventory is an important data base for retrieving all kind of glaciological indicators, and for visualizing, analysing and investigating glacier cover and its changes (Kääb et al. 2002; Paul et al. 2002, 2004). Glacier area loss is an important indicator for recent and current impacts of climate change in the reference area, climate change impact on the cryosphere systems and

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related glacier-hydrology in the headwaters and downstream of respective river basins like glacier lake outbreak floods (GLOFs) as described by Subba (2001).

The *glacier area percentage* (GAP) gives a general indication about the ice resources in a river basin and the degree of its glacial character. The latter influences a number of hydrological processes such as seasonality of river runoff, control of dry-season river discharge by glacier melt and the vulnerability of the catchment to climate change induced glacier changes. *Glacier hypsography* indicates how sensitive the glacier areas potentially are to climate changes and how the impacts of climate changes on glaciers might develop. Glacier hypsography is particularly important for monsoon-type glaciers, where a change in air temperature not only affects the degree of ice melt (glacier ablation) but also the degree of accumulation (solid or liquid).

The existence of *mountain permafrost* has significant effects on hydrology, slope stability and other natural hazards, sensitivity to climatic changes, landscape development, erosion processes, permafrost-glacier interactions, etc. (Harris et al. 2009). The *permafrost area percentage* gives a first general indication of the degree of the periglacial character of a region. The latter influences a number of processes such as mass turn-over and erosion processes, sensitivity/vulnerability of the catchment to climate change induced changes in the ground thermal regime, or probability of permafrost-related hazards, e.g. slope instabilities. The *permafrost area hypsography* indicates, in particular, the sensitivity/vulnerability of the landscape to climate-change induced ground changes, i.e. periglacial slope destabilisation.

6.3 Methods Applied

The 1970s glacier inventory compiled for the UBRB was mainly based on the Chinese Glacier Inventory. For the Wang Chu catchment in Bhutan, the baseline inventory was digitized from Corona satellite data from 1974. The year 2000 glacier inventories in the UBRB were mainly compiled from Landsat7 Enhanced Thematic Mapper (ETM+) multispectral satellite data. For the UDRB, the pre-existing glacier inventories were digitized from air photos of 1969 and 1998 (Lambrecht and Kuhn 2007).

The Chinese Glacier Inventory was carefully checked glacier by glacier for the Lhasa River test catchment and an additional test area in the north-western UBRB. Glaciers with obvious errors of digitization or georeference were excluded from the multi-temporal analyses. In the Lhasa River and Wang Chu river catchments, and the additional test region of the north-western UBRB, the glacier outlines for around the year 2000 were obtained by semi-automatic segmentation (Kääb et al. 2002; Paul et al. 2002; Frauenfelder and Kääb 2009). The resulting glacier area and its changes were also up-scaled to the entire UBRB using the Wang Chu, the Lhasa River and the north-western test area of the UBRB.

It should be noted that uncertainty regarding the representativeness of the three test areas for the glaciation of the entire UBRB associates uncertainty to the values calculated for the entire UBRB compared to the directly measured values for the test areas. This upscaling to the entire UBRB was done through relating the area change of a certain glacier size class in the test areas to the sample size of this class in the entire UBRB. The glacier volumes in the test areas were estimated using two widely used empirical area-volume relations.

The permafrost distribution in the UDRB was modelled as a function of the mean annual air temperature as derived from the elevation of the −2 °C isotherm and the mean temperature lapse rate in the area of concern, and the potential incoming short-wave radiation (Hoelzle 1996). Both factors, elevation and radiation, were derived using the SRTM elevation model. Since such permafrost model was for the first time applied to the UBRB, the model results were validated using a more physically based permafrost model in a small validation area, alongside with a rock glacier inventory that was compiled from high-resolution satellite data. For the UDRB, a model similar to the one described above was

Table 6.1 Glacier cover in river basins and areal changes between 1970 and 2000

Parameter	River basin			
	Lhasa River (UBRB)	Wang Chu (UBRB)	UBRB (*estimated from upscaling*)	Salzach River (UDRB)
Reference basin area (km^2)	32,752	4687	5,14,720	6688
Glacier area ~2000 (km^2)	429	50	14,400	79
Glacier area ~1970 (km^2)	535	60	17,580	95
Glacier area change per decade (%)	−7.1	−6.6	−7.5	−6.3
Glacier area ~2000 (%)	1.3	1.1	2.8	1.2
Glacier area ~1970 (%)	1.6	1.3	3.4	1.4

applied, but using an aspect-dependent probability threshold instead of a radiation term.

6.4 Results and Scenario Modelling

Glacier inventories of the Lhasa River and Wang Chu catchments have been produced. They are listed together with the results obtained from the Salzach tributary river of the UDRB in Table 6.1 and revealed:

i. The glacier area in the Lhasa River catchment is about eight times larger than in the Wang Chu catchment. The glacier area change, however, is similar in both catchments with around −7 % per decade, though slightly lower in the Wang Chu catchment, presumably due to the significant debris cover of the glacier tongues. Such debris cover reduces glacier ablation and thus reduces glacier mass loss and retreat.
ii. The glacier area loss in the Salzach catchment during ~1970 to ~2000 was similar but slightly lower as compared to the area loss in the UBRB catchments.
iii. Total glacier area percentages for the reference river catchments are low with values ranging between 1.1 and 1.3 % indicating that the Lhasa River catchment is slightly more glaciated. The glacier area percentage of the Salzach catchment is 1.2 % and lies between the one of Lhasa River and Wang Chu.
iv. The three catchments lost between 0.2 and 0.3 % in total glacier area percentage between the 1970s and about 2000. The total glacier area percentage for both UBRB catchments is about half of that for the entire UBRB. Glacier changes in the UBRB will thus have potentially slightly more impact than in the two UBRB test catchments investigated in detail.

The glacier hypsographs show that the maximum glacier areas are at around 5300 m altitude for the entire UBRB, 5200 m for the Wang Chu catchment, 5700 m for Lhasa River catchment and 2700 m for Salzach river catchment in the UDRB. The Lhasa River catchment high altitude glacier cover might therefore be less vulnerable to a certain rise in air temperature than the other catchments. Compared to the entire UBRB, the Lhasa River glacier cover is restricted to a comparably small elevation band. The Wang Chu catchment glacier cover shows a second peak at around 4500 m altitude representing the large debris-mantled glacier tongues that survive at lower elevations due to their debris cover insulation. These low-elevation glacier parts are particularly exposed to air temperature rise and could be stagnantly down-wasting. This process is known to support the development of glacier lakes which in turn are known to generate Glacier Lake Outbreak Floods (GLOFs).

By means of empirical area–volume scaling and upscaling to the entire basin it was found that, the glaciers in the UBRB lost about 20 % of

Table 6.2 Modelled permafrost areas (km^2) in the UBRB and the UDRB. (Lang et al. 2011; CC by 3.0 license)

Parameter	River basin			
	Lhasa River (UBRB)	Wang Chu (UBRB)	UBRB	Salzach River (UDRB)
Catchment area (km^2)	32,752	4687	514,720	6688
Permafrost area (km^2)				
Likely	10,026	70	76,836	–
Possible	6000	120	49,610	279
Total	16,026	190	126,446	279
Total without glaciers (1970s)	15,491	130	108,866	184
Permafrost area percentage (%)				
Total	49	4	25	4
Total without glaciers (1970s)	47	3	21	3

their volume between the period 1970 and 2000. This totals to an ice volume loss of about 175 km^3 which in turn equals to an annual loss of about 7 km^3/year representing a glacier mass balance deficit of about -0.3 m of water equivalent per year (cf. Kääb et al. 2012; Gardelle et al. 2013).

Permafrost distributions in the UBRB and the UDRB were modelled and interpreted together with glaciers, glacier lakes, steep terrain etc. in order to identify potential interactions and climate change impacts. The results have been listed in Table 6.2 and revealed:

i. Compared to the Lhasa River catchment (Xie et al. 2009) and the entire UBRB, the larger part of permafrost occurrence in the Wang Chu catchment is possible, but is considered as not really likely. This indicates a larger area of permafrost close to the melting point and thus a higher sensitivity/vulnerability of the permafrost in the Wang Chu catchment to changes in boundary conditions—most importantly air temperature and snow cover.

ii. The permafrost area percentage in the UBRB is comparably high with 20–25 %, underlining the strong periglacial character of the basin. For comparison, the glacier area percentage is significantly low with around 3 %. Nearly, half of the Lhasa River catchment is presumably underlain by permafrost, in contrast to 3–4 % for the Wang Chu. Periglacial processes dominate in the Lhasa River catchment, whereas they play only a minor role in the Wang Chu catchment. As a consequence, change in the ground thermal regime, due to climatic changes, will therefore have significantly more impact in the Lhasa River than the Wang Chu catchment (Liu et al. 2009; You et al. 2007).

iii. The largest permafrost areas in the UBRB and Lhasa River catchment are at altitudes around 5200 m and around 4900 m for the Wang Chu catchment. Because of the strong dependence of permafrost distribution to altitude the permafrost area histograms consequently reflect the topographic distribution of elevation. The significantly lower altitude of permafrost areas in the Wang Chu catchment indicate a significant sensitivity of permafrost to changes in air temperature and snow cover.

iv. In the Salzach basin within the UDRB, the area percentage underlain by permafrost is in the order of 3–4 %, perhaps even less, because the model applied to the UDRB allows slightly warmer conditions for the existence of permafrost compared to the UBRB permafrost model. Similar percentage figures are found for the entire UDRB as for the Salzach River catchment.

6.5 Impact of Climate Change

Glacier cover and permafrost distribution are in parts significantly different between the UDRB and the UBRB and their representative test catchments investigated. The UBRB has a strong periglacial character rather than a glacial one. In the UDRB, both the glacial and periglacial zones occupy comparably small areas. The Lhasa River

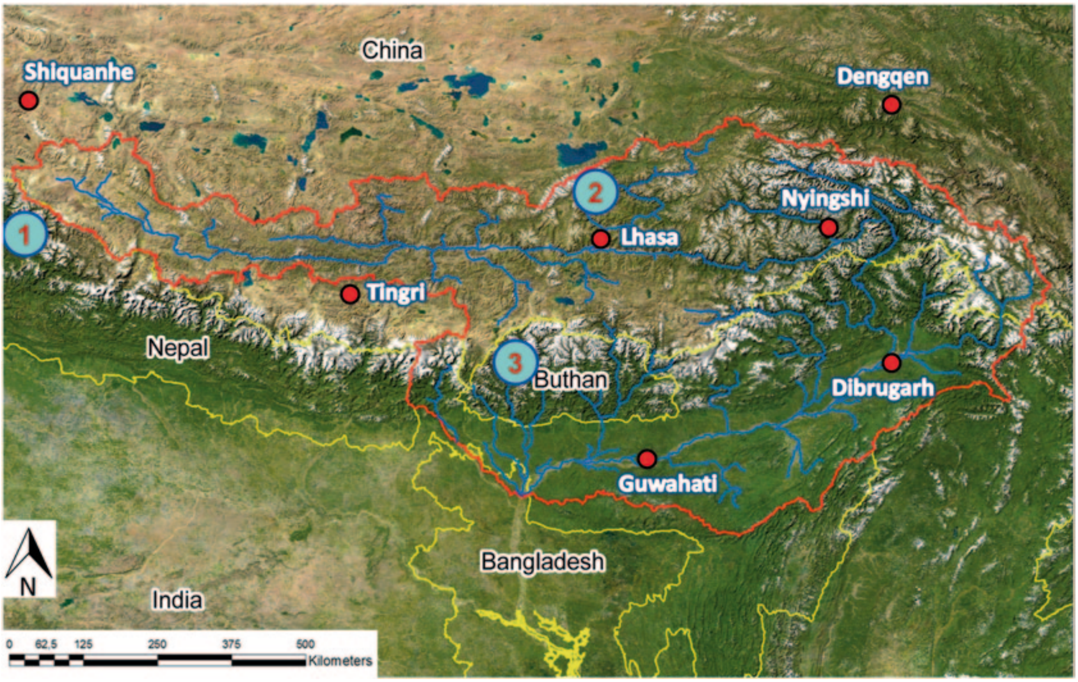

Fig. 6.1 Average reduction of glacier area per decade for three study regions: (1) North-west Nepal, area change approx. −8 %/10 yr (1980: ca. 450 km^2, 2000: ca. 370 km^2; Frauenfelder and Kääb 2009); (2) Lhasa River basin, approx. area change -7%/10 yr (Nyainqentanglha mountain range, see Table 6.1); (3) Wang Chu River basin, Bhutan, approx. area change −6−7 %/10 yr. (See also Table 6.1)

and Wang Chu catchments in the UBRB and the Salzach River catchment in the UDRB in the year 2000 had a glacier area percentage in the order of 1.1–1.6 %, the entire UBRB a percentage of around 3 %.

This percentage glacier area since the 1970s shrank by around 0.2 % due to a glacier area loss of around 6–7 % per decade. This corresponds to a release of water from the glacier storage since the 1970s in the order of 20 % for the entire UBRB (Kääb et al. 2012; Gardelle et al. 2013). The reduction of glacier cover elaborated for the UBRB is summarized in Fig. 6.1.

The mountain permafrost distribution in the UBRB was modelled for the first time revealing a total permafrost area percentage of about 20–25 % compared to around 3 % glacier area percentage. In contrast, the permafrost area in the UDRB is in the order of 3–4 % at maximum.

