Università
Ca'Foscari
Venezia

Scuola Dottorale di Ateneo
Graduate School

Dottorato di ricerca
in Scienza e Gestione dei Cambiamenti Climatici
Ciclo 25
Anno di discussione 2013

Climate change impact and vulnerability assessment of water resources systems: the case of Lower Brahmaputra River Basin

SETTORE SCIENTIFICO DISCIPLINARE DI AFFERENZA: GEO/04; SPS/10
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Dedicated to

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My beloved parents

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ABBREVIATIONS

ACI	adaptive capacity index
AMS	Annual Maxima Series
BARC	Bangladesh Agriculture Research Council
BFRI	Bangladesh Fisheries Research Institute
BIWTA	Bangladesh Inland Water Transport Authority
BRRI	Bangladesh Rice Research Institute
BWDB	Bangladesh Water Development Board
CCA	climate change adaptation
CBOs	community based organizations
DP	development pressure
ES	ecological security
FAP	Flood Action Plan
FCD/I	flood control, drainage and irrigation
FPCO	Flood Planning Coordination Organization
FVI	flood vulnerability index
FP	floodplain
GEV	Generalized Extreme Value
GL	Generalized Logistic
GCMs	Global circulation models
GEC	global environmental change
GWP	Global Water Partnership
HB	Himalayan belt
IWRM	Integrated water resources management
IPCC	Intergovernmental Panel on Climate Change
IBRD	International Bank for Reconstruction and Development
JJAS	June, July, August and September
LGED	Local Government Engineering Department
LGIs	local government institutions
LN3	Log Normal
LLP	low lift pumps
LBRB	Lower Brahmaputra River Basin

MC	Management challenges
MPO	Master Plan Organization
NWMP	National Water Management Plan
NWPo	National Water policy
NWRC	National Water Resources Council
PE3	Pearson type III
PCMDI	Program for Climate Model Diagnosis and Intercomparison
RVA	Range of Variability
RFWR	Renewable freshwater resources
RS	resources stress
SES	social-ecological system
SD	standard deviation
TP	Tibetan Plateau
TW	tube-wells
UNU-EHS	United Nations University – Institute for Environment and Human Security
VA	vulnerability assessment
VI	vulnerability index
WRM	water resources management
WARPO	Water Resources Planning Organization
WRS	water resources system
WSI	water stress index
WVI	water vulnerability index

ACKNOWLEDGEMENT

First of all, I would like to thank almighty God for giving me the ability to complete the work. I want to express my sincere and heartiest gratitude to my supervisor Prof. Carlo Giupponi of Ca' Foscari University of Venice and co-supervisor Dr. Fabrice Renaud of United Nations University – Institute for Environment & Human Security (UNU-EHS). Especially, I am grateful to Prof. Giupponi for his constant guidance, valuable advice, generous help and constructive discussion to carry out this research. I consider myself to be proud to have worked with him. I am also grateful to Dr. Fabrice Renaud for his guidance and suggestion and for providing me an excellent opportunity to work at the UNU-EHS, an international research institute.

I owe my special thanks to Dr. Walter Immerzeel and Prof. Marc Bierkens for giving me a nice opportunity to work at Physical Geography Department of Utrecht University. Contribution and support from Mr. Yoshi Wada, Dr. LH van Beek and Dr. Frederick Sperna Weiland of Utrecht University are highly acknowledged. During my stay in UNU-EHS, I am thankful to Ms. Maria Schwab for her contribution.

I am deeply grateful to Dr. Heiko Apel, Researcher of Hydrology Section of German Research Centre for Geoscience, Potsdam, Germany for his support and collaboration. I express my profound respect to my MSc Supervisor Prof. Mozzammel Hoque, Prof. Rezaur Rahman and other teachers of IWFM, BUET for their fruitful advices in different times. I would like to thank Dr. Jaroslav Mysiak of FEEM, Dr. Saleemul Huq of Independent University and Dr. Monirul Q. Mirza of Environment Canada for their suggestions.

I express my deepest thanks to Gianleo Frisari, Dragana Bojovic, Stefano Balbi, Vahid Mojtahid, Laura Bonzaningo. I also wish to expresss my thanks to Abidur Rahman Khan, Uthpal and my wife Suma for their support in different manners.

I am thankful to our PhD Secretariat, Agnese Boscarol and Maria Giovanna for their help.

Animesh Kumar Gain
January, 2013

ABSTRACT

According to UN-Water, water is the primary medium through which climate change influences the Earth's ecosystems and therefore people's livelihoods and wellbeing. Besides climatic change, current demographic trends, economic development and related land use changes have direct impact on increasing demand for freshwater resources. Taken together, the net effect of these supply and demand changes is affecting the vulnerability of water resources systems (WRSs), in which complex interactions of both natural and human elements of the social-ecological systems are in place. Therefore, for assessing vulnerability and risk of water resources system, the integrated contribution of several disciplines is required, enabling a comprehensive, but also complex, dynamic description of present state and future trends. With the aim to integrate the assessment of risks of complex WRS, this dissertation first focuses on the hydrologic impacts of climate change, with calculation of river flow thresholds, and the related water governance issues, and then it moves to the integrated assessment of vulnerability and risk of WRSs, with a focus on the development of operational approaches in the context of developing countries. The assessment has been conducted in the context of the Lower Brahmaputra River Basin (LBRB), where the hydrological impact of climate change is expected to be particularly strong because of snow melting in the Himalayas, alterations of the monsoon regimes, and sea level rise.

In *Chapter 1*, general introduction of the dissertation is discussed and research questions are formulated.

In *Chapter 2*, climate change impact on stream flows of the Lower Brahmaputra River Basin for IPCC A1B and A2 scenario has been assessed through multi-model weighted ensemble analysis, using model outputs from a global hydrological model forced with 12 different global climate models (GCMs). The results show that only a limited number of GCMs are required to reconstruct observed discharge. The effect of climate change on both low and high flows was then investigated with the weighted ensemble models. and the analysis shows that a very strong increase in peak flows is projected, which may, in combination with projected sea level change, have devastating effects for Bangladesh.

In *Chapter 3*, ecological flow thresholds and different damaging flood events of LBRB were calculated and climate change impact was investigated. The Ecological flow threshold was calculated using twenty-two ‘Range of Variability (RVA)’ parameters considering the range between ± 1 standard deviation from the mean of the natural flow. Damaging flood events were calculated using flood frequency analysis of Annual Maxima series and using the flood classification of Bangladesh. The results demonstrate that due to climate change, various parameters will exceed the threshold condition for both IPCC A1B and A2 scenarios: in particular, the monthly mean of low flow (January, February and March) and high flow (June, July and August) periods, 7-day average minimum flow, and yearly maximum flow. The consequences expected for the management of the WRS are reduction of aquatic biodiversity, loss of agricultural crops, food insecurity etc.

In *Chapter 4*, the dissertation moves from hydrological studies to the assessment of water governance status and trends, considering seven indicators that represent legal, political and administrative aspects. Changes are analysed by considering both the effects of evolving policy documents and the quality of governance perceived by water user groups. The results show that, according to the policy documents, all the governance dimensions should have significantly improved in recent times and they will further improve in the near future, but the actual implementation of these policies seems to be far behind what the policy documents indicate and, moreover, this gap has even been increasing over time.

In *Chapter 5*, the evolution of proposed approaches to vulnerability assessment related to water resources system has been reviewed and research gaps identified. To overcome these gaps a generalized assessment framework is developed and presented in details with reference to the context of the LBRB.

In *Chapter 6*, an operational system analysis approach and a simulation tool for risk assessment of the WRS has been developed within the broad and often inconsistent contexts of climate change adaptation and disaster risk reduction literatures, with the aim to support the decision making process. A rather innovative weighting and aggregation procedure to reflect stakeholders' and experts’ views in terms of aggregation of the multiple dimensions of risk assessment, has been implemented, by means of a non-additive aggregation operator, the Choquet integral, used to construct concise indexes, with the capability to manage and fine tune the aggregation algorithms with consideration of various aspects, such as compensatory or synergistic combinations depending on the specific variables to be aggregated and their relative values.

In *Chapter 7*, the main findings of each chapter have been summarized. The implications of the results are then described setting out the links to the future research. The results of this study are intended to be used for contributing to planned adaptation of water resources systems of Lower Brahmaputra River Basin.

Chapter 1 Introduction

Freshwater is a renewable resource, constantly recharged by the global cycle of evaporation and precipitation. However, the circulation rate of recharge has an upper limit to the amount of renewable freshwater resources (RFWR) available to human society, which is determined by the climate system. On the global scale, current withdrawals are well below this limit and if the water cycle is managed wisely, RFWR can cover human demand far into the future (Oki et al., 2006).

Why then should we be concerned about water scarcity?

The reason is the high variability and uneven distribution of water resource availability in time and space (Postel et al., 1996). As a consequence, more than two billion people live in highly water-stressed areas.

Temporal variations has the logical consequence that water volumes flowing during floods and wet seasons cannot be used during the low flow seasons unless storage systems i.e. reservoirs are in place, whereas, spatial uneven distribution indicates 'too much water' in delta and 'no water' in desert (Oki et al., 2006). In addition, climate change is expected to determine significant effect on water cycles, determining changes in the seasonal pattern of water resources. As a result, there is an increase of the probability of extreme events which influences the Earth's ecosystems, people's livelihoods and wellbeing (UN Water, 2009). Beside climatic change, current population growth, economic development and the related land use changes have direct impacts on increasing demand for freshwater resources (Sophocleous, 2004). Combined effects of these changes increase water related risks and the vulnerability of water resources systems (WRSs). However, reducing current vulnerability of the system is not a trivial task as the WRS is not just made of water. Rather, it is the resultant of complex interactions within the related social-ecological system (SES). Therefore, for assessing vulnerability of water resources system, traditional fragmented disciplinary approaches to water management should be replaced by more integrated system view approaches (e.g., Integrated Water Resources Management, and other similar paradigms). Such an integrated approach requires not only hydrologic impact studies, but also integrated contributions of several disciplines considering multiple ecological and socio-economic dimensions and decisional criteria and large numbers of possible alternatives, usually characterized by high uncertainty, complex interactions, and conflicting interests of multiple stakeholders.

Against this background, the main objective of the doctoral dissertation is to develop innovative methods and implement them to investigate current states and future trends as affected by climate change impacts and their relationships with the vulnerability of water resources system (WRS).

The various methodologies used or originally developed within the thesis have been applied to the Lower Brahmaputra River Basin (LBRB). The Brahmaputra is a major transboundary river which originates in the glaciated areas of the Kailash range in Tibet (China) and traverses through China, India, Bangladesh and Bhutan. Although its transboundary nature, there is no coordinated river basin management approach. In addition, climate change impact is expected to be particularly strong because of snow melting in the Himalayas, monsoon climate and sea level rise.

Within the broad objective mentioned above, the thesis attempts to answer the following specific research questions:

(a) Which hydrological impacts of climate change are to be expected in the Lower Brahmaputra River Basin (LBRB)?
(b) What are the thresholds of natural flow regime of LBRB and how climate change affects the thresholds?
(c) What are the changes of the diverse notions of water governance trend in lower part of the Brahmaputra basin (i.e., in Bangladesh)?
(d) What are the current research gaps of vulnerability assessment (VA) and how these gaps can be approached through a generalized framework?
(e) How to design a generalized methodological framework to provide support to quantitative assessment of vulnerability and risk and what could be its operational steps of implementation?

With an aim to investigate climate change impact and vulnerability of complex WRS at LBRB, the sequence of the dissertation follows the research questions set out above in subsequent chapters. Each individual chapter has been published (Chapter 2[*], 4[†] and 5[‡]),

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[*] Gain, A. K., Immerzeel, W. W., Sperna Weiland, F. C., & Bierkens, M. F. P. (2011). Impact of climate change on the stream flow of the Lower Brahmaputra: trends in high and low flows based on discharge-weighted ensemble modelling. *Hydrology and Earth System Sciences 15(5)*, 1537-1545.

[†] Gain, A. K., & Schwab, M. (2012). An assessment of water governance trends: the case of Bangladesh. *Water Policy 14 (5)*, 821-840.

submitted (Chapter 3[§]) or will be submitted soon (Chapter 6[**]) as an article to a peer reviewed journal. As a consequence, some chapters include repetitions of the methods described in previous chapters.

Chapter 2 begins with the assessment of climate change impact on streamflow of the Lower Brahmaputra River Basin. A novel method of discharge-weighted ensemble modelling has been applied using model outputs from a global hydrological model that are forced with 12 different global climate models (GCMs).

Chapter 3 investigates assessment of thresholds of hydrologic flow regime of LBRB. The ecological flow thresholds were calculated using the twenty-two Range of Variability (RVA) parameters considering the range between ± 1 standard deviation from the mean of the natural flow. The damaging flood event was calculated following flood frequency analysis of Annual Maxima Series (AMS) and using the flood classification of Bangladesh. The climate change induced altered flow regime of lower Brahmaputra River Basin was then investigated and compared with the calculated threshold flow.

From hydrological impact studies, **Chapter 4** moves to the assessment of water governance trend of Bangladesh. For investigating water governance trends, seven indicators representing legal, political and administrative aspects were considered. Changes of these indicators were analysed by considering both shifts indicated by policy documents and the quality of governance perceived by water user groups. The results show that according to the policy documents, all notions of governance have significantly improved and will further improve. However, according to water user groups, the actual implementation of these policies seems to be far behind what policy documents indicate.

Chapter 5 provides a generalized framework on vulnerability assessment (VA) of water resources system which is developed for potential application to developing countries. For developing the framework, the evolution of the concept of vulnerability assessment related to water resources have been reviewed. From the current practices, the research gaps were identified. With an aim to overcome these gaps, a generalized assessment framework

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[‡] Gain, A. K., Giupponi, C., & Renaud, F. (2012). Climate Change Adaptation and Vulnerability Assessment of Water Resources Systems in developing countries: A generalized framework and a feasibility study in Bangladesh. *Water 4 (2)*, 345-366.

[§] Gain, A. K., Apel, H., Renaud, F., & Giupponi, C. (2012). Threshold of hydrologic flow regime of a river and investigation of climate change impact – the case of lower Brahmaputra river Basin. Under Review, *Climatic Change*.

[**] Gain, A.K., & Giupponi, C. (2012). A dynamic assessment of water scarcity risk and climate change adaptation in Lower Brahmaputra River Basin. Will be submitted soon.

was developed and a feasibility study was presented in the context of the Lower Brahmaputra River Basin (LBRB).

Chapter 6, draws on the results from the other chapters to implement and operationalize the developed VA framework for LBRB through aggregation of indicators (incorporating previously assessed results) with the involvement of stakeholders.

Chapter 7 draws general conclusions based on the research presented in chapters 2 to 6. Based on the results, some policy recommendations are outlined. Several suggestions for future research are made.

Chapter 2 Impact of climate change on the stream flow of lower Brahmaputra: Trends in high and low flows based on discharge-weighted ensemble modelling

This chapter is based on:

Gain, A. K., Immerzeel, W. W., Sperna Weiland, F. C., & Bierkens, M. F. P. (2011). Impact of climate change on the stream flow of the lower Brahmaputra: trends in high and low flows based on discharge-weighted ensemble modelling. *Hydrology and Earth System Sciences*, *15*(5), 1537-1545. doi:10.5194/hess-15-1537-2011

Abstract

Climate change is likely to have significant effects on the hydrology. The Ganges-Brahmaputra river basin is one of the most vulnerable areas in the world as it is subject to the combined effects of glacier melt, extreme monsoon rainfall and sea level rise. To what extent climate change will impact river flow in the Brahmaputra basin is yet unclear, as climate model studies show ambiguous results. In this study we investigate the effect of climate change on both low and high flows of the lower Brahmaputra. We apply a novel method of discharge-weighted ensemble modeling using model outputs from a global hydrological models forced with 12 different global climate models (GCMs). Our analysis shows that only a limited number of GCMs are required to reconstruct observed discharge. Based on the GCM outputs and long-term records of observed flow at Bahadurabad station, our method results in a multi-model weighted ensemble of transient stream flow for the period 1961-2100. Using the constructed transients, we subsequently project future trends in low and high river flow. The analysis shows that extreme low flow conditions are likely to occur less frequent in the future. However a very strong increase in peak flows is projected, which may, in combination with projected sea level change, have devastating effects for Bangladesh. The methods presented in this study are more widely applicable, in that existing multi-model streamflow simulations from global hydrological models can be weighted against observed streamflow data to assess at first order the effects of climate change for specific river basins.

2.1 Introduction

Climate change is likely to lead to an intensification of the global hydrological cycle and to have a major impact on regional water resources (Arnell, 1999). The IPCC Fourth Assessment Report mentions with high likelihood that observed and projected increases in temperature, sea level rise and precipitation variability are the main causes for reported and projected impacts of climate change on water resources, resulting in an overall net negative impact on water availability and the health of freshwater ecosystems (Kundzewicz et al., 2007).

Among the river systems, the hydrological impact of climate change on Ganges-Brahmaputra Basin is expected to be particularly strong. There are three major reasons for this. First, stream flow is strongly influenced by the melt of snow and ice in the upstream part of the catchment. As 60 percent of the basin area has an elevation of over 2000 meter cryospheric processes are deemed important when considering basin hydrology. Projected rise in temperature will lead to increased glacial and snow melt, which could lead to increased summer flows in some river systems for a few decades, followed by a reduction in flow as the glaciers disappear and snowfall diminishes (Immerzeel, 2008). This is particularly true for the dry season when water availability is crucial for the irrigation systems. Immerzeel et al. (2010) stated that the Brahmaputra is most susceptible to reductions of flow, threatening the food security of an estimated 26 million people. Second, the Ganges-Brahmaputra basin is highly influenced by extreme monsoon rainfall and flooding (Mirza, 2002; Warrick et al., 1996). If climate change results in changes of both the intensity and reliability of the monsoon, it will affect both high and low flows leading to increased flooding but possibly also to increased variability of available water, both in space and time (Postel et al., 1996). The latter refers to the fact that discharging water during floods and wet seasons cannot be used during the low flow seasons unless large storage systems are in place (Oki and Kanae, 2006). Third, climate change induced sea level rise results coastal flooding and riverine flooding by causing back-water effect of the Ganges-Brahmaputra basin along the delta (Agrawala et al., 2005).

The objective of this study is to investigate trends in both high and low flow for the Lower Brahmaputra River that may arise as a result of climate change. Compared to previous assessments (Warrick et al., 1996; Mirza, 2002; Immerzeel, 2008; Immerzeel et al., 2010) we do not build a basin-specific hydrological model for this purpose. Instead, we use existing results of a global hydrological model that was forced by data from 12 global climate models (GCMs) (Sperna Weiland et al, 2010) in a weighted ensemble analysis. The noveltly in this approach lies in that GCM-weights are determined based on the proximity of the associated streamflow simulations to observed streamflow (see Sperna Weiland et al., (2011) for a first application of this method). This approach is an improvement of other methods that have previously been applied. Immerzeel (2008) for examples uses a multiple regression model to predict streamflow at Bahadurabad, but in this case the ensemble results of a physical based distributed hydrological model are matched to observed discharges and hydrological processes are likely to be captured more accurately in the results. Also, the method by which we construct transient stream flow time-series can be considered as novel. Based on the constructed time series of transient stream flow (for the years 1961-2100) we then project trends in low and high flow statistics for the A1B and A2 emission scenarios.

In the remaining part of the paper we first describe the methodology of constructing the transient future time series of river flow in detail. We then show and discuss the results related to the analysis of both low and high flow analysis and conclude the paper by reporting and discussing the major findings.

2.2 The Lower Brahmaputra River Basin

The Brahmaputra is a major transboundary river which originates in the glaciated areas of the Kailash range in Tibet (China) at an elevation of 5300 m above the sea level (m a.s.l.). The river has a length of 2900 km, drains an area of around 530000 km^2 and traverses four different countries (% of total catchment area in brackets): China (50.5%), India (33.6%), Bangladesh (8.1%) and Bhutan (7.8%). Average discharge of the Brahmaputra is approximately 20,000 m^3 s^{-1} (Immerzeel, 2008). The climate of the basin is monsoon driven with a distinct wet season from June to September, which accounts for 60-70% of the annual rainfall. Immerzeel (2008) categorized the Brahmaputra basin into three different physiographic zones: Tibetan Plateau (TP), Himalayan belt (HB), and the floodplain (FP). These zones respond differently to the anticipated climate change. TP covers 44.4% of the basin, with elevations of 3500 m and above, whereas, HB covers 28.6% of the basin with elevations ranging from 100 m a.s.l to 3500 m a.s.l. The area with an elevation of less than 100 m a.s.l. is considered as FP and comprises about 27% of the entire basin. This study is focusing on river flow in the lower Brahmaputra River Basin which belongs to the FP (Fig.

2.1). In the lower Brahmaputra, average temperature in winter is about 17°C and summer temperatures are on average as high as 27°C. Total annual precipitation is about 2354 mm concentrated in the monsoon months June, July, August and September (JJAS). The major discharge measuring station of the lower Brahmaputra is in Bahadurabad (Bangladesh). This is the only station in the lower Brahmaputra for which long-term observed records are available through the Bagladesh Water Development Board. The data are of high quality and used for planning purposes and major hydrological studies and flood forecasts, Therefore, long-term observed records from this station will be used to weigh the global hydrological model outputs resulting from the different GCMs.

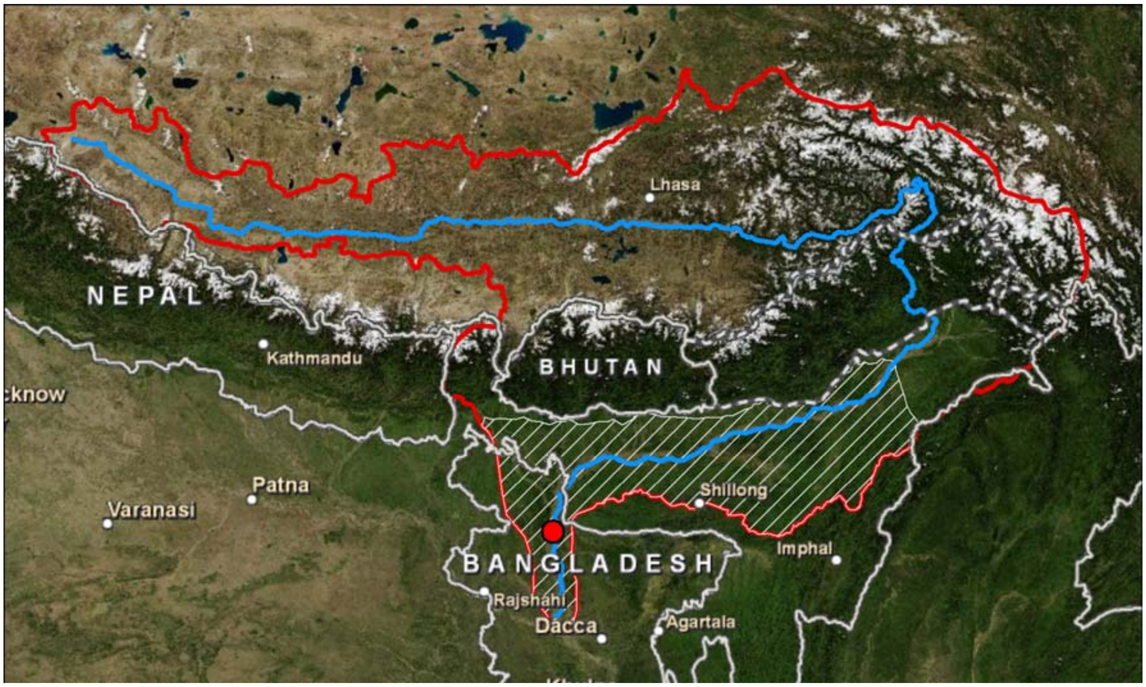


Figure 2.1 Overview of the Brahmaputra river basin (red polygon), the Brahmaputra river (blue line), the outlines of the lower Brahmaputra river basin (shaded white) and the Bahadurabad gauging station (red dot).

2.3 Methods

2.3.1 Creating an ensemble of discharge time series for the reference period

To investigate the impact of climate change on hydrology we have to rely on combinations of runs of climate models and hydrological models. When it comes to climate projections, there is no single best model but rather a pool of models or model components that must be interrogated (Knutti, 2008). Projected values of models are inherently uncertain, because a model can never fully describe the physical system and complete confirmation of model output through verification and validation is impossible (Oreskes et al., 1994; Parker, 2006). Therefore, a collection or ensemble of models is preferably used to characterize the uncertainty in projections, while the credibility of projected trends increases when multiple models point in the same direction. Moreover, the average of a multi-model ensemble often outperforms single models when compared with observations (Gleckler et al., 2008; Reichler and Kim 2008; Knutti, 2008).

This study considers multiple outputs of 12 Global circulation models (GCMs). The output of these GCMs were used to force the global hydrological model PCR-GLOBWB. PCR-GLOBWB (van Beek and Bierkens, 2009; Bierkens and van Beek, 2009) calculates for each grid cell (0.5° × 0.5° globally) and for each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers and between the top layer and the atmosphere (rainfall, evaporation and snow melt). The model also calculates canopy interception and snow storage. Sub-grid variability is taken into account by considering separately tall and short vegetation, open water, different soil types and the area fraction of saturated soil and the frequency distribution of groundwater depth based on the surface elevations of the 1 × 1 km Hydro1k data set. Fluxes between the lower soil reservoir and the groundwater reservoir are mostly downward, except for areas with shallow groundwater tables, where fluxes from the groundwater reservoir to the soil reservoirs are possible (i.e., capillary rise) during periods of low soil moisture content. The total specific runoff of a cell consists of saturation excess surface runoff, melt water that does not infiltrate, runoff from the second soil reservoir (interflow) and groundwater runoff (baseflow) from the lowest reservoir. To calculate river discharge, specific runoff is accumulated along the drainage network by means of kinematic wave routing including storage effects and evaporative losses from lakes, reservoirs and wetlands.

In a previous study (Sperna Weiland et al., 2010; 2011) the output of 12 GCMs (Fig. 2.2 for names) was used as input to PCR-GLOBWB. Daily precipitation and data to calculate daily reference potential evaporation were collected from the data portal of the Program for Climate Model Diagnosis and Intercomparison (PCMDI), https://esg.llnl.gov:8443/index.jsp). For each GCM model runs for two scenarios, A2 and A1B, were selected that represent the upper range of possible CO2 emissions. GCM runs comprised the 20C3M control experiment (1971-1990) and the future scenarios A1B and A2 (2081-2100). When multiple ensemble runs were available for one model, the first run was selected. Although the data portal does not provide all required parameters for the Hadley centre climate models, HADGEM1 has been included for it is frequently used in climate change studies. HADGEM1 data has been retrieved from the CERA-gateway, http://cera-www.dkrz.de.

Discharge data were extracted from the model output at the Bahadurabad station, for which also observed discharge data are available from 1973 to 2004. The observed and modelled monthly mean discharges for the overlapping period 1973-1990 are shown in Fig. 2.2. The figure shows that especially the output of MICRO, GFDL, GISS is similar to the observed data.

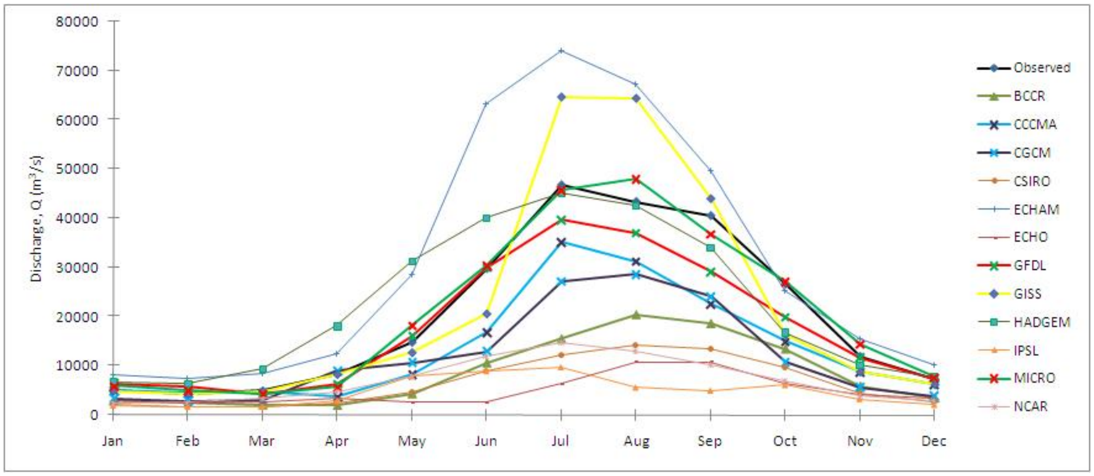


Figure 2.2 Comparison of monthly mean discharge as simulated by PCR-GLOBWB with different GCMs as input with that obtained from observed discharge at Bahadurabad station.

2.3.2 Ensemble weighting based on observed discharge

Rather than statistically downscaling each of the GCMs based on local meteorological data we attached a weight to each of the GCM-PCR-GLOBWB simulated outputs based on a novel method, following Sperna Weiland et al. (2011). Instead of weighting based on similarity of observed GCM-based input (e.g. rainfall), weighting is based on similarity of observed discharge. Using the mean monthly value of observed and simulated discharge during the overlapping period, a weighting factor for each model is computed according to Eq. (1).

$$w_i = \frac{e^{-\frac{1}{12}\sum_{j=1}^{j=12}\frac{(y_j - z_{ij})^2}{\sigma_i^2}}}{\sum_{i=1}^{i=12} e^{-\frac{1}{12}\sum_{j=1}^{j=12}\frac{(y_j - z_{ij})^2}{\sigma_i^2}}} . \quad (1)$$

Where, w is the weighting factor, j is month number, i is model number, σ_i the standard error of discharge observations ($m^3 s^{-1}$), which was assumed to be 25% of the observed value, y_j is the observed average discharge for each month j, and z_{ij} is the mean monthly discharge for model i and month j. The resulting weighting factors for those models with a significant non-zero value are shown in Table 2.1.

Table 2.1 Computed weighing factors for the different model forcings.

	MICRO	GFDL	GISS	CCCMA	CGCM	BCCR	HADGEM	NCAR	ECHAM
w_i	0.368	0.298	0.199	0.092	0.034	0.003	0.003	0.002	0.001

It shows that MICRO received the highest value, followed by GFDL, GISS, CCCMA, CGCM, BCCR, HADGEM, NCAR, and ECHAM. We apply a constant weights for the entire time series and do not vary weights for different months or flow conditions for robustness of the method. We validate this assumption by comparing the flow duration curve of the observations with the modelled discharges for the period between 1973 and 1995 in Fig. 2.3. The results show a good match between modelled and observed discharges and therefore we use a single set of weight for all conditions.

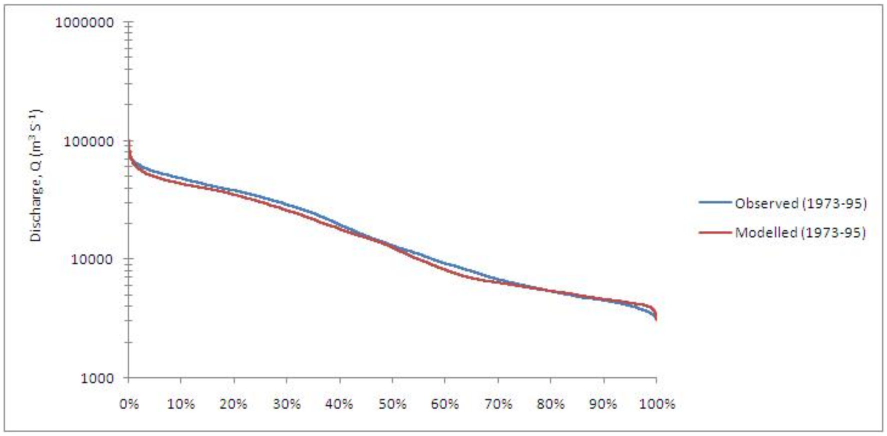


Figure 2.3 Comparison of flow duration curve between observed and weighted ensemble mean (modelled) discharge data for the period 1973-1995.

Using these weighting factors, the daily weighted ensemble average discharge (μ_z) and variance (σ_z^2) can be calculated for the periods of 1961 to 1990 and 2071 to 2100 according to Eqs. (2) and (3).

$$\mu_z = \sum_{i=1}^{i=12} w_i z_i \,, \tag{2}$$

$$\sigma_z^{\;2} = \sum_{i=1}^{i=12} w_i (z_i - \mu_z)^2 \tag{3}$$

2.3.3 Construction of a daily transient time series from 1961 to 2100

The 12 GCMs as obtained from the PCMDI used in Sperna Weiland et al. (2010) only provide runs for time slices (e.g. 1961-1990 and 2071-2100). There are transient runs for some of the GCMs (e.g. at CERA-gateway), but certainly not for all of them. Therefore, to simulate transient time series of discharge for the period 1961-2100, for each of the GCMs the following steps were taken: For each year between 1991 and 2070 a random year is selected either from the reference period or from the projected period. The probability of selecting a random year from the reference period or from the projected period for year *i* depends on how many years year *i* is separated from either the reference period or the projected period. For example the probability (P_r) that for the year 2000 a random year is selected from the reference period is 0.88 according to Eq. (4).

$$P_r(i) = 1 - \frac{(i-1990)}{(i-1990)+(2071-i)} \tag{4}$$

Using this approach a complete time series is constructed from 1991 to 2070, resulting in a full time series from 1961-2100. The full time series from 1961 to 2100 is used in the subsequent analysis of trends in high and low flows. Using this approach year to year variability is preserved in the constructed time-series. It should be noted however that, as we sample discharges directly, we may encounter welding problems between subsequent sampling years: jumps between 31 December and 1 January. However, because we are dealing with a summer Monsoon dominated runoff regime, where low flows occur during boreal winter, such welding problems are limited. Obviously, in case peak flows occur around the turning of the year, or for rivers with a very strong multi-year component, e.g. due to large groundwater reservoirs, such a construction would not work. In this case, one is required to construct transient meteorological time series first and use these as input to the hydrological model to simulate transient discharge time series.

We have validated our approach by artificially reconstructing a transient time series during the observational periods. We constructed a time series from 1980 to 1989 by sampling from the time slices 1970-1979 and 1990-1999 similar to what is described above. We then compare the daily data of the simulated transient ime series with the actual observations during 1980 to 1989 and derive a number of statistics. Our analysis shows that the person correlation coefficient is 0.85, the bias is -2.3%, the root mean square error is 9323 m^3/s and the Nash-Sutcliffe criterion for model efficiency equals 0.71. These numbers show that our approach is valid and that simulated discharge measure observed discharge well. It should be noted that this may be different for river basins where seasonality in discharge is less pronounced.

