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1. INTRODUCTION

The international community at the Johannesburg WSSD in 2002 agreed on a number of ambitious Millennium Development Goals (MDG; GWP 2004)) that have been addressed by the European Union (EU) Strategy for Sustainable Development and the European Water Initiative (EWI, EC 2003, 2004) with respect to water management. Addressing this challenge the EU Water Framework Directive (WFD) has been implemented (EC 2000) serving as a regulating tool for improved water management with international relevance.

Complement to the identification of the MDG in the past years awareness raised about Climate Change (CC) and the International Panel on Climate Change (IPCC) presented respective impacts on the global and continental level (IPCC 2007a, 2007b, 2007c). Today there is raising concern within the EC that CC will alter a wide spectrum of drivers that are likely to impact our global, continental and regional hydrological domains in terms of their natural environments and related socio-economic development (EC 2005, IPCC 2003, IUCN 2003).

Even if greenhouse gas emissions will be reduced CC will persist and consequently there is a significant need to develop flexible and adaptive management strategies to cope CC impacts on environment systems. To support the development of such strategies the IPCC published Special Report Emission Scenarios (SRES) which project global socio-economic development of the forthcoming decades and the related emission of Greenhouse Gases (GHG) that contribute to the global warming (IPCC 2000).

Addressing this demand the European Commission (EC) in its 6th Framework Program (6FP) by means of the Call FP6-2005-Global-4 'Global Change and Ecosystems' as specified by the Sub-Priority 1.1.6.3 in Area II and Area II.6 (Twinning European/third country river basins) funded a integrated research project named BRAHMATWINN which was carried out by an international consortium of European and Asian research teams between June 2006 and December 2009.

2. SCIENTIFIC BACKGROUND

Integrated Water Resources Management (IWRM) as defined by the Global Water Partnership (GWP-TAC 2000) is accepted to be a proper strategy to address complex issues related to the impacts of CC as it considers both the processes active in the natural environment (NE) of the river basin together with the socio-economic development of its human dimension (HD).

Mountains often have great spiritual, cultural and historical value for people, and therefore have been recognized in Chapter 13 of Agenda 21: *"As a major ecosystem representing the complex and inter-related ecology of our planet, alpine mountain environments are essential to the survival of the global ecosystem"* (EC 2003). Alpine mountain chains such as the Alps in Europe and the Himalaya in Asia have headwaters of major rivers in the world. In humid parts of the world, mountains provide 30% to 60% of downstream freshwater, and in semi-arid and arid environments this figure adds up to 70% to 95%.

2.1 Modelling Global Climate Change (GCC)

The IPCC recently compiled present global climate modelling state-of-the-art and results (IPCC, 2007a, 2007b, 2007c) from 21 different atmosphere-ocean global circulation models

(AOGCM) for defined emission scenarios (IPCC, 2000). They have been evaluated as multi-model datasets (MMD-A1B) in the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and project a strong warming over the 21st century. Warming greater than the global mean is projected for South Asia (3.3°C) and East Asia (3.3°C), and significant higher than the global mean in the continental interior of Asia, i.e. 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 e.g. the Alps, Himalaya and the Quinghai-Tibetan Plateau have presently reached an extent and speed that are without historical precedence (Frauenfelder et al. 2005, Karma et al. 2003, Paul et al. 2004, Ren et al. 2004, Subba, 2001). Enhanced by ongoing CC this is likely to have substantial impacts on the hydrological dynamics, i.e. a shift in seasonal river discharge, flood generation, and less summer runoff from melting snow and ice resources. Changing discharge regimes impact the implementation of IWRM both in the urban and rural domain and are likely to change vulnerabilities of sensitive management systems with respect to floods, droughts and erosion.

4. BRAHMATWINN PROJECT

The main objectives of the BRAHMTWINN project (01.06.2006 – 31.12.2009) are addressing these issues by *enhancing and improving capacity to support sustainable IWRM in river systems of alpine mountain massifs to cope with impacts from likely climate change, and to transfer professional IWRM know-how and Geoinformatics tools based on case studies carried out in two twinning European and Asian river basins:*

(1) The ***Upper Danube River Basin (UDRB)*** till the twon of Passau covers 76.653 km^2 with the majority parts in Germany (73 % in Baden Württemberg and Bavaria) and parts in Austria (24 %), and the remaining 3% in Switzerland, Italy and the Czech Republic.

(2) The ***Upper Brahmaputra River Basin (UBRB)*** as defined upstream of the town Guwahati in Assam, NE-India (A = 514.717 km^2) is shared by China (282.950 km^2), Bhutan (43.546 km^2) and NE-India (188.111 km^2), where in Assam the river forms a braided channel pattern with severe bank erosion.