6.6 Conclusions for Adaptive ILWRM

The water resources stored in glacier-ice in the UBRB as well as in the UDRB have shown a significant decrease in the past three decades and according to most SRES climate scenarios this trend will continue in the forthcoming decades as well. However, the actual down-stream impact of these changes to the run-off regime depends much on the distance to the glaciers. The small glacier area percentage of a few percent indicates that the glacier-impact on river run-off in the lower part of the river basins studied will be small (Kääb et al. 2012; Gardelle et al. 2013). This is in contrast to perceptions found in media and parts of the public, that the lowlands around the Himalaya will be heavily affected by river run-off changes due to glacier shrinkage. Such effects, however, increase towards the headwaters regions with glacier cover where depending on the glacier-climatic setting, and on the natural and socio-economic vulnerability, glacier shrinkage can thus have a significant impact on livelihoods of the population in glaciated high mountains.

The areas underlain by permafrost in the UBRB are significantly larger than the glaciated areas. The impacts of permafrost changes on the river-runoff are still hardly understood, but could in cases such as in the UBRB cause potentially large impacts.

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Wetlands and Their Dynamics

7

Norbert Exler, Iris Wagner and Georg A. Janauer

7.1 Objectives

In BRAHMATWINN the upper Danube river basin (UDRB) and the upper Brahmaputra river basin (UBRB) were selected as the representative catchments in two mountain-dominated geographical regions. Three test sites were selected in the UBRB: the Lhasa River catchment in Tibet/China, the Wang Chu river catchment in Bhutan, and the Assam reach of the Brahmaputra river. In the UDRB the Lech river and Salzach river catchments were studied. This chapter focuses primarily on the vegetation of wetlands, which are dynamic ecosystem elements, depending on their hydrological resources and thus prone to suffer from climate change impacts. Location, hydrological ecosystem functions (ESF), and ecosystem services (ESS) together with the vulnerability of wetlands were assessed.

7.2 State of the Art

Wetlands depend on the hydrology of their surface and subsurface water bodies. Assessing wetland conditions depends on a sufficiently dense network of recording stations and a digital elevation model which reflects the subtle terrain differences that determine hydrological connectivity. These data were available in the UDRB on local scale, but were missing in the major part of UBRB. A severe difficulty arose due to lack of ground-based vegetation data, and wetland survey data also lacked in the UBRB test regions. General information was available from the Global Lake and Wetland Database (Lehner and Döll 2004), the Corine Lake Cover for the UDRB (European Environment Agency), and local field data was provided by project partners and different wetland databases, for example, RAMSAR Site Information Service (http://www.ramsar.wetlands.org/), Global Wetland Inventory Database (IWMI, http://webmap.iwmi.org/mapper.asp), National Wetland Atlas of India (SAC 2011), and the "Natura 2000 network" (http://ec.europa.eu/environment/nature/natura2000/index_en.htm) of the European Commission Environment initiative for biodiversity. As these data sources provided quite heterogeneous information, the different data character was addressed by means of a specific methodology of wetland identification.

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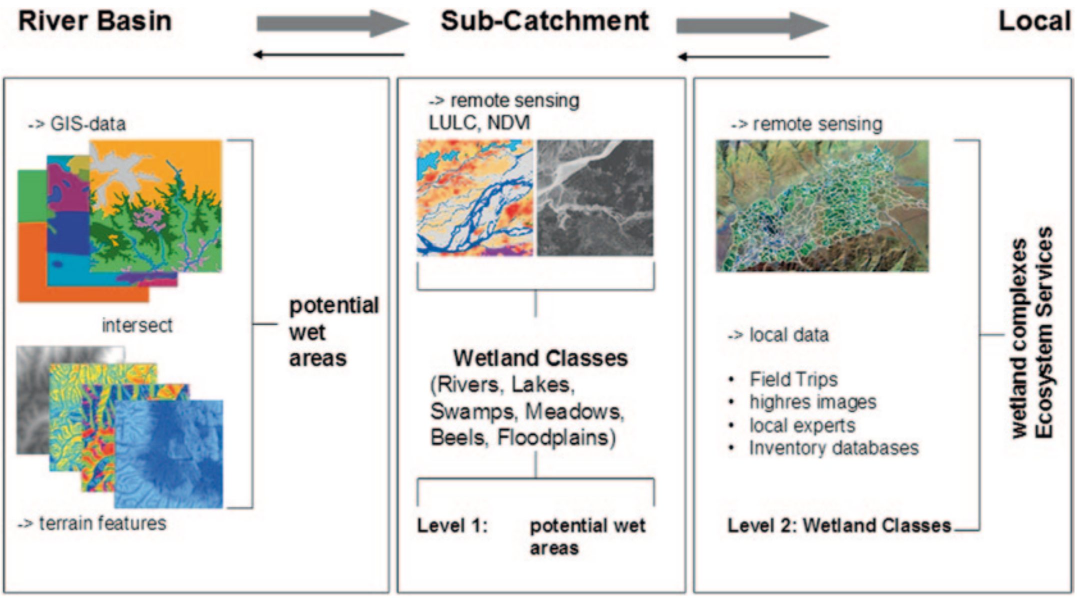

Fig. 7.1 Multi-scale approach to assess the wetland distribution from river basin, via sub-catchment to local scale

7.3 Methods Applied

ESF comprise of structural, spatial, and temporal processes of ecosystems (de Groot et al. 2002), and benefit the human wellbeing by means of ESS they provide, as evaluated in the Synthesis Report Wetland and Water (MEA 2005). Based on expert opinion on a global average pattern for wetlands we adapted the framework of ESS as discussed in the climate change section (MEA 2005) for classifying wetland classes at sub-catchment scale. ESS used to assess the biodiversity of the wetlands were refuge function, biological control, pollination resource, and genetic and medicinal resources. The vulnerability of the wetlands was assessed particularly with regard to the pressure of the human population on wetlands, and regarding the possible effects of climate change on wetland distribution.

7.4 Results

The wetland distribution was assessed by applying a multiscale approach, where global geo data and local data were aggregated at sub-catchment scale (Fig. 7.1).

Local and river basin scale were combined by a rule-based expert system at sub-catchment scale. Land use and land cover (LULC) classification and normalized difference vegetation index (NDVI) provided from the remote sensing analysis were used to identify alluvial areas, lakes, alpine swamps and meadows, floodplains, and flooded beels (Table 7.1) including geostatistical aspects.

The different wetland types were further classified into four hydrological classes are listed in Table 7.2.

An example of the four classes of level 1 classification of wetlands is given in Fig. 7.1 using remote sensing in the Lhasa River basin shown in Fig. 7.2.

7.5 Impact of Climate Change

Projected climate change effects for the period 2010–2080 show that glacier melting in high altitude areas of the UBRB and more irregular discharge and possibly longer low run-off periods in lower altitudes are likely, and these impacts will exert pronounced negative effects on a great number of presently existing

Table 7.1 Wetland classes, their dominant land cover for the UBRB and the UDRB and mode of delineation

Wetland class	Description	Derived from
Alluvials	UBRB/UDRB: water courses and their adjacent plains	Neighbor-functions of LULC classes (bare ground, water courses)
Lakes	UBRB/UDRB: permanent lakes (incl. glacial lakes, reservoirs, and tanks)	low NDVI values, International Centre for Integrated Mountain Development (ICIMOD) classification
Floodplains	UBRB: natural—seminatural floodplains next to alluvials UDRB: natural–artificial floodplains next to alluvials	Neighbor-functions LULC classes (wetlands, arable land, bare ground, open water, forests)
Alpine swamps	UBRB: high altitudinal swamp-complexes (~5000 m) UDRB: mires, bogs, fens	Neighbor-functions LULC classes (wetlands, bare ground, open water, alpine grassland);
Alpine meadows	UBRB: high altitudinal meadows (~ 5000 m)	High NDVI values within LULC class “Alpine grassland” and next to swamps
Beels	UBRB: low altitude wetland patches like ponds, oxbow lake/cut-off meander, water-logged areas, swamp/marsh next to cultivated land	ICIMOD classification, neighbor-functions LULC classes (wetlands, arable land, plantation, urban, rural, bare ground, forests)

Table 7.2 Hydrological wetland classes based on their hydrological dynamics

Hydrological class	Description of hydrological dynamics	Wetland class
Flooding	Seasonal flooding and inundation with sediment rich runoff from the adjacent river	Alluvials, floodplains, beels
Groundwater	Flooding from groundwater dynamics with seasonal rise and falling of groundwater level	Lakes, swamps
Hybrid	Characterized by a hybrid dynamics comprising of flooding from the adjacent river complemented by high groundwater levels	Beels, lakes
Slope	Located at footslopes, these wetlands are fed by interflow from the adjacent slopes	Swamps, meadows

wetlands. Additional impacts may arise from land-use changes, leading to a substitution of wetlands by farmland and settlements in the wake of present high population densities, and projected development. Essential livelihood capacities for the local population will be lost, when hydrological wetland ESS like clean drinking water resources, flood retention areas, and fundamental biodiversity resources become extinct.

The large wetland areas in the Brahmaputra valley provide important provision, regulation and supporting services, and a rich biodiversity—the overall relative magnitude was evaluated from high to medium value in Table 7.3 (Lang et al. 2011).

7.6 Conclusions for Adaptive ILWRM

Based on our assessment of wetlands in the UBRB, it is stated that a first prerequisite for adaptive ILWRM is more detailed information on the local water regime of wetlands, including a denser net of recording stations in floodplains and much more detailed elevation models, data sources that are missing so far. This information is needed to better determine wetland vulnerability on an individual level. Existing and future population pressure must be balanced with wetland areas and are required to sustain their essential environmental and hydrological ESS. Otherwise, impacts from climate change cannot be addressed effectively. This leads to the final

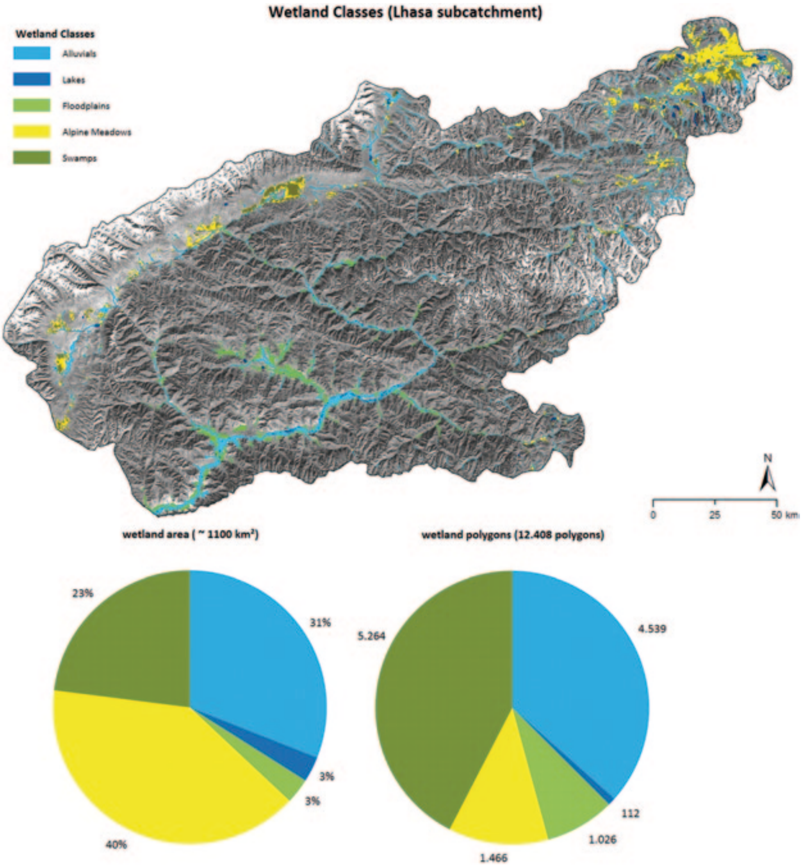

Fig. 7.2 Remote sensing based level 1 wetland classification given in Table 7.1 applied for the Lhasa River basin. (Lang et al. 2011; CC by 3.0 license)

conclusion that the integration of all relevant policy levels and science fields is needed to save wetlands and their ESS throughout the UBRB, despite the considerable difficulties to be expected (Zalewski 2000).

Table 7.3 Assessment scheme for hydrological ESS, biodiversity and vulnerability

Ecosystem Services and Vulnerability	Alluvial	Lakes	Flood-plains	Swamps	Meadows
Provisioning					
Food, Raw materials	2	1	1	2	2
Genetic, medicinal resources	3	3	3		
Fresh water	1	1	3	3	3
Regulating					
Climate regulation	3	1	1	1	2
Water regulation	1	3	1		
Water supply	2	1	1	3	
Waste treatment	1	2	1	2	3
Erosion control and sediment retention	2	3	2	3	3
Disturbance regulation	2	2	2	3	3
Supporting					
Refugia	1	1	1	2	2
Biological control	1	1	1	3	3
Pollination	3	3	3	3	3
Soil formation	2		2	3	3
Nutrient cycling	2	1	1	3	
Biodiversity					
Fauna and flora	2	2	2	3	3
overall median	2	1	1	3	3
variation (+ till -1)	1	1	1	0	0
Vulnerability					
Human Dimension	3	2	1	3	3
Climate Change	3	2	1	1	1

Relative magnitude according to (MEA 2005): 1 = high, 2 = medium, 3 = low

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Large Scale Distributed Hydrological Modelling

8

Monika Prasch, Thomas Marke, Ulrich Strasser and
Wolfram Mauser

The impact of climate change on water resources is one of the most essential issues for the population of mountain areas and their forelands in the future (Barnett et al. 2005). To identify appropriate adaptation strategies, water balance models must realistically describe and quantify the reactions of watersheds to climate change at the regional scale.