2.3.4 Extreme value analysis

The low-flow regime of a river can be analyzed in a variety of ways depending on the type of data availability and the type of output information required (Smakthin, 2001; Pyrce, 2004). Here we use the N-day minima approach. Traditionally, the annual minimum (AM) values have been used for low flow frequency analysis, as droughts particularly become an issue when they persist. We use a 7-day low flow frequency using a moving average for the A1B and A2 scenario from 1961 to 2000. To estimate trends in high flow frequencies we performed a traditional extreme value analysis based on yearly maxima for different time slices.

2.4 Results

2.4.1 Trends in discharge

We use linear trend analysis similar to Gain et al. (2007, 2008). Before analysing the trend of the complete data series, we compare the trend between modelled discharge and observed records during the overlapping period of 1973-1995. For the observed records, the trend was 195 $m^3\ s^{-1}\ yr^{-1}$ whereas this value of modelled data was 173 $m^3\ s^{-1}\ yr^{-1}$. This result shows that modelled outcomes are consistent with observed trend. Table 2.2 presents the annual and monthly trends in discharge. From 1961-2100 Trends are calculated by first calculating a trend parameter per GCM and then calculating the weighted mean trend and its variance using Eq. (2) and (3). From this it can be tested whether a trend is significant or not, using a two-sided t-test. Similarly, the goodness of fit coefficient, R^2 is first calculated for each GCM subsequently the weighted average over all models calculated. This analysis was done on both yearly average discharge as well as on discharge per month. Table 2.2 shows that on annual basis there is a strong positive trend in stream flow that is mainly caused by a strong increase in monsoon discharge. During the dry seasons a modest increase is observed. The only negative trend is found in May, but the correlation is small and the trend non-significant.

Seasonal average flow for both A1B and A2 scenario of four time slices are compared in the box-whisker plots of Fig. 2.4. Box plots were obtained by first calculating cumulative frequency distributions per GCM and then constructing a weighted cumulative frequency distribution by weighting values belonging to the same quantile. The statistics in the box plots are thus based on the weighted cumulative frequency distribution. Figure 2.4 shows that the strongest increase in both average and extreme discharge is predicted for the summer and autumn periods. It also shows that changes in discharge distributions are quite similar between scenarios, except for summer and autumn (i.e monsoon) maximum flows, where the increase is more pronounced for the more extreme A2 scenario. It should however be noted that future spring and early summer discharge may be underestimated as the model does not take into account the increase of melt from glaciers in the upstream parts of the basin, which does play an important role in the Brahmaputra (Immerzeel et al., 2010).

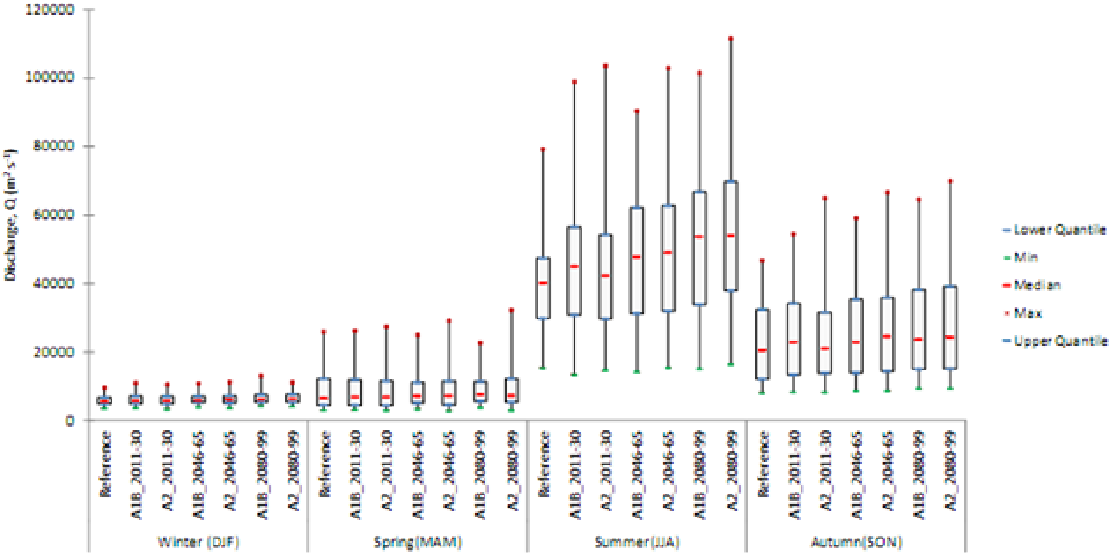


Figure 2.4 Box plots of stream flow for different seasons and for different time slices. Box plot represents the multi-model weighted variation over the season.

Table 2.2 Trends in monthly annual stream flow from 1961 to 2100. Trends and R^2 are first calculated per GCM and subsequently the weighted average calculated. All trends are significant at the 95% confidence level, except for the trend in May discharge for the A2 scenario.

	Trend ($m^3 s^{-1} yr^{-1}$)		R^2	
	A1B	A2	A1B	A2
Yearly Average	39	49	0.45	0.36
Jan	4	6	0.12	0.21
Feb	4	4	0.10	0.11
Mar	11	11	0.27	0.23
Apr	15	10	0.23	0.10
May	-13	-6	0.03	0.00
Jun	47	41	0.05	0.06
Jul	101	138	0.22	0.22
Aug	166	207	0.39	0.36
Sep	82	98	0.30	0.31
Oct	23	45	0.09	0.18
Nov	15	25	0.14	0.14
Dec	9	9	0.21	0.17

2.4.2 Flow duration curves

The Lower Brahmaputra River Basin (LBRB) is characterized by water shortages in the dry season and water excess and flooding during the monsoon months. To further understand the projected change in range of river discharge, we constructed flow duration curves (Smakhtin, 2001). First for each GCM a flow duration curve was estimated for four 20-year time slices. Next, for each time slice the weighted flow duration curve was calculated by weighting discharge for a given duration. Figures 2.5 and 2.6 provide the results for the A1B and A2 scenarios respectively. As can be seen, the Q90 and Q95 flows, commonly used as low flow indices (Pyrce, 2004), remain relatively constant for both scenarios, while the larger changes occur for the larger discharges, i.e. Q25 and up.

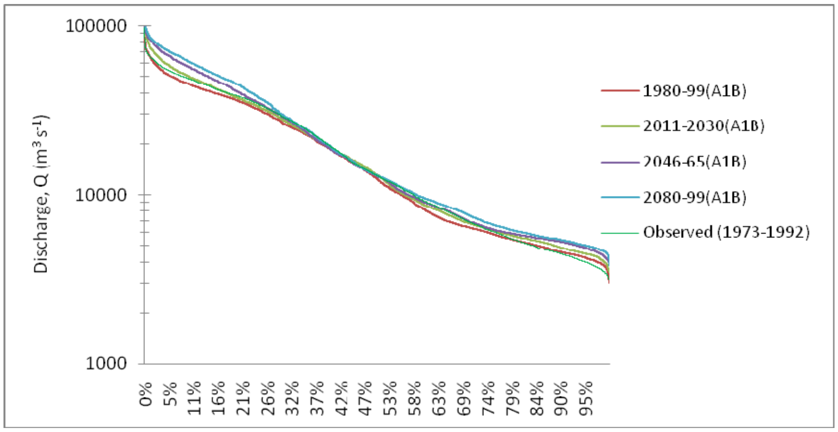


Figure 2.5 Flow duration curve for observed and multi-model weighted discharge of A1B scenario of four different time slices.

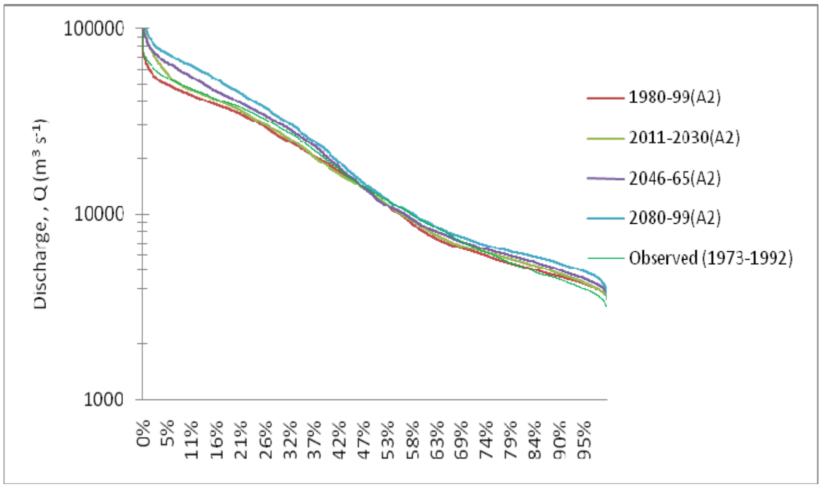


Figure 2.6 Flow duration curve for observed and multi-model weighted discharge of A2 scenario of four different time slices.

2.4.3 Extreme value analysis

2.4.3.1 Low flows

Extreme low flow conditions will generally have a negative impact on aquatic ecosystems, agriculture and domestic and industrial sectors. Low flow may occur due to reduced rainfall, elevated evapotranspiration, reduced water storage or cold temperatures with freezing soils causing a delayed release of melt water (Mauser et al., 2008). A combination of these causes may results in severe low-flow conditions that can impose limitations on above-mentioned sectors, resulting in substantial financial losses.

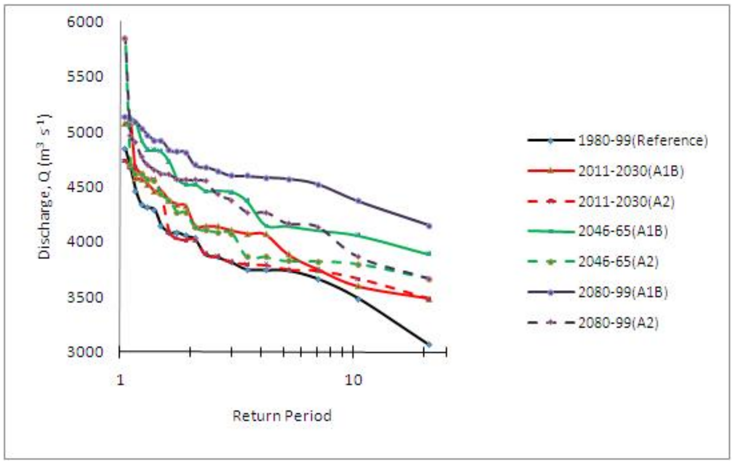


Figure 2.7 7-day low flow for different return periods for different scenario's and time slices as obtained from a weighted average of 12 model outputs.

Figure 2.7 shows a projected decrease in the likelihood of severe low flow events. This is because due to an increase in precipitation that outbalances the increase in evapo-transpiration. The differences between the scenarios and time slices increase over time and the A1B scenario yields a stronger increase in low flows than the A2 scenario, which may be related to a less strong decrease in evapo-transpiration due to a smaller projected temperature rise.

To show the difference between the 12 models we provide Fig. 2.8 which shows for the A1B scenario the weighted distribution as a boxplot of yearly average 7-day low flow. Figure 2.8 shows that the there is a large variation in low flows between model runs but that all model runs show an increase in 7-day low flow.

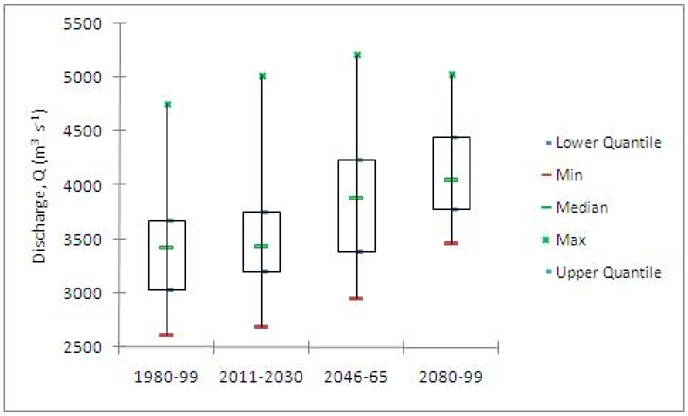


Figure 2.8 Box-whisker plot for yearly average 7-day low flow for A1B Scenario of 12 different weighted hydrological model outputs.

2.4.3.2 High flows

The results of the high flow analysis are shown in Fig. 2.9. The graphs are constructed the same way as Fig. 2.7, but now based on yearly maxima. Figure 2.9 shows a very strong increase in annual peak flow, which may have severe impact for flooding in the LBRB. In this case the A2 scenario is the most extreme in line with the steep increase in monsoon precipitation. The 1:10 year discharge is projected to increase from 82000 m^3 s^{-1} currently to 140000 m^3 s^{-1} by 2100 and a peak flow that currently occurs every 10 years will occur at least once every two years during the time slice 2080-2099. It is striking that for peak flows with larger return periods the strongest increase already occurs during the first 20 years. This could most likely be attributed to sampling variability resulting from performing the extreme analysis on relatively short 20 year time slices resulting in more than the expected number of randomly selected years from the 2071-2100 time slice. This could be corrected for by performing the analysis repeatedly for each model on multiple transients constructed by Eq. (4).

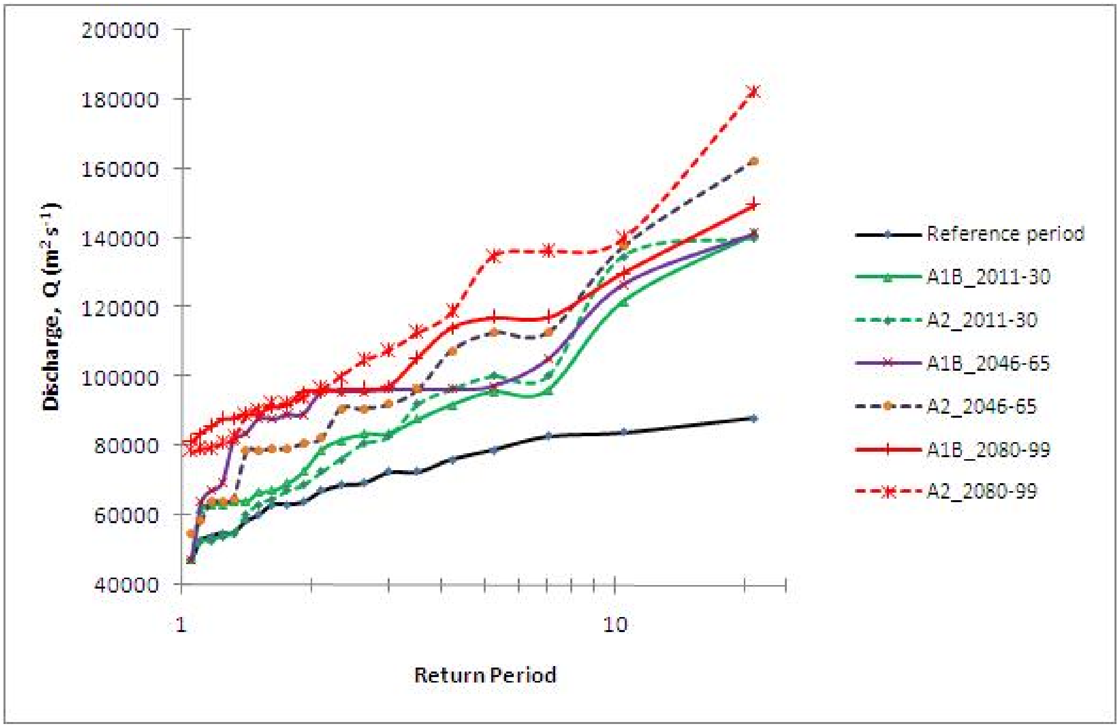


Figure 2.9 Annual peak flow for different return periods, time slices and scenario's obtained from a weighted average of extreme value analysis of the 12 model outputs.

2.5 Conclusions and discussions

In this study we applied a new method to construct a daily discharge time series from using a discharge-weighted ensemble based on inputs from 12 GCMs to a global hydrological model. Weighted discharge time series were subsequently used to analyze future trends in average flow and extreme flow results show that climate change is likely to improve dry season conditions in the LBRB. For both scenarios (A1B and A2), for all models and for all time slices both average flow and extreme low flow is projected to increase in size. Low flow conditions may even be slightly underestimated as the accelerated glacial melt in the upstream parts of the catchment may, albeit temporarily, further enhance low flow. The A1B scenario projects the strongest increase in low flow. On the other hand, our analysis also shows a large increase in peak flow size and frequency. The impact for the already highly flood prone plains of Bangladesh may be devastating, in particular in combination with the projected sea level rise. The A2 scenario projects the strongest increase in high flow.

For the assessment of streamflow of Ganges-Brahmaputra basin, previous studies (Warrick et al., 1996; Mirza, 2002; Immerzeel, 2008; Immerzeel et al., 2010) applied basin-specific hydrological model. Through statistical downscaling of six GCMs and using multiple regression analysis, Immerzeel (2008) found a sharp increase in the occurrence of average and extreme discharge of lower Brahmaputra for A2 and B2 storylines. Mirza (2002) used climate change scenarios from four GCMs as input into hydrological models and result of the study demonstrates substantial increases in mean peak discharges in the rivers of Ganges-Brahmaputra basin. But in our study, we use existing results of a global hydrological model that was forced by data from 12 global climate models (GCMs) in a weighted ensemble analysis. Through a weighting method, we prioritize these GCMs based on their relative performances and our analysis shows that the observed discharges can be simulated well using results of 4 GCMs.

The results in this paper show that all GCMs point toward an increase in discharge of the lower Brahmaputra river. However, it should be noted that there is quite some uncertainty about the change in South-Asian Monsoon strength, and most climate models have difficulty simulating mean monsoon characteristics and associated inter-annual precipitation variation (Annamalai et al., 2007; Yang et al., 2008). Experiments with regional climate models even show contradictory results (e.g. Kumar et al., 2006 vs. Ashfaq et al., 2009). However, given all the evidence, an increase in peak flow and flood frequency is likely and adaptive measures should be seriously considered.

In this paper we performed no model simulations of our own. Instead we made use of a repository of existing runs of a global hydrological model forced by a multi-model ensemble of climate data for both a reference period and 2071-2100 projections. Comparable weighting methods have been applied for GCM ensemble averaging of precipitation and temperature (see Giorgi and Mearns, 2002; Räisänen et al., 2010), but applying the approach to discharge is new. By weighting the simulated discharge with discharge observations a multi-model ensemble analysis of climate change effects could be made for a particular location, in this case the lower Brahmaputra at Bahadurabad station. Through this, a form of implicit downscaling is achieved that also takes account of inter-GCM uncertainty, because an ensemble of GCMs is used in reconstructing observed discharge. Moreover, the method, which allows for a very quick and cheap analysis of the effects of climate change plus uncertainty, is quite generic and can be used at other locations in the world with discharge observations. The method is applicable in any case where a hydrological model is forced with an ensemble of climate models and a sufficient long time series of observed discharges is available. The method can be easily improved to allow for the case that none of the models is doing a good job in reproducing discharge by adding bias-correction methods.

Ideally, the hydrological community could make a repository where the results of combinations of different GCMs and different global hydrological models are stored; both reference runs and projections for future time slices. Analyses by the method presented in this paper could then be done very quickly for any large river in the world, but now also taking the uncertainty about hydrological response into account. To have transient runs would be even better, but given that they are only available for a few GCMs at this time, transients could be constructed similar to our method for rivers with a strong seasonal signals as in our case. Alternatively, instead of interpolating discharge itself, one could also construct a transient of statistics by first estimating discharge statistics for each time slice and then interpolating changes of these statistics between time slices. In this study, the main assumption of the constructed transient series is that the inter-annual variability is preserved and is assumed to be same in future. Although similar assumption is considered in many studies, this has been rejected in a number of other studies e.g., Delgado et al., 2010; 2012. Therefore, future research is required considering the changes in inter-annual variability.

Acknowledgements

Part of this research was conducted while the first author was a guest at the Department of Physical Geography of University of Utrecht.

Chapter 3 Threshold of hydrologic flow regime of a river and investigation of climate change impact – the case of the Lower Brahmaputra River Basin

This chapter is based on:

Gain, A. K., Apel, H., Renaud, F., & Giupponi, C. (2012). Threshold of hydrologic flow regime of a river and investigation of climate change impact – the case of lower Brahmaputra river Basin. Under Review, *Climatic Change*.

Abstract

In order to contribute to the sustainability of social-ecological systems which depend on them, river flows should be maintained within their natural range of variation. For determining the extent of this natural range of variation, we assess in this study ecological flow thresholds and different damaging events to society in the context of the Lower Brahmaputra river basin. The Ecological flow threshold was calculated using twenty-two 'Range of Variability (RVA)' parameters considering the range between ± 1 standard deviation from the mean of the natural flow. Damaging flood events were calculated using flood frequency analysis of Annual Maxima series and using the flood classification of Bangladesh. Simulated climate change induced altered flow regime of the Lower Brahmaputra River Basin was then investigated and compared with the calculated threshold flows. The results of this study demonstrate that due to climate change, various parameters, i.e. monthly mean of low flow (January, February and March) and high flow (June, July and August) periods, 7-day average minimum flow, and yearly maximum flow will exceed the threshold condition for both A1B and A2 scenarios of the Intergovernmental Panel on Climate Change. The major findings in this research have a number of policy level implications for government agencies of the Lower Brahmaputra River Basin, specifically for Bangladesh. The calculated threshold may be used as a good basis for negotiation with other riparian countries of the basin. The methodological approach presented in this study can be applied in any river basin.

Keywords: *Ecological flow threshold; Climate Change; Riverflow; Range of variability (RVA); Brahmaputra*

3.1 Introduction

Dynamic flow patterns of a river must be maintained within a natural range of variation to promote the integrity and sustainability of not only ecological systems (Sanz et al. 2005), but also social systems. With respect to a proper functioning of a river, as a social-ecological system (SES), understanding the acceptable extent of alteration of natural flow is an important area of research. An SES is defined as a system that includes societal and ecological subsystems in mutual interaction (Gallopín 1991, 2006), and that links organization, resilience and dynamics (Gunderson et al. 1995). Natural flow variability creates and maintains the dynamics of in-channel and floodplain conditions and habitats that play a fundamental role for the functioning of aquatic and riparian species (Poff et al. 1997). High flows of different frequencies are important for channel maintenance, bird breeding, wetland flooding and maintenance of riparian vegetation. High flows effectively transport sediments, maintaining high benthic productivity and creating spawning habitat for fishes. Floods distribute and deposit river sediments over large areas of land that can replenish nutrients in top soils and make agricultural lands more fertile. As periodic flooding makes the land more fertile and productive, the populations of many ancient civilizations concentrated along the floodplains of many rivers, e.g. the Nile, the Tigris and the Yellow River (Tockner and Stanford 2002). Also, floodwaters often play an important role in recharging shallow aquifers underneath the floodplains, which supply natural springs, wells, rivers and lakes with fresh water. Similarly, periods of low flow are important for water quality maintenance through algae control (Smakthin et al. 2006). Low flows can also provide recruitment opportunities for riparian plant species in regions where floodplains are frequently inundated (Whatton et al. 1981).

However, determining thresholds of flow variability of a river SES is a complex procedure and very few studies have been conducted in this area (Richter et al. 1997, 2011). Based on ecological flow regime characteristics (i.e. magnitude, frequency, duration, timing and rate of change of flow) identified by Richter et al. (1996), Richter et al. (1997) proposed the 'Range of Variability Approach' (RVA) for determining thresholds of ecological flow. Besides determining the threshold of ecological flow, it is equally important to determine the flow regimes that affects the social system (e.g., maximum allowable flood that society can cope with and minimum allowable flow that is required for livelihoods and navigation).

Until now, the methods for determining threshold flows were applied for investigating the impact of dam construction, reservoir operation and other human induced alterations.

However, it is also important to investigate the impact of climate change on threshold flow that affects SESs, in this study the floodplain of the Lower Brahmaputra River Basin (LBRB), where population pressure is very high and the main economic activity is agriculture. About 65 million people of Bangladesh and India live at LBRB. The population is therefore highly dependent on a few ecosystem services such as provisioning services from soil and water for their direct livelihoods, and flow regime can have direct and indirect positive or negative impacts on these livelihoods. Climate change increases the already high variability in the temporal distribution of water, which creates two extremes: a water abundance regime with an excess of water leading to floods during the rainy season and a scarcity regime with very limited rainfall during the dry season (Gupta et al. 2005).

The objectives of this study were (1) to determine thresholds of natural flow regime for a social (through flood categories) and ecological system (through RVA parameters), in parallel and (2) to investigate climate change effects on the determined thresholds for the Lower Brahmaputra River Basin. The analysis allows us to provide insights on both the ecological and social dimensions of expected impacts of climate change of the studied river SES.

For determining ecological threshold flow, we apply the ‘RVA’ method proposed by Richter et al. (1997) and for determining damaging flood event to society we apply flood frequency analysis and the flood classification of Bangladesh (Mirza 2002). For investigation of climate change effects, we consider discharge of the Brahmaputra for the A1B and A2 scenarios of the IPCC, generated through multi-model weighted ensemble analysis by Gain et al. (2011). In determining threshold flows, the consideration of both ecological (i.e., application of RVA method) and social system (i.e., selection of damaging flood event to society) is a novel approach. The novelty can also be found in investigating climate change impact on the determined threshold flows. Moreover, the calculated threshold may be used as a good basis for negotiation with other riparian countries of Brahmaputra River Basin.

3.2 Study area

The Brahmaputra is a major transboundary river which drains an area of around 530,000 km^2 and crosses four different countries: China (50.5% of total catchment area), India (33.6%), Bangladesh (8.1%) and Bhutan (7.8%). Immerzeel (2008) categorized the Brahmaputra basin into three different physiographic zones: Tibetan Plateau (TP), Himalayan belt (HB), and the floodplain (FP). The area with an elevation of less than 100 m a.s.l. is considered as FP and comprises about 27% of the entire basin. This study focuses on river flow in the lower Brahmaputra River Basin which belongs to the FP (Fig. 2.1 of chapter 2), where the hydrological impact of climate change on the Lower Brahmaputra River Basin is expected to be particularly strong, because of mainly three reasons: glacier melt, extreme monsoon rainfall and sea level rise (Mirza 2002; Warrick et al. 1996; Immerzeel 2008; Immerzeel et al. 2010).

The major discharge measuring station of the lower Brahmaputra is in Bahadurabad (Bangladesh) for which long-term observed records are available through the Bangladesh Water Development Board. The data are of high quality and used in most hydrological studies for flood forecasting and other planning purposes (Gain et al. 2011). Therefore, long-term observed records from this station will be used in this study.

3.3 Methods

To investigate the impact of climate change on the threshold of hydrologic flow regime, we first analyze trend and independence of observation discharge series. We then calculate threshold of both ecological flow as well as different extent of floods. The investigated methods are illustrated in Fig. 3.1 and are discussed below.

3.3.1 Testing natural condition of discharge for the observation period

Daily discharge data are collected from the Bahadurabad station, for the observation period of 49 years from 1956 to 2004. However, in the data series, some data related to the dry season period were missing from 1996 to 2004. Therefore, ecological flow thresholds were calculated using the daily data series covering a period of 40 years (1956-1995). However, flood frequency analysis was carried out using the yearly maximum data (or Annual Maximum Series, AMS) covering a period of 49 years (1956-2004), as continuous data were found for high flow seasons. The first step to determine thresholds was to test whether the observation data is trend free or not. For this, we used a linear trend analysis following Gain et al. (2008), applied to annual maximum, average and minimum (7 day average) data series. The result of the trend tests indicates that all the series are trend free as the calculated value of trend statistics, T_c for each series is lower than critical value (2.02) at 5% significance level. For testing stochasticity, an independence test was then carried out. The result of independence test also shows that the calculated statistics of independence does not exceed the critical value (2.093) of the Student distribution (5% significance level). Therefore, all the data series can be considered trend free and independent, and thus can represent natural conditions of observed flow.

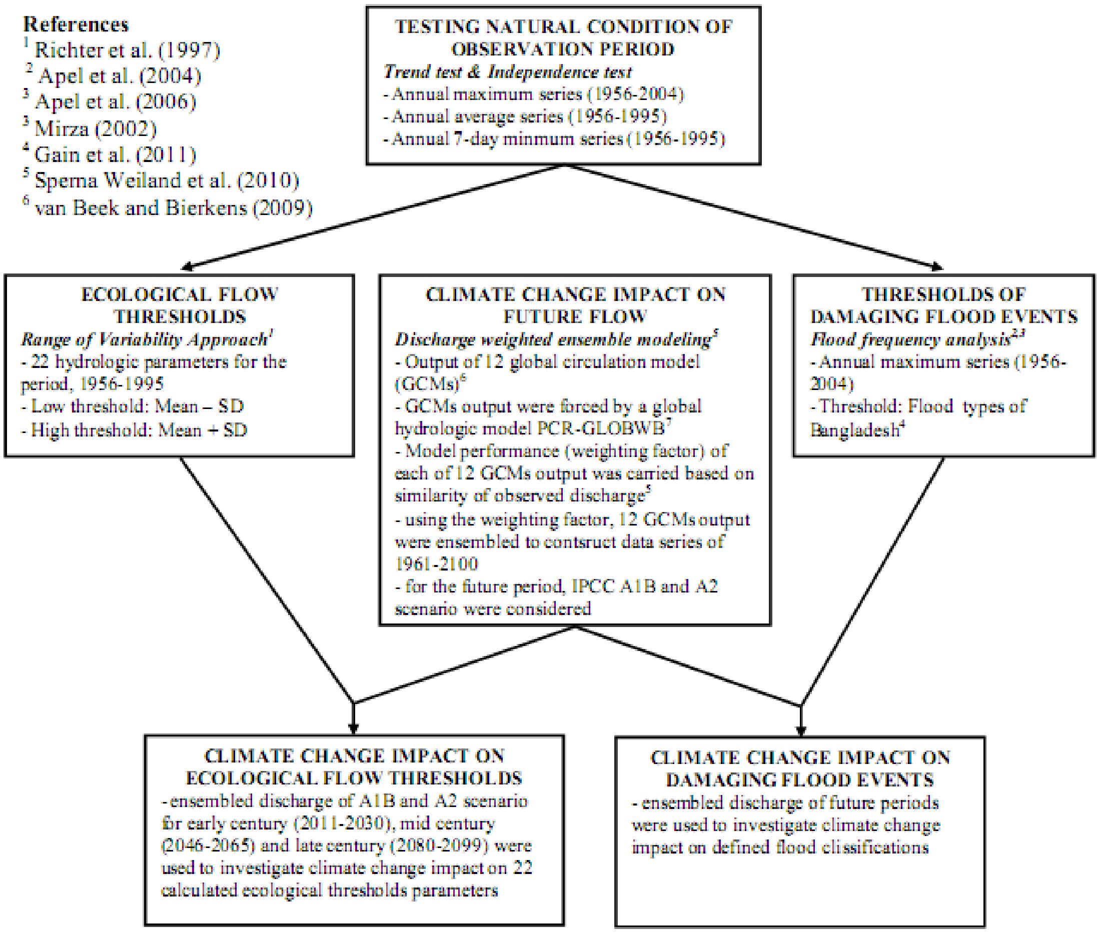


Figure 3.1 Flow chart of assessment of thresholds and climate change impact

3.3.2 Calculation of ecological flow threshold

Once the natural condition of flow was tested, the ecological flow thresholds of natural variability were analyzed. Reflecting different aspects of flow variability (magnitude, frequency, duration and timing of flows), Richter et al. (1997) proposed the ‘range of variability approach’ (RVA) which considers thirty-two hydrological parameters. However, many parameters that are used in the original RVA method are likely to be correlated with each other, as significant redundancy (multicollinearity) exists between many hydrologic parameters (Olden and Poff 2003). Monk et al. (2007) suggested a refined number of clearly defined hydrological parameters, where known duplication of hydrological information has been removed/minimized using hydrological understanding. Smakhtin et al. (2006) reduced the number of RVA flow parameters to sixteen. For assessing maximum and minimum flow, Smakhtin et al. (2006) considered only 1-day and 90-day average flows. However, maximum and minimum flows of 3-, 7- and 90-day average can capture different extent of droughts and floods information. Therefore, for assessing ecological flow thresholds, we considered twenty-two flow parameters of which twelve represent the mean flow value for each calendar month that can jointly capture the seasonal flow distribution, and which the remaining ten parameters (1-, 3-, 7-, 30- and 90-day maxima; 1-, 3-, 7-, 30- and 90-day minima) reflect the variability of maximum and minimum range and their different duration (Table 3.1).

In an altered flow regime (by means of climate change or human perturbation), those parameters should be maintained within the limits of their natural variability, which should be based on extensive ecological information, taking into account the ecological consequences of different flow regimes. However, setting flow targets based on ecological information is very difficult to achieve. In the absence of extensive ecological information, Richter et al. (1997) suggested several measure of dispersion (e.g., ±1 or 2 standard deviation, twentieth and eightieth percentile, etc) to use in setting initial threshold flows. The choice of the most appropriate measure of dispersion should be based on whether each parameter follows normal or skewed distribution and in the case of normal distribution one could use the standard deviation (SD) from the mean value as initial threshold flow. In order to select appropriate measure of dispersion, we tested the distribution of each of the 22 RVA parameters and we found that all the parameters follow normal distribution. Therefore, values at ± 1 SD from the mean were selected as thresholds for each of the twenty-two RVA parameters. Any considered parameter should thus stay in the limits

$(\text{mean} - \text{SD}) \leq \text{parameter} \leq (\text{mean} + \text{SD})$

Exceedance of these limits by a particular parameter may lead to considerable ecosystem stress over long time periods. We used this approach for setting initial flow thresholds in this study.

Table 3.1 Results of selected RVA parameter analysis (Unit: $m^3 s^{-1}$)

	Mean value of each parameter	Standard Deviation	RVA Threshold	
			Low	High
January	5056	851	4205	5907
February	4243	632	3611	4875
March	4774	807	3967	5581
April	8091	1860	6231	9951
May	15871	3994	11877	19865
June	31716	6437	25279	38153
July	46835	7113	39722	53948
August	43657	7386	36271	51043
September	37920	7371	30549	45291
October	24405	7190	17215	31595
November	11232	2754	8478	13986
December	6922	1364	5558	8286
1-day minimum	3869	553	3316	4422
3- day minimum	3890	533	3357	4423
7- day minimum	3943	519	3424	4462
30- day minimum	4161	638	3523	4799
90- day minimum	4632	715	3917	5347
1- day maximum	66225	11250	54975	77475
3- day maximum	65265	10830	54435	76095
7- day maximum	62836	9979	52858	72815
30- day maximum	53081	7584	45496	60665
90- day maximum	44334	5730	38604	50063

3.3.3 Flood frequency analysis and determination of damaging flood events

For determining damaging flood events to society, we test different flood classifications that are used in Bangladesh and are based on the extent of inundation, respective return periods and the level of physical damage (Mirza 2002) as shown in Table 3.2. During a normal flood (when probability of occurrence is more than 0.5 or equivalent return period is less than 2 years, cf. Table 3.2), about 21% of total land (in Bangladesh) is inundated and alluvial organic matter is deposited with beneficial effects on monsoon crops (Hofer and Messerli 1997).