The Lech River (Germany) and the Salzach River (Austria) as well as three reference catchments, i.e. the Lhasa River (Tibet, China), the Wang Chu (Bhutan) and the Brahmaputra flood plan in Assam (India) have been selected for detailed studies in the UDBR and the UBRB respectively. Meanwhile the UDRB has been subject to other international studies as well the UBRB has not been studied and analysed in such a comprehensive and integrated context as done in the BRAHMATWINN project before.

5. METHODICAL APPROACH

The objectives of the BRAHMATWINN project were realized by applying an integrated approach as introduced with the Jena Environment Analysis Toolset (Flügel 2009). It was realized by nineteen interdisciplinary research teams from Europe and Asia applying concepts, methods, and software technologies related to Geoinformatics when elaborating on the following project components:

(i) Downscaling of Atmosphere-Ocean General Circulation Model (AOGCM) results modelled for historical and projected 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) in the two twinning basins with special focus on land use/land cover (LULC), glacier retreat and wetlands.

(iii) Flood related vulnerability analysis with respect to the socio-economic development of the human dimension (HD)

(iv) Evaluation of the stage of IWRM implementation in the twinning basins and regionalization by means of Water Resources Response Units (WRRU).

(v) Hydrological modelling of the river basin water balances for the time series provided by the climate modelling exercises.

(vi) Identification of integrated indicators and "what-if?" scenarios with their associated story lines.

(vii) Development of adaptive IWRM options to mitigate obvious impacts of climate change taking into account the preferences of stakeholders interviewed.

(viii) Implementation of the JESAT component AIDIS and enhancement of the system towards an Integrated Land and Water Management System (ILWRMS).

6. RESULTS

The results presented herein summarize in brief the different project deliverables which are published in detail on the project home page (http://www.brahmatwinn.uni-jena.de/). They have been produced and analysed consecutively in three project phases according to the integrated structure of the project, i.e. the lower ranked objectives from above provided the know-how and data base required to elaborate on the higher ranked ones.

6.1 Downscaling of AOGCM results and projections

To estimate the impact of future climate change on the hydrology at the basin scale, climate projections with a suitable temporal and spatial resolution are essential input to hydrological models. However, projections from current AOGCMs have a grid resolution of about 200 km or more. Thus, AOGCM projections are inappropriate to assess the impact of climate change on a regional scale that is related to IWRM. Therefore ERA-40 re-analysis data rather than data from a general AOGCM simulation have been downscaled from about 1.125° grid spacing to about 0.5° in the UDRB and the UBRB. This minimised the influence of large scale circulation uncertainties on the downscaling results.

Using regional climate projections from the COSMO-CLM (COnsortium for Small-scale Modelling in CLimate Mode) allows analysing the impact of the climate change signal on the regional water balance in the UDRB and the UBRB. To generate several likely scenarios for the time period 1960-2100, the COSMO-CLM was driven by the GCM ECHAM5/MPIOM with four different SRES forcings.

6.1.1 ERA re-analysis 1957 - 2000

The climatology of ERA-40 re-analysis, COSMO-CLM, simulations and different observations for the UDRB and UBRB shows a generally temperate climate, the climate in South Asia is dominated by a monsoon system which supplies the region with up to 80% of the annual rainfall total. For both basins the analysis of the historical time series reveals:

(i) The COSMO-CLM performs clearly better in the UDRB than in the UBRB. However, considering the big uncertainties in the observations of precipitation, the COSMO-CLM performance in the UBRB is acceptable and shows much better results than the ERA-40 precipitation which has deficiencies in representing the orography.

(ii) By applying the dynamical downscaling method the downscaling of the hydro-meteorological parameters showed

- Temperature is projected to increase in both basins in the coming decades with the higher values in the region of the Tibetan Plateau. Thus, parameters directly dependent on temperature, like potential evapotranspiration will show similar trends. This will have a significant impact on the hydrology of the river basins.
- Precipitation trends are less clear. Annual precipitation is projected not to change significantly, but seasonal amounts are. Different climate change indicators, like the length of the longest dry periods, indicate more frequent and prolonged droughts.
- The projected increasing amount of (1-day and 5-day) spring precipitation in the UDRB in combination with increased spring snow melt due to higher temperatures in the Alps might even yield more intense and frequent flooding events.
- An increase in the number of consecutive dry days and in the maximum 5-day precipitation amount in the region of the Tibetan Plateau for the monsoon season, as well as large temperature trends indicate a highly sensitive region to future climate changes. For Assam, the positive trend in the number of consecutive dry days in the monsoon season indicates longer monsoon breaks.