8.1 Objectives

The overall objective of the hydrological modelling study within the BRAHMATWINN project was to quantify the historical and projected water balances of the UDRB and the UBRB and to provide insight into the distributed hydrological dynamics within both twinning basins. This was realized by elaborating on the following scientific objectives:

1. Regionalization of the modelled climate times series for the past and the projected IPCC scenarios provided by the climate modellers.
2. Applying the DANUBIA hydrological basin model component (Mauser and Ludwig 2002; Mauser and Bach 2009) to model the water balances at different time intervals.
3. Analysing the model results with respect to impact of climate change to the water balance and consequences for adaptive IWRM.

8.2 State of the Art

Hydrological water balance modelling nowadays applies remote sensing and GIS for process-based distributed river basin models (Krause 2002; Marke et al. 2011a, b; Mauser and Ludwig 2002; Mauser and Bach 2009). Their regionalisation concept is either based on raster cells applied as distributed model entities (Mauser and Ludwig 2002) or Hydrological Response Units (HRU) delineated by means of GIS analysis (Flügel 1995, 1996; Krause et al. 2006). Both concepts apply topological models derived from topographic landscape analysis and GIS modelling to route the modelled runoff components from the model entities to the river (Pfennig et al. 2009; Wolf et al. 2009). Therefore, distributed hydrological river basin models are best suited for climate change impact assessment and analysis

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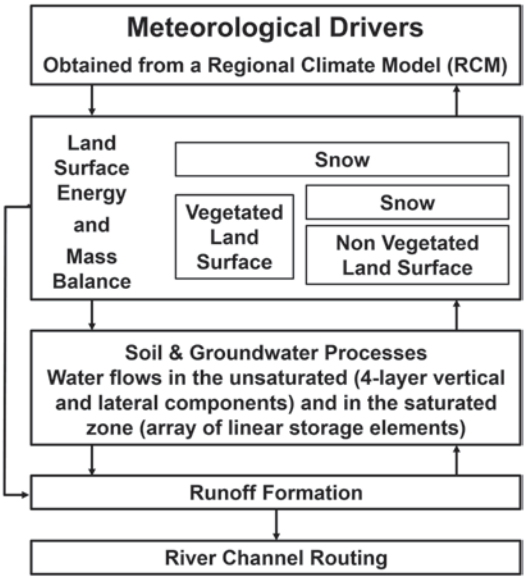

Fig. 8.1 Schematic diagram of the PROMET components and their interfaces (*arrows*) for data exchange. (Adapted from Mauser and Bach 2009)

(Krause and Hanisch 2009; Mauser and Ludwig 2002; Mauser and Bach 2009).

8.3 Methods Applied

The hydrological model component PROMET (Processes of Radiation, Mass and Energy Transfer) (Mauser and Bach 2009) of the decision support system DANUBIA (Mauser and Ludwig 2002) was applied and is herein referred to as the DANUBIA hydrological model. The latter is a physically based, distributed model, which strictly conserves mass and energy within as well as throughout all its components and feedbacks. The model applies 1 × 1 km raster elements as distributed model entities and runs on an hourly time step. As shown in Fig. 8.1, it consists of interacting components for meteorology, land surface energy and mass balance, vegetation, snow and ice, soil hydraulics and soil temperature, ground water, channel flow and hydraulic structures.

To provide the DANUBIA hydrological model with meteorological forcing from regional climate models in the required spatial resolution, further downscaling was applied to the CLM output by means of coupling the SCALMET (Scaling Meteorological variables) tool (Marke et al. 2011a), which has been successfully applied in the UDRB (Marke et al. 2011b).

SCALMET applies different scaling techniques, ranging from direct interpolation methods to quasi-physically based approaches, to adequately remap regional climate model outputs. With this tool air temperature, incoming long wave and short wave radiation, wind speed, precipitation, surface pressure and humidity are scaled down from the spatial resolution of CLM (50 × 50 km) to the (1 × 1 km) raster resolution required for the process description at the land surface scale.

Particularly in mountainous regions like the Brahmaputra headwater catchments this approach is important, because the coarse spatial resolution of the regional climate models cannot fully represent the scale of the environmental process variability. Furthermore, a temporal interpolation routine to disaggregate the 3 h values provided by the CLM model to an hourly time basis is implemented into SCALMET. As the downscaling techniques implemented in SCALMET are based on physical and statistical approaches, they do not require any further parameterization for the local domain of the river basin (Marke 2011b).

Besides the meteorological drivers, input data of topography, land use and land cover as well as soil texture are required on the raster field resolution. The digital elevation model was derived from SRTM data (http://srtm.csi.cgiar.org/) and then was stepwise upscaled from a resolution of 90 m up to 1 km per raster cell applying a bilinear interpolation method. Slope and aspect were derived from this digital elevation model. To include a suitable LULC data set, we use the public available LULC classification from MODIS/TERRA (Boston University 2008).

The digital Soil Map of the FAO/UNESCO (FAO-UNESCO 2003) represents the basis for the applied soil texture classification. These data are stored as a raster GIS structure for the DANUBIA hydrological model and are initialised at the beginning of the modelling.

Detailed information of soil physics and plant parameters, stored as data tables, are taken from literature and/or field campaigns. Mauser and Bach (2009) give an overview of the principles of the parameterization. The results of the DANUBIA hydrological model consist of both a specified set of output variables for selectable raster elements, and of spatially distributed fields for the catchment area, describing, for example the water balance and runoff components.

8.4 Results

The hydrological modelling was applied for the historical period from 1971 to 2000, driven by CLM ERA data provided by the climate modellers to validate the model results. The meteorological forcing used to drive DANUBIA in this model setup was provided from a CLM run, in which the regional climate model has been forced by ERA reanalysis data at the boundaries of the model domain. In the following, we focus on the UBRB. For the results for the UDRB, reference is made to Mauser and Bach (2009) and the GLOWA-Danube-Project (2009).

The averaged modelled water balance components for this historical time period in the UBRB is shown in Fig. 8.2 and can be described as follows:

1. The average annual precipitation provided by the downscaled CLM model is about 1550 mm and evapotranspiration is adding up to an annual average of 320 mm. The difference between precipitation and evaporation is the mean modelled basin discharge of about 19,810 m^3/s.
2. According to Jain et al. (2007), the average discharge near the confluence of the Brahmaputra with the Ganges River is 19,200 m^3/s. This value very well corresponds to the modelled discharge, although in general the latter is slightly overestimated by the model. Taking into account several uncertainties of the input data as well as the observations, the results justify or recommend the application of the DANUBIA hydrological model for future scenario projections in the UBRB.

ECHAM5 driven CLM runs with different forcing as defined by the A1B and B1 SRES scenarios of the IPCC (2000) for the projected time period from 2010 to 2080 were used as input time series for the hydrological model to quantify projected impacts of climate change on the water balance components of the UBRB. The results from this DANUBIA modelling exercises are shown in Fig. 8.3 as distributed average water balance components for the projected period from 2051 to 2080 for the A1B scenario. Compared to the historical period from 1971 to 2000 in Fig. 8.2, the projections shown in Fig. 8.3 reveal:

1. Change of precipitation for the total UBRB is only about −4 % but there are significant changes in the rainfall distribution. Meanwhile the Tibetan part of the basin receives similar annual rainfall, the Assam province in India will receive less and the southwards facing Himalaya slopes of Bhutan receive even more monsoon rainfall.
2. Evapotranspiration is likely to increase by 23 % because of the continuing temperature increase. The spatial distribution of evapotranspiration, however, is almost unchanged within the UBRB.
3. Runoff from the UBRB is likely to decrease in average by 28 % per year and this reduction is distributed unevenly over the basin. Meanwhile the Tibetan Yarlung Tsangpo headwater part and the floodplain of the Brahmaputra river in Assam will likely experience stronger dry spells, the runoff from the southwards facing Himalaya slopes of Bhutan will likely sustain their discharge regime.

This negative trend discussed for the A1B scenario is also apparent when applying the B1 scenario CLM meteorological forcing for the water balance modelling. This is shown in Fig. 8.4 and can be interpreted as follows:

1. When comparing the UBRB runoff projections for the two A1B and B1 scenarios, the negative trend of a decreasing water yield from the basin is evident. The ecological

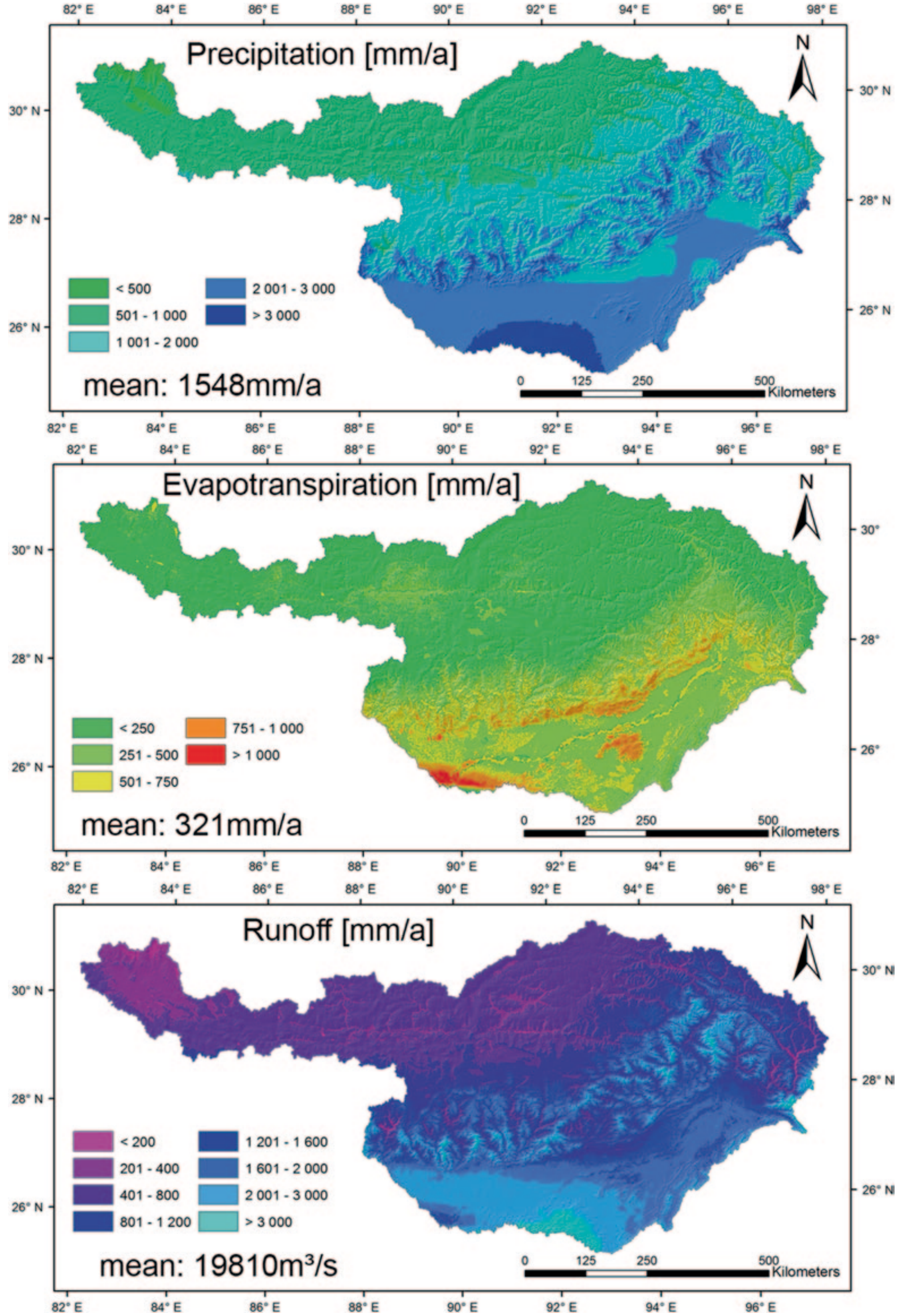

Fig. 8.2 Average modelled water balance components in the UBRB for the time period 1971–2000, applying CLM ERA meteorological input data