Similarly, moderate flood extent (with a probability of occurrence of 0.3 or return period of 3.33 years) is also beneficial for increasing soil fertility and local communities can easily cope with the disturbance. But in a severe flood event (return period of 10 years, cf. Table 3.2), economic losses are higher and evacuation measures are required. Other lower probability floods are even more damaging.

From Table 3.2, we can see that until one reaches a level of ‘moderate extent flood’ (with a return period of 3.33 years), people can cope with potential impacts with no external support. Therefore, we can consider ‘severe flood’ as a damaging flood event with return period of 10 years.

In order to determine the different extent of damaging flood events, flood frequency analysis of annual maximum series (AMS or yearly maximum flow) was carried out. For determining AMS, maximum discharge of each hydrological year (from 1st April to 31st March of the following year) was considered. In this study, the uncertainty of distribution functions was considered. Different distribution functions that are widely used in flood frequency analysis were adapted to the AMS: 3-Parameter Log Normal (LN3), Generalized Extreme Value (GEV), Generalized Logistic (GL), Pearson type III (PE3), and Gumbel. The parameters of the distributions were estimated by the methods of L-moments similar to Hosking and Wallis (1997). A composite distribution was then computed using the maximum likelihood weights of the functions (Apel et al. 2004, 2006). Using different distribution functions, flood volumes for different return periods were calculated.

3.3.4 Investigation of climate change impact

Once the threshold for ecological flow and damaging flood event is determined, we analyzed the extent of alteration of future flows under climate change scenarios. For investigating the possible climate change effects on future river flow, a multi-model ensemble analysis carried out by Gain et al. (2011) was used in this study.

Table 3.2 Flood classification of Bangladesh in terms of probability of occurrence, area inundated and physical damage (Source: Mirza 2002)

Types of floods	Parameters			
	Probability of occurrence (equivalent return period, in years)	Range of flooded area (km^2)	Percent of inundation	Parameters affected
Normal flood	>0.5 (<2)	31,000	21	- Contributes to increasing soil fertility - Cropping pattern is adjusted with inundation - Hampers normal human activities - Minimum economic loss
Moderate flood	0.3 (3.33)	31,000-38,000	21-26	- Contributes to increasing soil fertility - Damage limited to crops - Hampers human activity moderately - Moderate economic loss - People cope by themselves
Severe flood	0.10 (10)	38,000-50,000	26-34	- Damage to crops, infrastructures and certain urban centres - Hampers human activities severely - Economic loss is higher - Requires evacuation & relief operation
Catastrophic flood	0.05 (20)	50,000-57,000	34-38.5	- Hampers human activities drastically - Extensive damage to crops, cultured fisheries, lives and property in both urban and rural centres, all types of infrastructure, etc. - Requires extensive relief operation - Very high economic loss - Requires international support
Exceptional flood	<0.05 (>20)	>57,000	>38.5	- Hampers human activities exceptionally - Extensive damage to crops, cultured fisheries, lives and property in both urban and rural centres, all types of infrastructure, etc. - Requires extensive relief operation - Disrupts communication - Closing of educational institutions - Exceptional economic loss - Usually requires international support

Multiple outputs of twelve global circulation models (GCMs) for the control period (1961-1990) and the future scenarios A1B and A2 (2071-2100) of the IPCC were used to force the global hydrological model, PCR-GLOBWB (van Beek and Bierkens 2009; Bierkens and van Beek 2009). A1B and A2 scenarios were selected because they represent the already observed development of greenhouse gases and aerosol precursor emissions change best. The hydrological model (PCR-GLOBWB) calculates for each grid cell (0.5° × 0.5° globally) and for each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers and between the top layer and the atmosphere (rainfall, evaporation and snow melt). The parameterization of the global hydrological model PCR-GLOBWB is described in van Beek and Bierkens (2009). Multi-model ensemble discharge was calculated using a weighting factor on each of 12-model simulated discharge. The weight for each model was determined based on the similarity of mean monthly value of observed discharge with the model simulated discharge for the overlapping period (1973-1995). A constant weight was then applied for the entire time series and the approach was validated by comparing the flow duration curve of the observations with the modeled discharge. For both A1B and A2 scenario, the results of multi-model weighted variation (i.e., uncertainty estimation) of discharge are shown in Fig. 2.4 (of chapter 2) that represents seasonal average flows of four time slices (reference period 1980-99; 2011-30; 2046-65; 2080-99). Seasonal average flows were obtained by first calculating cumulative frequency distributions per GCM and then constructing a weighted cumulative frequency distribution by weighting values belonging to the same quantile. The statistics in the box plots are thus based on the weighted cumulative frequency distribution. Fig. 2.4 shows that the strongest increase in both average and extreme discharge is predicted for the summer and autumn periods. For a detailed description of future river flow assessment considered in this study, see Gain et al. (2011).

Due to climate change, flow regime of future periods can be altered and exceed the RVA threshold range (± 1 SD from mean values). For investigating the effects of climate change induced altered flow regime on determined thresholds, the percentage of altered flow regime years not meeting the RVA target was calculated for each of the twenty-two parameters.

3.4 Results

3.4.1 Ecological flow threshold

After characterizing and testing natural conditions of the observation series, we determined ecological flow thresholds of twenty-two RVA parameters, reflecting different aspects of flow variability (magnitude, frequency, duration and timing of flows), as shown in Table 3.1. For assessing mean and standard deviation values of each parameter (column 2 and column 3 of Table 3.1, respectively), we analyzed daily mean discharge series for a 40 years period (1956-1995). Minimum threshold (mean - 1 SD) and maximum threshold (mean + 1 SD) values for each parameter is shown in column 4 and column 5 of Table 3.1, respectively. During the reference period (1956-1995), about one-third of the total number of years exceeds the criteria of threshold, as the distribution is normal.

3.4.2 Damaging flood events

Based on the flood classification by Mirza (2002), we can classify the return periods of different floods. In order to determine different classes of floods, we need to analyze flood frequency based on the annual maximum series for the available 49 year record period (1956-2004). However, different statistical distributions are typically used for flood frequency analysis often leading to different results. For a certain design value the cumulative distribution function, cdf of annual failure probability, AFP of yearly maximum flow can be derived for each considered distribution function. Fig. 3.2 shows the five distribution functions and the observed data. Using different distribution functions, river flow is computed for floods of different return periods according to the Bangladesh flood classification (Table 3.3). For the Bahadurabad station, Fig. 3.2 shows that the effect of distribution uncertainty on AFP is very low.

Table 3.3 Computed discharge for different return periods

Return Period [years]	Different flood classification	Computed discharge (m^3s^{-1})					
		Gumbel	LN3	GL	PE3	GEV	Composite *
2	Normal flood	65606	66308	66433	66299	66278	66378
3.33	Moderate flood	72021	72775	72260	72845	72786	72434
10	Severe flood	83829	83607	82774	83699	83740	83123
20	Catastrophic flood	90792	89497	89298	89500	89628	89416
50	Exceptional flood	99805	96732	98383	96509	96673	97710
70		103088	99284	101905	98948	99087	100811
100		106559	101942	105768	101469	101557	104161

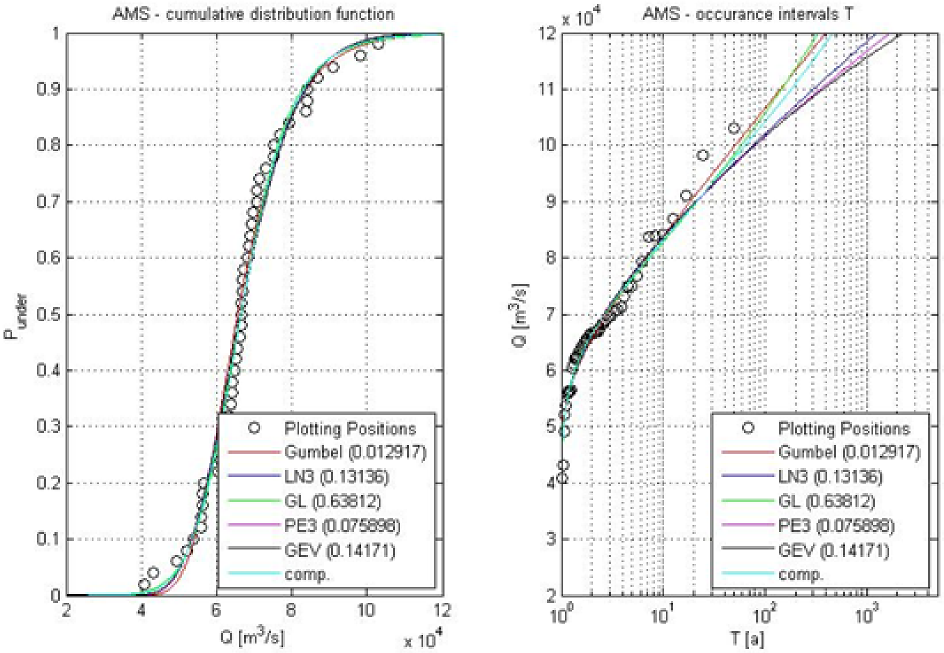


Figure 3.2 Plot of the fitted distributions and plotting positions for annual maximum series (AMS): a) cumulative probability (P_{under}) versus computed discharge (Q) of fitted distributions; b) computed discharge (Q) of fitted distributions versus return period (T)

3.4.3 Investigation of climate change effects on flows

In order to investigate climate change impacts for both A1B and A2 scenario of the IPCC, we categorized future periods into three time intervals (i.e., 2011-30, 2046-65, and 2080-99). These time intervals split the 21st century into three parts, i.e., early century (2011-2030), mid century (2046-2065) and late century (2080-2099) as described in IPCC Fourth Assessment Report (Meehl et al. 2007). The rate of exceedance of RVA threshold values for the reference period and for the future years was calculated by counting the number of years that would have failed to meet the threshold conditions and the calculation was carried out for both A1B and A2 scenarios (Table 3.4). As in the natural condition (reference period) the parameters follow normal distribution, the rate of exceedence can be expected up to 33%. However, under the effect of future climate change, this rate could be higher. As an example, results indicated that for the month of January 35% of the next 20 years (period 2011-30) in the A1B scenario would have passed the upper or lower limit of the thresholds. Similarly, for the periods 2046-65 and 2080-99, thresholds for A1B scenario are exceeded in 50% and 85% of the cases, respectively and for A2 scenario, in 70% and 80%, respectively.

The results also demonstrate that during low flow (January, February and March) and high flow (June, July and August) periods, the rate of exceedance is very high for both the A1B and A2 scenarios. In Fig. 3.3, monthly means for January (Fig. 3.3), February (Fig. 3.3) and March (Fig. 3.3) are plotted for the Brahmaputra River, whereas, Fig. 3.4 represents the monthly average flow of June (Fig. 3.4), July (Fig. 3.4), and August (Fig. 3.4). In some other months (October, November, December, and May) the exceedance rate of threshold values is very low. This is mainly due to the fact that in contrast to normal flow periods, climate change effect is very high in extreme low and high flow seasons.

7-day average yearly minimum flow for both A1B and A2 scenario are plotted for three different time periods and compared with the calculated low and high threshold values (Fig. 3.5a). Similarly, yearly maximum flows for both scenarios are also plotted in Fig. 3.5b. Simulated results of 7-day minimum flow indicated that for the periods 2011-30, 2046-65 and 2080-99, the rate of exceedence of thresholds for A1B scenario remain constant (30%) and for A2 scenario, in 35%, 35% and 40%, respectively. For yearly maximum flow of 2011-30, 2046-65 and 2080-99, thresholds for A1B scenario are exceeded in 65%, 75% and 90% respectively and for A2 scenario, in 65%, 80% and 95%, respectively.

For the observation period (1956-2004), the different extreme floods were classified and identified in section 3.3. We compared yearly maximum river flow with the different classes of floods. The rate of exceedance of different types of flood levels that is expected to occur under future climatic conditions is shown in Table 3.5. Simulated results indicate that in the near future (2011-30), 45% and 40% of the total years would have exceeded the 100-yr flood (calculated in the observation period) for A1B and A2 respectively. For the period 2080-99, the rate of exceedance is 100% for both scenarios. This high rate of exceedance is mainly due to the fact that Bangladesh is highly flood prone area and more frequent floods are expected in the coming years. Besides, for constructing future river flow, inter-annual variability is considered as stationary which might be the reason for the largest changes appear in the first 20 years period starting in 2011.

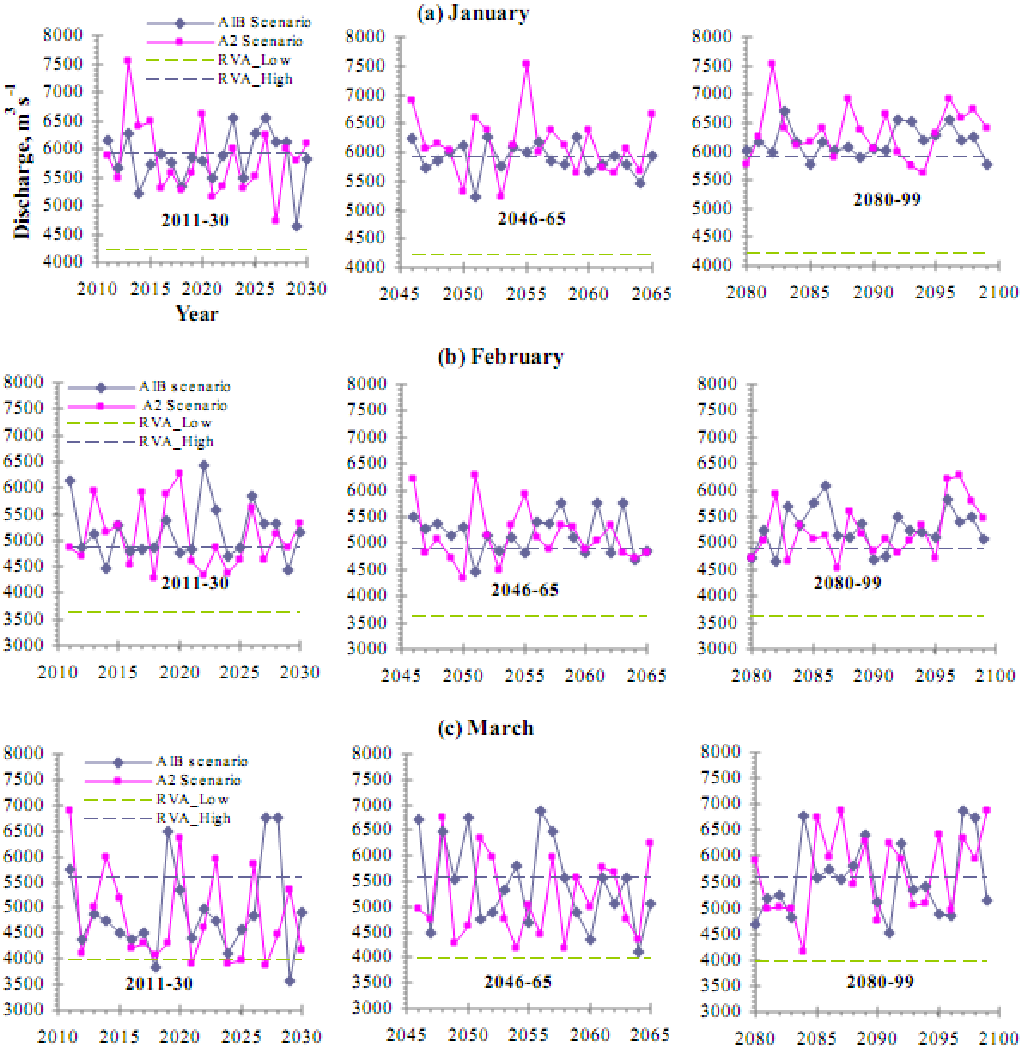
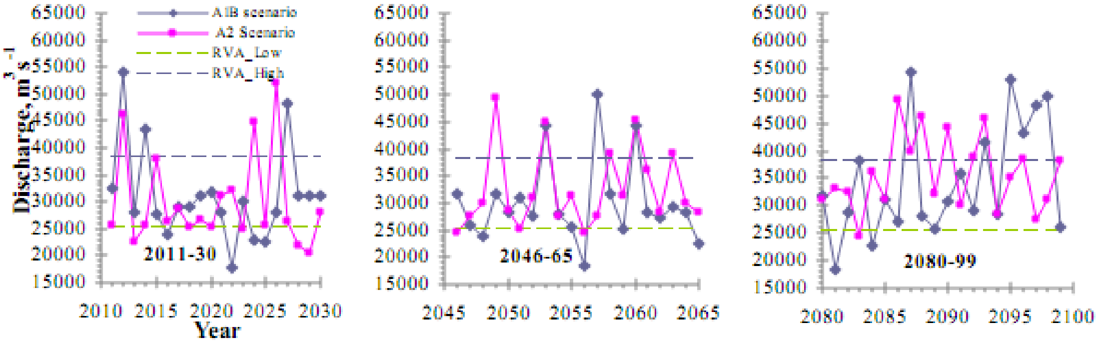


Figure 3.3 Comparison between threshold value and monthly means flow of A1B and A2 scenario at January (a); February (b); March (c)

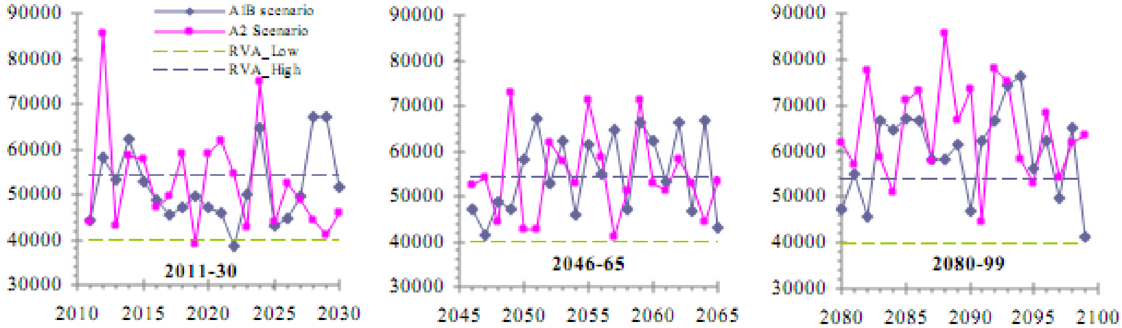
Table 3.4. Exceedance of threshold values of different RVA parameters in future climatic condition in percent

	Exceedance of threshold values for different time slices of A1B and A2 scenario (%)						
	1956-95	2011-2030		2046-2065		2080-2099	
	Reference	A1B	A2	A1B	A2	A1B	A2
January	28	35	40	50	70	85	80
February	28	50	45	65	55	80	70
March	32	30	40	35	40	35	55
April	25	30	40	35	40	35	35
May	30	30	35	30	35	30	40
June	33	35	35	35	40	45	45
July	30	30	45	50	40	75	85
August	33	55	40	75	75	90	95
September	28	35	30	40	35	45	40
October	28	25	30	25	30	30	25
November	25	25	30	25	30	40	40
December	30	30	35	50	35	50	40
1- day maximum	25	65	65	75	80	90	95
3- day maximum	28	45	45	50	55	70	75
7- day maximum	25	35	45	40	55	55	65
30- day maximum	33	35	40	45	55	45	60
90- day maximum	33	35	40	40	40	45	55
1-day minimum	30	30	35	35	35	35	35
3- day minimum	28	35	30	35	30	35	40
7- day minimum	28	30	35	30	35	30	40
30- day minimum	30	30	40	35	40	35	35
90- day minimum	30	30	35	30	35	30	40

(a) June



(b) July



(c) August

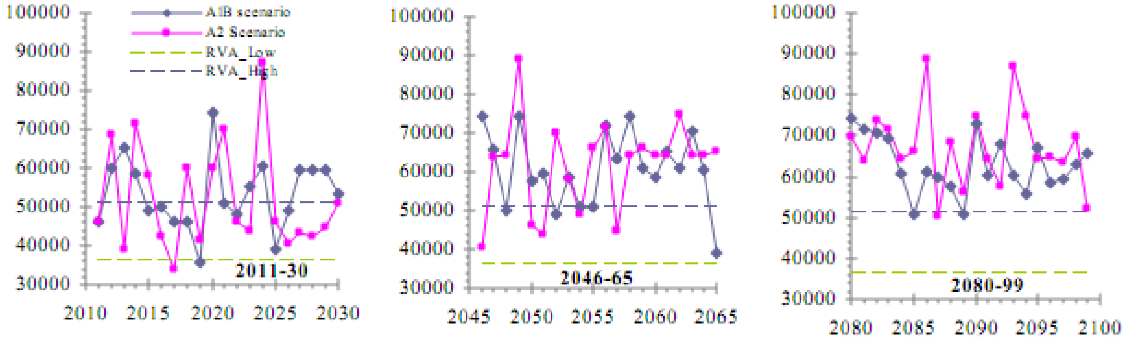
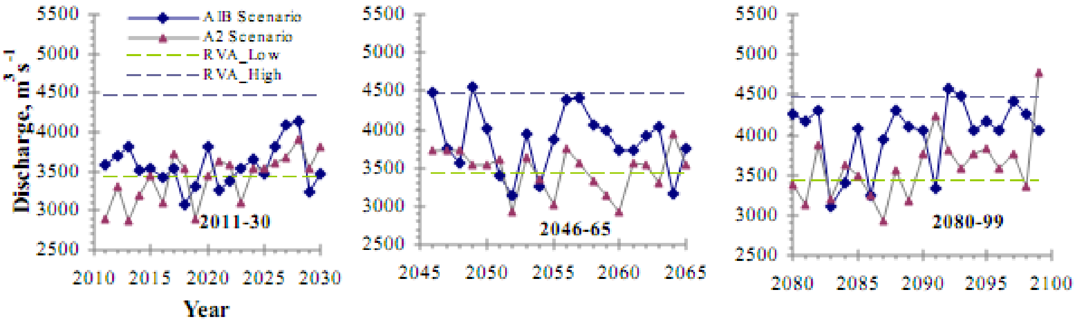


Figure 3.4 Comparison between threshold value and monthly means flow of A1B and A2 scenario at June (a); July (b); August (c)

(a) 7-day average Minimum



(b) Yearly Maximum Flow

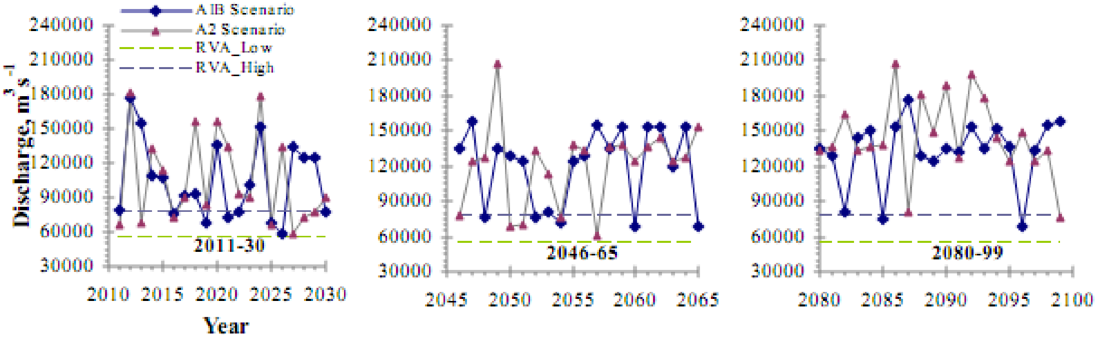


Figure 3.5. Comparison between threshold value and 7-day average yearly minimum flow (a); yearly maximum flow (b) of A1B and A2 scenario

Table 3.5 Percentage of exceedance of computed flow in future climatic condition

Return Period	Different flood classification	Computed discharge, m^3/s (composite distribution)	Exceedance of threshold values (compared to computed flow of observation period) [%]					
			2011-30 (A1B)	2011-30 (A2)	2046-65 (A1B)	2046-65 (A2)	2080-99 (A1B)	2080-99 (A1B)
2	Normal flood	66378	100	90	100	100	100	100
3.33	Moderate flood	72434	95	85	95	100	100	100
10	Severe flood	83123	80	60	95	85	100	100
20	Catastrophic flood	89416	65	45	85	80	100	100
50	Exceptional flood	97710	50	40	85	80	100	100
70		100811	50	40	85	80	100	100
100		104161	45	40	85	80	100	100

3.5 Discussion

With the aim of investigating climate change effects on future river flow, the results of multi-model ensemble analysis (Gain et al. 2011) were used in this study. A multi-model ensemble tends to give more reliable results than single model simulation (Gleckler et al. 2008; Reichler and Kim 2008; Knutti 2008). Unweighted multi-model means were used to ensemble models which were also used in reports of the IPCC. However, results of several studies showed that more reliable results are obtained by using projections of a cluster of better performing models (Smith and Chandler 2010) or calculating a weighted ensemble average (Sperna Weiland et al. 2012). In the weighted ensemble analysis, the individual GCM weights were derived from model performance and future ensemble convergence (Giorgi and Mearns 2002; Murphy et al. 2004; Min and Hense 2007; Räisänen et al. 2010). In this study, weights were determined by using the model performance, i.e., historical relationship between model outputs and observations. Although model agreement with observations is a necessary pre-condition for a model to be considered, it does not definitely prove that the model is correct for the right reason (Tebaldi and Knutti 2007). Nevertheless, as we can prove that the weighted ensemble mean outperforms un-weighted means in the presented case (Fig. 3.6 and Fig. 3.7), we argue that the use of the weighed ensemble mean is an appropriate choice to investigate climate change impacts.

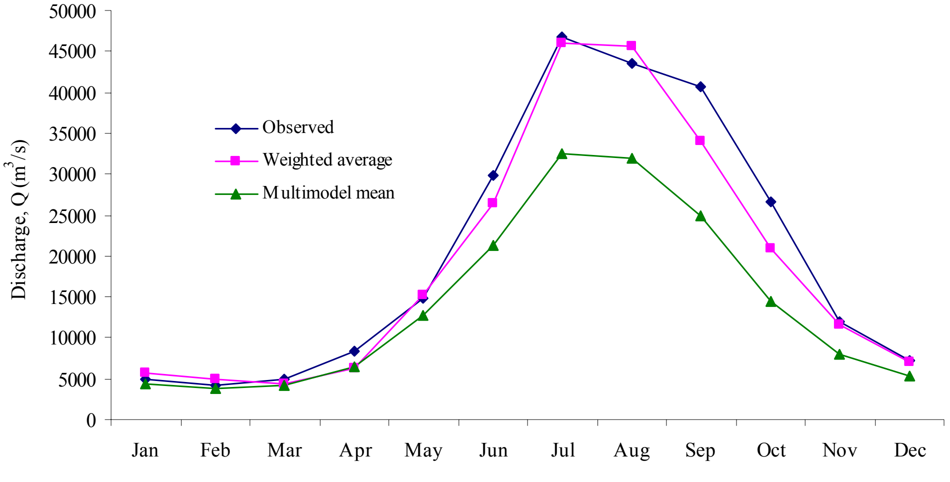


Figure 3.6 Comparison of weighted average and multi-model mean (of 12 GCMs) with monthly mean observed discharge for the period 1973-1995.

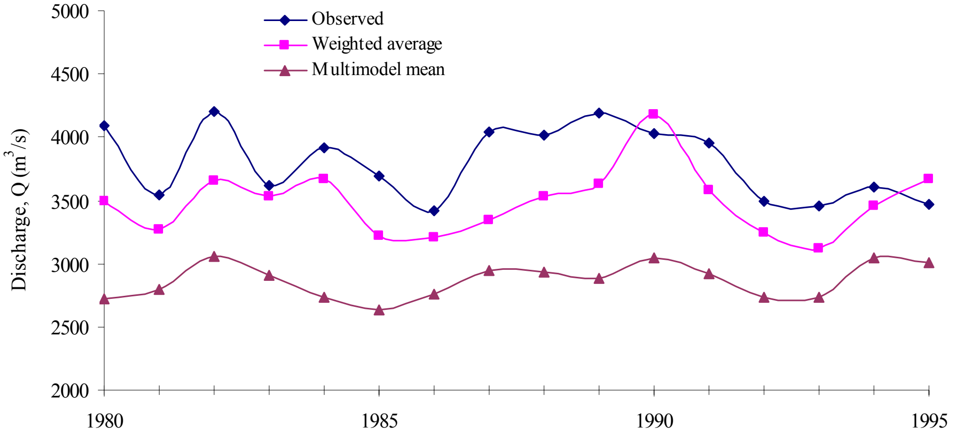


Figure 3.7 Comparison of weighted average and multi-model mean (of 12 GCMs) 7-day low flow with observed discharge for the period 1980-1995.

Using the RVA approach proposed by Richter at al. (1997), we first calculated ecological flow threshold values for the Lower Brahmaputra basin. From our analysis, exceedance rate of any of the RVA threshold parameters was less than 33% during the reference period (1956-1995). The different exceedance rate of stream flow for dry and wet months of the reference period can be considered as natural range of variation which is necessary to sustain the full native biodiversity and integrity of aquatic ecosystems, and ultimately to provide multiple services to the people living in the region.

Through modeling, we investigated the effects of climate change on the flow regime. This revealed that compared to the reference period, the ecological thresholds were frequently exceeded for the RVA parameters of average flow of January, February, June, July, August and yearly maximum flow for both IPCC scenarios A1B and A2 by the weighted ensemble mean. Due to climate change, the increased exceedence of the hydrologic parameters has important implications for stream processes and patterns (Poff et al. 1996). According to Poff and Ward (1990), the more a modified hydrological regime deviates from the historical norm, the greater the inferred ecological consequences. Aquatic ecosystems are highly sensitive to such modifications, as climate change induced altered flow regimes potentially interfere with the reproduction of many aquatic species, which eventually affect species composition and ecosystem productivity (Poff et al. 2002). Hydrologic modifications due to climatic changes affect the abiotic factors (river gradient, depth of water and river flow) of the Brahmaputra River and this has a strong bearing on its hydrobiology (Boruah and Biswas 2002). As a consequence, the population of about 200 species including the most spectacular animal, the river dolphin (*Platanista gangetica*) are expected to steadily decline from the basin (Biswas and Boruah 2000).

Flood frequency analysis revealed that in the lower Brahmaputra river, more frequent and more intense floods are expected to occur in future years, which has both social and ecological implications for the lower part of the basin in Bangladesh. Roughly 30 per cent of the total flood related damages are accounted for by loss of agricultural crops in Bangladesh. Rice is the main crop, which is highly dependent on the onset, retreat and magnitude of monsoon precipitation (Brammer et al. 1996). In particular, high-yielding 'aman rice' varieties are highly susceptible to floods as the flood peaks in August–September may affect sowing of the crop (Mirza 2002). Floods are also detrimental to monsoon vegetables and other crop varieties. Yearly crop damage could be about 0.5 million tons, but during an exceptional flood (with a return period greater than 20 years), damages could be more detrimental. As an example, crop damage for the flood years of 1987, 1988, and 1998 was estimated at 1.32, 2.10, and 3.0 million tons, respectively (Ahmed 2001). Damage due to floods has many more implications including direct loss in agricultural employment and indirect effects through sectoral linkages. Crop damage by floods and consequently food security can be considered a serious problem, even in a normal year in Bangladesh, with half of its population living below the poverty line. Flood related crop damage and unemployment make a large section of population extremely vulnerable to starvation, malnutrition and even death.

Our results have a number of policy level implications for government agencies of the lower Brahmaputra River Basin. First, calculated threshold flow of twenty-two RVA parameters can be used as initial targets for water resource, flood risk and ecosystem management in Bangladesh. The Bangladesh government could consider allowing human perturbation and development activities within these ranges. These criteria can also be used for water allocation to meet household, agriculture and industrial water demands. In trans-boundary river basin management, threshold of flow variability can be used as a basis for negotiation with other riparian countries and upstream flow control by reservoirs. Second, the government may consider damaging flood events when flow exceeds a 10-yr return period at Bahadurabad station, and accordingly can prepare planning and management activities for different flooding extents. Third, the results of climate change impact shows that for both A1B and A2 SRES scenarios, most of the considered periods may fail to meet the RVA threshold criteria, which means that significant changes in social-ecological system is expected to occur. Major species may not adapt to such changes, which will require planned adaptation, requiring the consolidation of relevant institutional mechanisms at various governance scales. Because of the high frequency of the threshold exceedance, planned adaptation strategies and targets need to be jointly discussed by the policy makers and river basin management authority of the region. For determining the threshold of natural variability of flow for both social-ecological system and investigating the climate change impact, the methodological approach presented in this study is applicable to other river basins.

3.6 Conclusion

Our analysis showed that under different scenarios of climate change most of the future years may exceed the RVA threshold criteria and more intense and more frequent flooding are expected to occur. The exceedance of threshold conditions is detrimental to aquatic ecosystems and agricultural crops, which eventually affect the social-ecological system of the basin.

The approach of hydrologic thresholds flow confirms its potential for use in planning and management of water resources which have impacts on coupled social-ecological system. In this study, thresholds have been calculated for ecological (i.e. through RVA approach) and social systems (i.e. flood categories) separately. But societal and ecological subsystems remain in mutual interaction and their states, interactions and feedback mechanisms need to be analyzed jointly in future studies, particularly when addressing sustainable development issues (Gallopín 2006).

In setting ecological threshold flows with the RVA approach, the study is mainly based on statistics. However, further research is required investigating the physical impact of hydrologic flow regime on ecosystems in detail (Monk et al. 2007). Similarly, for determining damaging flood events through flood frequency analysis, parameter uncertainty should be considered in future studies.

In this study we focused only on the expected impact of climate change on river flow thresholds. However, in reality, climate change and human induced perturbation (e.g., development of river infrastructure such as dams) happen concomitantly and interactively. The extent of hydrologic perturbation associated with human activities such as dam operations, flow diversion, groundwater pumping, or intensive land-use conversion has already been assessed in several studies (Richter et al. 1996, 1997; Mirza 1998). To investigate the combined impact of climate change and human induced perturbation, future studies are required aiming at a more in-depth understanding of the system, which with respect to ecosystems should also consider water quality issues.

Acknowledgement

Part of this research was conducted at Ca' Foscari University of Venice and at the United Nations University – Institute for Environment and Human Security (UNU-EHS), whose support is gratefully acknowledged. The authors are grateful to Bangladesh Water Development Board for providing the discharge data.

Chapter 4 An assessment of water governance trends: the case of Bangladesh

This chapter is based on:

Gain, A. K., & Schwab, M. (2012). An assessment of water governance trends: the case of Bangladesh. *Water Policy, 14* (5), 821-840. doi:10.2166/wp.2012.143

Abstract

Water governance is a complex regulatory process which continuously changes over time. In this study, we apply a novel approach to investigate trends in water governance regimes, using Bangladesh as an example. Among the diverse notions of governance, we consider seven indicators representing legal, political and administrative aspects. Changes are analysed by considering both shifts indicated by policy documents and the quality of governance perceived by water user groups. To get an overall picture, we aggregate all seven indicators based on the weightings provided by experts and water user groups. Our results show that, according to the policy documents, all notions of governance have significantly improved and will further improve. However, according to water user groups, the actual implementation of these policies seems to be far behind what the policy documents indicate and, moreover, this gap has even been increasing over time. Although only seven indicators might not do sufficient justice to the complexity of an issue such as governance, these results convey an understanding of observed and perceived tendencies in arenas of water management, making this approach a relevant contribution to a better informed decision-making.