6.1.2 SRES based CC projections

To assess the issue of changing climate in the twinning basins, seasonal trends of daily precipitation and temperature indicators were calculated for the simulation period 1960-2100, and the projections were normalized with respect to the reference period 1971-2000. The trends were tested for statistical significance at the 5% level using a linear model and indicate:

(i) Temperature projections show high regional and seasonal differences, but overall, the commitment scenario shows the smallest trends up to the year 2100, followed by the B1, A1B and finally the A2 scenario. However, up to the year 2080 most A1B trends are higher than those of the A2 scenario. This can be explained by the higher emissions of the A1B scenario at the beginning of the 21st century. Thus, the magnitude of the trends is generally in direct relation to the amount of greenhouse gas emissions of the single scenarios.

(ii) A1B was considered as the most likely one and B1 as a more optimistic one. However, the projected trends of the A1B and A2 scenario are close to each other. In the commitment scenario, constant greenhouse gas concentrations are assumed after the year 2000. Thus, it may be used as a control experiment to estimate the impacts of anthropogenic forcings on the climates in the two basins.

(iii) The projected precipitation trends are less unanimous than the temperature trends. No significant trends were found in the two basins for the annual precipitation amounts as seasonal and regional trends are compensating each other.

The results give sound evidence about climate change dynamics which will impact the hydrological process dynamics and runoff generation at present active in the UDRB and the

UBRB respectively. They provide a comprehensive scenario framework within which adaptive management options for sustainable IWRM can be developed and evaluated.

6.2 Assessment of the natural environment (NE)

The results obtained from this research activity provided comprehensive assessments and analysis of the basins' NE comprising (i) terrain analysis, (ii) glaciers, permafrost, (iii) LULC, (iv) groundwater and (v) eco-hydrological wetland studies. As discussed below they characterize and quantify the interactive process dynamics of the natural system's components that comprise the NE-framework for the socio-economic development:

6.2.1 Terrain classification

Topography was analysed in the UDRB and the UBRB based on the 90 m SRTM digital simulation model (DSM) resampled to a digital elevation model (DEM) of 1 km resolution providing the base maps of the basins. After removing sinks the DEM was classified according to morphometric and hydrological criteria required to delineate the Hydrological Response Units (HRU) as well as to parameters used to model permafrost distribution and slope instability. The analysis provided the following insight:

(i) Previous vertical accuracy assessments of the SRTM data seem a bit too optimistic, particularly for high mountain areas.

(ii) A trend of underestimating heights within interpolated areas and overestimating of their outside is observed.

(iii) Areas with interpolated surfaces (ex-voids) should not be used for terrain analysis or as test areas without checking the vertical accuracy.

6.2.2 Glacier retreat and permafrost distribution

Glacier retreat was derived from repeated glacier inventories and area-volume analysis in the test catchments and were upscaled for the total area of the twinning basins. They provided the following quantifications:

(i) Although the glacier area in the Lhasa river catchment is about 8 times larger than in the Wang Chu catchment the glacier area change in both areas is similar with about -7 % per decade.

(ii) The glaciers in the UBRB lost about 20 % of their volume between around 1970 and 2000 adding up to an ice volume loss of 175 km^3, about 7 km^2 per year, that represents a water equivalent of about 0.3 m per year.

Permafrost distribution in the UBRB and the UDRB was modelled and intersected with glaciers, glacier lakes, steep terrain etc. in order to identify potential interactions and climate change impacts. Results from this modelling exercise are:

(iii) The permafrost area in the UBRB is comparably high with 20-25 %, underlining the strong periglacial character of the basin. As a consequence, changes in the ground thermal regime due to climatic changes will therefore have significant impacts on slope stability.

(iv) In the UDRB, the permafrost area is in the order of 3-4 % because the model applied to the UDRB allows slightly warmer conditions for the existence of permafrost compared to the UBRB permafrost model.

6.2.3 Land use/land cover (LULC) classification

LULC was derived by means of remote sensing and the classifications have been validated and improved by ground-truthing missions and collection of GPS measured ground reference points. Change 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.

Due to cloud cover or other atmospheric effects (e.g. oblique sun angle due to winter season), as well as the constraints imposed by strong topographic effects, the LULC classification for 1990 was hampered. As an alternative for difficult conditions, the analysis was carried out using MODIS data sets, with a significant lower spatial resolution (250m) as compared to Landsat (30m), but with sufficient coverage. With a focus on bank erosion, the change of the river bed, along with increase or decrease of agricultural fields were investigated and provided the following input:

(i) In support to the evaluation of eco-hydrological relevant land-cover-types, high-resolution satellite imagery was used for a fine-scale LULC classification.

(ii) The validity of land use/land cover mapping in the study area using an expert classification system has been successful. The combination of Landsat satellite imagery with ancillary topographical and environmental data proved to be an effective technique. The developed expert system can also be used for image classification in areas with similar conditions. Although expert systems can improve the classification accuracy, there is still a far way off towards automatic classification.

(iii) In the context of BRAHMATWINN a harmonized LULC classification to enable the comparison of river basin conditions was achieved by settling on a common legend by consensus and to validate the approach during joint working sessions.