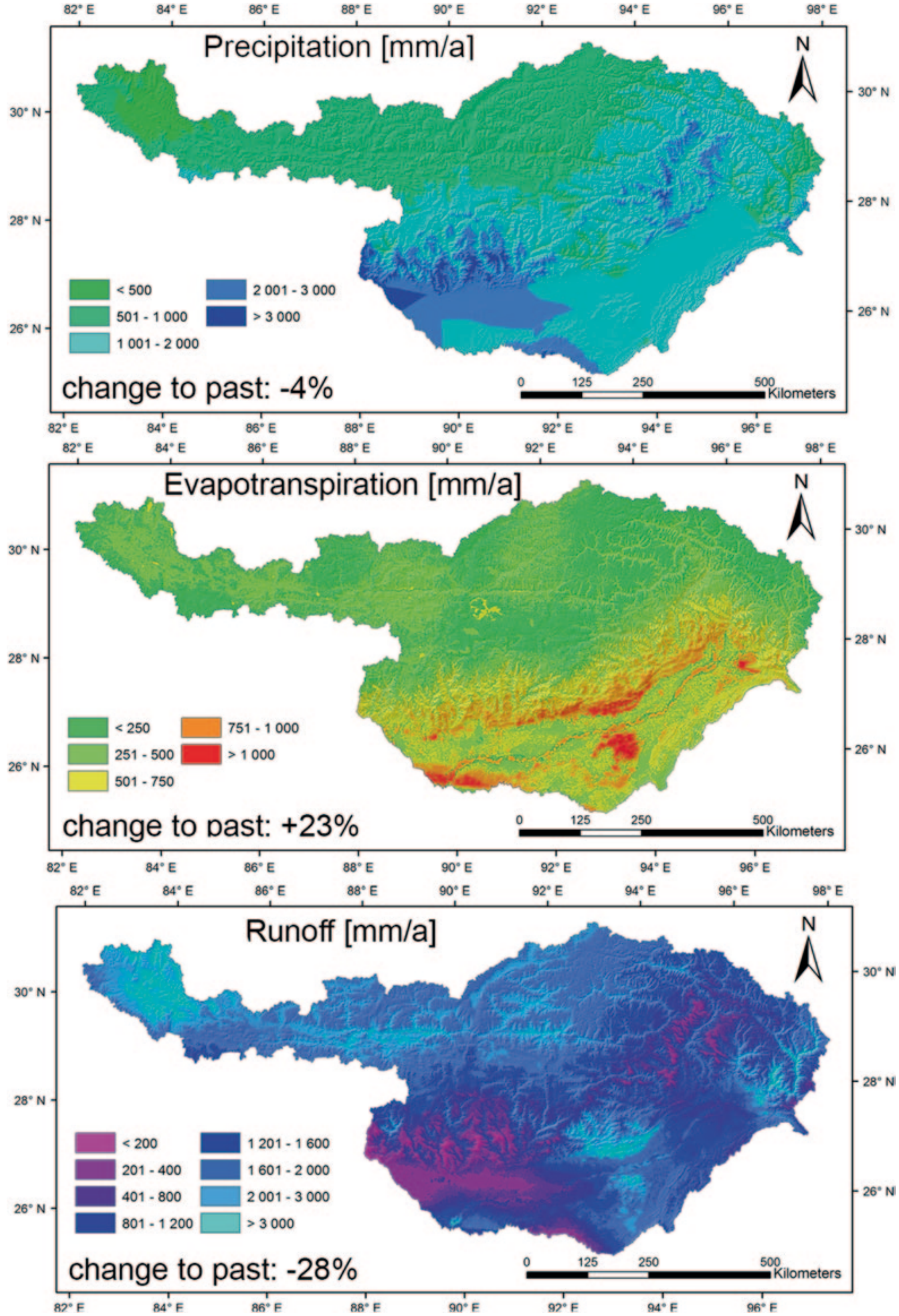

Fig. 8.3 Average modelled water balance components in the UBRB for the time period 2051 to 2080, applying the CLM Echam5 modelled meteorological IPCC SRES A1B projection (IPCC 2000) as input data

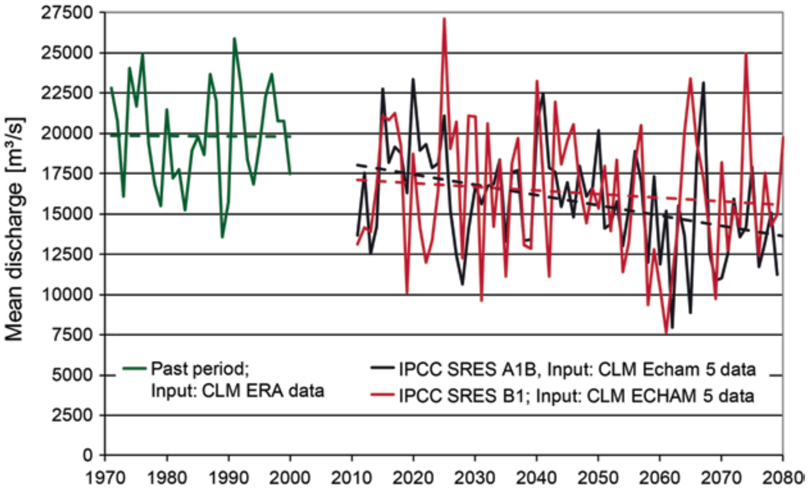

Fig. 8.4 Annual modelled discharge dynamics of the Brahmaputra River at the gauging station Guwahati, Assam, India in the past and for the time period 2011–2080, applying the CLM Echam5 modelled meteorological IPCC SRES B1 and A1B projection (IPCC 2000) as input data

friendlier designed B1 scenario, however, indicates a less serious decline of annual runoff if compared to the A1B scenario.

2. There is a distinct jump between the trend level for the historical time series 1970 till 2000 and the beginning of the climate projection period in 2010 which needs further to be looked into.

8.5 Impact of Climate Change

The discussion in the previous section clearly indicates that climate change projections for the A1B and B1 SRES scenarios have a significant impact on the hydrological dynamics of the water balance of the UBRB. Less projected rainfall input and increasing temperature result in higher evapotranspiration and in turn in reduced runoff from the basin. Although changes in the amount of precipitation are only moderate, the phase of precipitation will change due to the increasing temperature trend, so that effectively less snow will fall in the future. It should be noted that 'hot spots' of climate change impact have been identified in the upper catchment drained by the Yarlung Tsangpo in Tibet and in the Brahmaputra flood plains in Assam. Both areas are expected to show more severe dry periods with related impacts to agriculture, ESS and socio-economy in general.

8.6 Conclusions for ILWRM

According to the A1B and B1 projection scenarios, climate change will likely have significant impacts on ILWRM which can be described as follows:

1. The annual average water yield from the catchment will decrease with a continuous trend and consequently less water will be available for sustainable ILWRM.
2. In highly glaciered headwater catchments, melt water from glaciers and snow fields constitute river discharge volumes, meanwhile in the forelands monsoon precipitation and snowmelt runoff from the mountains control water availability (Prasch et al. 2013)
3. Changing precipitation in terms of volume and areal pattern and the general temperature increase are driving the hydrological dynamics of the UBRB water balance. Less precipitation will fall as snow and snow cover will melt faster than in historical times.

4. Increasing temperatures will enhance evapotranspiration which in turn is reducing the water available for runoff and groundwater recharge.
5. ILWRM in the river catchments of the southwards facing slopes of the Himalaya will sustain more or less unchanged since 1970 as the projected increase of temperature and evapotranspiration is likely to be compensated by higher precipitation input.

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Applying the Response Units (RU) Concept for ILWRM

9

Wolfgang-Albert Flügel, Jörg Pechstädt
and Anita Flemming

Integrated land and water resources management (ILWRM) must be understood as a continuous process of coordinating sustainable land and water resources management with the aims (1) to maximize the socioeconomic development and social welfare without (2) compromising the sustainability of vital ecosystems (GWP 2000) and their hydrological ecosystem functions (ESF) and ecosystem services (ESS) (Willaartsa et al. 2012). From a practical point of view ILWRM has to provide the administrative and technological means to (1) manage the available surface and subsurface water resource in the landscape of a river basin, (2) guarantee their sustainable recharge dynamics both in terms of water quantity and quality, and (3) protect water users and the society against destructive hazards like floods, droughts, and erosion.

9.1 Objectives

The main objectives of the basin analysis presented herein were (1) to apply the conceptual landscape model of response units (RU) for the delineation of hydrological response units (HRU) and (2) their enhancement to water resources response units (WRRU) by applying the results from the hydrological water balance modelling done by means of the DANUBIA hydrological model. The resulting WRRU were evaluated regarding their potential for providing decision support for implementing sustainable ILWRM.

9.2 State of the Art

ILWRM is based on a coordinated land and water resources management within a river basin and therefore in sufficient detail requires information about the distributed natural landscape components, for example, geology, soils, topography, and land use and land cover (LULC) within a river basin. The latter in their specific composition control the hydrological dynamics in landscape components and their recharge contributions to subsurface and surface water resources as response to the precipitation input (Flügel 1996). Aggregated in hydrological relevant landscape component assemblies their individual process structures are identified by means of an integrated system analysis (ISA) of the river basin (Flügel 2000) comprising field campaigns, stakeholder participation, and geographic information system

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(GIS) analysis. In result HRU are identified as model entities. They represent classified landscape associations delineated by means of digital GIS analysis and applying process relevant delineation criteria that specify the hydrological response of each entity within its HRU class (Flügel 1995). The distributed RU landscape model concept has been validated in numerous basin model studies (Fink et al. 2007; Flügel 1996; Flügel and Märker 2003; Helmschrot 2006a, b; Krause 2002; Krause and Flügel 2005; Krause et al. 2006; Krause and Hanisch 2009; Nepal et al. 2013) and proved its value for distributed water resources assessment, hydrological ESF and ESS analysis within a river basin.

The application of the RU landscape model requires a set of software tools that comprise and integrate different techniques of geoinformatics like remote sensing, GIS, a model framework system (MFS), distributed process models that apply RU as model entities, and a comprehensive data and information system (Flügel and Rijsberman 2003; Flügel 2007). The integrated land management system (ILMS) (Kralisch et al. 2012) has been developed as such a toolset for implementing sustainable ILWRM.

Enhancing the RU concept toward WRRU requires an objective function related to ILWRM. As BRAHMATWINN is strongly related to flood vulnerabilities the runoff generation and groundwater recharge dynamics were chosen as the main water resources components to be represented in their spatial distribution within the upper Brahmaputra river basin (UBRB) by means of the WRRU.

9.3 Methods Applied

The knowledge-based GIS methodology applied was three-fold and comprised in a *first step* the delineation of HRU in the UDRB and the UBRB by applying the knowledge based GIS analysis concept described by Flügel (1995, 1996). For this purpose the ISA was carried out (Flügel 2000) by means of field campaigns and hydrometeorological time series analysis. Digital basin maps of the UDRB and the UBRB were produced for LULC (Boston University 2008), soils (FAO 2003) and topography from reanalyzed Shuttle Radar Topography Mission (SRTM) data (Wolf et al. 2009). The HRU delineated for both twinning basins were aggregated according to Pfennig et al. (2009) by applying an area threshold value of 5 km^2.

In the *second step* the mean annual water balance components obtained from the DANUBIA hydrological modelling exercises were used as inputs for the delineation of the WRRU. The latter were generated with respect to (1) discharge generation by surface runoff and interflow and (2) groundwater recharge.

Finally, in a *third step* the distribution of WRRU classes for each HRU class were analyzed with respect to their contribution of dominant water balance components within the basin thereby linking their LULC, topography, and soil information from the HRU classes to the respective WRRU classes.

9.4 Results

HRU were delineated by means of GIS analysis for the UDRB and UBRB twinning basins. They represent the process based landscape model entities to which the results of the modelled water balances for the historical and the projected time periods provided by the DANUBIA hydrological model were referred to. The 1 × 1 km raster based average water balance components surface runoff, interflow and groundwater were aggregated with respect to runoff generation from surface runoff and interflow as given in Table 9.1 and shown for the aggregated surface runoff and interflow in Figs. 9.1 and 9.2 respectively. Together they reveal:

i. Surface runoff is very low in most of the Tibetan part of the UBRB located in lee of the alpine Himalaya mountain ridge but reaches moderate, high, and very high values at the southwards slopes of the Himalaya exposed in the windward direction during the summer Monsoon.
ii. The floodplain is also showing moderate till higher runoff contribution to river flow as

Table 9.1 Classes to aggregate surface runoff (SR) and interflow (Int)

Class no.	Ranking	SR (mm)		Int (mm)	
		From	To	From	To
1	Very low	0	125	0	125
2	Low	>125	250	>125	250
3	Moderate	>250	500	>250	500
4	High	>500	1000	>500	1000
5	Very high	>1000	5200	>1000	2188

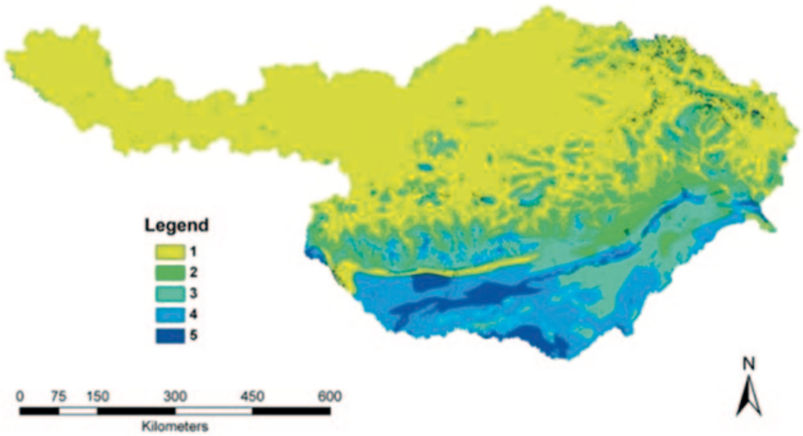

Fig. 9.1 Classification of surface runoff generation aggregated from 1 × 1 km raster model entities provided by the DANUBIA model for the time period 1970–2000. Class definitions are given in Table 9.1

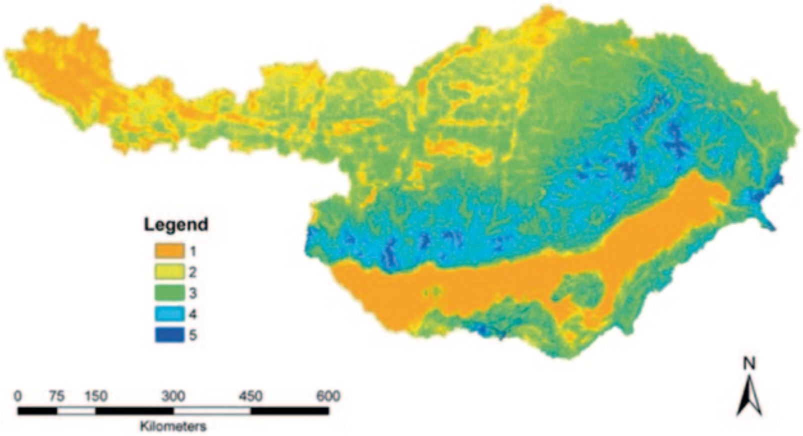

Fig. 9.2 Classification of interflow generation aggregated from 1 × 1 km raster model entities provided by the DANUBIA model for the time period 1970–2000. Class definitions are given in Table 9.1

most of the rain is either falling on wetlands, paddy fields, or the braided Brahmaputra river itself and directly contributes to runoff.

iii. The distribution of interflow classes is showing a more differentiated pattern and reflects the interaction of precipitation, topography, and LULC.

iv. Again the north-western parts of the UBRB in Tibet show very low and low runoff contribution by interflow.

v. Interflow contribution to river runoff is also low in the valley floors and especially in the floodplain of the Brahmaputra in Assam as there are no significant slopes driving this runoff component.
vi. Moving eastwards with precipitation increasing toward more than 3000 mm the interflow contribution becomes more moderate and eventually is reaching high and very high values at the most eastern part of the UBRB.
vii. The Himalayan slopes located windward to the summer monsoon also reach high and very high values of interflow contribution to river runoff.