Keywords*:* Bangladesh, Good governance, Index, Institution, Water Policy.

4.1 Introduction

The Second World Water Forum, held in The Hague in 2000, considered water governance to be a main issue for water related problems. Subsequent international meetings, such as the Bonn International Conference on Freshwater in 2001, the World Summit on Sustainable Development in Johannesburg in 2002, and the thirteenth session of the Commission on Sustainable Development in New York in 2005, have all seen improved governance in the water sector to be an overarching concern for meeting the water-related Millennium Development Goals (Tropp, 2007).

Governance comprises all the linkages and processes related to making choices and decisions with regard to water, and accounts for the groups involved in decision-making, both horizontally across sectors (e.g. between urban and rural areas), and vertically from local to international levels (Rogers & Hall, 2003). In natural resources decision making, it is difficult to make a clear distinction between ‘management’ and ‘governance’; some researchers even consider the terms to be substitutable. Biswas & Tortajada (2010), for example, stated that ‘sustainable water management’ and ‘integrated water resources management’, the most prevalent paradigms of the water sector in the past (1980–2000), have been replaced by the term ‘water governance’. Pahl-Wostl (2009) made a clear distinction between the two terms ‘management’ and ‘governance’, arguing that ‘management’ stands for activities such as analyzing and monitoring, developing and implementing measures to keep the state of the resources within desirable bounds, whilst ‘governance’, by contrast, considers actors and networks which help to formulate and implement environmental policies and/or policy instruments.

According to the Global Water Partnership (GWP), water governance is defined as the range of political, social, economic and administrative systems that are in place to regulate development and management of water resources and provision of water services at different levels of society (Rogers & Hall, 2003). Therefore, water governance is a highly complex regulatory process which continuously changes over time. These changes reflect a noticeable evolution from “old” to “new” forms of governance. The ‘old’ notion of governance can be regarded almost as a synonym for government. It described predominantly the effectiveness of bureaucracy and government branches in enforcing political decisions. The improved ‘new’ form of governance, by contrast, is considered to be a prerequisite for a commendable water resource management (Tropp, 2007). However, water managers are currently not fully aware of the development potentials of these “new” forms of governance.

In the case of developing countries such as Bangladesh, the problem is particularly severe. According to policy documents, water governance may have improved but implementation does not yet seem to be very effective. It is therefore important to gain a better understanding of changes in water governance, especially in many developing countries, where research in this area is very rare.

In this study, we apply a novel approach to investigate trends in water governance regimes and illustrate it with the example of Bangladesh, where overall governance structure is weak and climate change impacts on water resources are dominant (Gain et al., 2011). We consider changes in water governance which have been formally planned and advocated in policy documents, and account for the projected efficiency in their implementation over time. This study subsequently provides not only a trend analysis for water governance regimes but indicates why and where future problems can occur. This could therefore form the basis for a more informed and future-oriented policy-making where sustainable water governance is not only planned but where policies are put into action by ensuring good governance.

To help give a deeper understanding of the subject, Section 2 describes water governance in general, and key notions are selected to compose a new approach to analysis. Previous and current water governance in Bangladesh are discussed in Section 3 which provides background for the case study considered here. Section 4 then introduces the methodology for assessing general trends of governance in a more structured and analytical manner. The results of this analysis and their discussion are subsequently presented in Section 5. In the final section, the main results are summarized and a conclusion is drawn.

4.2 Notion of water governance

In the scientific literature, the most important features of good governance are often said to be accountability, transparency, participatory processes and decentralized decision making (Biswas & Tortajada, 2010). These features promise to ensure the proper allocation of resources in a timely and efficient manner. Assessing the prerequisites for good governance is, however, a difficult task. Valid indicators are hard to find, measuring them often implies a lack of reliability, and different characteristics of good governance involve competing notions (Vincent, 2007). Nevertheless, analyzing the characteristics of water governance regimes in a systematic way is an important task which has been approached by different scholars. Pahl-Wostl (2009), for example, identified four dimensions of good water governance: institutions (the relationship between formal and informal institutions), the role of actor groups (state and non-state actors), multi-level interactions (vertical as well as horizontal integration), and governance modes (bureaucratic hierarchies, markets and networks). Making a trend analysis of future water governance requires an analysis of the projected temporal variations of these dimensions. However, though relevant, the interactions of actors and the multi-level interactions across vertical and horizontal scales are hard to predict, and any predictions made would be fraught with high uncertainties. Therefore, we have only considered institutional change in our assessment of the general water governance trend.

A governance regime is determined by the relative strength of formal and informal institutions. Formal institutions are linked to the official channels of governmental bureaucracies and can be enforced by legal procedures. Informal institutions, by contrast, refer to socially shared rules such as social or cultural norms which are not written down and reflect local people's attitudes (Pahl-Wostl, 2009). Based on the compatibility of goals between formal and informal institutions, and on the effectiveness of formal institutions, Helmke & Levitsky (2004) derived an evaluative typology of governance. They considered highly effective formal institutions and a high compatibility of formal and informal institutions' goals to be the best case scenario, whilst worst case scenarios were typified by ineffective formal institutions, and by formal and informal institutions following conflicting goals.

Based on the degree to which water management is centralized, and the degree to which management is supply- or demand-oriented, Ashton *et al*. (2006) developed a conceptual framework for assessing the notion of institutional change. In this approach, the 'best' governance regime is highly decentralized in its decision making with a primary focus on demand-side oriented management. The management cadre in this case consists of scientists of various disciplines, and stakeholders representing the government and society. In the worst case, water management is highly centralized with a primary focus on supply-side options and the management cadre consists predominantly of engineers and hydrologists.

Saleth & Dinar (2004) analysed water institutions by using a two stage analytical approach (Figure 4.1). At the first level, the water institution is broken down in terms of its three broad institutional components: water law, water policy and water administration. At the second level, each of these institutional components is broken down further to identify their constituent institutional aspects: the water law component includes seven law-related institutional aspects; the water policy component includes seven policy-related institutional aspects; and the water administration component includes the administration-related institutional aspects (Figure 4.1).

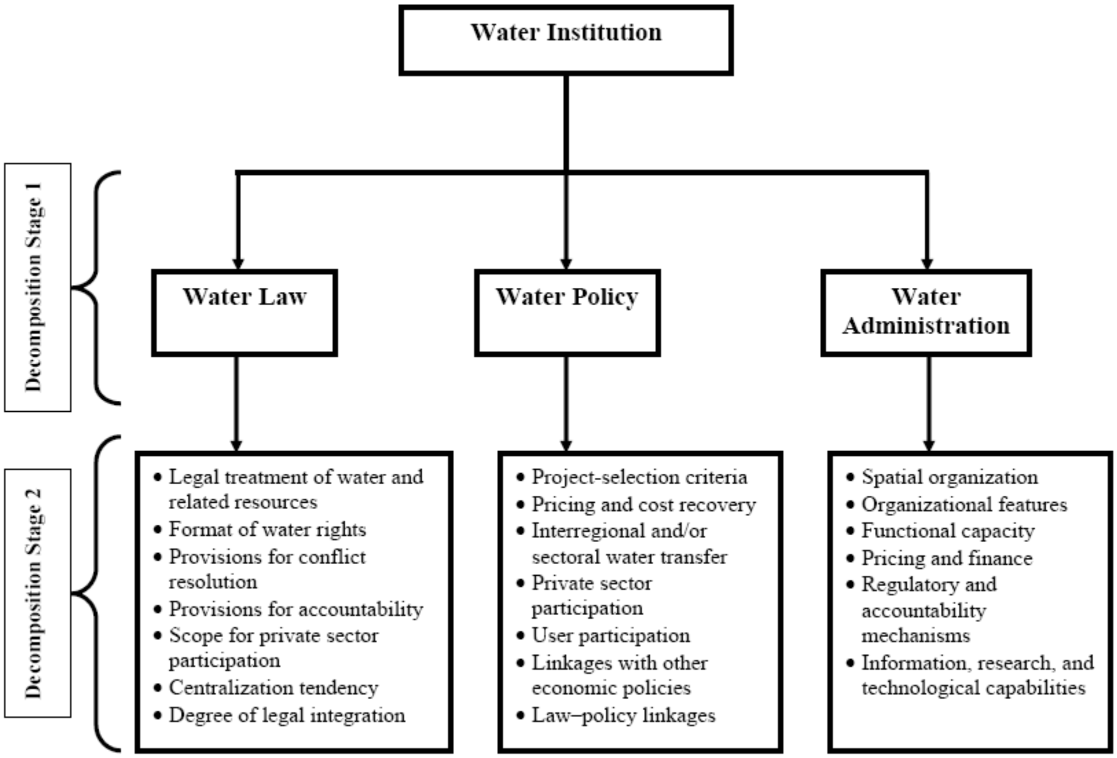


Figure 4.1 Analytical decomposition of water institution.

Based on the analytical procedure of Saleth & Dinar's (2004), the Institute of Water Policy at the Lee Kuan Yew School of Public Policy, Singapore, developed the Asia Water Governance Index (AWGI) which was constructed by weighting and aggregating the 20 components comprising the legal, policy and administrative dimensions (Araral & Yu, 2010). The index has a scale of 0 to 100, with 100 representing water governance "best practices". In developing the AWGI, about 102 water experts from 20 countries in Asia Pacific were surveyed. In this way, Araral & Yu (2010) aimed to enable policymakers to better understand how their countries manage their water resources, compared to other countries in the region in terms of legal, policy and administrative dimensions. However, it is often difficult for policy makers to differentiate between the 20 indicators proposed by Araral & Yu (2010). The scope of private sector participation in water law and private sector participation in water policy, for example, can confuse decision-makers and experts. Similarly, interregional water transfer depends on the spatial organization of water administration. Moreover, some indicators like prerequisites for accountability, good conflict resolution, degree of legal integration, law-policy linkages, as well as regulatory and accountability mechanisms are very difficult to measure, as it is very difficult to identify these indicators by analysing policy documents. A quantification of these indicators depends solely on the subjective judgement of the respondents, and policy makers may not accept this.

Based on a literature review and the value judgement of experts, our approach considers seven indicators reflecting the quality of water governance. These are: centralization/decentralization tendency, user participation, spatial organization of water administration, project selection criteria, water rights, cost-recovery status, and water pricing mechanism. Centralization/decentralization tendency refers to how water resources decision-making processes are accomplished through cooperation/integration of local authorities and decision-makers. User participation refers to the extent to which local people and stakeholders are involved in decision making processes. The spatial organization of water adminstration describes which regional divisions are considered by specific administrative bodies, ranging from geographic divisions to hydrological regional cooperation with co-riparian countries in the best cases. Project selection criteria indicate how water resources projects are selected, whether they are selected through political dictates or whether multiple criteria are considered in decision-making. The water rights status indicator refers to the existing system regarding water use, with no or unclear rights reflecting rather bad governance, and equitable permit systems and instream flows being good governance indicators. Cost recovery status refers to how the costs for water are recovered, ranging from no regulation, to fully subsidized cost recovery, right up to full cost recovery in the best cases. Finally, it is important to look at whether or not a specific organization exists to deal with water pricing.

These seven indicators provide a representative picture of the legal, policy and administrative dimensions of a water institution which is understandable and interpretable for decision-makers in the water field. The interdisciplinary nature of the indicators represents the sustainable development dimensions present, taking account of economic (e.g., cost recovery status, spatial organization of water pricing), social (e.g., user participation, water rights) and political (e.g., centralization/decentralization tendency; spatial organization of water administration) aspects of sustainable water governance. In addition, the environmental dimension of sustainability is addressed, in particular by the recognition of project selection criteria. Good governance can only be achieved when project selection is based on multiple criteria, which would also include environmental criteria. Moreover, the selected water governance indicators incorporate the principles of integrated water resources management (IWRM) as defined in GWP-TAC (2000)[††]. Both the spatial organization of water administration (e.g., river basin management) and centralization/decentralization tendency (e.g., decision-making body consists of an interdisciplinary team including stakeholders) aim at promoting the coordinated development and management of water, land and related resources. The resultant economic and social welfare is reflected in the indicators' cost recovery status, spatial organization of water pricing, user participation and water rights, which are the central prerequisites for integrated water governance. However, policy documents often advocate rather good water governance which is yet not seen in practice, suggesting that the implementation of these policies is often not very effective; in fact, sometimes policies are not implemented at all. We therefore analyze both how the status of these indicators evolves according to existing policy documents and also how effectively policy is implemented over time.

4.3 Water governance in Bangladesh

In this section, we review the policy documents which can indicate the past, present and future water governance situation in Bangladesh. We describe water sector development for the periods 1947–1988, 1989–1999, 2000–2010 and 2010–2025.

4.3.1 Water sector development 1947–1988

In 1959, water management was institutionalized and sole responsibility for it was given to the East Pakistan Water and Power Development Board Authority (EPWAPDA). In 1964, the EPWAPDA prepared a 20-year Water Master Plan, which was the beginning of water sector planning in Pakistan and subsequently the basis of the implementation of several big projects in the 1980s. With the aim of increasing agricultural production, the Master Plan was designed based on a strategy of massive flood control and drainage to be followed by irrigation projects. Moreover, emphasis was laid on the construction of embankments and polders over much of the country. The 1964 plan overemphasized large sector surface water interventions, which overlooked the country's ground water resources. After the independence of Bangladesh in 1971, responsibility for planning and management of water

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[††] IWRM is a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

resources was handed over to the newly created Bangladesh Water Development Board (BWDB). However, the focus within water management remained almost the same (particularly increasing agricultural production). In 1972, a study undertaken by the International Bank for Reconstruction and Development (IBRD) recommended a strategy of reduction and change in irrigation in winter, proposing the use of low lift pumps (LLP) and tube-wells (TW) – a major deviation from the 1964 Master Plan. Subsequently, the Government of Bangladesh recognized the need for institutional reforms and for a new Master Plan. In the course of these policies, the National Water Resources Council (NWRC) was established as an inter-ministerial body for water related policies. In preparation for the National Water Plan, a Master Plan Organization (MPO) was created in 1983, though the National Water Plan itself was not completed until 1986. During the period 1947–1988, water sector development followed a strictly sectoral approach with very little inter-sectoral communication. The role of water in other sectors, such as domestic water supply and sanitation, fisheries, navigation, industrial use, hydropower, ecology and nature and disaster management, remained mostly neglected (Ahmad, 2003). The main organization responsible for water policies, the BWDB, was inclined to seek predominantly structural engineering solutions, since the majority of planning was undertaken by civil engineering staff. By June 1990, BWDB constructed 7,555 km of embankments and 7,907 hydraulic structures as part of 437 projects (Thompson & Sultana, 1996). In the absence of other organizations, water resources management in Bangladesh became synonymous with flood control, drainage and irrigation (FCD/I).

4.3.2 Water Development 1989–1999

Bangladesh experienced two severe floods in 1987 and 1988 which caused massive infrastructural damage, loss of crops and the deaths of nearly 1,700 people (Haggart *et al.*, 1994). The event brought the issue of flood control and flood management on the agenda of international forums. Consequentially, in July 1989, the World Bank and the Government of Bangladesh recommended an integrated approach to flood mitigation. In December 1989, the Flood Action Plan (FAP) was endorsed by the representatives of the Government of Bangladesh with the aim of stabilizing food production and maintaining the country's capacity to feed an expanding population (Hanchett, 1997). At the beginning of the 1990s, a lack of public participation was identified by the government and by donors as the major cause for the poor operation and maintenance of the BWDB's flood control drainage (FCD) system. Therefore, at the second conference on the FAP in 1992, the Flood Planning Coordination Organization (FPCO) produced a set of guidelines for better participation in management projects (Duyne, 1998), which led in turn to the formulation of the *Guidelines for People's Participation in Water Development Projects*, (MoWR,1995) a policy document which was formally approved by the Ministry of Water Resources in July 1995.

In 1991, a National Water Policy (NWPo) was completed by the MPO which included the development of a number of planning models and analytical tools for defining and evaluating strategies. During this phase the country was divided (initially) into 173 catchments which were grouped into 60 planning areas, and further aggregated into five major hydrologic regions (Northeast, North-west, South-east, South-west and South-central). Also during this period the MPO prepared a draft water code and outlined proposals to institutionalise the process of planning and development of water resources (World Bank, 1997). To recast the NWP within the appropriate inter-sectoral focus, the MPO restructured it and, in 1991, initiated the Water Resources Planning Organization (WARPO) with a mandate to "evolve national policies and strategies for utilisation and conservation of water by all" (MoWR, 1999).

At the end of the FAP in 1995, the Bangladesh Water and Flood Management Strategy (BWFMS) was produced, and was the first long-term strategy for the water sector in Bangladesh. It envisaged both the formulation of an NWP and the preparation of a National Water Management Plan (NWMP) which would include national, regional and basic programs for water management.

As part of the decentralisation process, the Government of Bangladesh provided new responsibilities to local government institutions through enactment of the Upazila Parishad Act (1998), Schedule 2 of which specifically deals with development of the water resources sector, in particular relating to planning and management of small-scale water resources schemes below 1,000 hectares.

4.3.3 Water Development 2000–2010

The adoption of the National Water policy (NWPo) at the end of 1999 was a milestone towards good governance of water resources in Bangladesh. The stated goal of the NWPo was "to ensure progress towards fulfilling national goals of economic development, poverty alleviation, food security, public health and safety, a decent standard of living for the people and protection of the natural environment" (MoWR, 1999). Major institutional reforms and the role of the government, the private sector and of civil society in the management of water resources were defined in the NWPo. This also played an important role in accelerating the development of sustainable public and private water delivery systems, with appropriate legal and financial measures and incentives including formulation of water rights and water pricing.

The Bangladesh Water Act was drafted in 2009 as a means to integrating the management, development, utilization and protection of water resources. However, in early 2012 the act had still not been passed. Major improvements in the water management policy arena occurred during this decade. The sector matured greatly and was genuinely providing a more transparent and proactive approach to water management.

4.3.4 Future water planning 2011–2025

To facilitate the implementation of the NWPo, the government approved a 25-year National Water Management Plan (NWMP) in 2004, as the basis for future water management. The plan provides guidelines to develop programmes for better management of water resources in the country. The main element of the NWMP is its multi-use approach to water (not just flood protection but also irrigation, drinking water and other uses) and its emphasis on 'soft' approaches instead of just hard engineering approaches (WARPO, 2001).

4.4 Methodology

In this study, past, present and future water governance in Bangladesh was assessed on the basis of a policy document review and stakeholder consultations. For this evaluation, structured interviews with ten experts specializing in the water policy of Bangladesh were undertaken. In order to evaluate the effectiveness of each indicator, we also interviewed local water user groups alongside the water policy experts. They were asked to judge the past, current and future state of water governance regarding the selected indicators and to evaluate the implementation of policies related to these indicators. Among water user groups, we organized two focus group discussions asking the same questions. The minimum age of each respondent (both for water user groups and water policy experts) was 55 years so that they could provide more accurate information on past water governance, particularly since the 1980s.

In order to assess how each indicator evolved over time, we defined four time intervals (up to 1988, 1989–1999, 2000–2010 and 2011–2025). These intervals were selected based on milestones in Bangladesh’s history. The 1988 flood, for instance, is a decisive historical event in Bangladesh, which people remember and refer to, making it easier for them to differentiate between processes before and after this event. In 1999, the NWP was formulated, representing a major shift in policy and bringing about decisive changes in water governance. The year 2000 has a highly symbolic character, representing the transition to a new millennium and is therefore a point in time that people can easily remember. The subsequent period, the “present”, was defined to be the time between 2000 and 2010, the year before our survey (which was carried out in 2011. The future is represented by the period 2011–2025, the official planning horizon of Bangladesh’s policy documents.

Table 4.1 Attributes of numeric scores (0–10) for each indicator

Indicators	**Numeric scores**					
	0	2	4	6	8	10
Centralization tendency	Highly centralized	→				Highly decentralized
User participation	Not participatory	→				Complete participatory
Water administration	No administration	Geographic division	Hybrid in geographic and hydrologic region	Broad hydrologic region	Hydrological region cooperation with co-riparian countries	River basin authority (e.g., WFD)
Project selection criteria	No rules	Political dictate	Single factor (equity/ecological/ benefit–cost ratio)	→		Multicriteria analysis
Water rights	No rights	Unclear	Common or state property	Permit system without considering equity	Permit system with considering equity	Permit system considering both equity & instream flow
Cost recovery status	Non existent	Full subsidy	Partial subsidy	Partial recovery	→	Full cost recovery
Independent body of water pricing	Not existent					Existent

We applied a value function approach as there was no reliable data for most of the indicators and for the changes over time available. A value function can be defined as a mathematical representation of human judgment. It aims to make the evaluation of a stakeholder explicit by expressing the quality of an indicator as a value score (Beinat, 1997). In our analysis, the value scores range from 0 to 10, where a value of 0 indicates the worst performance and 10 represents the best available performance. Further, we also identified, where possible, the attributes of indicators which were each given a value between 0 and 10 (see Table 4.1 for a description of the indicators and their values). There were no defined characteristics to assess the degree of centralization and user participation, and the stakeholders therefore judged the indicator in the form of a value ranging from low via medium to high fulfillment of it. To assess all the other indicators, certain governance characteristics were defined for each value. In the case of project selection criteria, rules were not defined for the intermediate values between 4 and 10, whilst “4” meant that only a single factor was considered in project selections and “10” represented the consideration of multiple factors. Similarly, for cost recovery status, rules were not defined for intermediate values greater than 6 and less than 10. In the case of the independent body of water pricing, only the values “0” or “10” were considered, representing whether an independent body of water pricing existed or not. The intermediate attributes of the other indicators were determined following the conceptual frameworks of Araral & Yu (2010), Ashton *et al.* (2006), Helmke & Levitsky (2004) and Pahl-Wostl (2009).

In order to get an overall picture of water governance, we aggregated all seven indicators based on the weighting factor provided by the experts and water user groups.

4.5 Results and discussion

An analysis of relevant policy documents and a consultation of water policy experts facilitated an identification of policies indicating tendencies in terms of the seven identified water governance indicators over time. These developments are illustrated by the darker bars in Figures 4.2-4.9. The actual perceived quality of governance is judged according to experts’ and water user groups’ perceptions regarding the effectiveness of the relevant policies. The average opinion of involved experts and user group is subsequently depicted as the lighted shaded bars in Figures 4.2-4.9. The results of the judgments for each indicator are discussed below.

4.5.1 Centralization tendency

Figure 4.2 shows how the centralization/decentralization tendency in Bangladesh's water sector evolves over time in policy documents and how the policies are perceived by stakeholders. In the figure, the lowest value, 0, represents a highly centralized structure of water resources decision making, in which case only one or very few central level organizations are responsible for decision making; moreover, the management cadre consists predominantly of staff with a single disciplinary background (mainly engineers and hydrologists). At the other end of the spectrum, the highest value, 10, represents a highly decentralized structure, where decision making is accomplished by several local and national level institutions with the involvement of local people; furthermore, there is a management cadre present whose staff have a much wider range of skills, including policy specialists, social scientists, economists, lawyers, engineers, hydrologists and ecologists. The dark and light bars both indicate that up to 1988 water resources decision making was highly centralised. This goes back to the fact that, from 1959, water management was organized by a single authority, the EPWAPDA and, after independence, by the BWDB, hereafter referred to as the 'Water Board' (Chowdhury & Rasul, 2011). During this time, policies were planned and carried out almost exclusively by the engineers and hydrologists of the Water Board. During the period 1989–1999, policies indicated an increase in decentralization which was also perceived by the interviewed stakeholders. In 1991, the National Water Plan was completed and (as we have already seen) in the course of this, Bangladesh was divided into 173 catchments grouped into 60 planning areas and further aggregated into five regions. Moreover, the Government of Bangladesh planned to delegate new responsibilities to local governmental institutions, which was also meant to increase decentralization. Nevertheless, these changes led to a still rather centralized decision-making, according to both the policy analysis in this study and stakeholder perception. This can be explained by the fact that it was still the Water Board which played the central role in decision making. A rapid improvement with regard to decentralization can be seen in the decentralization policies from 2000–2010 which are represented by an attributed value of 7 points in Figure 4.2. At the end of 1999, the NWPo was put into action, two major objectives of which were: (1) to bring about an institutional change facilitating the decentralization of water resources management; and (2) to develop a legal and regulatory environment allowing for such a process of decentralization (MoWR, 1999). These two objectives played a major role in increasing decentralization from 2001 to 2010. In this period, as well as the Water Board, the Local Government Engineering

Department (LGED) attained responsibility for small-scale (less than 5000 ha) water resources projects including local stakeholders (Gupta *et al.*, 2005). The actual implementation of these policies however, seems to have been rather ineffective. In contrast to what policy documents advocated, stakeholders perceived the situation to be still very centralized (with a value of 3). This is also attested by independent studies analyzing the water governance situation in Bangladesh. The Asia Water Governance index, for example, rated Bangladesh as having achieved only a minor degree of decentralization compared to other Asian countries (Araral & Yu, 2010). For the future, the Government of Bangladesh is planning further progress withdrawing authority from central government agencies and giving more responsibility to local institutions and the private sector, thereby emphazing stakeholder participation (WARPO, 2001). In our analysis, this is reflected by an ascribed increase in decentralization up to a value of more than 8 points. The interviewed stakeholders, however, did not think that these policies will come into effect. They predicted that water governance will continue to have a rather centralized water governance regime. Low trust in government policies, which is also found for the other six water governance indicators analysed here, is a major reason for this view. It reflects a generally low political and legal accountability in the country (see e.g. Araral & Yu, 2010; Marshall & Jagger, 2008).

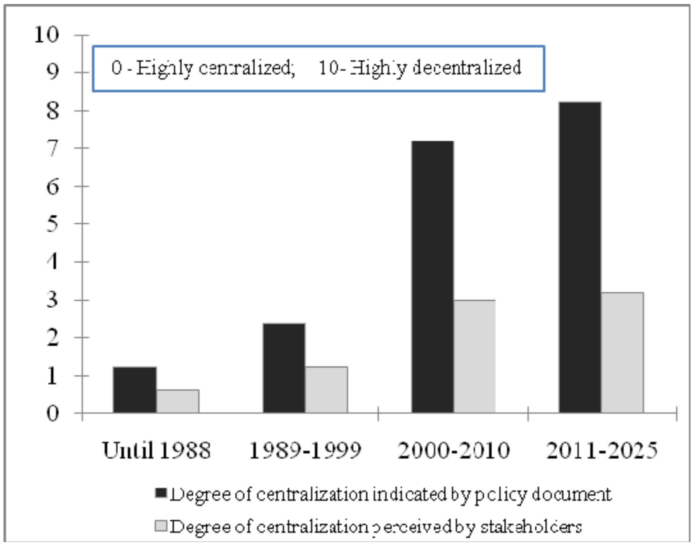

Figure 4.2 Changes in the degree of centralization indicated by policy documents and perceived by stakeholders.

4.5.2 User participation

User participation refers to the extent to which local people and stakeholders are involved in decision-making processes. How the level of user participation changes over time in the policy documents, and also in the perception of the user groups, is shown in Figure 4.3. According to the subjective evaluation of experts and an analysis of policy documents, the extent of user participation in decision-making processes has substantially increased and is also expected to increase in future. Before 1989, local people were not involved in any decision-making process regarding water resources. This changed in 1990, when the BWDB System Rehabilitation Project allowed for farmers' participation in water project planning for the first time. At the beginning of 1992, the Flood Planning Coordination Organization (FPCO) intended to increase participation with the introduction of participation guidelines. These developments are reflected in an increase (1 to 3 points) in the attributed governance value given in this study. Nevertheless, these policies were barely perceived by the interviewed water user groups, which did not see much of a change in participation compared to the period before 1989. In 1999, the NWPo saw the achievement of water management objectives through broad public participation as one of its major goals (MoWR, 1999), leading to the formulation of a guideline for public participation in 2000. These developments can be seen in a rapid increase in participation in Figure 4.3. For the future (up to 2025), the Government emphasize stakeholder participation by involving local government institutions (LGIs), community based organizations (CBOs) and the private sector (WARPO, 2001). In spite of these developments, water user groups still think that they are widely ignored in decision making; although they perceive an increase in participation, that participation is weaker than advocated in the policy documents, with the majority of policy documents not yet implemented and, the water user groups feel, not expected to be implemented in the near future. Comparing these results with, for example, the Asia Water Governance Index which measures the legal scope of private and user participation, shows a similar picture of rather low participation. Low trust in future policies can again be explained by the low general accountability of government policies in Bangladesh.

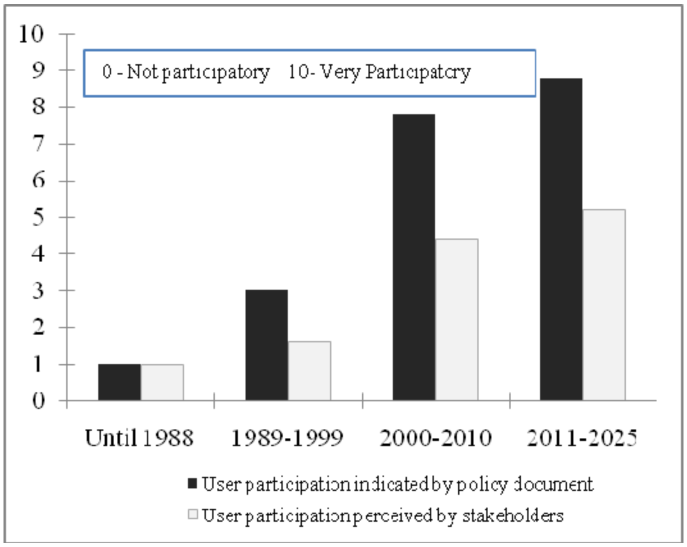

Figure 4.3 Changes in the extent of user participation indicated by policy documents and perceived by stakeholders.

4.5.3 Spatial organization of water administration

This indicator refers to whether or not separate administrative bodies exist for water management. According to the stakeholders consulted, good water governance continuously increased with regard to this criterion over the past decades and will continue to do so over the next 15 years. This perception is based on decisive developments and planning from official sides. Before 1988, hydrologic boundaries were not mentioned in policy documents. During the period 1989–2000, the MPO or WARPO divided Bangladesh into 173 catchments which were grouped into 60 planning areas. However, this seemed to have no effect on the perception of local stakeholders interviewed in this study, who did not see any changes during the period 1989–1999 in the spatial organization of water administration (see Figure 4.4). Later in 1999, the NWPo advocated the delineation of hydrological regions based on appropriate natural features for planning and development of water resource governance. These policies are reflected in the perception of the interviewed water user groups, who saw a significant improvement in the water administration towards a spatial organization oriented at broader hydrological regions. Furthermore, the NWPo emphasized the establishment of a system for exchange of data and information for the management of shared water resources with riparian countries. Since then, several agreements have been made, especially with India on Ganges river management issues. However, the issues of greatest conflict, those of sharing waters during the dry season have, as yet, not been touched (Chowdhury, 2010). Due to such issues, cooperation with riparian countries was not fully recognized by the interviewed stakeholders and the situation is not expected to improve much in the future (see Figure 4.4). In the water resources planning documents, however, the government intends to work towards international river basin planning to realize the rivers' full potential benefits (WARPO, 2001), indicating good water governance (see Figure 4.4).

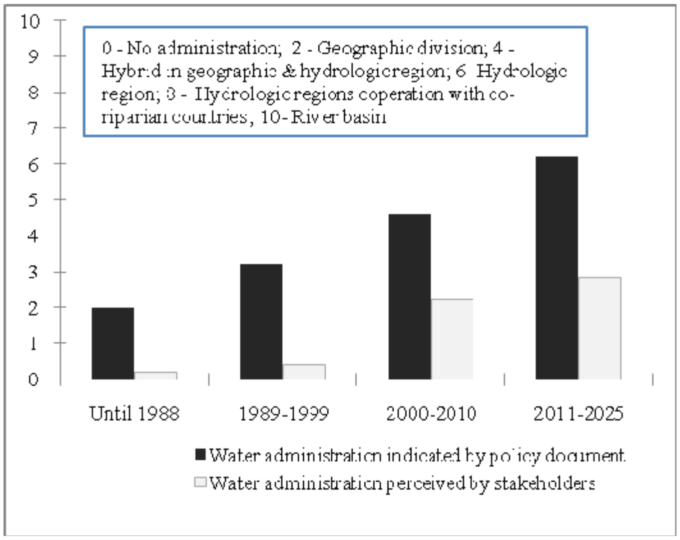

Figure 4.4 Spatial organization of water administration in different years indicated by policy documents and perceived by water user groups

4.5.4 Project selection criteria

This water governance indicator points to how water resources projects are selected, whether they are selected through political dictates or whether multiple criteria are considered in decision making. In the case of Bangladesh, water governance has improved with regard to this criterion, especially in the last decade, and it is projected to arrive at a highly beneficial multi-criteria project-selection process in the future, according to policy documents (see Figure 4.5). Governance trends up to 1988 can be explained by the domination of an authoritarian political regime where projects were dictated in a top-down manner. Only in 1991 was a democratic government formed in Bangladesh, setting the basis for the introduction of a project-selection regime. Nevertheless, this change was not perceived by our locally interviewed stakeholders who did not see a move towards a more democratic approach to overall project selection criteria. This can be traced back to the fact that, even after 1988, political dictatorship still plays a major role in project selection. For example, until 1991, the FAP was never debated in Parliament and no public consultation was carried out prior to project implementation (see the shift from light bars to shaded bars in Figure 4.5). In 1999, the NWPo officially incorporated multi-objective analysis for the selection and appraisal of water resources projects. The consequences of this policy seemed, however, not to arrive at the local level. The majority of local water user groups stated in the group discussion that projects were still selected in a top-down manner, without considering single or multiple criteria contributing to a more sustainable project planning and implementation; for the future, local water user groups expected only a slight change towards multiple criteria decision-making. This is still far from what policy documents themselves indicate for 2025, advocating multi-criteria analysis at the forefront of important projects. This can, again, to a great extent be explained by a lacking of accountability in politics in Bangladesh.