6.2.4 Groundwater vulnerability

The general lack of data on all levels was the most limiting factor of the entire groundwater investigation. The use of the DRASTIC model method to assess aquifer vulnerability is a way to compensate for this constraint as the required input data can be derived or estimated using generally available geographical data. However the following findings of the groundwater vulnerability assessment should be considered as an realistic overview which needs further validation:

(i) Depth of groundwater was based on data provided by Indian Institute of Technology in Roorkee and the depth to groundwater was interpolated using natural neighbourhood procedure for 52 referenced shallow dug wells measured once or several times during the years 2000 till 2006.

(ii) Aquifer and soil media were derived from a study on groundwater resources of India identifying 4 prevailing groups of aquifers, and the three DRASTIC categories concerning soil properties were derived from the Assam soil map which is based on USDA system.

(iii) The interpretation is based on the DRASTIC INDEX weighting formula and corresponding indicators of aquifer vulnerability are determined by weighted sums. The output coverage contains graphical representation based on raster data analysis corresponding to the DRASTIC INDEX values.

6.2.5 Eco-hydrology and wetland characteristics

The eco-hydrological studies of biodiversity and wetland classification focussed on the Assam region of the Brahmaputra basin as wetlands in Tibet could not be investigated in more detail because of political unrest and consequent travel restrictions. The framework provided by the Synthesis Report Wetland and Water (Millennium Ecosystem Assessment, 2005) was adapted for the wetland classes found in the twinning basins, at sub-catchment scale and were validated by field trips. Vulnerability of the wetlands was assessed particularly with regard to the pressure of the adjacent human population on wetlands and to the possible effects of climate change on the wetland distribution. The following findings can be presented:

(i) The region is characterized by three terrestrial eco-regions within the *Tropical and Subtropical Moist Broadleaf Forests* biome, of which the semi evergreen forest eco-region of the Yarlung Tsangpo (name of the river in Tibet) valley has the highest proportion within the river corridor. Agriculture and settlements are the main driving forces for pollution.

(ii) Local scale and river basin scale were combined by a rule-based expert system at sub-catchment scale, which uses the LULC classification and the Normalized Difference Vegetation Index (NDVI) obtained from remote sensing as basis to identify alluvial areas, lakes, alpine swamps and meadows, floodplains and beels. The latter are typical lake-like water bodies of different size connected with the river during floods located in Assam and Bhutan. These different wetland classes were further differentiated into four hydrological classes according to their dominant hydrological dynamics.

(iii) Projected glacier melting in high altitude areas of the UBRB and more irregular discharge and possibly longer low run-off periods in lower altitudes have negative impacts on a great number of existing wetlands. Additional impacts may arise from land-use changes, leading to a substitution of wetlands by farmland and settlements in response to high population growth pressure.

(iv) Essential livelihood capacities for the local population will be lost if wetland ecosystem services (EES) like clean drinking water resources, flood retention areas and fundamental biodiversity resources will be reduced..

6.2.6 Delineation of Hydrological Response Units (HRU)

HRU were delineated based on thorough hydrological system analyses in a Geographical Information System (GIS) based on detailed data pre-processing and the harmonization of data sets by means of GIS models as follows:

(i) Morphometric information was classified from the DEM and evaluated based on hydrological know-how regarding their relevance for runoff generation.

(ii) The reclassified datasets were combined in the GIS by using overlay analysis yielding a set of classified polygon features. They have similar characteristics within their border, but differ if compared to their neighbours.

(iii) After eliminating the smallest polygons and joining the attributes, the final HRU were delineated.

6.3 Vulnerability analysis

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. Key to the approach is the development of appropriate indicators based upon established and tested techniques involving stakeholders. This was realized by means of a DELPHI approach integrating perceptions of experts through statistical weights, census data. Additional information was obtained from remote sensing data to integrate environmental indicators and proxies which could not be derived directly from other data sources. Results from the socio-economic studies carried out in the twinning basins highlight the importance of applied Geoinformatics when integrating the socio-economic dimension in IWRM.

By adapting conceptual RU approach in the Salzach catchment Vulnerability Units (VulnUs) have been delineated by means of knowledge based GIS analysis and reveal:

(i) 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 Factors within the susceptibility domains “housing”, “infrastructure” and “assets” and the social capacity domain “early warning” received the highest ranks

(ii) 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

(iii) 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 transdisciplinary approaches).

(iv) The method allows the assessment of vulnerability independent from administrative boundaries, 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 and presents them with VulnUs which represent a common characteristic of vulnerability. Next to that, the advantage is to decompose the units into its underlying domains.

For Assam vulnerabilities were elaborated based upon expert weighted census data complemented by statistical analysis. The extent of the 2007 flood has been used as an indicator of hazard distribution and revealed:

(i) The high vulnerability populations tend to be in those areas that are rural and prone to flooding (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.