WRRU are delineated based on the classified surface runoff and interflow distribution by combining them according to their contribution to river runoff and consequent flood generation. The resulting nine WRRU classes are listed in Table 9.2 and are shown in Fig. 9.3 in their distributed pattern. They have overlapping class limits as they have been designed to provide information with respect to their dominant process dynamics generating flood in the river system which is a priority subject for water management.

In combination with Table 9.2 the visual analysis of Fig. 9.3 allows for the following interpretations:

i. The very dry character of the north-western part of the UBRB is confirmed as both surface runoff and interflow are very low till low and this situation holds for about a third of the UBRB located in Tibet. Discharge in the Yarlung Tsangpo from this part of the basin is mainly supported by snow and glaciers melts with little contribution from rainfall.
ii. About 33 % of the UBRB mainly located in Tibet and the flood plain of Assam is characterized by moderate low runoff contributions from surface runoff and interflow summing up in average to an annual maximum of 625 mm.
iii. The Himalaya mountain ridge clearly shows up as a high runoff contributing region with a distinct differentiation in (1) moderate till moderate high river runoff contribution in the north-west facing slopes in the lee of the ridge and (2) high till extremely high contributions to river runoff and floods from the south facing slopes windward to the summer monsoon.
iv. The floodplain of the Brahmaputra in Assam is another characteristic region in the UBRB. The runoff contribution in this flat flood plain ranges between moderate low and moderate high and is mainly the result of the high rainfall input on water bodies, wetlands, and saturated soils that directly contribute to the river runoff. Higher mountains in the south-east of Assam, however, produce high till extremely high runoff contributions from corresponding high monsoon rainfall.

The results presented in Fig. 9.3 have been further condensed in Table 9.3 and clearly point out the two-fold hydrological runoff contribution of the UBRB:

i. The distribution of the WRRU areas is skewed toward the dry WRRU meanwhile the runoff contribution is almost normal distributed.
ii. About 57 % of the basin represented by WRRU class 1, 2, and 3 and mainly located in Tibet, generates only 25 % of the basin runoff contribution; meanwhile, WRRU class 7 and 8 located in the monsoon receiving mountains contribute 15 %.

In a further methodical GIS analysis, the WRRU classes were overlain with the distributed HRU delineated in the first GIS analysis for the UBRB. In addition to the information about LULC, soils, and topography each HRU class will afterward contain additional information about their WRRU distribution and their contribution to river hydrographs from surface runoff and interflow.

9.5 Impact of Global Climate Change

The application of the conceptual RU landscape model by means of HRU and WRRU provide information of distributed runoff contribution within the twinning basins. If the methodical steps two and three are repeated for water balance components modelled for historical and projected time periods the GIS analysis will provide the following information:

Table 9.2 WRRU discharge height classes (mm) obtained by adding surface runoff (SR) and interflow (Int) classes from Table 9.1

WRRU class no.	Classes merged		Ranking			Discharge height (mm)		% area in UBRB		Runoff (m^3/s*km^2)	
	SR	Int	SR	Int	WRRU	From	To	%		From	To
1	1	1	Very low	Very low	Very low	0	250	16.84	16.84	0.000	0,008
2	1	2	Very low	Low	Low	125	375	1.67	16.73	0.004	0,012
	2	1	Low	Very low				15.06			
3	2	2	Low	Low	Moderate low	250	625	0.42	22.95	0.008	0,020
	3	1	Moderate	Very low				4.16			
	1	3	Very low	Moderate				18.37			
4	1	4	Very low	High	Moderate	500	1125	11.94	21.14	0.016	0,036
	2	3	Low	Moderate				1.37			
	3	2	Moderate	Low				0.53			
	4	1	High	Very low				7.30			
5	1	5	Very low	Very high	Moderate high	625	5325	0.63	9.38	0.020	0,169
	2	4	Low	High				3.87			
	3	3	Moderate	Moderate				1.38			
	4	2	High	Low				1.08			
	5	1	Very high	Very low				2.42			
6	2	5	Low	Very high	High	1000	5450	0.44	6.86	0.032	0,173
	3	4	Moderate	High				4.19			
	4	3	High	Moderate				2.02			
	5	2	Very high	Low				0.21			
7	3	5	Very high	Moderate	Very high	1250	5700	0.61	3.77	0.040	0,181
	4	4	High	High				2.88			
	5	3	Moderate	Very high				0.28			
8	4	5	Very high	High	Extremely high	1500	7400	0.51	0.82	0.048	0,235
	5	4	Very high	Very high				0.25			
	5	5	High	Very high				0.06			
9	6	6	Receives precipitation directly			Open water		1.51	1.51	All precipitation	

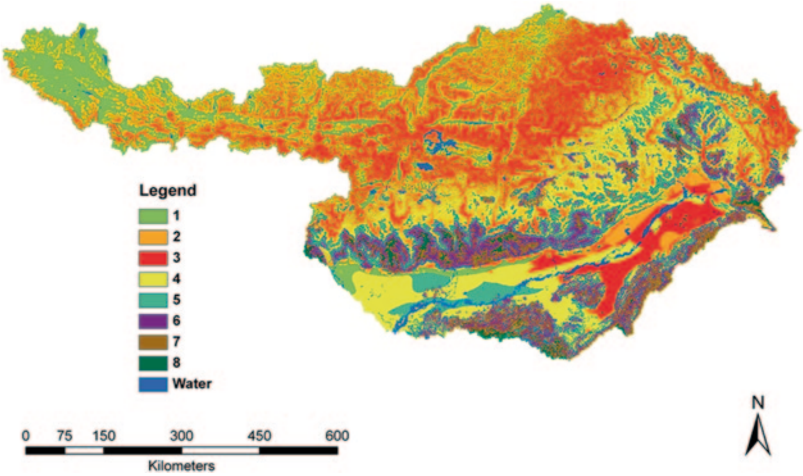

Fig. 9.3 Distribution of WRRU in the UBRB by merging HRU attributes and DANUBIA model results with respect to flood contribution by surface runoff and interflow for the time period 1970–2000. Class definitions are given in Table 9.2

Table 9.3 Distribution and accumulated WRRU area (A) and their runoff contribution (RC)

WRRU class	Distribution		Accumulation	
	A (%)	RC (%)	A (%)	RC (%)
1	16.8	3.4	16.8	3.4
2	16.7	5.1	33.6	8.5
3	23.0	16.3	56.5	24.8
4	21.1	27.1	77.7	51.9
5	9.4	19.0	87.0	70.9
6	6.9	14.0	93.9	84.9
7	3.8	10.9	97.7	95.8
8	0.8	4.3	98.5	100.0
9	1.5		100.0	

i. Spatial distribution of classified runoff generation as surface runoff and interflow from the WRRU for visual inspection and digital evaluation.
ii. Analysis of flood and drought generation from the spatial distributed runoff contribution of HRU classes and their georeferenced HRU entities.
iii. Spatial distributed impact assessment of climate change to the HRU related runoff contribution and its dynamics with respect to surface runoff and interflow by means of GIS based change detection.

9.6 Conclusions for ILWRM

The application of the RU conceptual landscape model offers substantial progress for a hydrological and process oriented water balance analysis in river basins. The hydrological system analysis in this regard yields the definition of process based criteria to delineate HRU by means of GIS analysis. They represent distributed and process based landscape entities of unique hydrological system response if compared with their neighboring HRU. Based on modelled water balance components WRRU complementary provide information about the distributed contribution of surface runoff and interflow to river hydrographs.

Joining the HRU and WRRU concept will associate the LULC, soil and topography attributes of the HRU with the modelled water balance components of the WRRU. Depending on the in-depth GIS analysis the elaborated results will have different degree of detail and quantification.

Calculating the individual runoff generation of each HRU class will provide water and land managers with the means to link the natural landscape features, e.g. LULC, soil, geology, and climate with the water yield produced from each HRU class and its individual georeferenced HRU entities. The RU concept as presented herein thereby is providing the geoinformatics means to coordinate land and water management for sustainable ILWRM and the assessment of multiscale impacts from changing LULC and climate on river basin water balances.

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Vulnerability Assessment and Scenarios

10

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and Fiifi Amoako Johnson

This chapter provides an overview of the assessment of socio-economic vulnerability to floods in the context of climate change in the Salzach catchment (UDRB) as well as for the floodplains in Assam (UBRB). The assessment adapts a conceptual framework of the IPCC defining vulnerability. Within both assessments spatially-explicit and expert-based approaches are applied to provide an integrative assessment linking to ILWRM. Next to the assessment of present-day conditions, future scenarios of socio-economic vulnerability are provided building on the SRES framework. Socio-economic issues are major drivers and subjects of climate change and it is inevitable to analyse them within an integrative assessment through the application of a vulnerability approach.

10.1 Objectives

The objectives of the socio-economic studies were, firstly to integrate spatially distributed socio-economic assessment into IWRM and secondly to develop innovative Geoinformatics methods to provide a flood related vulnerability assessment for the Salzach catchment (UDRB) and the Brahmaputra River floodplains of Assam (UBRB).

10.2 State of the Art

To integrate, next to various indicators reflecting the natural environment, the socio-economic dimension, the vulnerability approach has been chosen and modelled through GIS methods. The conceptualisation of vulnerability builds on the approach developed by IPCC (2001) and is embedded in the function describing risk, which reflects the hazard and vulnerability dimension. Currently, a gap in concepts exists between the climate change and disaster-risk research community which is discussed in several papers (Adger 2006; Birkmann 2006). Here, we define vulnerability as a function of adaptive capacity and sensitivity. The approach developed should furthermore link the missing gap between HRU and WRRU and allow the integration of "social" issues. Two major case studies, Brahmaputra/Assam (India) and the Salzach catchment (Austria) have been chosen to develop and implement the methodology for the UBRB and the UDRB respectively.

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10.3 Methods Applied

Vulnerability modelling provides a spatial and conceptual framework, by which to integrate project findings in the context of socio-economics, hazard impact and governance through the analysis of sensitivity and adaptive capacity in relation to climate change (IPCC 2007). Key to the approach is the development of appropriate indicators based upon established and tested techniques like the DELPHI approach (Helmer 1966), and the implementation of Creative System Modelling (CSM) Workshops as described in the NetSyMoD Approach (Giupponi et al. 2008) which both capture and validate stakeholder expertise and understanding of critical vulnerabilities. As the data requirements differ essentially, adapted methodologies have been developed and applied to assess the current state of vulnerability. However, both approaches integrate perceptions of experts through statistical weights, census data and additional information from remote sensing data to integrate environmental indicators and proxies which could not be derived directly from other data sources.

In the Salzach case study, a regionalisation approach has been applied (Kienberger et al. 2009a) which models homogenous units of vulnerability (VulnUs). This approach is built on the concept of Geons, which acts as a framework for the regionalization of continuous spatial information according to defined parameters of homogeneity (Lang et al. 2008).

In the Assam, case study of the UBRB, a statistical approach, has been applied, which models vulnerability based upon expert weighted census values for ~15,000 communities in Assam as well as aggregated to the Tehsil (administrative unit in Assam) level (Kienberger et al. 2009b).

10.4 Results

Results from the comprehensive socio-economic studies carried out in the twinning basins are presented in each one example for the Salzach catchment (UDRB) and for the floodplain of the Brahmaputra River in Assam (UBRB) to highlight the importance of applied Geoinformatics when integrating the socio-economic dimension in ILWRM.

By adapting the conceptual RU approach in the Salzach catchment VulnUs have been delineated by means of knowledge based GIS analysis and are shown in Fig. 10.1. They can be interpreted as follows:

1. From a general perspective, populated areas are the most vulnerable ones—due to the clear socio-economic focus (indicators on buildings, population etc.) of this study and the weighting of different indicators
2. Factors within the susceptibility domains “housing”, “infrastructure” and “assets” and the social capacity domain “early warning” received the highest ranks
3. The ten most vulnerable areas are equally distributed over the test area site and are located at important local population centres reflecting shortfalls within different vulnerability domains
4. The detailed disaggregated modelling of socio-economic vulnerability strongly depends on the availability of data. The grid-based census data for Austria proved to be an appropriate basis to implement such an approach
5. The integration of expert knowledge through weighting of indicators helped to quantify and relate the different relationships of vulnerability domains whereas other approaches lack data or cannot be implemented due to the characteristics of indicators and data (quantitative vs. qualitative multi- and trans-disciplinary approaches)
6. The method allows the assessment of vulnerability independent from administrative units, but also applies an aggregation mode which reflects homogenous vulnerability units. This supports decision makers to reflect on complex issues such as vulnerability on a sub-administrative level, but derives units which represent a common characteristic of vulnerability. Next to that, the advantage is to decompose the units into their underlying domains.