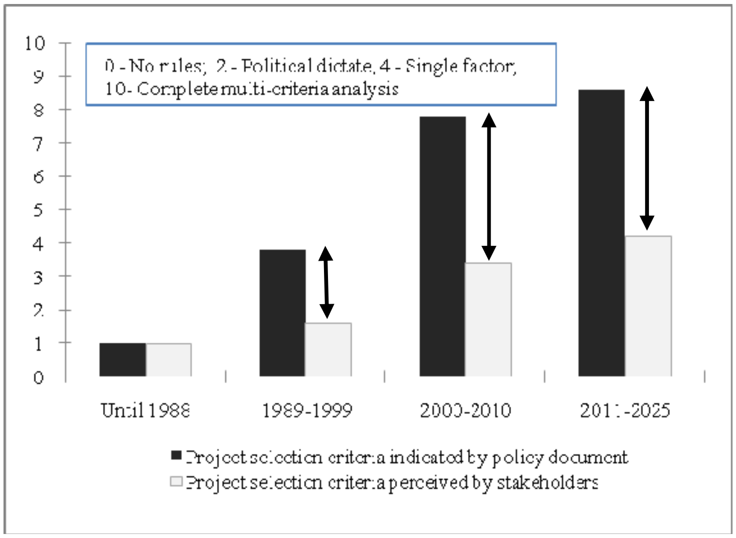

Figure 4.5 Changes of the project selection criteria indicated by policy documents and perceived by stakeholders.

4.5.5 Water rights

The water rights regime is another important factor to be considered when talking about good water governance. This indicator refers to whether water rights are, in the worst case, non-existent, whether they are relatively unclear or, in the best case, regulated by a permit system whilst considering both equity and instream flows. Before 1988, there were no defined water rights, which, in our study, is reflected by a very low value for both the policies advocated in the documents and for the actual situation perceived by local stakeholders (see Figure 4.6). The NWPo mentions that the allocation of water aims to ensure equitable distribution, efficient development and an allocation based on in-stream needs. The National planning document (WARPO, 2001) keeps emphasis on an enabling environment which ensures a clarification of rights by regulation of water use in areas of water scarcity and by protecting downstream users' needs (WARPO, 2001). It also mentions that water rights may be conferred on private and community bodies to provide secure, defensible and enforceable ownership/usufructuary rights to attract private investment. In order to provide a defined water use right, the government is planning to approve a National Water Act, although in early 2012 the act had still not been approved.

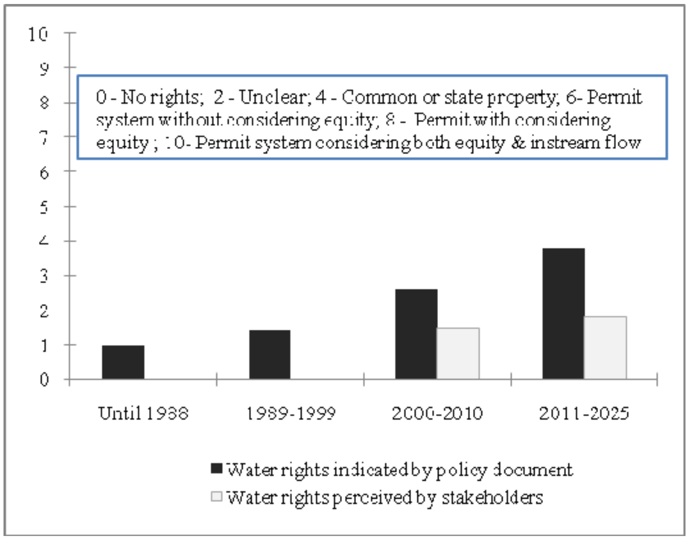

Figure 4.6 Changes of the water rights status indicated by policy documents and perceived by stakeholders.

4.5.6 Cost recovery status

Cost recovery status is another important factor to be considered, and refers to the way that costs for water management are covered: whether they are, for example, fully subsidized or whether they are covered completely by appropriate service charges. Before 1999, cost recovery status was not discussed in any policy documents. At the end of 1999, the NWPo recognized that a system of cost-recovery, pricing and economic incentives/dis-incentives was necessary to balance supply and demand of water. The cost recovery for FCD projects was not envisaged in this policy. For FCDI projects, water rates were to be charged for operation and maintenance as per government rules. Moreover, the policy document (MoWR, 1999) points out that there should be a safety net implemented for the so-called 'hard-core poor' and that educational and religious institutions should be free of charge. These developments can also be seen in the current and predicted trend towards a partial cost recovery indicated by the shaded bars in Figure 4.7; the same trend is also recognized by the local water user groups (light bars in Figure 4.7), though to a minor extent. This can be explained by the fact that policies are often formulated in a very vague way so that their interpretation and implementation not only vary a lot but so that they are sometimes not implemented at all. There is, for example, no explicit time frame given for the implementation of policies. It is simply described as 'near future' (Biswas & Adank 2004). It was planned that cost recovery should be introduced slowly by sensitization/consultation with local communities (WARPO, 2001). In the development strategy of the water management plan (WARPO, 2001), the Government recognized that changes in the institutional and financial framework could provide incentives, with the aim of full cost recovery of services in the future.

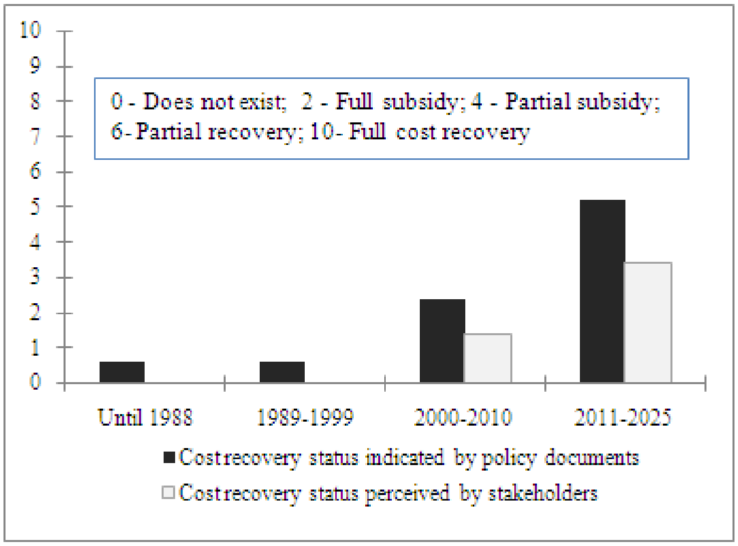

Figure 4.7 Changes of cost recovery status indicated by policy documents and perceived by stakeholders.

4.5.7 Water pricing

With regard to good water governance, the existence of an independent body for water pricing is a further important factor to be considered. If such a body exists, it would be reflected by a "10" in the value function for our indicator, representing the highest performance with regard to governance quality. In Bangladesh, so far, there is no separate organization dealing with water pricing, though the Draft Water Act (2010) stated that a separate organization for water pricing would be founded in the future. These developments were reflected in our analysis and are depicted in Figure 4.8. In contrast to the situation with other good governance characteristics, the water user groups seemed to trust in the policy plans and stated that such an institution would exist in the future.

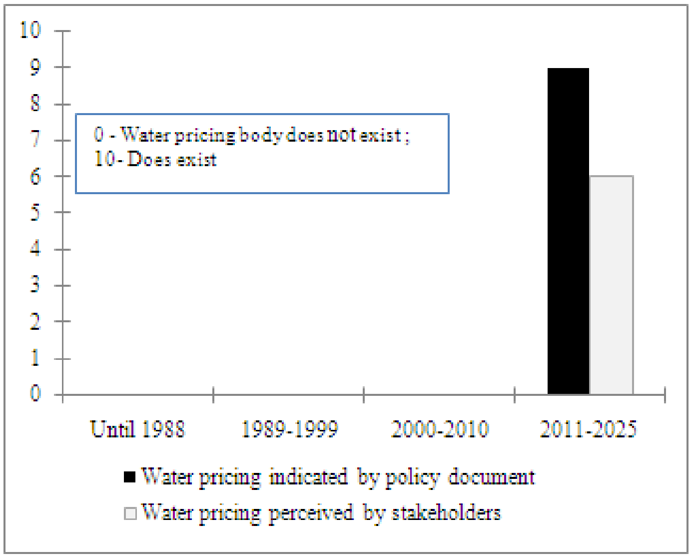

Figure 4.8 Existence of a water pricing body indicated by policy documents and perceived by stakeholders.

4.5.8 Aggregate water governance

After analysing each of the selected indicators, we aggregated them to compose an index of good water governance. The weighting factor for each indicator was calculated based on their relative importance judged by the experts and water user groups who partcipated in the survey. The average weighting factor for each selected indicator is shown in Table 4.2.

Table 4.2 Average weighting factor for each selected indicator of water governance

	Centralization tendency	User participation	Water administration	Project selection criteria	water rights	cost recovery	water pricing
Weighting factor	0.25	0.25	0.15	0.15	0.05	0.12	0.03

The stakeholders and experts perceived centralization and user participation to be the most important factors contributing to good water governance, together representing a share of more than 50% of the overall governance index. This is because local people already experienced the effect of centralized decision making by the BWDB and the continuous neglect of public participation. Water administration, project selection criteria and cost recovery status were also considered to be rather important factors contributing almost equally to good water governance, and these are now frequently discussed in different projects. Together, they were judged to contribute a share of nearly 50% to the aggregated index. The water rights regime and the existence of an independent water pricing body, by contrast, seem to be perceived to play an insignificant role by our interviewees, and together they take a share of 7% of the overall governance indicator. In the opinion of our interviewees, the existence of a permit system as part of the water rights can sometimes exclude minority communities, which may even add a negative notion to good governance. Similarly, our stakeholders thought that the existence of an independent body for water pricing can neglect rather than improve poverty and equity issues, two highly important factors for a country such as Bangladesh.

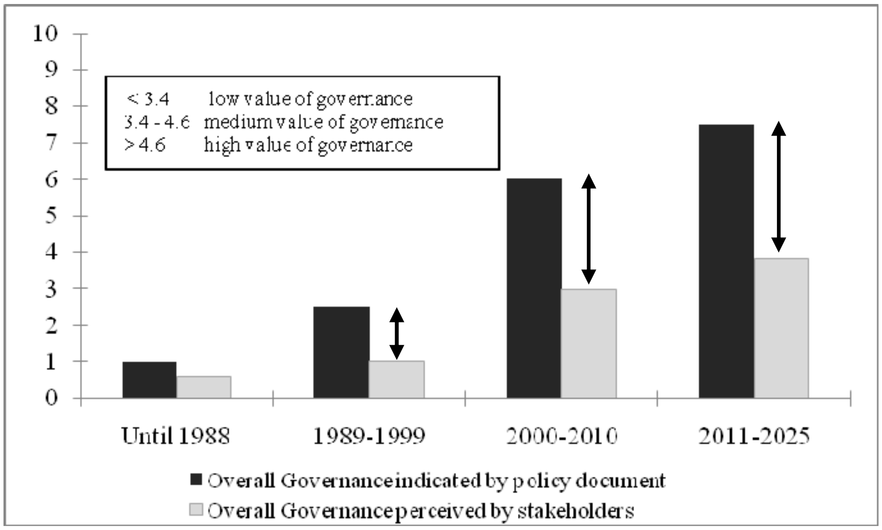

Figure 4.9 Trend of aggregate water governance indicated by policy documents and perceived by stakeholders.

Using these weighting factors, the policy-indicated and perceived values for the seven indicators were aggregated to an overall water governance index. The calculation summary of the index development is shown in Table 4.3. The trend in overall water governance policies and the perception of their effectiveness is depicted in Figure 4.9, which reveals that the water policies which have been formulated over the years point to an improvement of water governance, especially in the period between 2000 and 2010 and indicate that this trend is expected to continue, though to a smaller extent. This can mainly be explained by a substantial increase in decentralization, an improvement in user participation and changes in the project selection criteria – three indicators which not only developed rapidly between 2000 and 2010 but which are also judged to be highly important with regard to good governance. Nevertheless, user groups ascribed little effectiveness to the policies formulated and did not trust that they could achieve the goals envisaged. Moreover, this trust in policies seemed to have even decreased, and could further decrease, indicated by a widening gap between the light and shaded bars in Figure 4.9.

Table 4.3 Summary of indicator values and aggregation to an overall governance index over time [a]

	Indicators	Until 1988	1989–1999	2000–2010	2011–2025
1.	**Centralization tendency**				
	According to Policy documents	1.2	2.4	7.2	8.2
	Perception of stakeholders	0.6	1.2	3	3.2
2.	**User's Participation**				
	According to Policy documents	1	3	7.8	8.8
	Perception of stakeholders	1	1.6	4.4	5.2
3.	**Water administration**				
	According to Policy documents	2	3.2	4.6	6.2
	Perception of stakeholders	0.2	0.4	2.2	2.8
4.	**Project selection criteria**				
	According to Policy documents	1	3.8	7.8	8.6
	Perception of stakeholders	1	1.6	3.4	4.2
5.	**Water rights**				
	According to Policy documents	1	1.4	2.6	3.8
	Perception of stakeholders	0	0	1.5	1.8
6.	**Cost recovery**				
	According to Policy documents	0.6	0.6	2.4	5.2
	Perception of stakeholders	0	0	1.4	3.4
7.	**Water pricing**				
	According to Policy documents	0	0	0	9
	Perception of stakeholders	0	0	0	6
	Index				
	Governance	1	2.5	6	7.5
	Effectiveness	0.60	1	3	3.85

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[a] Indicator values lower than 3.4 are depicted in a dark grey shade, and represent low values of governance; The values ranging between 3.4–6.6 are depicted in a medium grey shade and represent medium values of governace; The values greater than 6.6 are depicted in a light grey shade and represent high values of governance.

This can partly be explained by the lack of accountability of regulatory politics and weak legal enforcement as shown by other studies such as the AWGI (Araral & Yu, 2010). The World Bank's Worldwide Governance Indicators (Kaufmann *et al.*, 2010), moreover, indicate adverse and (in comparison to the end of the 1990s) even deteriorating trends in regulatory quality, rule of law and control of corruption. This could explain why the gap between policy formulation and its implementation has widened since the end of the 1990s and is predicted to increase even further in the future. Trust in policies seems to be particularly low with regard to decentralization tendencies, project selection criteria and water administration. This is as a result of the Water Board still being the main decision-making body and from the fact that projects are still selected in a rather top-down manner, often dictated by the Water Board itself. The lack of trust in a better water administration can be explained by only minor international engagement with regard to the relevant coordinated water policies. In short, the lack of accountability of policies in general is not only contributing to a more adverse perception of these policies but is also affecting trust in all other kinds of policies, and therefore having a significant impact on the overall water governance index.

An aggregation of a set of water governance indicators for Bangladesh provides a good foundation for a comparison with other countries. In the case of Bangladesh, water governance is found to be rather poor, while that of Singapore is considered to be rather good; an analysis using the indicators presented in this paper confirms that Singapore has a highly developed governance system (Araral & Yu, 2010). Singapore has implemented an extremely efficient decentralized system (i.e. good demand and supply management practices), with well-balanced public and private sector participation (Luan, 2010). Moreover, efficiency and equity find consideration in an integrated institutional approach to water management (Tortajada, 2006; Luan, 2010). A more in-depth comparison between these two systems of water governance might not only show strategic points of intervention for a country such as Bangladesh but could also point out some specific measures to be taken in order to strengthen its governance system.

4.6 Conclusions

"Management of water pervades the entire society and economy of Bangladesh (…). Every citizen in Bangladesh has a legitimate and acute interest in water policy" (Wood, 1999).

This is why the analysis of water governance and its development over time is so vital to Bangladesh, especially in order to provide the basis for a more informed water governance. The approach presented here has used seven indicators to reveal the qualitative nature of past, present and future water governance. We found that, according to the policy documents, all notions of governance significantly improved over time and that it is expected to improve further until 2025. However, the actual implementation of these policies is often perceived differently by the water user groups, who are the people having the most "legitimate and acute interest in water policy" (Wood, 1999). Moreover, it has been shown that this gap between official water governance policies and actual implementation is even increasing over time.

We are aware that the seven indicators considered in this study might not do sufficient justice to the complexity of an issue like governance. Gender equity, for instance, could not be explicitly addressed within the scope of this study, although it is recognized as one of the IWRM Dublin principles (ICWE, 1992)[‡‡]. In Bangladesh, women play an important role in water resources management, as it is they who are the main users of water not only for productive purposes but also (and especially) for domestic use. Nevertheless, there exists a gender gap in access to water resources and in the decision making related to the governance of water. This fact, might not find explicit consideration in this study but it is implicitly acknowledged in indicators such as user participation and project selection criteria where gender equality may play an important role. However, these results convey an understanding of observed and perceived tendencies in the arenas of water management. In the words of John Maynard Keynes (1883–1946), "it is better to be roughly right than precisely wrong" (Meinke *et al.,* 2009); showing a sometimes rather unclear picture still gives a better idea of a situation than having no picture at all. This is particularly true in the case of a crucial topic such as water governance which touches everybody's daily life, whether in a nutritional, hygenic, social or economic sense, to name just a few. Using this structured and analytical approach can reveal which areas of governance are considered to be the most important and which of these fields show the greatest drawbacks. This shows past policy failures and indicates strategic points of intervention for future policies. Moreover, analysing policy documents and comparing them with the opinions of experts and user groups offers a differenciated analysis, and allow us to identify whether drawbacks in water governance are a

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[‡‡] Dublin Principle 3 states that women play a central part in the provision, management and safeguard of water.

matter of the absence of appropriate policies or the ineffectiveness of their implementation. Despite the survey's limited representativeness regarding its geographical and quantitative magnitude, this study provides a way to depict good water governance in a structured and robust way, conveying an overall picture of the governance situation in Bangladesh and providing a good basis on which to undertake larger, more representative surveys not only in Bangladesh but also in other geographical contexts.

Chapter 5 Climate Change Adaptation and Vulnerability Assessment of Water Resources Systems in Developing Countries: A Generalized Framework and a Feasibility Study in Bangladesh

This chapter is based on:

Gain, A. K., Giupponi, C., & Renaud, F. (2012). Climate Change Adaptation and Vulnerability Assessment of Water Resources Systems in developing countries: A generalized framework and a feasibility study in Bangladesh. Water, 4 (2), 345-366. doi:10.3390/w4020345

Abstract

Water is the primary medium through which climate change influences the Earth's ecosystems and therefore people's livelihoods and wellbeing. Besides climatic change, current demographic trends, economic development and related land use changes have direct impact on increasing demand for freshwater resources. Taken together, the net effect of these supply and demand changes is affecting the vulnerability of water resources. The concept of 'vulnerability' is not straightforward as there is no universally accepted approach for assessing vulnerability. In this study, we review the evolution of approaches to vulnerability assessment related to water resources. From the current practices, we identify research gaps, and approaches to overcome these gaps a generalized assessment framework is developed. A feasibility study is then presented in the context of the Lower Brahmaputra River Basin (LBRB). The results of the feasibility study identify the current main constraints (e.g., lack of institutional coordination) and opportunities (e.g., adaptation) of LBRB. The results of this study can be helpful for innovative research and management initiatives and the described framework can be widely used as a guideline for the vulnerability assessment of water resources systems, particularly in developing countries.

Keywords: vulnerability; water resources; climate change; decision-making; adaptation; lower Brahmaputra river basin

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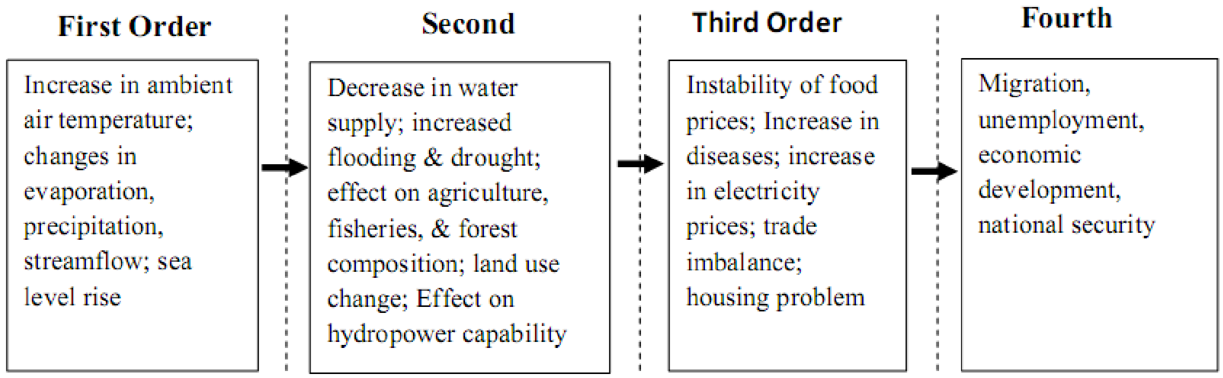
5.1 Introduction

Freshwater systems are part of larger ecosystems which sustain life and all social and economic processes. The provision of freshwater is therefore an ecosystem service which, when disrupted, threatens both the health of ecological systems and human wellbeing, which are in complex interaction (MEA, 2005). Through the primary medium of water, climate change influences the Earth's ecosystems, people's livelihoods, and general human wellbeing (UN-Water, 2009). Scientists within the Intergovernmental Panel on Climate Change (IPCC) expect that the present increase in greenhouse gas concentrations will have direct first-order effects on the global hydrological cycle, with impacts on water availability and demand (Bates et al., 2005). These changes will in turn create other higher order effects (Chalecki and Gleick, 1999), which are shown in Figure 5.1. Overall at the global level, a net negative impact on water availability and on the health of freshwater ecosystems is foreseen (Kundzewicz et al., 2007), and thus a cascade of negative consequences is expected to affect social and ecological systems and their processes.

Figure 5.1 Different order climate change effects on water resources.



Besides climate, there are other drivers of change, such as increased population pressure, economic development and urbanization trends. These drivers of change are closely linked to each other and pose complex management problems for land and water resources. As populations grow and move to cities—and as their income levels increase or decrease—their demand for water resources changes both spatially and temporally. Taken together, the net effects of these supply and demand changes in areas of increasing population, can translate into increases in the vulnerability of water resources systems, which can create major challenges for future management of water resources for human and ecosystem needs. As stated above, climate change can contribute further to exacerbate problems, in particular when considering medium to long term projected impacts. There is therefore a need to assess the vulnerability of water resources systems for enhanced management strategies, also including robust adaptation measures for future sustainable water use.

Vulnerability assessment is not straightforward, in particular because there is no universally accepted concept for vulnerability. For example, Thywissen (2006) lists 35 definitions of the term. The plurality of the definitions leads, as expected, to very diverse assessment frameworks and methods (Cutter, 1996; Jones, 2001; Brooks and Adger, 2005; Turner et al, 2003; Luers, 2005; Füssel and Klein, 2006; Füssel, 2007). Some authors even argue that by principle, vulnerability cannot be measured as it does not denote observable phenomena (Moss et al., 2001; Patt et al., 2008) while, according to Hinkel (2011), the opportunity arises to make this theoretical concept operational. Indicators can provide the means for doing so and, in particular, make the assessment of vulnerability possible, as we propose herein with the methodological framework for the assessment of the vulnerability of water resources, within the broader context of climate change adaptation, and with a specific emphasis on operational implementation in developing countries.

Water resources systems are complex in nature and consist of four inter-linked sub-systems: individuals, organizations, society and environment (Simonovic, 2009). As a consequence, management issues should generally consider multiple decisional criteria and large numbers of possible alternatives, usually characterized by high uncertainty, complex interactions, and conflicting interests of multiple stakeholders, but also of a multiplicity of compartments, such as river, land or coastal ecosystems, or different economic sectors (Hyde et al., 2004). Due to this dual complexity (*i.e.*, complexity in vulnerability assessment itself and complexity of water resources management), not many studies of vulnerability assessment of water resources systems are available to date. The issue of vulnerability was first brought to the attention of policy makers in an international context in the field of water resources management in 1992 at the Dublin Conference (Tessendorf, 1992) (Dublin Principle 1 states that fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment). Later, several studies on the vulnerability assessment of water resources systems were carried out at various geographical scales, e.g., global scale (Vörösmarty et al., 2000), large scale trans-boundary river basin (Babel and Wahid, 2009; Hamouda et al., 2009) regional scale (Hurd et al., 1999; Sullivan, 2011) and also in small scale watersheds (Pandey et al., 2009; Gober and Kirkwood, 2010; Pandey et al., 2010; Pandey et al., 2011). A few studies e.g., Balica *et al.* (2009) also include the variation of vulnerability value across different spatial scales, ranging from river basins to urban areas. In some of these studies (Vörösmarty et al., 2000; Hurd et al, 1999; Gober and Kirkwood, 2010) vulnerability is considered only as a physical component of water resources and these studies focus on water resources availability rather than how society and the ecosystem deal with water (Pandey et al., 2011). Global and large scale studies usually cannot provide the detailed information that is required for appropriate adaptation and management actions (Pandey et al., 2010). Other studies (Hamouda et al., 2009; Pandey et al., 2009; Pandey et al., 2010; Pandey et al., 2011) incorporate important components (*i.e.*, exposure, sensitivity, adaptive capacity) of vulnerability in their assessment, but limited stakeholders' involvement can produce subjective biases and limited credibility. Typically a dichotomy exists between engineering science approaches and those focused on the human dimension, with the first commonly lacking adequate consideration of stakeholders' involvement as required by the most relevant international references in the field, such as the Dublin Principles (Tessendorff, 1992) (Dublin Principle 2 states that water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels). Similarly, a society cannot improve without the support of innovative scientific ideas and technical knowledge.

Given the above, the specific objective of this study is to propose a generalized framework for scientifically based vulnerability assessment to support participatory decision making processes in the field of water resources management (WRM), with a specific interest for climate change adaptation (CCA). In developing such a framework, the following section reviews the most recent international literature, while the framework itself is described in Section 3. Section 4 introduces the Lower Brahmaputra River Basin (LBRB), the case study utilized for preliminary feasibility analysis of the proposed approach with its potential implementation on the LBRB area and discusses the results of a survey with local experts and stakeholders. Finally, Section 5 concludes the results discussing the operationalization of the framework and the experiences in the study case and identifies future research needs.

5.2 Vulnerability Assessment Models and Frameworks

5.2.1 Framing the Concept of Vulnerability

The scientific use of the term 'vulnerability' has its roots in geography and natural hazards research but this term is now a central concept in a variety of other research contexts such as ecology, public health, poverty and development, livelihood and food security, sustainability science, land use change, and climate change impacts and adaptation. Each disciplinary field defines 'vulnerability' in different ways. Birkman (Birkmann, 2006) provides an overview of the evolution of the different spheres of widening vulnerability concepts evolving from intrinsic risk factors to a much broader multidimensional concept, encompassing physical, social, economic, environmental and institutional features. Within such broader vision, different schools of thought have developed and some of them are of specific interest here: (i) the climate change adaptation (CCA) community (Füssel and Klein, 2006; Füssel, 2007; Adger, 2006; Gallopin, 2006); (ii) the disaster risk reduction (DRR) community (Wisner et al, 2004; Bogardi and Birkmann, 2004; Cardona, 2001); and (iii) the global environmental change (GEC) and sustainability science community (Turner et al., 2003; Bohle, 2001). The assessment of vulnerability is intrinsically linked to the notion of these different schools of thought. Each of these conceptual approaches can lead to the formulation of diverse policies. As a consequence, Eakin *et al.* (2009) suggest that the trade-off between alternative approaches should always be made explicit.

The DRR school of thought was established in 1970s and views disasters as having socio-economic and political origins (Torry et al., 1979; Torry, 1978). Later, it considered the wider social, political, environmental and economic dimensions of hazards (Mercer, 2010). The strategies for DRR include hazard, vulnerability and coping capacity assessments, as well as understanding the community's ability to reduce its own risks (Wisner et al., 2004). More recently, CCA policy negotiations have started considering ways to reduce vulnerability to the expected impacts of climate change. Although the DRR and CCA communities have both been engaged in reducing socio-economic vulnerability to natural hazards, they have given different definitions and conceptualizations of the same terminology (Mercer, 2010; Thomalla et al., 2006; Renaud and Perez, 2010). For example, the conceptualization of vulnerability by the DRR community (UN/ISDR, 2004) is different from the conceptualization by the CCA community (IPCC, 2007). The International Strategy for Disaster Reduction (UN/ISDR) defines vulnerability as the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR, 2004) whereas the IPCC defined 'vulnerability' as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC, 2001). Hinkel (2011) criticizes the definition of the IPCC as being too vague and the resulting difficulty in making it operational. However, the definition provided by the IPCC is one of the most generic available, and thus it could be considered as a basis for further refinement, such as was the case of the global environmental change and sustainability science communities, who introduced the notion of the coupled social-ecological system (SES), also referred to as human-environment system, in conceptualizing vulnerability (Turner et al., 2003). We follow the IPCC definition of vulnerability for the purpose of this research.

Notwithstanding the terminology problems, there is an evident and urgent need for vulnerability assessment of coupled systems for adaptation to the foreseeable consequences of climate change (Renaud and Perez, 2010). In climate change adaptation, vulnerability assessment for the future is considered as the forward-looking aspects of vulnerability. Hinkel (2011) states that forward looking aspects are one of the most important characteristics of vulnerability and their incorporation in the assessment is one of the most challenging tasks. Indeed a forward-looking approach should be considered as a prerequisite for any study targeting adaptation to climate change. According to Füssel (2007), for climate change vulnerability assessment, more specifications are required and at least four fundamental dimensions should be incorporated in the assessment, *i.e.*, the system, the attribute(s) of concern, the specific hazard and the temporal reference. The system of analysis is typically a coupled social-ecological system, a population group, an economic sector, a geographical region, or a natural system, and the examples of attributes of concern may include human lives and health, the existence, income and cultural identity of a community, or the biodiversity, carbon sequestration potential and timber productivity of a forest ecosystem. Hazards can be related to climatic variables, such as extreme rainfall events and the consequent flood risk. The temporal reference when dealing with the CCA typically considers a rather wide future time frame, long enough to appreciate the effects or expected changes of climatic variables. According to these four dimensions, the assessment context for our research could thus be defined as: “vulnerability of water resources systems to climate change at the river basin or sub-basin scale, over the next 50 years”.

5.2.2 System View in Water Resources Management and Decision Making

Considering water resources systems (WRS), individuals, organizations and society can be considered as a social system which is nested within an ecological system (Simonovic, 2009). Therefore, it is the complex interactions of the social-ecological system that make decision making more and more difficult in the WRS and the traditional fragmented approach of water management has to be replaced by more holistic system view approaches (UN-Water, 2008). Integrated Water Resources Management (IWRM) is such an approach that has been widely accepted internationally as the way forward for efficient and equitable management of water resources.

The Global Water Partnership defined “IWRM as a process, which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystem” (GWP-TAC, 2000). Within the concept of IWRM, the *United Nations World Water Development Report 3* describes the decision-making process of water resources in more comprehensive way (UNESCO, 2009). According to this approach, water managers inform the initial steps of the decision-making process and participate in planning the appropriate responses, interacting with the principal actors (policy makers) and with the managers of other sectors. Water managers address the demands of water users to meet the life-sustaining requirements of people (social dimension) and the needs of other species (ecological dimension) and to create and support livelihoods, by implementing an iterative and adaptive participatory process. Although IWRM is considered by a majority of scientists and experts as useful theoretical framework, it is now openly debated whether it is truly effective in terms of operational implementation. The IWRM approach can nevertheless provide an opportunity for the development of a method for vulnerability assessment, which thus becomes one of the main components of the process to manage water resources with a holistic approach targeting the whole WRS.

5.2.3 Indices for the Assessment of Vulnerability of Water Resources

With the aim of providing quantitative assessment of vulnerability, several indices have been proposed in the field of water resources. Very often, vulnerability assessment of water resources incorporates only physical components consisting, for example, of water scarcity calculations using the water scarcity index which can be defined as the ratio of water demanded to the supplied volumes. Following this index, a number of studies have been carried out at the global scale (Vörösmarty et al., 2000; Oki et al., 2001 ; Oki et al., 2003; Alcamo et al., 2003; Oki and Kanae, 2006; Islam et al., 2007). However, annual level assessment of water scarcity does not incorporate the fact of inter-annual seasonality. For example, large parts of monsoon Asia suffer from severe water scarcity in dry periods while the average annual resource availability appears to be plentiful. In addition to this, as stated above, the water scarcity calculation considers water only as a 'physical resource', rather than as one component of a much broader and more complex WRS.

With a more holistic system view of water resources, several recent studies (e.g., Babel and Wahid, 2009; Hamouda et al., 2009; Panday et al., 2009; Pandey et al., 2010; Balica et al., 2009) have conducted vulnerability assessment and proposed other concise indices. Pandey *et al.* (2009) attempted to provide an operational definition of vulnerability as the ratio of water stress index (WSI) to adaptive capacity index (ACI) and compare the results among three sub-watersheds (*i.e.*, Manamatta, Palung and Range) of the Bagmati River Basin. In this assessment, WSI was calculated from the aggregation of four water stress parameters (e.g., water variation, water scarcity, water resource exploitation and water pollution) and ACI was calculated from the aggregation of the parameters of natural capacity, physical capacity, human resource capacity, and economic capacity. Considering social, economic, environmental and physical components, Balica *et al.* (2009) constructed a flood vulnerability index (FVI) that was applied to compare vulnerability among three different spatial scales: river basin, sub-catchment and urban areas. In several other studies (e.g., Babel and Wahid, 2009; Pandey et al, 2010; Huahg and Cai, 2009), 'vulnerability of a river basin' is expressed as a function of resources stress (RS), development pressure (DP), ecological security (ES) and management challenges (MC). RS, DP, ES and MC are considered as components of vulnerability and each component has several parameters. In the assessment, aggregation of the parameters between water stress and water variation, water exploitation and safe drinking water inaccessibility, water pollution and ecosystem deterioration, water use efficiency, improved sanitation accessibility and conflict management capacity represents RS, DP, ES and MC respectively. The vulnerability index (*VI*) is calculated by aggregating four vulnerability components with equal weights given to the parameters, as shown in Equation (1).

$$\mathrm{VI} = \sum\nolimits_{i=1}^{n} [(\sum\nolimits_{j=1}^{m_i} x_{ij} \times w_{ij}) \times W_{ij}] \tag{1}$$

where VI is vulnerability index; n is the number of vulnerability components; m_i is the number of parameters in the ith component; x_{ij} is the jth parameter in the ith component; w_{ij} is the weight to the jth parameter in the ith component; and W_i is the weight given to the ith component.

The indicators and the variables that are considered in these studies were not selected with the involvement of local stakeholders. However, it is necessary to investigate local perceptions in order to identify appropriate indicators that can play an important role for effective decision making. Very recently, Sullivan (2011) developed a water vulnerability index (WVI), in which indicators were identified by local stakeholders in municipalities in the South African portion of Orange River Basin. The WVI is calculated based on two major dimensions: vulnerability of water systems which is considered as supply-driven vulnerability and vulnerability of water users which is termed as demand-driven vulnerability.

From the above review, we can summarize some conceptual gaps. Firstly, the lack of consideration of forward-looking aspects (or future aspects) is one of the main shortcomings of vulnerability assessment in general, and vulnerability assessment of water resources systems in particular. Secondly, instead of annual level assessment of water scarcity, seasonal variations reflecting water abundance and scarcity regimes should be considered. Thirdly, for vulnerability assessment of water resources systems, it is necessary to move from static (usually cartographic) indexes (*i.e.*, physical water scarcity index) to more complex assessments based upon the concept of social-ecological system. Fourthly, vulnerability assessment should be accomplished through involving stakeholders.