(ii) 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 in the UDRB and the UBRB. A condensed vulnerability index, consisting of proxy variables, has been identified and its indicators projected under a correlation with future GDP and population scenarios. This exercise provided the following complement CC related insight:

(i) In the Salzach catchment, 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 and B1. Lower values show the 2-group scenarios A2 and B2 which have a more regional oriented focus than the globalised 1-group scenarios

(ii) In Assam indicators shows a reduction in general vulnerability, and the analysis clearly shows that GDP and population growth impacts on household and community factors that predict socioeconomic vulnerability to climate hazards. Parameters of importance in this regard are the proportions of (1) the population working in agriculture, (2) roads that are metalled, (3) households with a television, (4) houses with burnt brick wall, and (5) 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.

(iii) From the socio-economic perspective the most pessimistic scenario is A2 while agreeing that the best is B1.

6.4 Analysis of present IWRM implemented in the twinning basins

Integrated Water Resources Management (IWRM) is understood as continuous process striving to optimize administrative and technological means to (1) manage the available surface and subsurface water resources, (2) guarantee their sustainable recharge dynamics both in terms of water quantity and quality, and (3) protect water users and the society against destructive flood and drought hazards. The water management components in place within both twinning basins have been evaluated according to these criteria.

6.4.1 Upper Danube River Basin (UDRB)

IWRM in the UDRB is mainly based on bilateral agreements and is embedded into the regional co-operation of the countries sharing the Danube River basin within the framework of IHP UNESCO. This process was further driven by the establishment of the International Commission for the Protection of the Danube River (ICPDR) in 1998 and the implementation of the European Water Framework Directive (WFD) in 2000. Priority water- and land related management issues at present are:

(i) Flood protection, hydropower generation and water allocation by means of runoff regulation in all major tributaries of the UDRB and reservoirs in the Alps that are managed according to the snow and glacier melt dynamics.

(ii) Environmental flow requirements, wetland rehabilitation and groundwater recharge as protective IWRM activities to sustain the characteristic landscapes within the UDRB and to maintain a sustainable agriculture and sustainable development of the tourist industry.

(iii) Water allocation to urban, rural and industrial consumers, and protection of groundwater aquifers against pollution from agriculture.

(iv) Within the alpine mountain environment of the Alps IWRM also includes landscape related issues such as mud-flows and avalanches, preventive measures against glacier lake outbreaks, slope stability during storm events, and snow and glacier melt dynamics.

6.4.2 Upper Brahamputra River Basin (UBRB)

IWRM in the UBRB must be analysed in view of the sensitive geo-political situation with ongoing territorial disputes. Consequently transboundary water management is mainly based on national regulations, i.e. between the states of India and transboundary co-operation between countries sharing the Brahmaputra River basin is either nonexistent or still in the initial phase. Nevertheless there are existing agreements at the trans-boundary level but their implementation is lacking. At present water resources management in the UBRB comprises the following water and land management issues:

(i) Having a total flood prone area of 3.2 million ha the protection and prediction of floods is of highest priority. Predictive rainfall-runoff modelling, however, has not been implemented efficiently and is snow melt estimates and a sophisticated management of natural retention reservoirs in the NE-Indian flood plains.

(ii) Glacier lake outburst floods (GLOFs) especially in Tibet and Bhutan require a specific monitoring and management strategy with respect to glacier lakes and unstable border moraines.

(iii) Improved and sustainable water supply and sanitation, treatment of waste water and mining discharges are focal points for IWRM combining water quantity and water quality management.

(iv) Identification of ‘hot spots’ of bank erosion in the river stretch is another priority task as in the last forty years Assam lost about 4.500 km^2 of productive farm land due to bank erosion. Deforestation is producing soil erosion producing and complement sediment input to the Brahmaputra River.

(v) Identification of environmental flow requirements to sustain wetlands on the Tibetan plateau and the NE-Indian flood plains.

6.4.3 Delineation of Water Resources Response Units (WRRU)

The WRRU concept is merging the HRU approach with the distributed mean annual water balance components obtained from the DANUBIA hydrological model with special focus on flood generation by surface runoff and interflow. The latter were classified by means of overlay analysis in a GIS, and flood generation was related to LULC, topography and soils thereby enhancing the RU concept for a process related water balance analysis as a base for implementing IWRM in river basins.