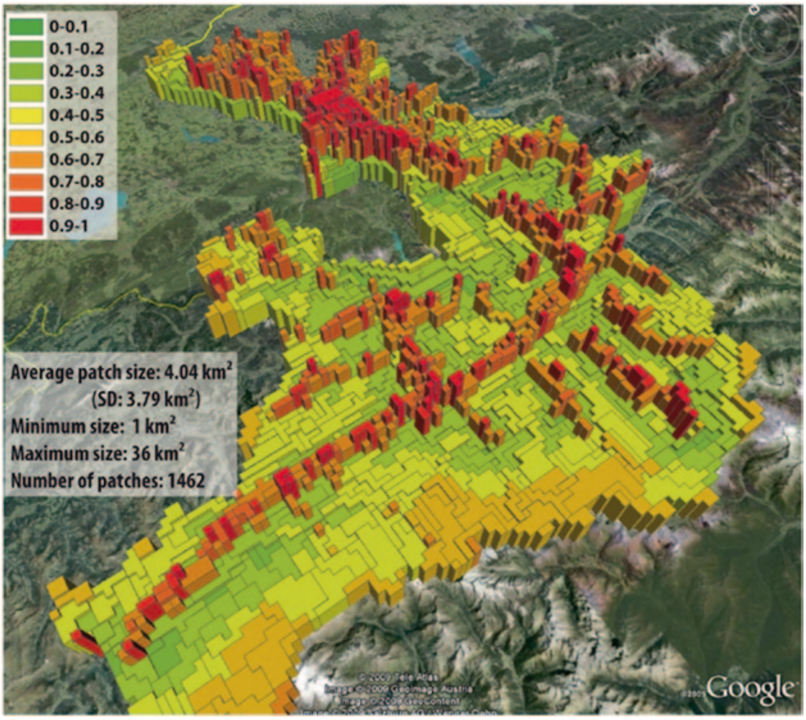

Fig. 10.1 Classification of vulnerability units (VulnUs) for the Salzach river case study in the UDRB. (Kienberger et al. 2009a, CC by 3.0 license)

For Assam, vulnerabilities were elaborated based upon expert weighted census data complemented by statistical analysis. The extent of the 2001 flood is used as an indicator of hazard distribution in Fig. 10.2 and the latter reveals:

1. The high vulnerability populations tend to be in those areas that are rural and prone to flooding like wetlands. This is to be expected where populations are exposed to the damaging effects of flooding, as well poorer populations being marginalised to these areas more generally.
2. Vulnerability and asset play a diametrically opposite role here with vulnerable populations tending to be in areas with little or no substantive infra-structure. The low vulnerability regions in the east are predominantly cities and high asset value tea plantations whereas the high vulnerability regions in the east and the west tend to be in low asset areas.

Future socio-economic vulnerability scenarios following SRES projections (A1, A2, B1, B2) for the time steps 2000, 2020 and 2050 have been modelled for both case studies. The methodology has been applied in a similar manner in both areas. A condensed vulnerability index, consisting of proxy variables, has been identified and its indicators projected under a correlation with future GDP and population scenarios. In the Salzach catchment (Fig. 10.3), the general pattern among the different scenarios show a similar distribution, with an amplification of the maximum values, especially in urban dominated areas. The highest vulnerability scores and change rates can be observed within the scenarios A1 (Fig. 10.3) and B1 (not shown). Lower values show the 2-group scenarios A2 and B2 which have a more regional oriented focus than the globalised 1-group scenarios.

Estimates of socio-economic vulnerability (and also for specific domains of sensitivity and adaptive capacity) to climate hazards (e.g. floods, droughts, bank erosion) were derived for communities and Tehsils as administrative units in the

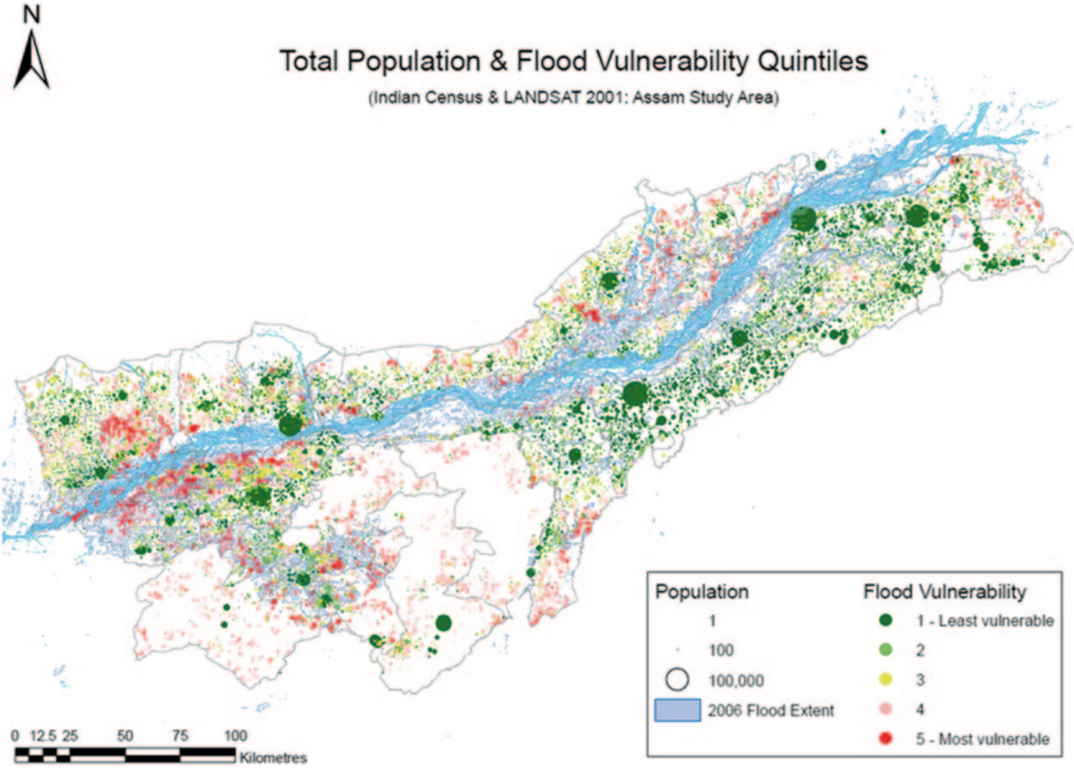

Fig. 10.2 Classification of vulnerability to the 2006 flood for the 15,000 mapped settlements on the floodplain of the Brahmaputra river in Assam, India applying the geo-referenced census data 2001 and a weighted indicator concept. (Hutton et al. 2011, CC by 3.0 license)

Assam Study Area. In this follow-up study, the main aim is to investigate by how much the level of the estimated vulnerability for each Tehsil will increase or decrease depending on governments, policy directions and social values, under the four scenarios developed by TERI. However, these results are based on all India GDP estimates and Assam is exposed to a disproportionate level of hazard which limits development. Thus, it is important to recognise that the vulnerability levels shown in these scenarios are best case scenarios and it is much more likely that the retarding effects of climate change hazards will keep the vulnerability close to that of the year 2001.

Altogether 18 individual variables were identified that are significantly correlated (>±0.5) with the vulnerability score. A multivariate regression analysis was then used to identify the predictors of level of the vulnerability. To satisfy the assumptions of normality and constant variance, the vulnerability scores were log transformed. Table 10.1 shows the estimated coefficients for the significant predictors (p-value <0.05) along with the estimated standard errors, t and p-values. It is important to note that, there was a high level of co-linearity between some of the variables. Where two or more variables were collinear, only the strongest predictor was included in the model. The estimated Adjusted R-square indicates that, the five significant indicators explain 91.7 % of the variability in vulnerability scores.

In Assam, Fig. 10.4 shows a reduction in general vulnerability along the lines of current status. The analysis carried out in previous phases of BRAHMATWINN not discussed here, showed that the most vulnerable (lowest quintile) Tehsils in the Assam study area are Na-Duar, Majbat, Dhakuakhana (Part-I), Dhakuakhana (Part-II), Helem, Bhuragaon, Kadam, Phuloni, Naobaicha,

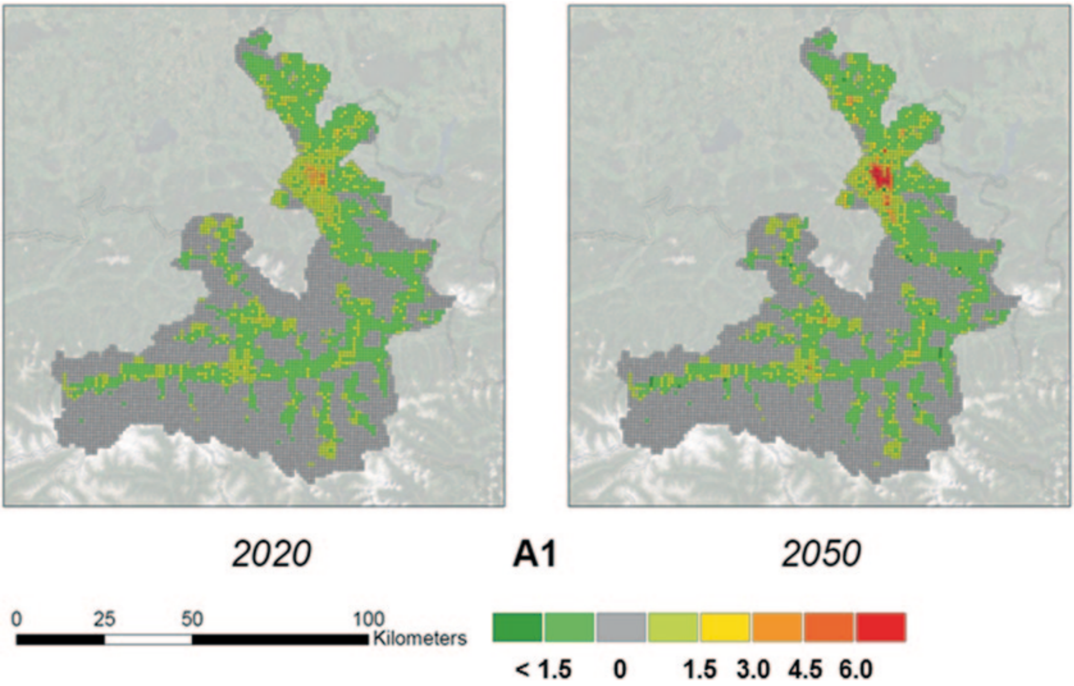

Fig. 10.3 Change rates of the vulnerability index (max. 100) per grid cell for the IPCC SRES A1 scenario (IPCC 2000) relative to the baseline 2000 for the Salzach river catchment. (Giannini et al. 2011, CC by 3.0 license)

Table 10.1 Estimated coefficients for the log of the vulnerability score

	Coeff.	Std. error	*t*-value	*p*-value
Constant	1.456	0.728	2.001	0.049
Proportion of the population working in agriculture (x_1)	1.240	0.520	2.386	0.020
Proportion of roads that are metalled (x_2)	−1.264	0.160	−7.899	0.000
Proportion of households with a television (x_3)	−2.251	0.990	−2.273	0.026
Proportion of houses with burnt brick wall (x_4)	−3.174	1.198	−2.649	0.010
Proportion of households using firewood for cooking (x_5)	2.246	0.577	3.891	0.000
Adjusted R-square = 91.7 %	–	–	–	–

Silonijan, Donka, Subansiri (Part-I), Sissibargaon, Subansiri (Part-II). Figure 10.4 is showing the level of vulnerability in 2001 and those projected by 2050 in the SRES scenarios A1 and A2 by deciles.

The analysis reveals that GDP and population growth impacts on household and community factors that predict socio-economic vulnerability to climate hazards such as the proportion of the population working in agriculture, proportion of metal roofs, proportion of households with a television, proportion of houses with burnt brick wall and proportion of households using firewood for cooking. The impact of GDP and population growth is highest in areas where levels of vulnerability are already high. The results clearly depicts that a slow growth in population with a concurrent rapid growth in GDP is important in reducing levels of vulnerability.

For example, comparing the calculations from scenarios A1 and B1 for 2050, it can be noted that under scenario B1 population growth is 0.534 and real GDP growth is 20.453 and for A1 population growth is 0.858 and real GDP growth is 36.688, nonetheless although scenario B1 has a lower GDP compared to scenario A1, it impact on reducing levels of vulnerability is stronger be-

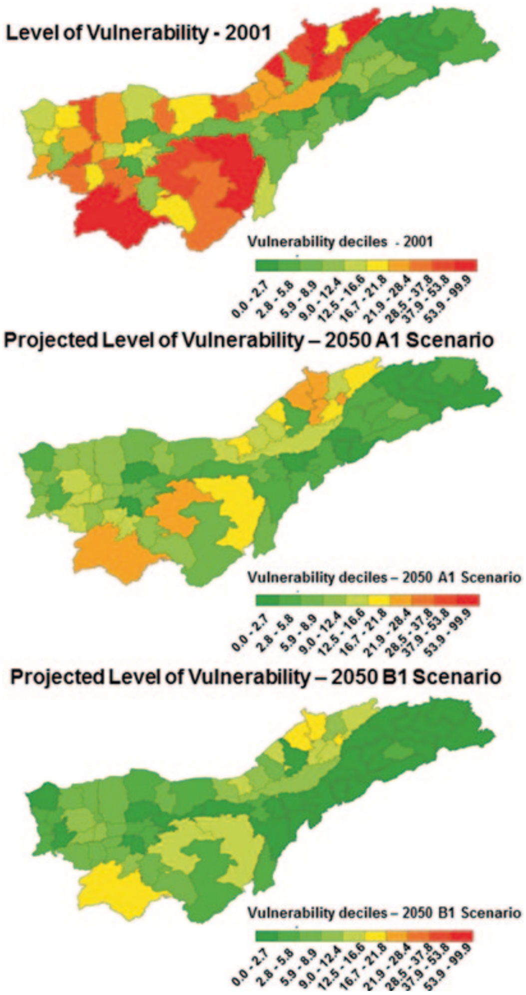

Fig. 10.4 District vulnerabilities in 2001 and for IPCC SRES scenario A1 and B1 (IPCC 2000) in the Assam study area

cause of the low population growth rate. It should be noted that, although all four SRES scenarios are analysed in this context, the final conclusions are based on those that are regarded as most optimistic (B1) and pessimistic (A1) from the greenhouse gas emissions perspective.