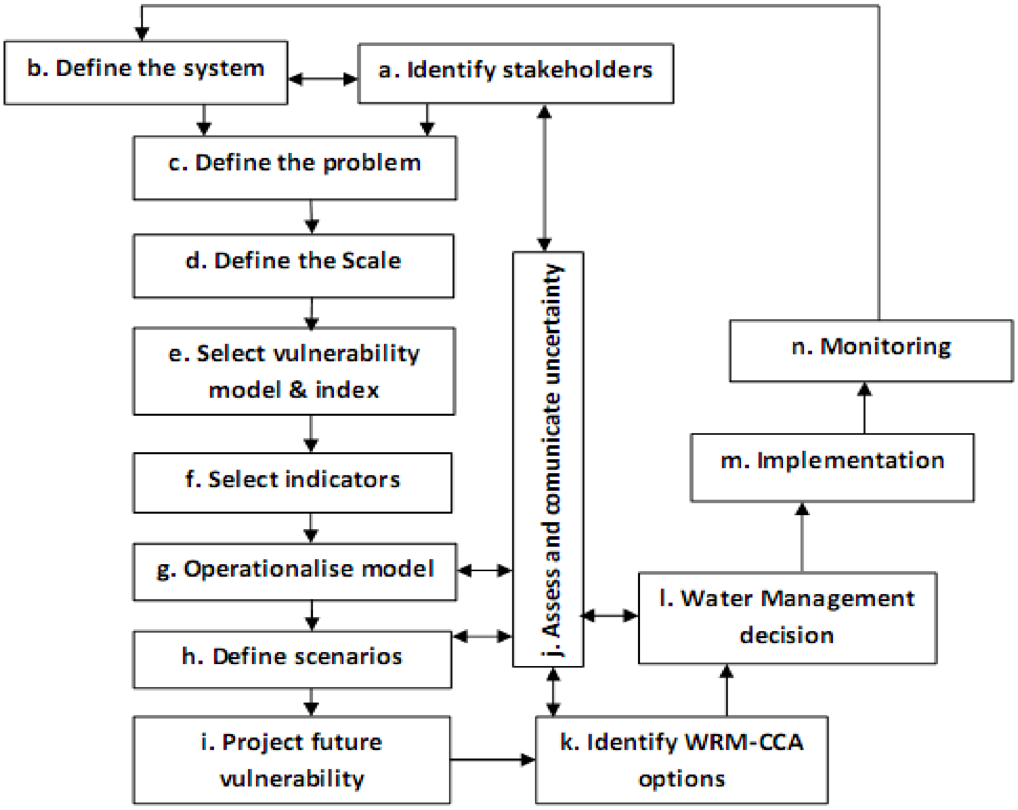
5.3 Proposed Framework of Vulnerability Assessment for Water Resources System

In order to overcome the conceptual gaps identified in Section 5.2, we propose and describe a logical sequence of steps for vulnerability assessment of water resources systems which is shown in Figure 5.2. In the following description, each step of Figure 5.2 is represented by letter, a–n. For example, step 1 (identify key stakeholders) is shown as Figure 5.2a.

In the framework, the first—iterative—step of the assessment is to identify stakeholders and with the involvement of them it is required to define the water resources system (Figure 5.2a,b). Stakeholders are individuals or groups whose interests are affected by a system or a decision as well as those whose activities significantly affect the system. To reduce the risks of failing to identify key stakeholders, robust methods are therefore needed. With the involvement of these stakeholders, the water resources system can be defined and the problem is to be explored (Figure 5.2c) in order to identify most important concerns and conflicts of the system.

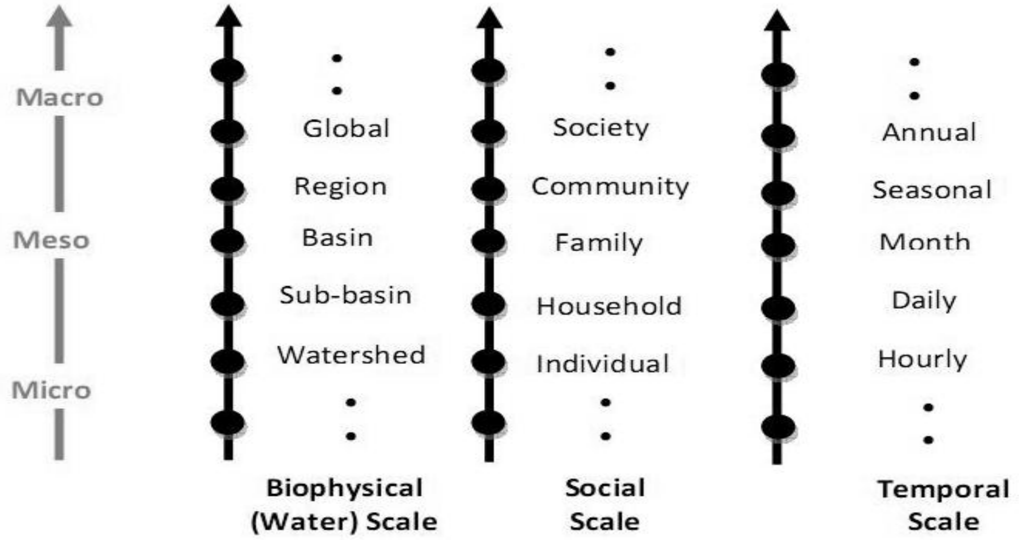
Once the system's boundaries are defined, both spatial and temporal scales of the study (Figure 5.2d) need to be determined with the involvement of stakeholders. To capture the vulnerability of the water resources system, different types of scales have to be considered: a scale representing the physical water resources subsystem, a scale representing the social subsystem, and if necessary, an additional scale that contains temporal and administrative aspect (Balica et al., 2009). Figure 5.3 (adapted from Cash et al., 2006; Damm, 2010) shows the distinct types of scales and respective levels that may be relevant to the water resources system. The bio-physical (water resources) scale ranges from a single watershed to the global hydrologic system. Among the mentioned scales, at least, spatial and temporal units of analysis need to be congruent with the purpose of the assessment. Depending on the purpose of water resources decision making, any of the hydrologic boundaries (watershed, sub-basin, basin, region, *etc.*) can be considered as the standard level for the spatial scale.

Figure 5.2 Steps of the proposed framework for vulnerability assessment of water resources system.



After having defined the system and chosen both spatial and temporal scales, the next step is to select a vulnerability model for the assessment (Figure 5.2e**)**. To date, a number of vulnerability assessment models have been developed by different research communities as described above. Depending on the purpose of the analysis, we can identify which of the models could better represent the system. The selected models can be later adapted to better account for the dynamics of the system under study.

Figure 5.3 Schematic illustrations of different scales and levels (adapted from Cash et al, 2006; Damm, 2010).



Once the scale of the assessment is identified and the vulnerability assessment model of the water resources is selected, the next step is to select representative indicators (Figure 5.2f). Adger *et al.* (2004) identify two general approaches for indicator selection: (i) the deductive approach which is based on a theoretical understanding of relationships, and (ii) the inductive approach which is based on statistical relationships among a large number of variables. An inductive approach needs one or more proxy variable for vulnerability as the benchmark against which indicators are tested. However, the paradox is that the need for vulnerability indicators is because there is no such quantifiable element of vulnerability. Therefore, we recommend a deductive approach for indicator selection. In a deductive approach, concepts need to be operationlized in order to test variables empirically: first, to create an understanding of the investigated phenomena and the processes involved; second, to identify the main processes to be included in the study; and, finally, we can move to select the best possible indicators for these factors and processes (Adger et al, 2004). Subsequently, different indicator approaches that cope with similar objectives may be reviewed in order to retrieve a list of prominent indicators that might be valid for the specific problem. Then, a pre-selection of potential indicators can take place. These indicators are tested carefully following respective selection criteria, data quality, and statistical correlations. In order to validate representative indicators, involvement of water managers, researchers, other resources managers, policy makers and key stakeholders is essential (Damm, 2010). Subsequently, the final indicator set can be defined, that comprehensively represents the system identified at the beginning of the procedure. This step is followed by data collection. Vulnerability assessment is an integrated assessment which requires social, economic and physical data. Therefore, sources of these data are diverse. For hydrologic and socio-economic data, secondary sources held by e.g., national statistics offices, relevant government and non-government organizations can be used. At the same time, information derived from public participation and stakeholder focus group discussions can also be used.

Model operationlization (Figure 5.2g) usually also involves aggregation and possibly weighting for the calculation of a concise index. The analytical hierarchy process (AHP), proposed by Saaty (1980), is perhaps the most widely used method for aggregating indicators and evaluating and ranking alternatives within a decision making process, but many other methods exists, in particular within the broadest family of Multi-Criteria Decision Methods. To aggregate indicators, it is necessary to normalize them. There exist a number of different normalization functions for a variety of different indicators. The most common application is to determine desirable and least acceptable (best and worst) values and to normalize the measured value between the two threshold values. The type of normalization function depends on the indicator under consideration and the preferences of the decision maker. Given the often not immediate relationship of indicator values with the objective of the assessment, the application of value function can play an important role. Value functions are mathematical representations of human judgments which offer the possibility of treating people's values and judgments explicitly, logically and systematically (Beinat, 1997). To construct composite indicator value and or index, the weighting of indicators are then to be carried out reflecting stakeholders' views.

Given the uncertainty pervading future projections, and in particular those considering climatic changes, vulnerability assessment for supporting CCA, has to consider multiple scenarios representing plausible future directions of development of the most important variables (and related indicators) in the area of interest (Figure 5.2h). A scenario is a coherent, internally consistent and plausible description of a possible future state of the world (IPCC, 2007). In the vulnerability assessment of water resources, both climatic as well as socio-economic scenarios for business-as-usual and policy options are important. Climate scenarios are scenarios of climatic conditions, whereas socio-economic scenarios are scenarios of the state and size of the population and economy. For collecting the needed indicator values, outputs of simulation models are used. For example, the impact of climate change on water resources is usually estimated by defining scenarios of changes in climate conditions, simulated by general circulation models (GCMs), and linking them to a hydrological model to predict changes in river runoff, groundwater recharge and extraction rates. Similarly, the hydrologic model can be parameterized with data coming from economic models (e.g., general or partial equilibrium models) and providing estimations of the most important variables of the social system, including for example land use. The outputs of the hydrologic model are then used as input of this indicator based approach. Similarly, for other socio-economic indicators, multiple scenarios have the additional advantage that a better understanding of the system under consideration is obtained.

Once the vulnerability is assessed for both the present and for future scenario (Figure 5.2i), the next step is to identify adaptation options that may reduce the vulnerability (Figure 5.2k). Uncertainties of the results should be communicated among the stakeholders (Figure 5.2j). Policy makers, local stakeholders and interdisciplinary researchers are to be involved in identifying appropriate adaptation options. Based on the vulnerability assessment results and identified options, water management decisions are to be taken with the involvement of stakeholders (Figure 5.2l). This process has natural consequences on the implementation of a decision taken. The basis of results obtained and the decision taken is in fact an adaptive management process from which we can identify a series of preferred options that is to be implemented (Figure 5.2m,n). For improved decision making, the process then starts again in an iterative manner.

5.4 Feasibility Assessment of Proposed Framework in Lower Brahmaputra River Basin (LBRB) Context

The main purpose of the generalized framework is to provide a guideline that can be useful for water resources decision making, facilitating in particular the consideration of a new dimension in water resources management, namely climatic change trends and thus integrating climate change adaptation into operational planning and management practices. Describing a generalized framework, detailed background information representing a system is required. In this case, the context of LBRB is defined for providing and describing the generalized framework. The feasibility study in the part of LBRB (in Bangladesh) was aimed at providing a preliminary test of the framework's potential for practical implementation and important feedback for its refinement and finalization.

5.4.1 Lower Brahmaputra River Basin (LBRB): Context of Vulnerability Assessment

The Brahmaputra is a major transboundary river which has a catchment area of around 530,000 km^2 and crosses four different countries (China, India, Bangladesh and Bhutan). Immerzeel (2008) categorized the Brahmaputra basin into three different physiographic zones: Tibetan Plateau (TP), Himalayan belt (HB), and the floodplain (FP). The FP area, with an elevation of less than 100 m above the sea level which comprises about 27% of the entire Brahmaputra basin comprising parts of Bangladesh and North-East India is called the Lower Brahmaputra River Basin (Immerzeel, 2008; Gain et al., 2011). More than 10 million people live in LBRB.

The hydrological impact of climate change on the LBRB is expected to be particularly strong because of two principal reasons. First, the projected rise in temperature will lead to increased glacial and snow melt, which could lead to increased summer flows in the river system for a few decades, followed by a reduction in flow as the glaciers disappear and snowfall diminishes (Immerzeel, 2008). Second, an important characteristic of the basin is the influence of the monsoon climate (Mirza, 2002; Warrick et al., 1996) which is characterized by a seasonal change of wind direction, carrying no moisture during the dry season (from September to June), whereas, the winds from the ocean carry a lot of moisture leading to heavy rains during the rest of the year. Beside climatic changes, unplanned economic development, significant population pressure, land use change, upstream water withdrawal and urbanization directly affect water resources. Thus, climatic and non-climatic factors are responsible for changes in supply and demand of water resources, affecting the quantity and quality of water, which in turn has an impact on the society, the economy and the environment of the country.

5.4.2 Design of the Feasibility Study

For the practical implementation of the generalized framework and its refinement at LBRB context, the feasibility study was carried out involving key stakeholders in Bangladesh. With the involvement of the same stakeholders, a complete description of the proposed framework (*i.e.*, description of each step) was also provided that could represent the core problems of water resources in the LBRB.

Table 5.1 Categorization of involved experts.

Categorization of participants in terms of their current activities	Number
University professors who are also responsible for water resources planning for the government of Bangladesh	3
Representative from the government organizations who are dealing with large scale water projects	3
Representative from the government organizations who are dealing with small scale water projects	4
NGO representatives who are responsible for water planning and management	7
University teachers (Lecturer & Asst. Professor) with research interest in water management	5
PhD researchers with research topic related to water management in Bangladesh	5
Representative from local government	3

In order to identify the key stakeholders in the LBRB, organizations which play an important role in water management were selected. The lists of such organizations can be found in the Bangladesh Water Sector Review developed by the Asian Development Bank (ADB, 2003). These organizations are the National Water Resources Council (NWRC), Water Resources Planning Organizations (WARPO), the Bangladesh Water Development Board (BWDB), the Local Government Engineering Department (LGED), several Non Governmental Organizations, several universities and research institutes, and water management associations (WMAs). Key personnel of these organizations were involved in the evaluation of the framework and also in the identification of elements of each of the defined components/steps that can represent the water resources problem of the LBRB. For the evaluation, a workshop was arranged and the framework was presented to 20 participants. A structured questionnaire (Annex A) was also provided for feedback. In addition to this, personal interviews were carried out with 10 relevant decision makers who were not able to attend the workshop. Therefore, a total of 30 experts were involved in the evaluation. The functions or current activities of these 30 participants are presented in Table 5.1. The interviews were carried out with the same questionnaire (Annex, published as online supplementary material) used during the workshop and which incorporated aspects covering the evaluation of the proposed framework as a whole, the usefulness of the framework for water resources decision making, and the extent of the important steps that are incorporated in the proposed framework. Other aspects covered by the questionnaire were: the main concerns of Bangladesh and whether these concerns can be addressed by the generalized framework; steps of the framework which should be added/removed/refined; and questions related to the main weaknesses and strengths of the framework.

5.4.3 Experts' Judgement on Proposed Framework

With the involvement of key stakeholders in Bangladesh, we could carry out an analysis of the feasibility of practical implementation of the proposed framework. Stakeholders could evaluate the framework as 'excellent', 'very good', 'good', 'fair', 'poor', 'very poor'. However, in the evaluation, 21 participants out of 30 (70%) considered the overall framework to be 'excellent', 20% considered it to be 'very good' and 10% considered it to be 'good'. In evaluating the usefulness of the framework for water resources decision making in the LBRB, about 17% of the experts considered it to be 'excellent', 40% considered it to be 'very good', 33% considered it to be 'good' and 10 % considered it to be 'fair'. Those who considered the usefulness of the framework to be 'good' and 'fair' had several concerns. First, according to their opinion, the current socio-economic settings and institutional and legislative context of Bangladesh may not allow to involve stakeholders to participate in all the steps of the decision making process. This is because people's participation is still very weak in current water management practices. For implementing participatory process, there is a great challenge of developing local capacities for water management which may still require improved adaptive management techniques through better education. Therefore, participants thought that it is not necessary to involve stakeholders in several steps, *i.e.*, defining the scale and selecting the vulnerability model. Second, they argue that less emphasis is given on operation and maintenance as well as monitoring and evaluation, although it is mentioned in the framework. WARPO (1999) also identified inefficient operation and maintenance as the prime causes of the malfunctioning of projects and usually post-evaluation of these projects with respect to their performance and impacts has not been carried out. In evaluating how important steps are incorporated in the framework, about 33% of total participants considered the framework to be 'excellent', whereas, 44% considered it to be 'very good' and 23 % to be 'good'.

According to the experts, the main concerns in terms of vulnerability assessment of the water resources system of the LBRB are water shortages during the dry season, flooding during the wet season, river bank erosion, institutional challenges, as well as other factors. Main institutional challenges are the lack of coordination among different agencies and sectors which may have resulted in various water related problems. However, 47% of the experts thought that all of these concerns could be addressed by this generic framework and 53% of the experts thought that most of these concerns could be addressed in the proposed framework.

The proposed generalized framework was considered to have as its main strengths the consideration of present but also future vulnerability, the participatory approach to decision making, uncertainty assessment and its communication among the stakeholders and the adaptability of the framework to any vulnerability concerns related to water resources. According to experts' opinions, the main weaknesses of the framework lie in the incorporation of stakeholders in all the steps which could be challenging, lack of coordination among agencies and sectors, monitoring and evaluation with the involvement of key stakeholders and government strategies of upstream countries which were not reflected in the framework. Considering all these issues, a revised framework was prepared which is described below.

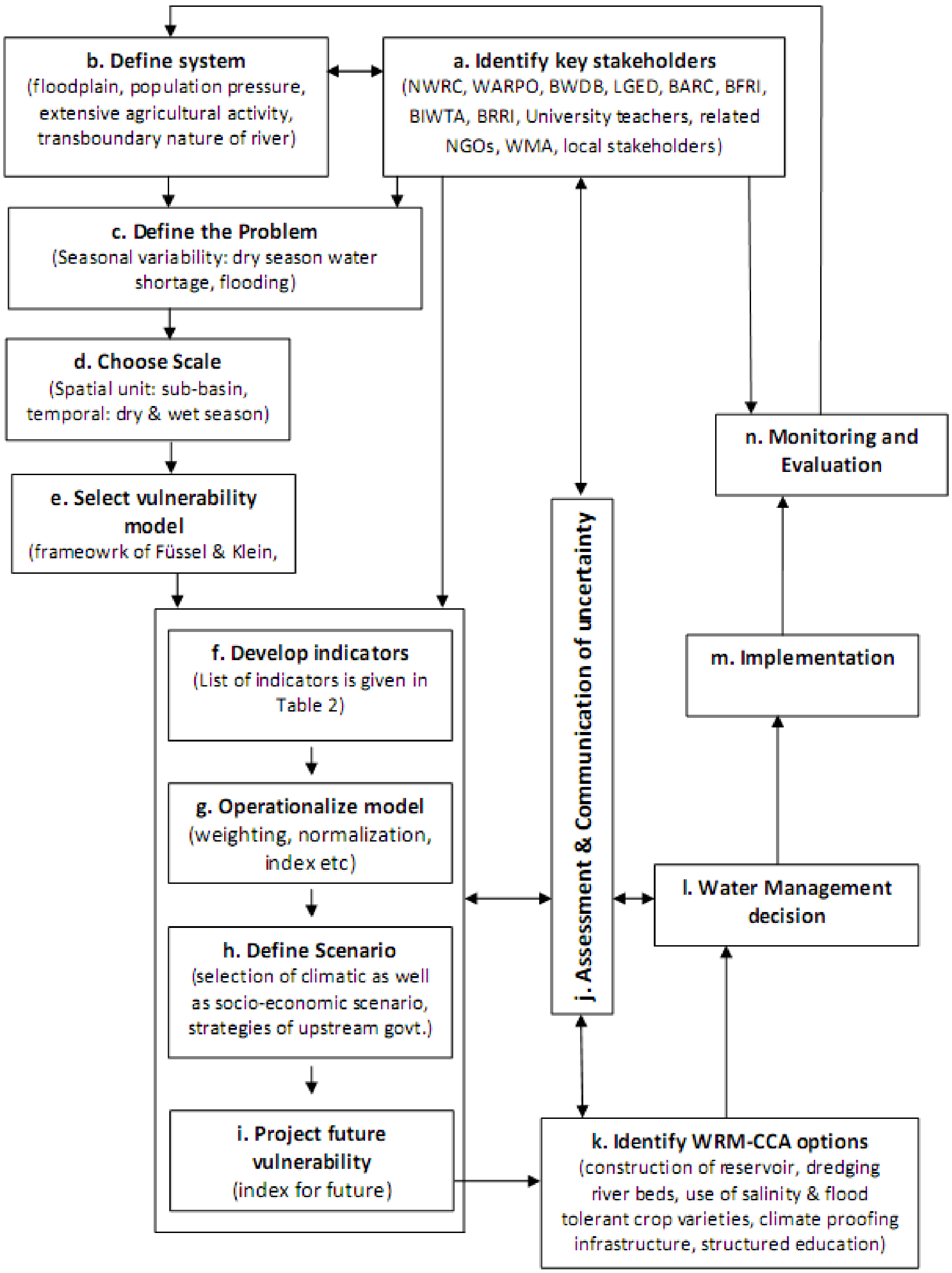
5.4.4 Results of the Feasibility Study and Revised Framework for LBRB

Based on evaluation of collected information and the suggestions provided by the local experts, our proposed generalized framework was adapted and filled with preliminary results. In the revised framework, stakeholder involvement was considered in major steps instead of all steps, as this issue was one of the major concerns for the local experts. Following the feasibility study, also other agencies were to be selected. The results are placed in Figure 5.4a. In the framework, the step 'monitoring and evaluation' was considered in the participatory way involving stakeholders (Figure 5.4n). Government strategies of upstream countries were considered in the step 'Define scenario' (Figure 5.4h). With the involvement of the same stakeholders we also identified components of each step that could provide a complete description of the proposed framework in the LBRB context which is schematized in Figure 5.4.

Key stakeholder identification is one of the main steps in the framework on which coordinated planning and development depends. Lack of coordination among key sectors may lead to complex problems. For example, uncoordinated planning and development between transportation and water sectors in the past led to a complex road network, restricted drainage, increased water logging and damming of seasonal streams (Gupta et al., 2005). Therefore, beside water management authorities identified as described in Section 5.4.2, key stakeholders from few other agencies were added which includes Bangladesh Agriculture Research Council (BARC), Bangladesh Rice Research Institute (BRRI), Bangladesh Inland Water Transport Authority (BIWTA), Bangladesh Fisheries Research Institute (BFRI). With the involvement of these stakeholders (see Figure 5.4a), the social-ecological system of the LBRB should be characterized. The LBRB is characterized as the floodplain with transboundary river where population pressure is high and the main economic activity is agriculture (Figure 5.4b). Dry season water shortages, flooding during the rainy season, and the river bank erosion are the main concerns with poor water management practices (Figure 5.4c). The region is also dominated by South-Asian monsoons which are responsible for the high variability in the temporal distribution of water, which creates two extremes: a water abundance regime with an excess of water leading to floods during the rainy season and a scarcity regime with no rainfall during the dry season (Gupta et al., 2005). The impact of climate change is expected to be high in monsoon dominated regions.

Based on the defined system, spatial and temporal units of analysis need to be selected (Figure 5.4d). The Brahmaputra crosses several countries and there is no integrated trans-boundary river basin planning approach. The sub-basin of the lower-Brahmaputra that is included in the geographical boundary of Bangladesh is considered as the spatial unit (the shaded white area of geographical Boundary of Bangladesh shown in Figure 2.1). Although, the lower part of the basin is considered as spatial unit, dealing with such trans-boundary river basin cross-scale considerations also need to be accounted for, including policies in riparian countries. In the case of temporal scales, we consider the scale of analysis as the dry (September–March) and the wet season (April–August). This is because, in the context of the LBRB, water flows are highly variable in the dry and wet season. Assessments of annual flows do not incorporate this variation and its associated impacts. A seasonal assessment is therefore to be considered for the analysis in the LBRB context. Given the purposes, study periods can be identified. Long term climate policies are now dealing with the assessment up to 2100. However, in vulnerability assessment, it is difficult to consider long time spans because we cannot easily predict the future of social sub-systems. We can only make projections for several years depending on institutional strategies. In the context of the LBRB, it is recommended that projections be made for the next 40 years—until 2050. This is because in Bangladesh long term investments in water-related projects are based on this duration and institutional policies are also developed considering this timeframe (WARPO, 2001).

Figure 5.4 Vulnerability assessment of water resources system: revision of the proposed generalized framework for implementation in the LBRB.



Given the purpose of vulnerability assessment in the LBRB as climate change adaptation, we propose to refer to the modified adaptation policy assessment model for vulnerability assessment provided by (Füssel and Klein, 2006), which is now applied other ongoing studies by the authors. In this model, vulnerability is decomposed as the component of exposure, sensitivity, resilience and coping capacity. In this case the most representative indicators that can address the problem were selected for each component of vulnerability with the involvement of key stakeholders. The list of indicators is given in Table 5.2. With the involvement of stakeholders, indicators need to be prioritized through weighting. Data normalization is also required (Figure 4g). For assessing future vulnerability, climatic as well as different socio-economic scenarios should be selected. Uncertainties in climate change predictions need to be reduced through reliable methods of downscaling from Global Circulation Models and hydrologic models. In this case, multi-model ensemble analysis can play an important role. For assessing future river flow scenario of LBRB, Gain *et al.* (2011) applied such approaches which can be incorporated in this study (in Figure 2.4). Government strategies of upstream countries need to be considered for assessing future vulnerability (Figure 5.4h). This is often quite complex and information between riparian countries can be difficult. After assessing present and future vulnerability, adaptation options need to be selected. During the workshop, involved stakeholders suggested building a reservoir as an adaptation strategy in Bangladesh that can store flood water for solving the dry season water shortage problem. They also suggested other adaptation measures like, dredging of river beds, salinity and flood resilient crop varieties, guidelines on climate proofing of infrastructure, structured education among local people (Figure 5.4k).

After selection of the appropriate adaptation options, water resources decision making should be implemented in a participatory way through improved monitoring and evaluation which may require integrating policies and updating existing national plans (Figure 5.4l–n). Various existing regulatory frameworks can be used or have to be further developed to implement decisions. In Bangladesh, the National Water Policy was already formulated in 1999 by the National Water Resources Council (NWRC), which plays a central role in water resources decision making. Besides the NWRC, the Water Resources Planning Organization (WARPO), the Bangladesh Water Development Board (BWDB) and the Local Government Engineering Department (LGED) are the principal bodies for water resources planning and decision making. With the collaboration of these organizations, existing regulatory frameworks can be used to implement the water resources decision and if require, they can also be further developed.

Table 5.2 Indicators of vulnerability components.

Main Components	Sub-components	Acronym	Definition and selected indicator
Exposure	Water availability	WA	Future available water was calculated through assessing future riverflow of lower Brahmaputra (at Bahadurabad station) under different climate scenario (A1B & A2). Indicator: Riverflow of Brahmaputra at Bahadurabad station (m^3/s); source: Gain et al., 2011.
Sensitivity	Water Demand	WD	Agricultural, domestic, industrial and in stream water demand increase the sensitivity for the study area. Indicator: Total water demand, which is the aggregation of agricultural, domestic, industrial and instream water demand (m^3/s); source: Mondal et al., 2010.
	Infrastructure pressures at Upstream	IP	The sensitivity induced by alterations of the river flow at upstream deriving from barrages, dams, etc. which may increase the sensitivity. Indicator: Hydroelectrical installed capacity (MW); source: own elaborations on data from the development plans of the Central Electrical Authority of India (http://www.cea.nic.in/)
	Forest Cover at upstream	FC	One of the most important strategies for controlling runoff and erosion risks, thus limiting the probability of flood events downstream. Indicator: Area forest cover at north-east India (km^2); source: Bujarbarua and Baruah, 2009.
Resilience	Agricultural production	AP	An activity that contributes to the maintenance of land with positive potential for limiting the impacts of climate change. Indicator: amount of rice production (ton), a proxy of agricultural production; source: BARC.
Coping capacity	Water Governance	WG	The status of water governance can determine the capacity for the management of various problems of water resources. Indicator: perceived trend of composite water governance (numeric value between 0 to 1); Source: Gain and Schwab, 2012.
	Poverty	P	A second index of the economic wealth of the population, here derived from the projections of the indicator “incidence of poverty”; source: Titumir and Rahman, 2011.

5.5 Conclusions

In this study, the concepts of vulnerability assessment for water resources systems was reviewed, with the aim of facilitating the work of those who are active in the field of water management in developing countries by moving towards operational solutions. We identified several conceptual gaps which were: (i) consideration of forward looking aspects (or future aspects) of vulnerability, (ii) seasonal level assessment reflecting both water abundance and scarcity regimes, (iii) a move towards dynamic assessments based upon the concept of social-ecological system, and participatory modeling.

In order to suggest a means to overcome these gaps, we developed a generalized methodological framework for vulnerability assessment and support the identification of preferable adaptation measures. A feasibility study of the proposed framework was carried out in the LBRB. Reflecting the feedback of local experts, some components of the framework were revised and all of them were defined in terms of specific solutions and contents in view of a possible future implementation in the specific context of the LBRB.

The proposed framework (in its revised version) organizes the various steps of vulnerability assessment in a transparent way that allows identifying the needs of methods, tools and data. The results of the feasibility study in Bangladesh showed the current main constraints which include: (i) weaknesses in local capacities for water management, (ii) lack of institutional coordination, and (iii) inefficient monitoring and evaluation. However, the feasibility study can benefit water managers in other areas having similar characteristics and problems (e.g., consideration of seasonal variability of water regimes in terms of both floods and droughts; up-stream–down-stream relationships, *etc.*).

Vulnerability assessment in this way may also play a significant role in identifying planned adaptation measures. In the water resources system, climate change adaptation should be framed within existing policies and other regulatory mechanisms and that may require further developments to facilitate mainstreaming. Further research is needed to identify main constraints limiting the potential for vulnerability assessments and climate change adaptation to be implemented into operational water resources management and planning. Such constraints could differ in nature and, in particular, could be related to institutional capacities and the efficient management of collaborative and participatory approaches. Water managers of any river basin or researchers in this field can follow these guidelines in order to assess vulnerability of water resources.

Acknowledgments

Part of this research was conducted at Ca’ Foscari University of Venice and at the United Nations University—Institute for Environment and Human Security (UNU-EHS).

Chapter 6 A dynamic assessment of water scarcity risk and climate change adaptation in Lower Brahmaputra River Basin

This chapter is based on:

Gain, A.K., & Giupponi, C. (2012). A dynamic assessment of water scarcity risk and climate change adaptation in Lower Brahmaputra River Basin. In preparation.

Abstract

The notions of vulnerability and risk and the approaches for their assessment, differ greatly according various schools of thought over recent times. For example, the traditional conceptualization of vulnerability by the disaster risk reduction (DRR) community is different from that of the climate change adaptation (CCA) community. However, with the recent publication of the Intergovernmental Panel on Climate Change (IPCC-SREX Report), a substantial move from the CCA community towards the concepts and definitions consolidated in the DRR could be observed. In this study we provide an operational system analysis approach and a simulation tool for water scarcity risk assessment that has been developed within the broad context of climate change adaptation and disaster risk management with an aim to support decision making processes. The methodology has been applied in the Lower Brahmaputra River Basin, a region where hydrological impact of climate change is expected to be strong. In the assessment of risk, indicators - selected based on the previously developed framework by Gain et al (2012) and Giupponi et al. (2012) which were further reframed consistent with the recent release of the IPCC-SREX Report– are used to describe past and future trends of model variables, and their trajectories are used to explore possible trends of risk and adaptation needs. As the notion of risk is the result of combined effect of different social and ecological variables which can not be objectively measured by using a well-defined static or dynamic model, a subjective approach for its estimate is used through a non-additive aggregation operator to construct concise indexes with a weighting procedure reflecting stakeholders' preferences. The results of this study are intended to be used for contributing to planned adaptation of water resources systems, in Lower Brahmapura River Basin.

Keywords: vulnerability, risk, water scarcity, climate change adaptation, system analysis, decision-making

6.1 Introduction

Through the primary medium of water, climate change influences the Earth's ecosystems, people's livelihoods, and in general human wellbeing. Scientists within the Intergovernmental Panel on Climate Change (IPCC) expect that the present unprecedented increase in greenhouse gas concentrations will have direct first-order effects on the global hydrological cycle, with impacts on both water availability and demand (Bates et al., 2008). These changes will in turn create other higher order effects and thus a cascade of negative consequences is expected to affect social and ecological systems and their processes. Besides climate, there are other drivers of change, e.g. increased population pressure, economic development and urbanization trends. Consequently, the net effects of these supply and demand changes can translate into increases in the vulnerability and risk of water resources systems. There is therefore a need to assess the vulnerability and risk of water resources systems for enhanced management strategies, also including robust adaptation measures for future sustainable water use (Gain et al., 2012). For assessing vulnerability and risk of water resources system and defining climate change adaptation policies and measures, the integrated contribution of several disciplines is required, enabling a comprehensive, but also complex, dynamic description of present state and future trends.

However, the notions of vulnerability and risk and the approaches for their assessment, differ greatly according various schools of thought over recent times e.g., the climate change adaptation (CCA) and the disaster risk reduction (DRR). Although different communities (ie., CCA, DRR, GEC) have all been engaged in the analysis of socio-economic vulnerability to natural hazards and other environmental problems, they have given different definitions and conceptualizations of the same terminology (Thomalla et al., 2006; Mercer, 2010; Renaud and Perez, 2010). For example, the traditional conceptualization of vulnerability by the disaster risk reduction (DRR) community (UN/ISDR, 2004) is different from that of the climate change adaptation (CCA) community (IPCC, 2007). Therefore, the two communities have followed independent paths of development. But there is a need for achieving greater synergy between the two communities to advance sustainable development (Birkmann and Teichman, 2010). Recently the IPCC has released a special report on 'Managing the risks of extreme events and disasters to advance climate change adaptation' (IPCC-SREX Report) in which a substantial move from the CCA community towards the concepts and definitions consolidated in the DRR could be observed (IPCC, 2012). In spite of such conceptual development of vulnerability and risk definitions and frameworks, operational quantitative assessment tools are still rare.

In addition to the plurality of vulnerability and risk concepts, water resources systems are complex in nature and consist of four inter-linked sub-systems: individuals, organizations, society and environment. As a consequence, management issues should generally consider multiple decisional criteria and large numbers of possible alternatives, usually characterized by high uncertainty, complex interactions, and conflicting interests of multiple stakeholders, but also of a multiplicity of compartments, such as river, land or coastal ecosystems, or different economic sectors (Hyde et al., 2004).