6.5 Hydrological modelling

The DANUBIA hydrological model was applied for the historical period from 1971 to 2000, driven by the modelled climate data provided by the climate modellers (see 6.1). Input data fields of topography, LULC, soil texture as well as glacier properties with a spatial resolution of 1 x 1 km were derived from SRTM data, the digital Soil Map of the FAO/UNESCO, and MODIS/TERRA respectively. The glacier model used data derived from the Chinese glacier inventory. Detailed information of soil physics and plant parameters, stored as data tables, are taken from literature and complement field campaigns. The modelling exercises for the historical time span 1960 till 2000 and the SRES projections till 2080 required considerable computing power and provided the following outcomes:

(i) In both twinning basins a reduction of the mean annual runoff is simulated indicating the likelihood of decreasing water availability. The magnitude of the trends varies according to the chosen SRES setup. While there is no significant trend for the commitment scenario, the strongest decrease is modelled for B1 in the UDRB. In the Asian test site a decreasing is simulated for all four scenarios, which rises in magnitude from the commitment to the A1B scenario conditions.

(ii) Reasons for the predicted discharge reduction are related to the projected precipitation dynamics. Whereas in the UBRB precipitation is becoming less in all four scenarios, there is no significant trend in the UDRB except for the B1 scenario with a precipitation decrease. Furthermore the decreasing trend of snowfall during the past period from 1971 to 2000 continues in both basins for all four scenarios except for the commitment run. Projected increasing temperatures as well as longer vegetation periods result in an increasing evapotranspiration n both basins.

(iii) In the south-western parts of the UDRB a decrease in runoff can be seen whereas in the eastern parts an increase in runoff is simulated. Moreover the annual evapotranspiration increases in the low and high mountain ranges due to higher temperatures and accordingly longer growing seasons.

(iv) The Tibetan parts of the UBRB show an increase of water availability, whereas in Assam in India the runoff will decrease according to the decreasing precipitation pattern. With increasing precipitation in the Tibetan parts the evapotranspiration also increases a little whereas in Assam both an increasing as well as a decreasing trend is simulated.

(v) In all scenarios runoff will decrease in the UDRB especially during the summer month. This trend goes on in the last period of the scenario time. In the UBRB runoff will decrease in all four scenarios in the first 30 years of the modelled future period, especially during the summer months. The decreasing trend is going on in the second period from 2051 to 2080.

(vi) Due to increasing air temperatures the melting periods will be longer in the future, thus the influence of ice melt during the future period from 2011 to 2040 increases compared to the past. Afterwards a new balance will be established.

6.6 Identification of integrated indicators

A set of integrated indicators was identified in both basins that quantify the key environmental, social, economic, and governance aspects related to climate change impacts and IWRM and thereby support the processes of IWRM strategy development. The NetSyMoD approach has been applied which relies on the DPSIR (Driving Forces – Pressures – State – Impacts – Responses) framework (EEA, 1999) for problem conceptualisation and indicator selection. There are six steps envisaged within this methodology and two phases in particular have been used to build the Integrated Indicator Table (IIT): ***Firstly*** Problem Analysis, and ***secondly*** Creative System Modelling. The resulting IIT has a multi-level structure in which the indicators are organised in four categories:

(i) **Themes** aim at characterising a sustainability framework, and comprise the environment, social, economic and governance components:

(ii) **Domain** to identify a particular Environmental, Social, Economic or Governance issue (e.g. LULC change, Environmental Hazards, Livelihoods/Assets, Health/Sanitation, Energy, Economic development, Education, Institutional and legislative frameworks…).

(iii) **Sub-domains** account for the diversity of each case study area through different sets of indicators thereby constituting the interface between the quantitative and qualitative data sets.

(iv) **Indicators** quantify sub-domains

For instance the domain ***Climate*** was subdivided into four sub-domains: *Precipitation*, *Temperature*, *Aridity* and *Evapotranspiration*, each of them quantified by one or more *indicator*.

6.7 Development of "what-if?" scenarios

Increasing emphasis is given on public participation in IWRM and to the role that could be played by information technologies (IT), such as Decision Support System (DSS) tools. The latter provide the ground for bridging the scientific contributions (i.e. by further elaborating model outcomes) and decision/policy making processes, including the management of the participation of different actors (e.g. policy makers, local experts, dwellers, etc.).

Future socio-economic vulnerability scenarios following the SRES projections (A1, A2, B1, B2) for the time steps 2000, 2020 and 2050 have been modelled. As no projections regarding the governance environment have been made in the SRES "what-if?" storylines the latter have been deconstructed to identify the particular strands relevant to water, land and disaster management, and the resulting projected governance frameworks used to flesh-out the SRES storylines. These strands include the

- potential for institutional and international co-operation,
- relative balancing of economic, social and environmental concerns,
- capacity for land use control; and
- the likelihood of effective enforcement.

Each response strategy was then evaluated against the projected governance strengths and weaknesses derived from the SRES storylines, and against the legal and institutional reality in the relevant basin state.

In result respective SRES related “what-if?” scenario storylines were derived and evaluated with respect to the socio-economic and physical characteristics identified in the SRES storylines as regards the potential governance situation in 2100. This then allows an evaluation of those IWRM response strategies that seem most appropriate for the storylines based on the projected governance situations.