From the socio-economic perspective the most pessimistic scenario is A2 (not presented here), while agreeing that the best is B1. As such we can present two maps of scenarios for vulnerability at 2050. It should also be noted that these are based on economic growth rates for all India which is an overestimate of the growth rate for Assam. This is most probably due to the economically repressive effect of natural hazards in the region. Thus the scenarios presented represent a best possible case and it may still closely resemble the case as in 2001. It is possible with an increase in hazard in the region through climate change that the real situation will resemble more closely that of 2001.

10.5 Impact of Climate Change

The Geoinformatics tools applied proved to be very useful to analyse the spatial context of vulnerabilities and statistical analysis is furthermore offering interpretative potential. As shown in Figs. 10.3 and 10.4, climate change is impacting vulnerabilities with respect to flooding both in the test catchment of the Salzach river in the UDRB and in the Indian State of Assam in the UBRB. Meanwhile, vulnerability in the Salzach catchment is increasing in urban dominated areas one can see a substantial reduction in overall vulnerability in Assam. Reasons for these likely changes will potentially be countered by increases in exposure to hazard and require a more detailed case analysis which is beyond the scope of this chapter.

10.6 Conclusion for ILWRM

To maintain an *integrated* and *adaptive* approach to ILWRM, a socio-economic framework is required. With the presented approaches, it is possible to spatially model vulnerability explicitly and apply it to future scenarios based on GDP and population projections. Challenges still arise in the integration of various compartments of an ILWRM approach, not only between social and natural sciences but also within the underlying sub-dimensions. However, as socio-economic issues are major drivers and subjects of climate change, it is inevitable to analyse them through the application of a vulnerability approach.

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11

Adaptive IWRM Responses to Cope with "What-If?" Scenarios

Valentina Giannini, Andrew Allan, Craig W. Hutton and Carlo Giupponi

In Chaps. 2 to 9, various Geoinformatic approaches have been presented, that comprise the interdisciplinary systems analysis of the natural environment and its human dimension applied in the BRAHMATWINN project. Together with the vulnerability analysis introduced in the previous chapter, they provide a comprehensive assessment of the BRAHMATWINN basins environment and a quantifying analysis of the mechanisms and impacts of climate change on the hydrological dynamics, the availability of water balance components and vulnerability. This holistic system approach will be completed in this chapter by applying Geoinformatics for adapting existing and developing new IWRM strategies within the context of socio-economic vulnerability, institutional capacities and governance.

11.1 Objectives

The overall objective is to describe the process through which responses to cope with vulnerability to flood risk from the impact of climate change can be defined in a participatory process, and then validated with reference to the existing governance framework.

Responses are here defined with reference to the *Responses* node in the DPSIR (*D*riving forces, *P*ressures, *S*tate, *I*mpacts, *R*esponses) framework (EEA 1999). Climate change is investigated according to possible scenarios, which are derived from IPCC SRES (IPCC 2000)—these scenarios merely "provide an alternative image of how the future might unfold" (Alcamo 2001) rather than setting out predictions. These possible scenarios, defined here as "what-if?" scenarios, are the result of the downscaling of general circulation models as described in Chap. 4, and of further simulations of the consequence, these changed climatic condition will have on the ecosystems and on the modelled water balance components presented in Chap. 8.

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11.2 State of the Art

Local actors (policy makers, disciplinary experts and other stakeholders) hold necessary information that should be included in any decision-making process aimed at the definition of responses to cope with climate change impacts (Renn 2006). Within the BRAHMATWINN project they not only have experience in facing similar climatic conditions, but also will most likely be the ones developing or implementing future responses to climate change in terms of IWRM strategies. The inclusion of local actors from the commencement of the project will provide outputs, which will be relevant for the case study areas, and thus suited to fulfil society's needs and likewise can increase the implementation potential of the BRAHMATWINN research outputs.

Each of the storylines for the SRES scenarios makes certain assumptions about the balance of the socio-economic drivers in place in 2050. They do not make projections regarding the governance regimes expected to support the scenarios. It is recognised, however, that the extent to which response options may be considered potentially effective or not depends to a significant degree on the governance and policy positions in place in the applicable geographical area (Ministerial Declaration Hague 2000). It is thus difficult to assess the suitability of a response option on the SRES storylines alone because it is not clear if the existing governance capacity implicit in the scenarios will be able to support it.

11.3 Methods Applied

The Geoinformatics approach adopted for the analysis of alternative ILWRM responses to decrease vulnerability to flood risk is based on the NetSyMoD methodological framework (Giupponi et al. 2006, 2008; www.netsymod.eu) for the management of participatory modelling and decision-making processes. The framework is organised in six main phases, structured in an iterative way. The first three phases, e.g. *Actors' Analysis, Problem Analysis* and *Creative System Modelling* provide a list of issues and possible responses to them. The decision support system *DSS Design* phase consists in the development of a set of alternative IWRM responses and in the identification of the tools and indicators needed for their assessment.

The subsequent (fifth) phase named *Analysis of Options* is performed with the mDSS (Mulino DSS) software (Giupponi 2007; Giupponi et al. 2004) through Multi Criteria Decision Analysis (MCDA), with a set of techniques aiming at the elicitation and aggregation of decision preferences (Figueira et al. 2005). They assist decision/policy makers in identifying the preferred responses from a range of alternatives in an environment of conflicting and competing criteria and interests (Belton and Stewart 2002). The last sixth phase, *Actions and Monitoring*, is beyond the scope of the BRAHMATWINN project but should otherwise be carried out by local policy makers, in case of uptake of the project outcomes for future IWRM implementation plans, and for validation purposes, in order to acquire evidences for subsequent cycles of adaptive management.

Although the governance framework is important for the implementation of response options, the SRES scenarios do not attempt to incorporate governance characteristics. Consequently, the characteristics of the governance system that would be needed to support the storylines must be determined so that the practicality of the response options can be further assessed. The SRES storylines must therefore be deconstructed to identify the particular strands relevant to water, land and disaster management and the resulting projected governance frameworks used to flesh-out these storylines. These strands include the potential for institutional and international cooperation; the relative balancing of economic, social and environmental concerns; the capacity for land use control; and the likelihood of effective enforcement.

The responses identified during an ad hoc workshop with local actors organized within the NetSyMoD methodology are then compared and ranked against each of these more developed storylines in an effort to find the strategies that most conform to the governance projection in each. An estimation of the timescale which each strategy would need to be implemented is made,

Table 11.1 Criteria belonging to the environmental, social and economic theme of sustainability

Environmental		Social		Economic	
Vulnerability	0.145	Population dynamics	0.132	Agricultural production	0.103
Basin morphology	0.125	Poverty	0.125	Energy production	0.101
Forest management	0.113	Infrastructure pressures	0.100	Employment	0.056

differentiating broadly between the short (2001–2020) and the long (2020–2050) term. Because of difficulties resulting from the mismatch between the SRES and BRAHMATWINN time horizons, the governance projections are derived from the underlying socioeconomic drivers of the former, thereby ensuring mutual consistency.

11.4 Results

Results obtained from these comprehensive studies have been differentiated firstly into those related to the appreciation of local actors to cope with flood vulnerabilities as discussed in the previous section, and secondly into the discussion of responses related to the governance and legal framework.

11.4.1 Evaluation of IWRM Responses to Cope with Vulnerability

Local actors when confronted with this vulnerability prediction during a workshop held at ICIMOD in Kathmandu, Nepal during November 2008 were asked to evaluate the effectiveness of responses to decrease vulnerability and cope with flood risk, which should increase because of climate change. Four categories of responses, defined according to outcomes of previous local actors' workshops (Guwahati, India, April 2007; Thimphu, Bhutan, October 2007; Salzburg, Austria, October 2008) have been presented to the local actors in the workshop. They are (Giannini et al. 2011):

i. ***ENG-LAND*:** Engineering Solutions and Land Management (e.g. dam construction, river network maintenance, soil conservation practices, etc.);
ii. ***GOV-INST*:** Investments in Governance and Institutional Strength (e.g. accountability and transparency in government actions, enforcement of existing regulations, flood insurance, etc.);
iii. ***KNOW-CAP*:** Knowledge Improvement and Capacity Building (e.g. awareness raising activities, dissemination of scientific knowledge, training of public employees, etc.);
iv. ***PLANNING*:** Solution-based on planning instruments (e.g. disaster risk management, flood risk zoning for hazard prevention, land use planning, relief and rehabilitation plans).

To be able to evaluate the responses, local actors were asked first to select and weight criteria found in the Integrated Indicator Table, which has been created in previous phases of the project by merging results of local actors' workshops with research conducted by BRAHMATWINN project partners. Local actors were involved in a voting exercise, which produced a list of nine criteria shown in Table 11.1 to be selected for supporting MCDA. Three of them belong to the environmental theme, three criteria belong to the social theme, and the remaining three criteria belong to the economic theme, thus providing insight on all the three pillars of sustainability. Subsequently these nine criteria have been weighted by each actor and averaged to obtain a comprehensive picture of their relative importance, as shown below.

Actors were subsequently involved in the evaluation of effectiveness of the responses through the compilation of a matrix, in which scores according to a *Likert scale* ranging between "very high effectiveness (1)" and "very low effectiveness (5)" had to be attributed.

The outcome of this exercise is that responses based on the category *PLANNING* should be preferred (Ceccato et al. 2009). This result is confirmed both:

- when the average analysis matrix is used and responses are ranked in a single step, and
- in case the evaluation is carried out until the final ranking in parallel according to the

preferences of individuals, and the ranking outcomes are combined at the end by adopting the Borda rule, a group decision-making routine available in the mDSS software (Ceccato et al. 2009).

The consistent result is therefore that *PLANNING* responses (i.e. disaster risk management, flood risk zoning for hazard prevention, land use planning, relief and rehabilitation plans) are considered by the involved local actors as the most promising responses in terms of effectiveness to cope with vulnerability due to flood risk under the pressure of climate change.

11.4.2 Responses Within the Governance Framework

The responses to the SRES A1, A2, B1 and B2 (IPCC 2000) have been analysed from the perspective of their appropriateness to the projected governance frameworks. For example, the issues and corresponding response strategies that were raised by stakeholders in the local actors' workshop in Guwahati were evaluated against the projected governance regimes for the storylines of each scenario and ranked according to their suitability for each (4 indicating the most appropriate and 1 showing the storyline with which the response has least in common). The final scores for each storyline were then added up and are listed in Table 11.2.

In effect Table 11.2 shows those strategies most in accord with what the storylines might reflect and generate the following comments:

Comment 1 Both A1 and A2 scenarios depend on a high quality foundation of good governance and this would demand effective participation of communities at all levels, contrary to what may at first sight be the case. In the A2 and B2 scenarios the storylines that ostensibly rely on community involvement most heavily, participation at the local levels would be necessary, but would not function well at the national level. Strategies that encourage and enable participation at the community level only would best be suited to the A2 and B2 scenarios.

Comment 2 Note that although hazard zoning forms part of Indian union water policy currently, it is difficult to see how it could work in Assam, given that the floodplain coincides with the bulk of the productive farmland in the state.

11.5 Impacts of Climate Change

The impact of climate change depends on the scenario one considers. The broad conclusions from the evaluation of the responses against the governance context suggest that while the A2 and B2 scenarios were the least compatible scenarios (scoring 36 and 41 respectively), B1 ranked as the best (62, and the most 4-rated responses), with A1 closely following (52). The relatively heavy weighting of economic interests in the A1 scenario is most consistent with effective disaster risk management and infrastructure investment. Given the correlation between high income levels and good governance (Kaufmann et al. 2005), the A1 scenario would also suggest good accountability and transparency in government actions, along with effective enforcement, characteristics that would be shared with the B1 scenario.

11.6 Conclusions for IWRM

In terms of the specific responses preferred by the stakeholders, A1 would seem best suited to Disaster Risk Management. It would however be less strong on the environmental protection front. Given the increased focus of the B1 scenario on environmental and social issues, along with its greater potential for vertical and horizontal sectoral integration, better integration of Land Use Planning with impacts on water and disaster risk management might be expected—one of the stakeholders' preferred solutions.

This would also suggest that flood risk zoning for hazard prevention might be more successful in B1 than in A1, the implication from the latter being that hard engineering solutions would be the norm where urban sprawl resulted in greater recourse to hard infrastructural remedies. Finally, the focus of B1 on social issues, coupled with the

Table 11.2 Evaluation of suitability of Assam response strategies against projected governance characteristics of IPCC SERS climate change scenarios A1, A2, B1 and B2 (IPCC 2000)

Issue	Response strategy	A1	A2	B1	B2	Time Slice
Awareness of population on risks, conservation and IWRM	Increase awareness of the population on risks, conservation and IWRM	2	1	4	3	2001–2020
Integration of research in decision-making	Integration and coordination among different sectors of research and decision-making	3	2	4	1	2001–2020
Community involvement in decision-making *See comment 1*	Improve community involvement and foster participatory processes for decision-making	1	3	2	4	2001–2020
	Foster livelihood practices based on conservation, rehabilitation and sustainability	2	1	4	3	2020–2050
Early warning system *See comment 2*	Early warning system	4	1	3	2	2001–2020
	Disaster risk management	4	1	3	2	2001–2020
	Hazard zonation	3	1	4	2	2001–2020
IWRM	Design and implement IWRM plans	3	1	4		2001–2020
Long term vision and measures vs. short term engineering solutions	Multi-purpose dam construction	4	2	3		2020–2050
	Flood and erosion control	3	4	2		2020–2050
	Land use planning	2	1	4		2001–2020
	Environmental impact assessment for new dams	3	1	4		2001–2020
Relief and rehabilitation	Design and implement relief and rehabilitation plans	3	1	4		2001–2020
	Soil conservation efforts	1	4	2		2001–2020
	Renaturation	1	4	2		2020–2050
Policy making and implementation of laws	Accountability and transparency in government actions	3	2	3		2020–2050
	Implement and enforce existing laws and design new and more effective laws	3	2	3		2001–2020
Coordination among institutions	Resolve conflicts and strengthen coordination among institutions	3	2	4		2001–2020
Inter-state conflict, cross boundary issues	Inter-state coordination and conflict resolution	4	2	3		2020–2050
	Totals	*52*	*36*	*62*		

reasonably high levels of household incomes, would indicate that the effectiveness of Relief and Rehabilitation Plans (RRP) would be higher than in A1.