Due to this dual complexity (*i.e.*, complexity in vulnerability and risk assessment itself and complexity of water resources management), not many studies of risk assessment of water resources systems are available to date. Several studies on the vulnerability assessment of water resources systems were carried out at various geographical scales, e.g., global scale (Vorosmarty et al., 2000), large scale trans-boundary river basin (Babel and Wahid, 2009; Hamouda et al., 2009), regional scale (Hurd et al., 1999; Sullivan, 2011) and also in small scale watersheds (Pandey et al., 2009; Gober and Kirkood, 2010; Pandey et al., 2010). In the context of vulnerability assessment of water resources systems, several research gaps were identified by Gain et al., (2012). Firstly, the conceptual vulnerability assessment tools are rarely made operational. Secondly, the lack of consideration of forward-looking aspects (or future aspects) is one of the main shortcomings of vulnerability assessment (Hinkel, 2011) in general, and vulnerability assessment of water resources systems in particular. Thirdly, for vulnerability assessment of water resources systems, it is necessary to move from static (usually cartographic) indexes (i.e., physical water scarcity index) to more complex assessments based upon the concept of SES. Fourthly, vulnerability assessment should be accomplished through involving stakeholders. In order to overcome these gaps, few studies were recently initiated. For example, Gain et al., (2012) developed a generalized assessment framework with its feasibility in the context of the Lower Brahmaputra River Basin (LBRB) and Giupponi et al. (2012) provided a dynamic assessment tool of vulnerability to floods considering stakeholders' preferences in the aggregation of indicators.

Implementing the generalized framework developed by Gain et al., (2012) and the vulnerability assessment model proposed by Giupponi et al., (2012), the objective of this study is to provide an operational system analysis approach and a simulation tool for water scarcity risk assessment that has been developed according to the recent development of the literature (see SREX Report; IPCC, 2012). The methodology has been applied in the Lower Brahmaputra River Basin, a region where hydrological impact of climate change is expected to be strong. The results are aimed at supporting the implementation of innovative participatory decision making processes, with a specific interest on facilitating the mainstreaming of climate change adaptation and disaster risk reduction measure in the field of water resources management.

6.2 Materials and Methods

6.2.1 Study area

Brahmaputra is a major transboundary river which drains an area of around 530,000 km^2 and crosses four different countries: China (50.5% % of total catchment area), India (33.6%), Bangladesh (8.1%) and Bhutan (7.8%). Immerzeel (2008) categorized the Brahmaputra basin into three different physiographic zones: Tibetan Plateau (TP), Himalayan belt (HB), and the floodplain (FP). The FP area with an elevation of less than 100 m above the sea level is considered as the Lower Brahmaputra River Basin (LBRB) and comprises about 27% of the entire basin. The sub-basin of the LBRB that is included in the geographical boundary of Bangladesh is considered as the spatial unit (Figure 2.1). Among river systems, the hydrological impact of climate change on the LBRB is expected to be particularly strong, because of several reasons e.g., Himalayan snow melting, monsoon, and sea level rise (Immerzeel, 2008; Gain et al., 2011). These climatic factors hampers the ecological thresholds (Gain et al., 2012) affecting both flooding and water scarcity as 'too much water' (i.e., flooding) during wet season and 'too little water' (i.e., water scarcity) during dry season are two sides of the same coin – both occur in same geographical location in different seasons of the year. Although dry season water scarcity is another important issue (Babel and Wahid, 2008), most of the studies for the LBRB focus on only one aspect i.e., flooding (Warrick et al., 1996; Mirza, 2002; Ghosh and Dutta, 2012). Immerzeel et al. (2010) stated that during dry season the Brahmaputra is most susceptible to reductions of flow, threatening the food security of an estimated 26 million people. For the Brahmaputra Basin, the inflows of large volumes of surface water are confined to a relatively short monsoon season. During the dry season, which lasts between November and May, there is a serious water shortage with demand exceeding availability by about 50% as, population pressure and economic development of the region is expected to increase at a faster rate than that of other regions (Gain et al, 2012).

6.2.2 Conceptual framework for vulnerability assessment and climate change adaptation

Given the purpose of risk assessment in the LBRB, at least two distinct research streams are of greatest interest for our work: DRR and CCA. While the DRR community drives more emphasis on the concept of risk, the CCA research stream, mainly under the auspices of the Intergovernmental Panel on Climate Change (IPCC), is more focused on the assessment of vulnerability. In the DRR studies, vulnerability is considered as a physical/environmental input for the quantification of risk. Instead, CCA research considers vulnerability as an output deriving from social conditions and processes such as adaptation or maladaptation. Within the CCA field, Giupponi et al., (2012) developed a dynamic assessment model upon the adaptation policy assessment framework proposed by Füssel and Klein (2006), while Gain et al. (2012) developed a generalized framework for vulnerability assessment and climate change adaptation of water resources systems. This work developed upon the two references mentioned above and proposes an operational assessment tool consistent with the most recent evolution of concepts provided by the SREX Report (IPCC, 2012) for water scarcity risk assessment as shown in Figure 6.1.

For water resources decision making and climate change adaptation, Gain et al., (2012) described several important steps (i.e., a-n, 14 steps). This paper focuses in particular on the steps from ‘define the problem’ to ‘project future risk’ (step c to i of Figure 6.1).

With the involvement of the selected stakeholders, the social-ecological systems of the LBRB were characterized as the floodplain with transboundary river where population pressure is high and the main economic activity is agriculture. Dry season water shortages, flooding during the rainy season, and river bank erosion were the main concerns with poor water management practices.

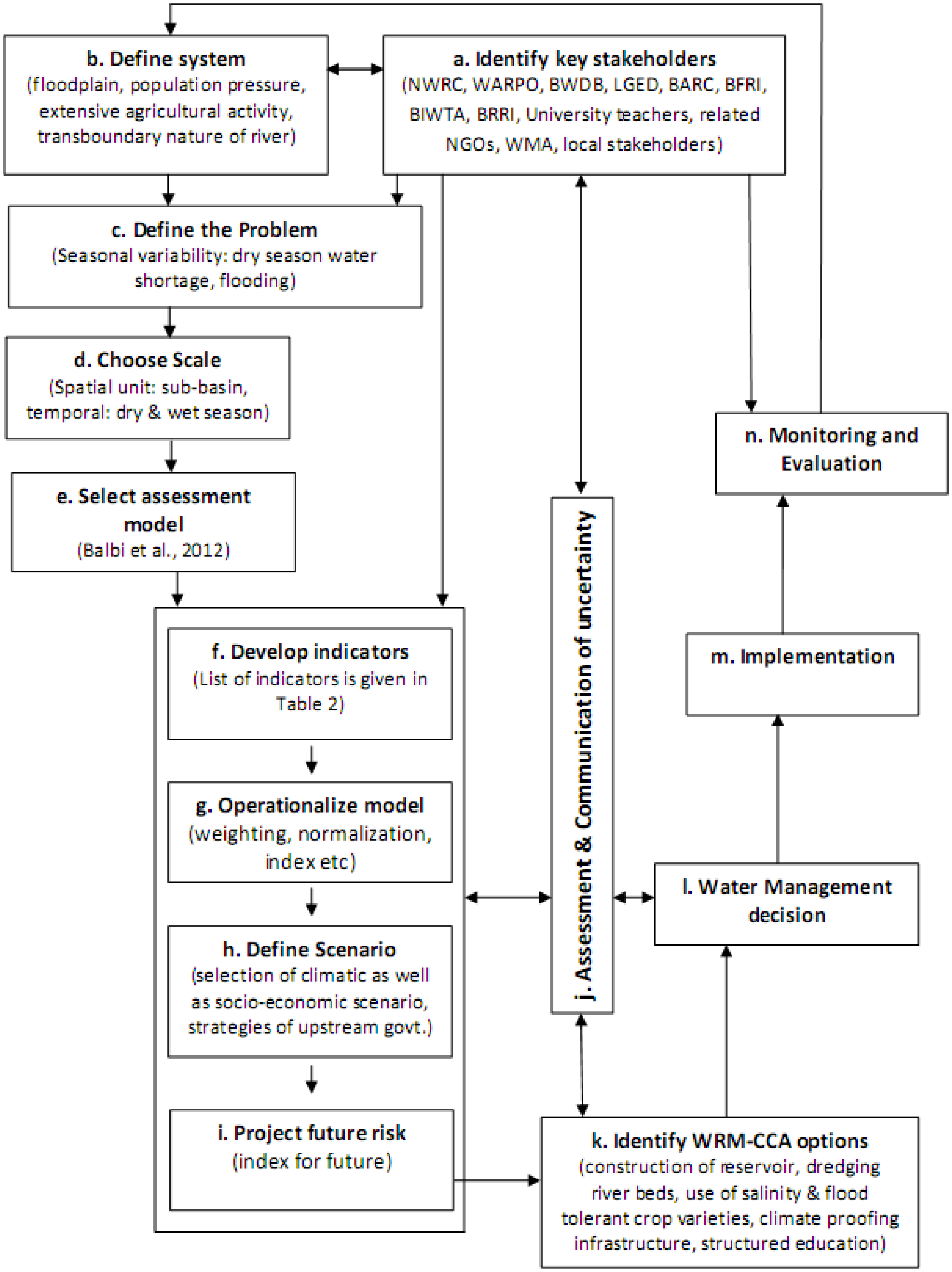


Figure 6.1 Generalized framework for risk assessment of water resources system in the context of LBRB (adapted from Gain et al. (2012)).

The high variability in the temporal distribution of water creates two extremes: a water abundance regime with an excess of water leading to floods during the rainy season and a scarcity regime with very little rainfall during the dry season (Gupta et al., 2005). Most of the studies have focused on floods, only very few consider dry season and related water shortages. Therefore, in this study we focus on dry season water scarcity. The Brahmaputra crosses several countries and there is no integrated trans-boundary river basin planning approach. The sub-basin of the Lower-Brahmaputra that is included in the geographical boundary of Bangladesh is considered as the spatial unit. Although, the lower part of the basin is considered as spatial unit, dealing with such trans-boundary river basin cross-scale considerations also need to be accounted for, including policies in riparian countries. For reliable projections, study periods were selected until 2025, as we can only make projections for several years depending on institutional strategies.

6.2.3 Selection of assessment model and indicators

According to the recent development of literature (see IPCC, 2012), the assessment model of Giupponi et al., (2012) is further framed in which 'disaster risk' is considered as an output and is decomposed into hazard, exposure, and social vulnerability (Figure 6.2).

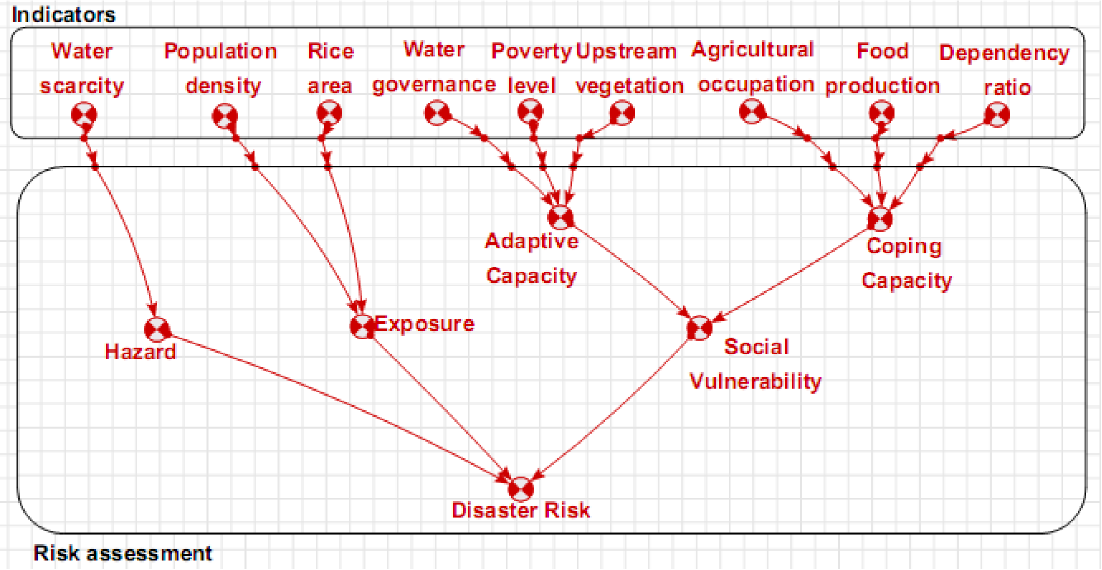


Figure 6.2. Formalisation of water scarcity risk assessment model

‘Hazard’ refers to the future occurrence or intensity of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements (IPCC, 2012). In most cases, hazard is considered as a physical event e.g., floods, landslides, earthquakes etc. and the intensity of such event can be directly assessed by using return period or probability analysis. However, there are also some slow processes of hazards (i.e., water scarcity, drought) that can not be directly assessed. In order to provide notion of these hazards, some indices are usually used e.g., water scarcity index (WSI), Standardized Precipitation Index (SPI). In this study, dry season water scarcity is considered as hazard and intensity of which is calculated by using WSI defined by Hoekstra et al. (2012).

‘Exposure’ refers to the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected, whereas, ‘social vulnerability’ consists of ‘coping capacity’ (i.e., ability to react to and reduce the adverse effects of experienced hazards) and ‘adaptive capacity’ (i.e., ability to anticipate and transform structure, functioning, or organization to better survive hazards) (IPCC, 2012). For assessing water scarcity risk in the LBRB, preliminary indicators were selected through involvement of key stakeholders, (see Gain et al., 2012). The most suitable indicators in terms of appropriateness with respect to the study area considered (i.e., LBRB) and data availability were selected to describe the trends of the components of risk over the past and also in the future projections. In brief, population density and rice cultivated area are considered as ‘exposure’, water governance, upstream vegetation and poverty level as ‘adaptive capacity’ and agricultural occupation, food production, dependency ratio as coping capacity. The final list of indicators is given in Table 1. The trajectories of indicators were based on the available information and projections for the years between 1975 to 2025. In brief, blue water scarcity (Hoekstra et al., 2012) for IPCC A1B scenario were calculated using global hydrological model PCRGLOB-WB (Gain and Wada, 2012). The past and future trajectories of population density, rice area, poverty level, upstream vegetation, agricultural occupation, food production and dependency ratio were collected from national statistics of Bangladesh and other published reports. Quantified past and future water governance trend calculated by Gain and Schwab (2012) was incorporated as the trajectories of water governance. The data source of each of the selected indicators is also given in Table 6.1.

Table 6.1 Sub-domains and indicators

Sub-domain	Acronym	Definition and selected indicator
Water scarcity	WS	The inexorable rise in demand for water has led to a growing scarcity of freshwater. Indicator: dry season blue water scarcity which is defined as the ratio of total blue water withdrawal to the blue water availability for the dry season period. source: GAIN AND WADA (2012).
Population density	PD	Here associated to the number of people exposed to water scarcity through the proxy indicator, population density (*number of persons per km*^{2}) for Bangladesh. source: MOHAMMAD 2009.
Rice area	RA	Compared to other land use category, total area (thousand hectare) under rice contributes to increase high exposure to water scarcity; source: BBS.
Water governance	WG	The status of water governance can determine the long term capacity for the management of various problems of water resources. Indicator: perceived trend of composite water governance; source: GAIN AND SCHWAB (2012).
Poverty level	PL	A higher number of poor people lead to decrease adaptive capacity. Indicator: Percentage of total people living below the poverty line; source: BBS (2006).
Upstream vegetation	UV	Upstream vegetation reduces sedimentation at downstream, eventually ensures water availability in the dry season. Indicators: area of forest cover; source: PANDIT ET AL (2009).
Agricultural occupation	AO	People who are involved with agriculture are likely to be affected by climate change induced water scarcity. Indicator: percentage of agricultural occupation; source: RAHMAN AND ISLAM (2003)
Food production	FP	An activity that contributes to the maintenance of land with positive potential for limiting the impacts of climate change. Indicator: ratio of produced food grain to requirement, a proxy of agricultural production; source: BBS, DAE.
Dependency ratio	DR	Indicator: % of dependent population. Population with higher DR leads to decreased coping capacity; source: BBS (2006); ISLAM AND NATH (2012).

6.2.4 Normalization of the indicators

A preliminary step for the aggregation of indicators is normalization, as the indicators in a data set often have different measurement units. Several normalization techniques exist in literature (OECD, 2008) and the best choice depends on the indicator under consideration and the preferences of the decision maker. Given the often not immediate relationship of indicator values with the objective of the assessment, the application of value function considering upper and lower thresholds can play an important role. Value functions are mathematical representations of human judgments which offer the possibility of treating people's values and judgments explicitly, logically and systematically (Beinat, 1997). In order to apply value function, determination of upper and lower thresholds and intermediate functions are required, which can be achieved through expert knowledge. However, sometimes it is very difficult to achieve such thresholds and function. For the water scarcity indicator, we derived value function considering the scarcity classification of Hoekstra et al., (2012) in which, upper bound of low, moderate and high scarcity was represented by the values 0.25, 0.50 and 1 respectively. For the population density, poverty level, and dependency ratio we ranked using a long term (1960-2011) data set of World Bank, and thus we found the function of the values with lower and upper threshold. The same function was then applied to normalize the collected values of each of these three indicators. In the case of agricultural occupation, expert judgement was applied to derive the value function. According to the expert opinion, agricultural occupation should be between 45% and 60% as the main economic activity of the study area is agriculture. Increase or decrease of this range reduces the social coping capacity. Considering this expert knowledge, the function was derived for normalization. For water governance and ratio of food production to availability, we have absolute values, therefore we do not require to normalize then. However, for the other two indicators (rice area, upstream vegetation), sufficient information was not available to derive value function. Therefore, for the sake of simplicity the Min-Max normalization approach was applied to the values of those indicators and this can be accepted as already applied by others e.g., Giupponi et al., (2012); Ebert and Welsch (2004). The trajectories of each indicators (with original measurement unit), normalized function and normalized value are shown in Figure 6.3 and 6.4.

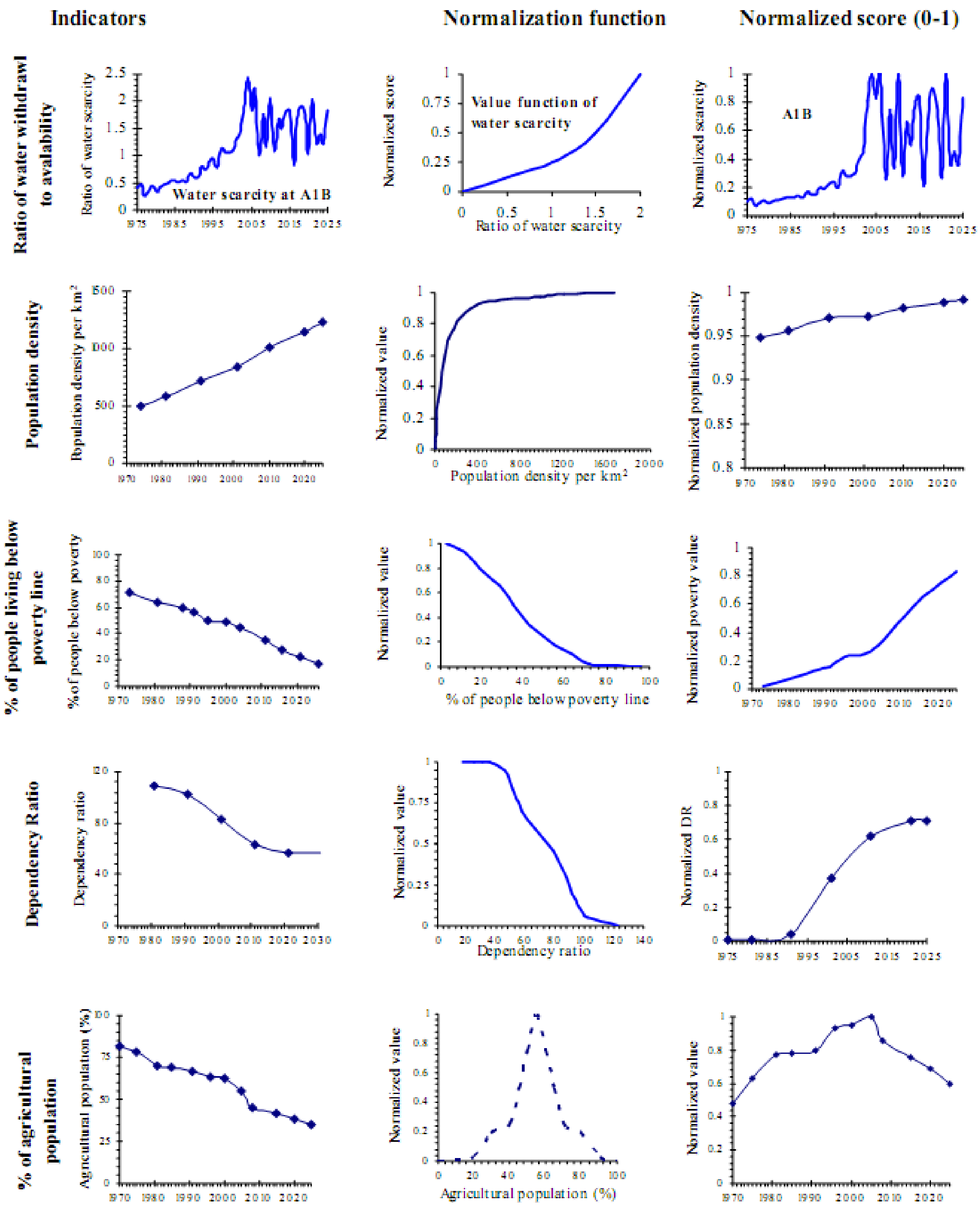


Fig. 6.3 Normalization of the indicators (value function approach)

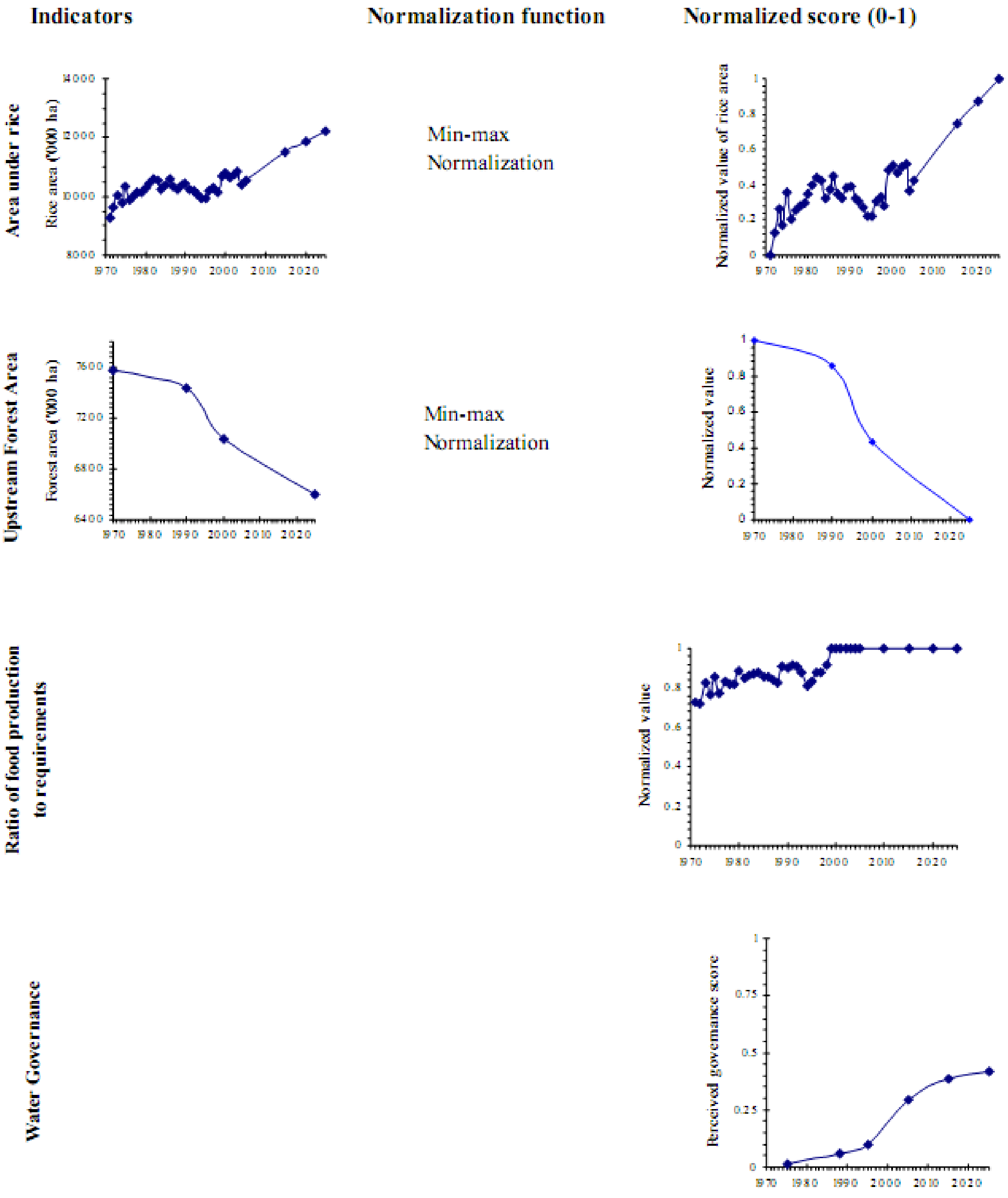


Figure 6.4 Min-Max Normalization for Rice Area and upstream forest area and absolute value for water governance and ratio of food production to requirement

6.2.5 Aggregation operators and development of index

Notion of water scarcity risk is the result of combined effect of different social and ecological variables. As a consequence, the risk can not be objectively measured by using a well-defined static or dynamic model. Instead, a subjective way for its estimate can be accomplished and fuzzy logic seems to be particularly appropriate for the assessment of risk of such SES (Giupponi et al., 2012). In this context, all the (normalised) factors that are used to compute the "risk" index are transformed into real numbers between zero and one (normalisation phase), and can be subsequently treated as fuzzy variables. The final outcome (i.e. the risk index) is the result of a hierarchical combination of several indicators that need to be aggregated in each node in which they converge. To aggregate them, suitable aggregation algorithms need to be selected, in accordance with the logic of the conceptual model, but also according to the elicited preference of the decision makers (DMs). Aggregation of indicators is obviously not a trivial task since the chosen (among many) methodology has meaningful impacts on the computation of the final index; furthermore, the choice of the aggregation method typically involves trade-offs between loss of information, computational complexity, adherence to Decision Makers' (DM) preference structure, transparency of procedure. Among the different aggregation methods, weighted averages (WA), geometric averages (GA) and non-additive measures (NAM) are important (Grabish, 1996). WAs are typically compensatory (i.e. a bad score in one criterion can be offset by a good score in another one) and more importantly they are not able to consider any interaction between the criteria, while GAs can cover only a smaller set of preference structures: those at the limit of logical conjunction and logical disjunction. However, the NAM with the Choquet Integral have been introduced to overcome the main drawbacks of above methods and thus represents a more generalised approach (Giupponi et al., 2012). Therefore, NAM with the Choquet Integral similar to the Giupponi et al., (2012) was selected as the aggregation operator for the assessment model. Description of the method is discussed below.

To aggregate all the indicators within NAM context (with the Choquet Integral), a series of parameters were elicited through questionnaires among the decision makers. Following Despic and Simonovic (2012), where all the [0,1] combinations of criteria $(x_1,...,x_n)$ are considered for each node of the aggregation tree; "0" corresponds to the *worst* case, while "1" for the *best* one. If *n* is the number of the indicators converging into a node, the aim of the stakeholder elicitation is to collect a score (measure), in this case in the scale [0,1], for $2^n - 2$ combinations, which are all the possible combinations among the criteria converging in the considered node (the number of question is $2^n - 2$ since the border conditions are already fixed (i.e. the first and the last cases, where criteria are respectively all "worst" - 0,0,0 - and all "best"- 1,1,1 - are already set at 0 and 1, respectively). The outcome of the questionnaire interview is thus to collect a numerical score to each row of the matrix containing all the possible combinations of the criteria chosen at each level. Below (Table 6.2) an example with three sub-domains (C1; C2; C3) is expanded, in which $2^3 - 2 = 6$ values of weights μ (1); μ (2); μ (3); μ (1,2); μ (1,3); μ (2,3) are required:

Table 6.2 elicitation of weights for a node of 3 indicators

	(C1,C2,C3)	**Weights**	**Values**
1	(0,0,0)	μ(0)	0
2	(1,0,0)	μ(1)	?
3	(0,1,0)	μ(2)	?
4	(0,0,1)	μ(3)	?
5	(1,1,0)	μ1,2)	?
6	(1,0,1)	μ(1,3)	?
7	(0,1,1)	μ(2,3)	?
8	(1,1,1)	μ(1,2,3)	1

However, when collecting the weights, the monotonicity principle should be respected, meaning that the if a combination where only one criterion is "best" is given a certain measure μ, all combinations including that criterion in the "best" case should be given a measure at least equal to μ. In practice, for the monotonicity principle line 5 can't have a measure lower than measures in lines 2 and 3, line 6 lower than 2 and 4, and line 7 lower than lines 3 and 4.

In order to collect such weights, usually best/worst questionnaire similar to Despic and Simonovic (2000) and Giupponi et al., (2012) is used. However, for the stakeholders such questionnaire has proven to be quite a time and resource consuming task, more worryingly, quite confusing and sometimes obscure and most of the times this can lead to questionnaires left incomplete or filled violating basic requirements of monotonicity principle. Instead of asking the exact numerical values to any of the $2^n - 2$ combinations, a suitable questionnaire was designed similar to Frisari et al., (2012) focusing the questions on the qualitative characterization. For a node of 3 indicators, for example, the survey moves in sequential steps. First, it asks the expert to assign values representing each indicator's relevant importance against the others. Second question asks the expert to evaluate couples of indicators together and identify coalitions with synergies, redundancies or additive properties. The final question asks to identify and rank an eventual relationship of complementarity or substitutability between all the indicators when considered together. However, for a node of 2 indicators only, a second question is not necessary. In the elicitation of weights from the stakeholders' preferences, the questionnaire used in this study is given in Annex B. The specific numerical measures are then assigned in a second stage by applying a set of simple pre-imposed conditions in a numerical computation program (Frisari et al., 2012), in which preference expressions and rankings are linked to particular values of the Orness Index (OI). The program tries to compute a set of values for $2^n - 2$ combinations (to fill the column 'Values' of Table 6.2) that yields the OI consistent with the level of complementarity expressed by the expert for the overall set and that, at the same time, satisfies the conditions on the interactions between the indicators (when considered in couples) and the relative importance of the indicators when taken individually.

Now the procedure of the Choquet integral as described in Giupponi et al., (2012) is mentioned below. In case of a greater relevance of one of the indicators in determining the state of the aggregated index (for example let's say that Poverty Level is considered more important than the others, for determining the Adaptive Capacity), measures of rows 2; 3; and 4 of Table 6.2 could become 0.20; 0.15; 0.15); and in case we thought that good status of poverty level combined with a good status of water governance could provide synergic effect the weight in row could be 0.45 (greater than the sum of 0.20 and 0.15).

Let $(x_1,\ldots, x_n)$ be the values of the normalized criteria; first of all, we need to order this vector which will become $(x_{(1)},\ldots, x_{(n)})$, in such a way that $x_{(1)} < x_{(2)} <\ldots< x_{(n)}$. Now let us consider 3 criteria (sub-domains) such that $n = 3$; let $(x_1, x_2, x_3) = (0.3, 0.8, 0.1)$; first of all, we have to order these criteria:

$(x_{(1)}, x_{(2)}, x_{(3)}) = (0.1, 0.3, 0.8)$ since $x_3 < x_1 < x_2$

The Choquet integral $C\mu\ (x1, x2, x3)$ is thus calculated as follows:

1. (1, 1, 1) : $x_{(1)} \bullet \mu(1, 2, 3) = 0.1 \bullet \mu(1, 2, 3) = 0.1$ (which corresponds to $x_{(3)}$)
2. (1, 1, 0): $(x_{(2)} - x_{(1)}) \bullet \mu(1, 2) = (0.3 - 0.1) \bullet \mu(1, 2) = 0.2 \bullet \mu(1, 2)$

   (0, 1, 0): $(x_{(3)} - x_{(2)}) \bullet \mu(2) = (0.8 - 0.3) \bullet \mu(2) = 0.5 \bullet \mu(2)$

In order to simplify the implementation of the procedure in the simulation software Simile, the parameters of the Möbius transform are later calculated. There is a two-way relation between the non additive measures (μ), i.e. the elicited measures, and the Möbius coefficients (m):

$$m_\mu(S) = \sum_{T \subseteq S} (-1)^{s-t} \mu(T) \qquad [2]$$

In the example with three sub-domains the Möbius coefficients are :

$$m(1) = \mu(1)$$
$$m(2) = \mu(2)$$
$$m(3) = \mu(3)$$
$$m(1,2) = \mu(1,2) - [\mu(1) + \mu(2)]$$
$$m(1,3) = \mu(1,3) - [\mu(1) + \mu(3)]$$
$$m(2,3) = \mu(2,3) - [\mu(2) + \mu(3)]$$
$$m(1,2,3) = \mu(1,2,3) - [\mu(1,2) + \mu(1,3) + \mu(2,3)] + [\mu(1) + \mu(2) + \mu(3)]$$

where the coalition coefficient m(T) can be both positive, negative or null; if positive, it means that there is synergic interaction between the criteria (indicators) belonging to the coalition T while if negative, there is redundancy interaction (or conflicting). If null, no interaction exists.

Using the Möbius coefficients, given that the Choquet integral is computable as:

$$C_\mu(x_1, x_2, .., x_n) = \sum_{T \subseteq N} m_\mu(T) \min_{i \in T} \{x_i\} \qquad [3]$$

with three sub-domains (x_1, x_2, x_3), the Choquet integral is calculated as follows:

$$C_m(x_1, x_2, x_3) = m_{(1)} \bullet x_1 + m_{(2)} \bullet x_2 + m_{(3)} \bullet x_3 + m_{(1,2)} \bullet \min(x_1, x_2) + m_{(1,3)} \bullet \min(x_1, x_3) + m_{(2,3)} \bullet \min(x_2, x_3) + \quad + m_{(1,2,3)} \bullet \min(x_1, x_2, x_3)$$

The outcome of the Choquet integral measure provides the opportunity to introduce sets of aggregation allowing the management of compensation and additiveness (Giupponi et al., 2012) which was then implemented in a system dynamic modelling environment.