The “what-if?” scenarios derived were applied in the Salzach River basin and in the Assam NE-India case studies, under the same scenario conditions and following a joint methodology. A condensed vulnerability index, consisting of proxy variables, has been identified and its indicators projected under a correlation with future GDP and population scenarios.

6.8 Adaptive IWRM scenarios to cope with “what-if?” scenarios

The Geoinformatics approach adopted for the analysis of alternative IWRM responses to decrease vulnerability to flood risk is based on the six phases of the NetSyMoD methodological framework (www.netsymod.eu) for the management of participatory modelling and decision processes. The first three phases, e.g. *Actors’ Analysis, Problem Analysis, Creative System Modelling* provide a list of issues and possible responses to them and have been elaborated from local actors’ workshops. The forth *decision support system (DSS) design* phase resulted in a set of alternative IWRM responses and in the identification of the tools and indicators needed for their assessment. The fifth phase named *Analysis of Options* is performed with the Mulino DSS (mDSS) software through Multi Criteria Decision Analysis (MCDA).

6.8.1 Responses to cope with vulnerabilities

Four categories of responses have been defined from outcomes of previous local actors’ workshops (Guwahati, India, April 2007; Thimphu, Bhutan, October 2007; Salzburg, Austria, October 2008):

(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 evaluate the responses, local actors selected and weighted criteria found in the Integrated Indicator Table in result produced a list of nine criteria to be selected for supporting MCDA. Each three of them belong to the environmental, the social theme, and the economic theme, thus providing insight on all the three pillars of sustainability. 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 consistent result is 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.

6.8.2 Responses within the governance framework

The responses to the SRES A1, A2, B1 and B2 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 show those strategies most in accord with what the storylines might reflect and generate the following interpretations:

(i) 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.

(ii) 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.

(iii) Strategies that encourage and enable participation at the community level only would best be suited to the A2 and B2 scenarios.

(iv) 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.

6.9 Integrated Land and Water Resources Management System (ILWRMS)

The ILWRMS developed in BRAHMATWINN supplies users and decision makers with sophisticated integrated information system that will ***firstly*** present the results and data obtained in BRAHMATWINN and ***secondly*** provides tools applied in the twinning UDRB and UBRB basins to support decision making. This was realized in the ILWRMS by providing the following services and functionalities:

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

The ILWRMS comprises the functionality of a Data Information System Tool (DIST) and decision support. It provides sophisticated data query and analysis functionalities, offers basic statistic analysis for basin time series and spatial queries via populated GIS maps.

The user is guided through the system by means of user friendly graphical user interfaces (GUI) and a comprehensive help system is implemented to provide additional information for data and GIS map input, queries, and spatial searches. The ILWRMS also offers a sophisticated visualization system 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 BRAHMTWINN 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) that provides first insight into the functionality of the system.

7. CONCLUSIONS FOR IWRMS AND IMPACTS OF CLIMATE CHANGE

The comprehensive assessment and analysis research studies carried out by the BRAHMATWINN project in the UDRB and UBRB provided numerous insights of natural and socio-economic process dynamics of IWRM and impacts that can most likely be expected from ongoing CC. Meanwhile it enhanced existing know-how in this regard in the UDRB the project provided significant new knowledge in the UBRB that has not been available before on this transboundary scale.

With respect to IWRM and impacts of climate change the following conclusions were derived for both twinning basins:

(1) Temperature is projected to increase in both basins in the coming decades with the higher values in the region of the Tibetan Plateau. Thus, parameters directly dependent on temperature, like potential evapotranspiration, are also assumed to show clear trends. This will have a severe impact on the hydrology of the river basins.

(2) Precipitation trends are less clear. Annual precipitation is projected not to change significantly, but seasonal amounts are. Different climate change indicators, like the length of the longest dry periods, indicate more frequent and prolonged droughts. However, there is no simultaneous tendency to less flooding events. The projected increasing amount of (1-day and 5-day) spring precipitation in the UDRB in combination with increased spring snow melt due to higher temperatures in the Alps might even yield more intense and frequent flooding events.

(3) An increase in the number of consecutive dry days and in the maximum 5-day precipitation amount in the region of the Tibetan Plateau for the monsoon season, as well as large temperature trends indicate a highly sensitive region to future climate changes. The positive trend iof the number of consecutive dry days for the monsoon season in Assam indicate longer monsoon breaks.

(4) In this study a specific model combination was used, and applying a different AOGCM to drive the COSMO-CLM would most likely result in slightly changed regional projections. The HadCM3 AOGCM for example projects larger increases of precipitation in the UBRB than the ECHAM5/MPIOM. Thus, the COSMO-CLM may be expected to project slightly larger precipitation trends too, if driven by the HadCM3, and this uncertainty clearly has to be considered.