The conclusion must therefore be that the B1 storyline fits best with the responses put forward by local actors in response to the local issues, with A1 being less appropriate. Ironically, however, it appears from the existing Governance and Policy frameworks in place in Assam currently, that the Assamese government is strongest in areas that are perhaps more aligned with the A1 scenario, especially given its focus on technical solutions—Early Warning Systems and Multi-purpose Dam Construction. It remains to be seen how these A1-focused areas of strength could be translated to fulfil the B1 scenario and thereby fit better with what stakeholders appear to want.

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Integrated Land and Water Resources Management System (ILWRMS)

12

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The comprehensive integrated system analysis (ISA), modelling studies, spatial analysis of water balance components, and the integrated socioeconomic analysis and scenario evaluation discussed in the previous chapters must be made available to local actors, decision makers, and planners as otherwise they will be stand-alone information with little value for sustainable integrated land and water resources management (ILWRM). This research challenge was addressed by the development of an ILWRMS based on the sophisticated ILMS*info* data information system applied as one of the integrated land management system (ILMS) components (Kralisch et al. 2012). This component was enhanced by complement software developments and modelling tools (Flügel and Busch 2011) toward an ILWRMS. It should be noted, however, that the system presented in brief herein is under a continuous development by integrating demands and requirements identified by users of the system in various applied research projects (Zander et al. 2012).

12.1 Objectives

The overall objective of the ILWRMS development was to supply users and decision makers with sophisticated integrated information system that will ***firstly*** present the results and data obtained in BRAHMATWINN and ***secondly***, provide tools applied in the twinning UDRB and UBRB basins to support decision making with respect to ILWRM. In addressing these objectives the following scientific and technical requirements have been realized to provide the following services and functionalities of the ILWRMS:

i. User friendly graphical user interfaces (GUI) for populating the system based on the full implementation of the ISO 19115 standard and carrying out data and information queries.
ii. Representation of the river basin real world by an adaptive data model allowing for extensions depending on the progress of the system's understanding and knowledge achieved.
iii. Import and export functionality and management of GIS digital data layers that have a geographic reference specified by common coordinate systems.
iv. Integration of the different kinds of data and indicators for the design of "what-if-scenarios" applied for the evaluation of prognostic

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system management options during the decision making processes striving for sustainable IWRM.

12.2 State of the Art

As discussed above IWRM should be based on the principles of integrated systems analysis (Flügel 2000) elaborating on know-how and professional expertise obtained from previous research. Integrated techniques and model toolsets are appropriate means to contribute to the establishment of sustainable ILWRM (Flügel 2000, 2009, 2011; Flügel and Busch 2011), and innovative geoinformatics techniques providing the means to represent spatial heterogeneity for decision support (Kralisch et al. 2007, 2012). Decision support systems (DSS), like the mDSS (Giupponi 2007; Giupponi et al. 2004), support interaction with complex models and communication of their results.

An ILWRMS must manage various ILWRM related data and information, i.e., station time series data related to water quantity and quality, socioeconomic data, and digital GIS maps that present the spatial distribution of such information within the landscape. Furthermore, it must provide indicators that are either directly derived from data stored in the system or that have been uploaded from results obtained with other analysis tools.

The ILMS component ILMS*info* (Kralisch et al. 2012; Zander et al. 2012) has been applied as the River Basin Information System (RBIS) for the upper Danube river basin (UDRB) (DanubeRBIS) and the upper Brahmaputra river basin (UBRB) (BrahmaRBIS), respectively. It has implemented the complete ISO 19115 metadata model, and enhancements of this model are realized by extended lookup tables (LUT). The system employed the Minnesota Map Server (MMS) and makes use of the GIS functionalities provided by PostGIS. Digital GIS maps can be imported and exported in all standard formats via the Web. It provides the required services by using a hierarchical, multi-tier object relational data model shown in Fig. 12.1.

BrahmaRBIS and DanubeRBIS have been populated with all essential results from the BRAHMATWINN project and link to the Mulino-DSS, the DANUBIA hydrological model, and the J2000 model suite (Kralisch et al. 2009).

12.3 Applied Methods

The following components developed by the BRAHMATWINN project partners have been identified as relevant for the ILWRMS development:

i. The ILMS component ILMS*info* (Kralisch et al. 2012; Zander et al. 2012) as the knowledge base for the decision support component (Flügel and Busch 2011).
ii. The DANUBIA hydrological model (Mauser and Ludwig 2002; Mauser and Bach 2009; Prasch et al. 2011).
iii. The NetSyMoD methodology and its mDSS decision support system (Giupponi et al. 2004).

Additional software enhancement has been developed for the ILWRMS to provide additional functionalities for the analysis of terabytes of modelled data, handling of indicators for decision support via the evaluation of "what-if?" scenarios and population of story line descriptions for "what-if?" scenarios.

12.4 Results

The ILWRMS developed in BRAHMATWINN comprises the functionality of a decision information support tool (DIST) and a DSS. It provides sophisticated data query and analysis functionalities, offers basic statistical analysis for basin time series and spatial queries via thematic GIS maps. The user is guided through the system by means of user-friendly graphical user interfaces shown as an example in Fig. 12.2. A comprehensive help system is implemented to provide additional information for data and GIS map input, queries, and spatial searches.

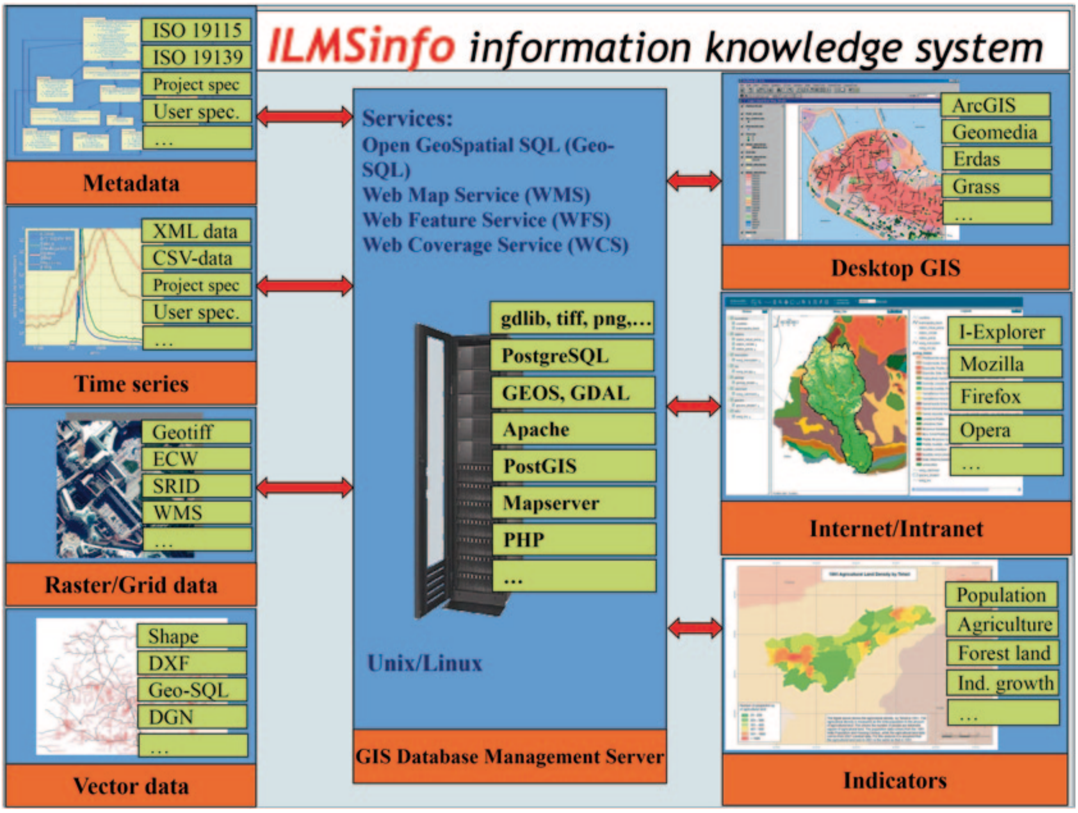
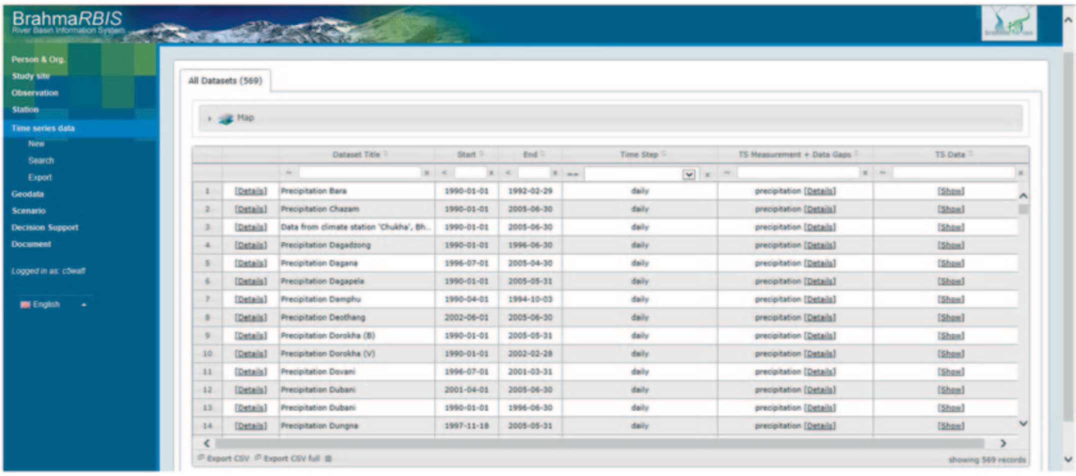


Fig. 12.1 Structural design of the data model applied in the ILWRMS



		Dataset Title	Start	End	Time Step	TS Measurement + Data Gaps	TS Data
1	[Details]	Precipitation Bara	1990-01-01	1992-02-29	daily	precipitation [Details]	[Show]
2	[Details]	Precipitation Chazam	1990-01-01	2005-06-30	daily	precipitation [Details]	[Show]
3	[Details]	Data from climate station 'Chukha', Bh...	1990-01-01	2005-06-30	daily	precipitation [Details]	[Show]
4	[Details]	Precipitation Dagadzong	1990-01-01	1996-06-30	daily	precipitation [Details]	[Show]
5	[Details]	Precipitation Dagana	1996-07-01	2005-04-30	daily	precipitation [Details]	[Show]
6	[Details]	Precipitation Dagapela	1990-01-01	2005-05-31	daily	precipitation [Details]	[Show]
7	[Details]	Precipitation Damphu	1990-04-01	1994-10-03	daily	precipitation [Details]	[Show]
8	[Details]	Precipitation Deothang	2002-06-01	2005-06-30	daily	precipitation [Details]	[Show]
9	[Details]	Precipitation Dorokha (B)	1990-01-01	2005-05-31	daily	precipitation [Details]	[Show]
10	[Details]	Precipitation Dorokha (V)	1990-01-01	2002-02-28	daily	precipitation [Details]	[Show]
11	[Details]	Precipitation Dovani	1996-07-01	2001-03-31	daily	precipitation [Details]	[Show]
12	[Details]	Precipitation Dubani	2001-04-01	2005-06-30	daily	precipitation [Details]	[Show]
13	[Details]	Precipitation Dubani	1990-01-01	1996-06-30	daily	precipitation [Details]	[Show]
14	[Details]	Precipitation Dungna	1997-11-18	2005-05-31	daily	precipitation [Details]	[Show]

showing 569 records

Fig. 12.2 User friendly GUI for the interaction of the user with the ILWRMS

The system also offers sophisticated visualization for GIS maps, data time series, screenshots and is linking to the Google map system for spatial station location and search selection. The functionality of the GUI has been evaluated by BRAHMATWINN stakeholders and users and is subject of continuous improvement. Guests can access the system by using the URL (http://leutra.geogr.uni-jena.de/brahmaRBIS/metadata/login.php?url=start.php), thereby supporting the dissemination of the system within the scientific user community and providing first insight into its functionality.

12.5 Conclusion for ILWRM

Coordinated land and water management is a prerequisite for the implementation of a sustainable ILWRM process. Innovative technologies for comprehensive system assessment, modelling of landscape process dynamics, and socioeconomic analysis have been developed. They require a common and user friendly platform like ILMS to present the results and integrated functionality to local actors, decision makers, and planners.

The ILWRMS developed by the BRAHMATWINN project is an important step forward in this direction and has been extensively tested by BRAHMATWINN local actors and stakeholders. It has been implemented at various partner sites and training has been provided to develop capacities for using the system.

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