(5) The water resources bound in glacier-ice in both twinning basins have decreased significantly in the recent decades. This trend will according to most climate scenarios continue although the actual down-stream impact of these changes to the run-off regime will become less significant with increasing distance to the glacier covered headwaters.

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

(7) In general the region of Assam can be considered as a one with significantly high aquifer vulnerability regarding floods. The main reason is a presence of very shallow aquifers in all over the area, where the typical depth to groundwater below surface ranges up to 5 meters.

(8) The importance of wetlands as a source of livelihood services and quality is often not appreciated well enough by the local population and population growth therefore is directly linked with progressing drainage of wetlands. The challenge is to get relevant policy levels, decision making parties and stakeholders, involved to appreciate the value of wetlands with respect to their unique biodiversity, and hydrological ecosystem functions (ESF) and related ecosystem services (ESS).

(9) In the European context of the UDRB vulnerability is strongly characterized through assets, whereas in the Assam region of the Asian UBRB a strong focus lies on the defining characteristics of poverty at the community level. As such, in the Asian context, it is possible that a map of asset vulnerability is the inverse of a vulnerability map based upon community vulnerability. Both reside within a distinct governance and legal context which clearly delineates the complex associations between vulnerability and the strengths and weaknesses of policy and its implementation.

(10) Building on a joint conceptual framework, for each case study area specific indicators have been identified depending on the availability of datasets but even more on the characteristics of vulnerability in the specific areas and the input from different stakeholder workshops, which identified relevant vulnerability indicators. To this end such domains as gender, which has a strong EU imperative were not given substantial weighting due to local expert opinion and despite partner expertise prioritising such a domain.

(11) To implement successfully measures in regard to disaster risk reduction and climate change adaptation actors from national governments, provincial administrations and local authorities need to plan interventions based on specific locations. The spatial representation of risk, visualising the extent of hazard or the distribution of vulnerability is therefore needed to successfully implement and address such strategies.

(12) Additionally there is a substantive body of work to be undertaken to effectively include the diverse and substantial impact of governance on vulnerability and its spatial distribution. Currently the proxies for the mapping of effective governance are highly limited and such methodologies to address this critical area are needed

(13) IWRM implementation in the UBRB is lacking due to conflicts between up- and downstream countries and inappropriate governance structures. There is a clear need to improve the appreciation of upstream-downstream relations and associated land management challenges (e.g. soil erosion, landslides, and deforestation).

(14) Attempts to improve the situation are promising, like i.e. Bhutan’s commitment to the MDG targets and the protection of water resources applying the ‘polluter pays’ principle. Similar concepts are partly implemented or planned in the neighboring countries Tibet/China and India.

(15) Implementing the WRRU concept will provide water and land managers with the means to link the natural landscape environment, e.g. LULC, soil, geology and climate with the water yield produced from each HRU thereby providing the means to coordinate and adapt land and water management for sustainable IWRM with respect to CC impact on river basin water balances.

(16) The creation of the IIT enabled the integration of two processes, one stakeholder/end-user driven, and the other researcher driven. The framework (Theme, Domain, Sub-domain, Indicator) can thus be seen as the interface between the contributions of stakeholders and BRAHMATWINN research partners towards the formalization of the problem.

(17) Comprehensive system analysis and modelling should be integrated into the process of defining integrated indicators, as well as in the workshop discussions with local actors and stakeholders, to enhance their appreciation of pressing IWRM needs.

(18) Under the assumption that climate will develop according to the CLM ECHAM 5 model output for the applied SRES setups, CC will have a significant impact on the hydrological dynamics of the water balance in the UDRB and the UBRB as less water will be available in both basins. Reasons for the decrease predominantly are less precipitation and higher evapotranspiration due to rising air temperatures.

(19) Less water will be available for hydropower production, which is the main renewable power source in both twinning basins. Furthermore the changes will affect agriculture in higher elevation regions, as the growing season due to higher temperatures will be extended if compared to the past.

(20) The vulnerability analysis shows that GDP and population growth impacts on household and community factors that predict socio-economic vulnerability to climate hazards. The impact of GDP and population growth is highest in areas where levels of vulnerability are already high. A slow growth in population with a concurrent rapid growth in GDP is important in reducing levels of vulnerability.

(21) The impact of climate change depends on the IPCC 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, B1 is ranked as the best setup with A1 closely following.

(22) Given the correlation between high income levels and good governance the A1 scenario suggest good accountability and transparency in government actions, along with effective enforcement, characteristics that would be shared with the B1 scenario.

(23) Coordinated land and water management is a prerequisite for the implementation of a sustainable IWRM process. Innovative technologies for comprehensive system assessment, modelling of landscape process dynamics and socio-economic analysis require a common and user friendly platform to present the results and integrated functionality to local actors, decision makers and planners.

(24) 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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