6.3 Results

Within the conceptual model presented in section 6.2.2 and using the indicator values reported in Table 6.1, the model has been implemented in the system dynamic environment (Figure 6.5). Normalized values of each indicator (Figure 6.3 and 6.4) were used to assess risk. For the calculation of the Choquet integral at every convergence node, required variables were shown in Figure 6.5. The calculation has been done through the elicitation of weight by the stakeholders following the methods presented in previous section. For the demonstration purposes of such aggregation methods, only six stakeholders were considered who have expertise on water management of Lower Brahmaputra River Basin especially in Bangladesh. The average value of Möbius coefficients calculated from the stakeholders' interview is presented in Table 6.3. The results of orness value (Table 6.3) are close to zero (< 0.5) which indicate that aggregated variables are in non-compensative combination.

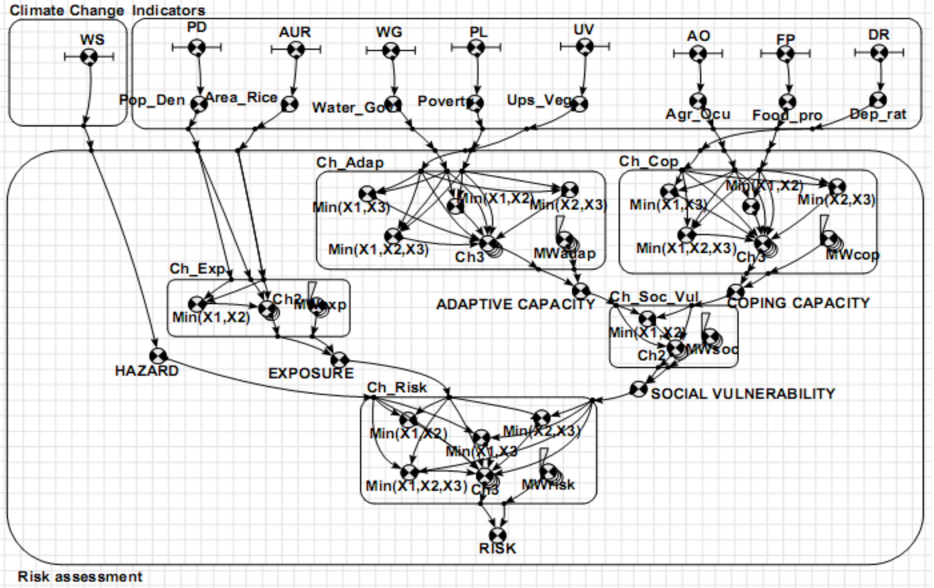


Figure 6.5 System dynamic model of risk assessment through Choquet weighting procedure

Using the normalized indicators (Figure 6.3 and 6.4) and elicited parameters (Table 6.3) the model was run for the year between 1975 and 2025. The simulated results of the selected indicators are shown in Figure 6.6 and Figure 6.7. The dry season water scarcity hazard for IPCC A1B scenario shows increasing trend (see Figure 6.7) which is mainly due to the fact that during most of the future years of the dry season (November to May) water demands will highly exceed water availability. Climate change is responsible for the supply side changes (i.e., water availability) of water resources whereas, population pressure, economic development and urbanization trends increase the demand pressure of the study area.

Table 6.3 Average values of parameters elicited from stakeholders

Aggregation of three indicators					
	Combinations	Measure	Adaptive capacity	Coping capacity	Risk
1	(0,0,0)	μ(0)	0.000	0.000	0.000
2	(1,0,0)	μ(1)	0.172	0.148	0.089
3	(0,1,0)	μ(2)	0.188	0.181	0.079
4	(0,0,1)	μ(3)	0.126	0.193	0.213
5	(1,1,0)	μ1,2)	0.172	0.285	0.283
6	(1,0,1)	μ(1,3)	0.081	0.038	0.061
7	(0,1,1)	μ(2,3)	0.133	0.018	0.121
8	(1,1,1)	μ(1,2,3)	0.126	0.133	0.151
	Orness		0.307	0.319	0.268
Aggregation of two indicators					
	Combinations	Measure	Exposure	Social Vulnerability	
1	(0,0)	μ(0)	0.000	0.000	
2	(1,0)	μ(1)	0.341	0.080	
3	(0,1)	μ(2)	0.301	0.061	
4	(1,1)	μ(1,2)	0.357	0.861	
	Orness		0.321	0.070	

Similarly aggregated exposure also shows positive trend as increased tendency of population density and rice area are highly exposed to water scarcity hazards (Figure 6.7). However, the notion of adaptive capacity changes with the function of water governance, poverty level and upstream vegetation. Figure 6.6 illustrates that the status of water governance and poverty improve and will further improve for the future whereas, upstream vegetation cover reduces significantly due to high rate of deforestation. Similarly, the combined effect of agricultural occupation, food production and dependency ration affects coping capacities. Social vulnerability is the aggregation of the opposite values of adaptive and coping capacity which shows decreasing trend for the future (Figure 6.7). Combining water scarcity, exposure and social vulnerability through non-additive measure, the notion of aggregated risk is shown in dark blue line of Figure 6.7 and the results depict that water scarcity risk is increased and fluctuated with the function of hazard.

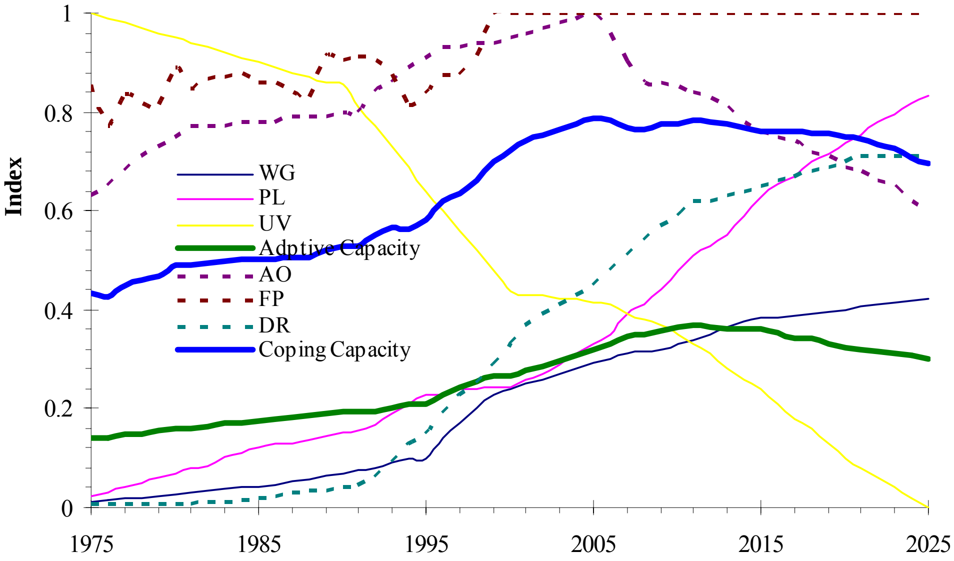


Figure 6.6 Simulated results of Adaptive Capacity and Coping Capacity variables

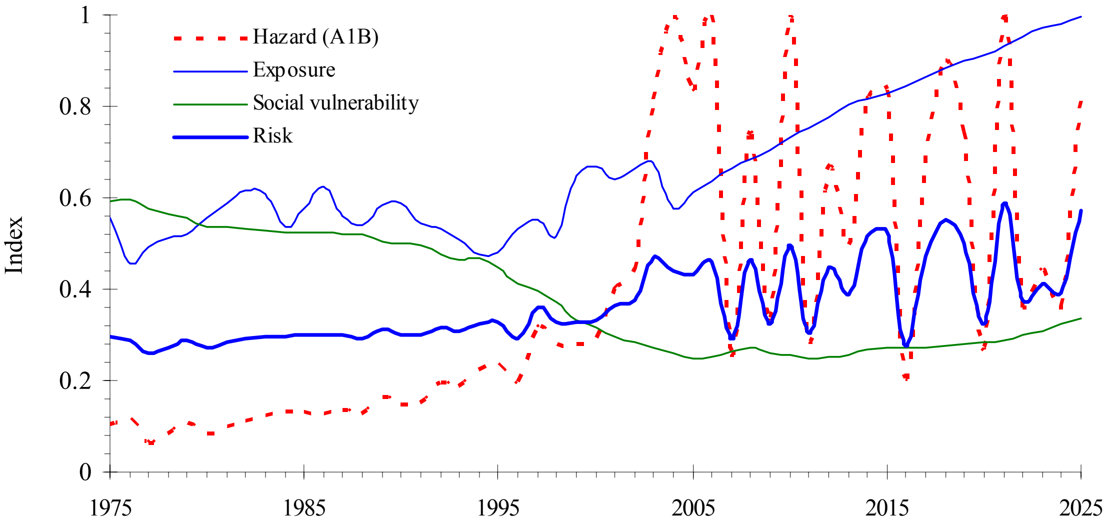


Figure 6.7. Simulated results of hazard, exposure, social vulnerability and risk

6.4 Conclusion

For assessing water scarcity risk in the Lower Brahmaputra River Basin, an operational system analysis approach was implemented. In the integrated assessment of risk, quantitative indicators were used to describe past and future trends of model variables, and their trajectories were used to explore possible trends of risks and adaptation needs. To construct concise indexes, a non-additive aggregation operator (Choquet integral) was used with a weighting procedure reflecting the preferences of a small number of stakeholders, in this case only six. The results illustrate that during dry season water scarcity risk is increasing in the future years, which requires special attention to the decision makers of LBRB. Therefore, the results of this study are intended to be used for contributing to planned adaptation of water resources systems, in Lower Brahmaputra River Basin, especially in Bangladesh.

In order to reduce water scarcity risk, adaptation options need to be selected in a participatory way which may not only include physical measures of reducing water scarcity intensity but also other short and long term planning for reducing exposure and increasing adaptive and coping capacity. The intensity of water scarcity hazard can be reduced through dry season flow augumentation by constructing artificial reservoirs, although the buffering capacity by storage systems (i.e., reservoirs) is small over the Ganges-Brahmaputra basin throughout upstream and downstream reach. Sometimes, construction of reservoirs by upstream countries aggravates water scarcity to downstream countries and conflicts arise. The transboundary river basin management approach could be useful to implement such structural measures. As the river is shared by India, China and Bangladesh, cooperation among these countries are important to establish co-basin management. As the region (LBRB) is one of the most densely populated area with high development activities, long term sustainable planning (population control, land use policy) is required to reduce water demand pressure. Some other non-structural measures are important for reducing exposure and social vulnerability which may include development of water scarcity early warning system, proper implementation of water policy, reduction of poverty etc.

To reduce water scarcity risk and to ensure livelihood security, planned adaptation strategies and targets need to be jointly discussed by the policy makers and river basin management authority of the region requiring the consolidation of relevant institutional mechanisms at various governance scales.

Chapter 7 Main Conclusions

In order to investigate climate change impact and vulnerability assessment of water resources system, a number of research questions were set out in chapter 1. The answers of those research questions were presented in the preceding chapters which include research topics ranging from hydrological impact studies to operational system analysis approaches for vulnerability assessment of the water resources system. This last chapter summarizes the main findings of each of the previous chapters, describing the implication of the results of the present study and setting out the links to the future research in this area.

7.1 Summary of the findings

- In *Chapter 2*, climate change impact on streamflow of the Lower Brahmaputra River Basin for IPCC A1B and A2 scenario has been assessed through multi-model weighted ensemble analysis using model outputs from a global hydrological model that are forced with 12 different global climate models (GCMs). The results show that only a limited number of GCMs are required to reconstruct observed discharge. The effect of climate change on both low and high flows was then investigated and the analysis shows that a very strong increase in peak flows is projected.
- In *Chapter 3*, ecological flow thresholds and different damaging flood events of LBRB were calculated and climate change impact was investigated. The Ecological flow threshold was calculated using twenty-two 'Range of Variability (RVA)' parameters considering the range between ± 1 standard deviation from the mean of the natural flow. Damaging flood events were calculated using flood frequency analysis of Annual Maxima series and using the flood classification of Bangladesh. The results demonstrated that due to climate change, various parameters will exceed the threshold condition for both IPCC A1B and A2 scenarios.
- In *Chapter 4*, the dissertation moves from hydrological studies to the assessment of water governance trend considering seven indicators that represent legal, political and administrative aspects of water governance. Changes are analysed by considering both shifts indicated by policy documents and the quality of governance perceived by water user groups. The results show that, according to the policy documents, all notions of governance have significantly improved and will further improve, but the actual

implementation of these policies seems to be far behind what the policy documents indicate and, moreover, this gap has even been increasing over time.

- In *Chapter 5*, the evolution of approaches to vulnerability assessment related to water resources systems was reviewed and from the current practices research gaps were identified. To overcome these gaps a generalized assessment framework is developed in the context of the Lower Brahmaputra River Basin (LBRB).
- In *Chapter 6*, an operational system analysis approach and a simulation tool for risk assessment of the water resources systems was developed within the broad context of climate change adaptation and disaster risk reduction with an aim to support decision making processes. With a weighting procedure reflecting stakeholders' preferences, a non-additive aggregation operator is used to construct concise indexes. The results suggest that during dry season water scarcity risk is increasing in the future years. Therefore, it requires special attention to the decision makers of LBRB.

7.2 Implication

Climate change is one of the most pressing global problems of our time. This is resulting in greater variations in weather patterns which eventually create various hazards e.g., floods, droughts, tropical storms, and sea level rise. The Lower Brahmaputra River Basin especially Bangladesh consists largely of a low, flat topographic area, 60% of which is lower than 6 m above sea level. The region is extremely vulnerable to these climatic impacts because of its geographical location, high population density, high levels of poverty, and the reliance of many livelihoods on climate-sensitive sectors, particularly rural agriculture and fisheries. Moreover, the Brahmaputra is a transboundary river shared with India, Butan and China. The main problems in water management arise from the flat topography where no potential storage of water is possible and because of the marked difference between wet and dry seasons. Flood events occur frequently during the wet season, which are able to inundate up to 65% of the country, while droughts are a general cause of water scarcity during the dry season. Considering climate change impact and other development pressures on water resources, development of proper adaptation plans, poverty alleviation and better quality of life through sustainable development are some of the main objectives for the government of the country. In order to achieve these objectives, an integrated approach is required through contribution of several disciplines.

Through combination of several articles (from Chapter 2 to 6), this dissertation has made an attempt to provide climate change adaptation and disaster risk management for LBRB (especially Bangladesh) in a systematic manner. Scientific and policy implication of the dissertation are as follows.

- The discharge weighted ensemble modelling presented in *Chapter 2* provides an impact of climate change on future riverflow projecting a very strong increase in peak flows. In combination with projected sea level change, this may have devastating effects for Bangladesh of which water resources planners should be concerned.
- *In Chapter 3*, the exceedence of threshold parameters due to climate change has an implication on the deterioration of social and ecological systems of the LBRB, requiring planned adaptation through the consolidation of relevant institutional mechanisms. Therefore, calculated threshold flow of twenty-two RVA parameters can be used as initial targets for water allocation to meet household, agriculture and industrial water demands. In trans-boundary river basin management, threshold of flow variability can be used as a basis for negotiation with other riparian countries and upstream flow control by reservoirs.
- The analysis of water governance trend in Bangladesh (presented in *Chapter 4*) demonstrates that instead of formulating new policies, the existing policies should be implemented in a participatory way.
- In the context of developing countries e.g., Bangladesh, a generalized integrated decision making framework was then (in Chapter 5) developed to support climate change adaptation. The hydrological impact studies (in Chapter 2 and 3) and assessment of water governance trend (in Chapter 4) can be used as input variables in the framework. The developed framework can play a significant role in identifying planned adaptation measures of Bangladesh in a systematic way.
- Integrating climate change adaptation and disaster risk management, the developed decision making framework is implemented for water scarcity risk assessment in the Lower Brahmaputra River Basin. The results demonstrate that during dry season water scarcity risk is increasing in future years, which requires special attention to the decision makers of LBRB. In reducing water scarcity risk and ensuring livelihood security, planned adaptation strategies and targets need to be jointly discussed by the policy makers and river basin management authority of the region requiring the consolidation of relevant institutional mechanisms at various governance scales.

7.3 Limitation and recommendation

Investigating climate change effects on future river flow (Chapter 2), multi-model weighted ensemble analysis (Gain et al. 2011) were used considering the model performance, i.e., historical relationship between model outputs and observations. However, for a more reliable derivation of individual GCM weights, additional research is required considering both model performance and future ensemble convergence (Giorgi and Mearns 2002; Murphy et al. 2004). In addition, the main assumption of the constructed transient series was the preservation of inter-annual variability which was assumed to be same in future. Although similar assumption is considered in many studies, this has been rejected in a number of other studies e.g., Delgado et al., 2010; 2012. Therefore, future research is required considering the changes in inter-annual variability. In chapter 3, threshold flows were calculated based on statistical relationship of observed flow. Direct ecological consequences were not investigated when calculating thresholds and additional research is required in this direction. In the assessment of water governance (Chapter 4), only seven indicators were considered that might not do sufficient justice to the complexity of an issue such an issue. This can only convey an understanding of observed and perceived tendencies in arenas of water management, making this approach a relevant contribution to a better informed decision-making. In chapter 5 a water resources decision making framework was developed considering stakeholders views and several important steps of the framework has been implemented in Chapter 6. For the demonstration purposes of water resources decision making only a few numbers of stakeholders were considered. Although the results of this study can be helpful for innovative research and management initiatives which are intended to be used for contributing to planned adaptation of water resources systems, a representative number of stakeholders is required for the actual decision making.

Water resources system of LBRB (especially Bangladesh) is affected by several factors e.g., climate change, upstream intervention and other development activities. However, in this study upstream intervention is not considered which includes construction of dams and massive deforestation by upstream countries. Massive deforestation of the mountainsides has significantly reduced the Himalaya's capacity to absorb the monsoon rains, and it has greatly increased the amount of eroded soil that is carried by the flood waters.

In the integrated assessment of risk, future study is required to model also upstream development. Based upon hydrological, hydrogeological, and agro-ecological characteristics, a regional water management plans should be formulated. These plans must identify areas where exploitation of water should be constrained or prohibited and outline sustainable methods of exploitation. Bangladesh's requirements for the sustainable management of trans-boundary water resources and the preservation of national ecosystems should be identified and the cooperation of neighboring countries sought through binding agreements.

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Appendix A:

Questionnaire for the evaluation of proposed framework of vulnerability assessment

A. Respondent's Identification:
Name and Surname:
Organization:
Position:
Address:
Email:

B. generalized framework
1. Evaluate the proposed framework as a whole:

☐ Excellent ☐ Very good ☐ Good ☐ Fair ☐ Poor ☐ Very poor

Notes:____

2. To what extent the generalized framework can be useful for water resource decision making in the country, given the current institutional and legislative context?

☐ Excellent ☐ Very good ☐ Good ☐ Fair ☐ Poor ☐ Very poor

Please specify:

3. To what extent the important steps are incorporated in the framework?

☐ Excellent ☐ Very good ☐ Good ☐ Fair ☐ Poor ☐ Very poor

Notes:____

4. According to your opinion which steps of the proposed framework should be added/removed/refined?

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C. Lower Brahmaputra River Basin (LBRB in Bangladesh) Context

1. What are the main concerns in terms of vulnerability assessment of water resources system in LBRB (Bangladesh)? (e.g., (a) flooding, (b) water shortage, (c) river bank erosion, (d) navigation problem, etc)

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(b) To what extent the framework can address these concerns?

☐ all concern ☐ most concern ☐ some concern ☐ no concern

Notes:____
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2. In terms of vulnerability assessment, which indicators can best represent the problems of LBRB? Please specify, under different dimensions:

Dimensions	**Potential list of indicators**
Environmental	Surface water discharge
	Groundwater availability
	Forest cover
	Loss of land due to erosion
	Wastewater/ surface water
	Wetland coverage
Social	Agriculture demand
	Domestic water demand
	Dependency ratio
	Population without access to safe drinking water source/ total population

Economic	Industrial water demand
	Agricultural production
	Fisheries production
	Income per capita
	GDP
	Non-agricultural employment
Institutional	Water governance

D. Conclusions

1. What are the main strengths of the framework?

2. What are the main weaknesses of the framework?

Appendix B:

Questionnaire for the elicitation of weights for the aggregation of indicators and simulation of risk over time

1) HAZARD: *defined as the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources (IPCC-SREX, 2012).*

According to the results of the participatory process carried out in the Lower Brahmaputra River basin, hazard can be assessed by focusing on following sub-domain:

1. *Water scarcity: The inexorable rise in demand for water has led to a growing scarcity of freshwater. Indicator: dry season blue water scarcity which is defined as the ratio of total blue water consumption to the blue water availability for the dry season period.*

2) EXPOSURE: *defined as the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected (IPCC-SREX, 2012).*

Exposure can be assessed by focusing in particular on the performances of two indicators:

1. *Population density (PD): defines number of persons per km^2. A higher number of population density –value at "best"- leads to increase high exposure to hazard.*
2. *Rice area (RA): refers total area (thousand hectare) under rice. A higher number of crop area –value at "best"- leads to increase high exposure to hazard.*

<u>Question 2.1</u>: Consider the relative importance of each indicator. Please allocate 100 points among them

Indicators	*Values*
PD	
RA	
Total	*100*

<u>Question 2.2</u>: Consider the indicators PD & RA together. What is the relationship between them when overall 'exposure' is considered? Do you think that the indicators PD &RA need to perform best at the same time to have an overall highest value of exposure (therefore those are complementary indicators)? Or an overall highest value of exposure could be obtained just with a highest value of only one indicator (therefore those are substitutable indicators). Please choose the following options:

☐ *Perfect Complementarity (logical conjunction): high values of the indicators are possible if and only if the indicators PD & RA are at best;*
☐ *High Complementarity: high value of 'exposure' is possible when indicators PD & RA are at higher values; not necessarily required best values of PD and RA;*
☐ *Neither Complementarity nor Substitability: all indicators, when at best, concur in different but comparable ways to the result (positive or negative) of the index (i.e.exposure);*
☐ *High Substitutability: Any one of the two indicators (PD, RA), when at worst, can be highly compensated by other indicator at best (usually associated with one or more redundant coalitions);*
☐ *Perfect Substitutability: Each indicator with worst value can be replaced by other indicator at best.*

3) ADAPTIVE CAPACITY: *defined as the combination of the strengths, attributes, and resources available to an individual, community, society, or organization (ex-ante hazard) that can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities (IPCC-SREX, 2012).*

The adaptive capacity can be assessed by focusing in particular on the performances of three indicators:

1. *Water governance (WG): refers trend of aggregated water governance index similar to Gain and Schwab (2012). A higher number of index value –value at "best"- leads to increased adaptive capacity.*
2. *Poverty level (PL): defines number of people living below the poverty line. A higher number of index value –value at "best"- leads to increased adaptive capacity.*
3. *Upstream vegetation (UV): refers area of forest cover. A higher number of index value –value at "best"- leads to increased adaptive capacity.*

<u>Question 3.1:</u> Consider the relative importance of each indicator. Please allocate 100 points among them

Indicators	*Total*
WG	
PL	
UV	
Total	*100*

<u>Question 3.2:</u> Can you identify any combination in which there are synergies or redundancies between two indicators? If there is neither synergy nor redundancy between any combination, the combination would be additive. Please choose one

Indicators	*Strong synergy*	*synergy*	*neither*	*redundancy*	*Strong redundancy*
WG & PL					
PL & UV					
UV & WG					

Question 3.3: Consider all the indicators together. What is the relationship between them when overall 'adaptive capacity' is considered? Do you think that all the indicators (WG, PL, UV) need to perform best at the same time to have an overall highest value of 'adaptive capacity' (therefore those are being complementary indicators)? Or an overall highest value of adaptive capacity could be obtained just with a highest value only one/two indicator(s) (therefore those are being substitutable indicators). Please choose the following options:

☐ *Perfect Complementarity*
☐ *High Complementarity (logical conjunction)*
☐ *Neither Complementarity nor Substitutability*
☐ *High Substitutability*
☐ *Perfect Substitutability*

4) COPING CAPACITY: *defined as the ability of people, organizations, and systems, using available skills, resources, and opportunities, to address, manage, and overcome (ex-post hazard) adverse conditions (IPCC-SREX, 2012).*

The coping capacity can be assessed by focusing in particular on the performances of three indicators:

1. *Agricultural occupation (AO): refers percentage of agricultural occupation. A higher number of index value –value at "best"- leads to increased coping capacity.*
2. *Food production (FP): refers ratio of produced food to required food. A higher number of index value –value at "best"- leads to increased coping capacity.*
3. *Dependency ratio (DR): refers ratio of female to male population. A higher number of index value –value at "best"- leads to increased coping capacity.*

<u>Question 4.1:</u> Consider the relative importance of each indicator. Please allocate 100 points among them

Indicators	*Values*
AO	
FP	
DR	
Total	*100*

<u>Question 4.2:</u> Can you identify any combination in which there are synergies or redundancies between two indicators? If there is neither synergy nor redundancy between any combination, the combination would be additive. Please choose one

Indicators	*Strong synergy*	*synergy*	*neither*	*redundancy*	*Strong redundancy*
AO & FP					
FP & DR					
DR & AO					

Question 4.3: Consider all the indicators together. What is the relationship between them when overall 'coping capacity' is considered? Do you think that all the indicators (AO, FP, DR) need to perform best at the same time to have an overall highest value of coping capacity (therefore those are being complementary indicators)? Or an overall highest value of coping capacity could be obtained just with a highest value only one/two indicator(s) (therefore those are being substitutable indicators of each other). Please choose the following options:

☐ *Perfect Complementarity (logical conjunction):*
☐ *High Complementarity:*
☐ *Neither Complementarity nor Substitutability:*
☐ *High Substitutability:*
☐ *Perfect Substitutability:*

5) SOCIAL VULNERABILITY: *defined as the characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects of a hazard. (UNISDR, 2009).*

The social vulnerability can be assessed by combining two indices deriving from the calculations described above:

1. *Adaptive capacity (AC): A higher number of adaptive capacity –value at "best"- leads to increased social vulnerability.*
2. *Coping capacity (CC): A higher number of social capacity –value at "best"- leads to increased social vulnerability.*

Question 5.1: Consider the relative importance of each indicator. Please allocate 100 points among them

Indicators	*Values*
AC	
CC	
Total	*100*

Question 5.2: Consider the indicators, AC and CC together. What is the relationship between them when overall 'social vulnerability' is considered? Do you think that AC and CC need to perform best at the same time to have an overall highest value of social vulnerability (therefore those are being complementary indicators)? Or an overall highest value of social vulnerability could be obtained just with a highest value only one indicator (therefore those are being substitutable indicators of each other). Please choose the following options:

☐ *Perfect Complementarity*
☐ *High Complementarity (logical conjunction)*
☐ *Neither Complementarity nor Substitutability*
☐ *High Substitutability*
☐ *Perfect Substitutability*

6) RISK: *defined as the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery (IPCC-SREX, 2012).*

The risk can be assessed by combining three indices deriving from the calculations described above:

1. *Hazard (HA): A higher number of hazard value –value at "best"- leads to increased risk.*
2. *Exposure (EX): A higher number of exposure value –value at "best"- leads to increased risk.*
3. *Social vulnerability (SV): A higher number of social vulnerability value –value at "best"- leads to increased risk.*

<u>Question 6.1:</u> Consider the relative importance of each indicator. Please allocate 100 points among them

Indicators	*Values*
HA	
EX	
SV	
Total	*100*

<u>Question 6.2:</u> Can you identify any combination in which there are synergies or redundancies between two indicators? If there is neither synergy nor redundancy between any combination, the combination would be additive. Please choose one

Indicators	*Strong synergy*	*synergy*	*neither*	*redundancy*	*Strong redundancy*
HA & EX					
EX & SV					
SV & HA					

<u>Question 6.3:</u> Consider all the indicators together. What is the relationship between them when overall 'exposure' is considered? Do you think that all the indicators (HA, EX, SV) need to perform best at the same time to have an overall highest value of risk (therefore those are being complementary indicators)? Or an overall highest value of risk could be obtained just with a highest value only one/two indicator(s) (therefore those are being substitutable indicators of each other). Please choose the following options:

☐ *Perfect Complementarity (logical conjunction)*
☐ *High Complementarity*
☐ *Neither Complementarity nor Substitability*
☐ *High Substitutability*
☐ *Perfect Substitutability*

Curriculumn Vitae

Animesh Kumar Gain was born on 01 February 1983 in Khulna, Bangladesh. In 2005, he obtained his Bachelor of Science (BSc.) in Environmental Science from Khulna University (Bangladesh). On 2008, he achieved a Master of Science (MSc) in Water Resources Development from Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET). His MSc thesis was on ‘Flood risk assessment of Dhaka City’, supervised by Professor M Mozzammel Hoque. During and after of his MSc, he worked on flood management and climate change adaptation in several research organizations of Bangladesh i.e., Environment and Population research Center and Bangladesh Unnayan Parishad. He started this PhD programme (Science and Management of Climate Change) in 2009 at the Ca’ Foscari University of Venice. His PhD research is mainly supervised by Prof. Carlo Giupponi of Ca’ Foscari University of Venice and by Dr. Fabrice Renaud of United Nations University-Institute for Environment and Human Security. Part of his research has been conducted at Physical Geography group at Utrecht University and United Nations University-Institute for Environment and Human Security (UNU-EHS). At Utrecht University, he worked with Dr. Walter Immerzeel and Prof. Dr. Ir. M. Bierkens, when he was a guest researcher there. During his visiting research period of UNU-EHS, he worked with Dr. Fabrice Renaud. He was also affiliated researcher of Euro-Mediterranean Centre on Climate Change (CMCC), an Italian research centre dedicated to climate related research. After finishing his PhD, he will remain working in the field of climate change impact and adaptation of water resources system.

Selected Publications

Peer reviewed papers

Gain, A. K., Immerzeel, W. W., Sperna Weiland, F. C., & Bierkens, M. F. P. (2011). Impact of climate change on the stream flow of the lower Brahmaputra: trends in high and low flows based on discharge-weighted ensemble modelling. *Hydrology and Earth System Sciences*, *15*(5), 1537-1545. doi:10.5194/hess-15-1537-2011

Gain, A. K., Giupponi, C., & Renaud, F. (2012). Climate Change Adaptation and Vulnerability Assessment of Water Resources Systems in developing countries: A generalized framework and a feasibility study in Bangladesh. *Water*, *4* (2), 345-366. doi:10.3390/w4020345

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Gain, A. K., Walsh, C. L., (2012). Impact of Farakka Barrage on the ecological flow threshold of Lower Ganges River Basin (Bangladesh). *Environmental Monitoring and Assessment,* Submitted.

Gain, A. K., Wada, Y., (2012). Assessment of future water scarcity at different scales of Brahmaputra River Basin. *Science of the Total Environment,* Submitted.

Gain, A. K., & Giupponi, C. (2012). A dynamic assessment of water scarcity risk and climate change adaptation in Lower Brahmaputra River Basin. *In preparation*.

Conference abstracts/proceedings/oral presentation

Gain, A.K. (2013) The gap between formulation and implementation of policies: the case of Bangladesh water governance. ***Earth System Governance Tokyo Conference*, *Tokyo, Japan*,** January 28-31, 2013.

Giupponi, C., Balbi, S., Briceño, S., Brilly, M., Di Baldassarre, G., **Gain, A.K.,** Gallina, V., Marcomini, A., Mojtahed, V., Ranzi, R., Torresan, S. (2012). On evaluating the benefits of risk prevention: the KULTURisk framework. ***EGU Leonardo Conference 2012 – Hydrology and Society***, ***Torino, Italy***, November 14–16, 2012.

Gain, A.K., Giupponi, C. (2012). A Dynamic Science-Policy Interface for the Assessment of Vulnerability and Climate Change Adaptation of Water Resources System at Lower Brahmaputra River Basin. ***Berlin Conference on the Human Dimensions of Global Environmental Change, Berlin, Germany***, October 5-6, 2012.

Gain, A.K. (2012**).** A Dynamic Approach of Climate Change Adaptation and Vulnerability Assessment of Water Resources System at Lower Brahmaputra River Basin. ***European Science Foundation (ESF) Junior Summit on 'Water: Unite and Divide, Interdisciplinary approaches for a sustainable future', Stresa, Italy***, August 27-30, 2012.

Balbi, S., Bhandari, S., **Gain, A.K.,** & Giupponi, C. (2012). Future dynamics of irrigation water demand in the farming landscape of the Venice Lagoon Watershed under the pressure of climate change. *Proceedings of* ***6th International Congress on Environmental Modelling and Software (iEMSs)***, ***Leipzig, Germany***, *July 1-5, 2012*.

Gain, A.K. (2011). Climate change impact on streamflow of Lower Brahmaputra River" Presented in the *Graduate Climate Conference 2011,* ***Massachusetts Institute of Technology, USA,*** October 28-30, 2011.

Gain, A.K. (2011). Vulnerability assessment of water resources system: Lower Brahmaputra River Basin. ***Brown International Advanced Research Institute (BIARI) on 'Climate Change and Its Impacts: Water in a Changing Climate', Brown University, Providence, USA***. June 11-25, 2011.

Gain, A.K. (2010). Assessment of vulnerability to climate change of Water Resources in Bangladesh" Presented in the *First International Symposium on Climate Protection and Resource Conservation for Young Academics 'Global Climate Change – approaches to international cooperation',* ***Bonn, Germany,*** May 18-21, 2010.

Estratto per riassunto della tesi di dottorato

Studente: Animesh Kumar Gain matricola: 955706

Dottorato: Scienze e Gestione dei Cambiamenti Climatici

Ciclo: 25

Titolo della tesi : Climate change impact and vulnerability assessment of water resources systems: the case of Lower Bramaputra River Basin

Abstract:

English

Besides climatic change, current demographic trends, economic development and related land use changes have direct impact on increasing demand for freshwater resources. Taken together, the net effect of these supply and demand changes is affecting the vulnerability of water resources systems (WRSs), in which complex interactions of the social-ecological systems are in place. Therefore, for assessing vulnerability and risk of WRSs, the integrated contribution of several disciplines is required, enabling a comprehensive, but also dynamic description of present state and future trends. With the aim to integrate the assessment of risks of complex WRSs, this dissertation first focuses on the hydrologic impacts of climate change, with calculation of river flow thresholds, and the related water governance issues, and then it moves to the integrated assessment of vulnerability and risk of WRSs, with a focus on the development of operational approaches in the context of developing countries. The assessment has been conducted in the context of the Lower Brahmaputra River Basin (LBRB).

Italiano

Oltre ai cambiamenti climatici, l'evoluzione demografica, lo sviluppo economico e le relative variazioni di uso del suolo hanno un impatto diretto sulla crescente domanda di risorse di acqua dolce. Nel loro insieme, l'effetto netto di questi cambiamenti della domanda e dell'offerta sta interessando la vulnerabilità dei sistemi idrici (WRS). Pertanto, per valutare la vulnerabilità dei e il rischio per i WRSs, è necessaria non solo l’integrazione dei contributi di diverse discipline, consentendo un approccio globale, ma anche la rappresentazione dinamica delle tendenze attuali e future. Con l'obiettivo di integrare la valutazione dei rischi dei complessi WRS, questa tesi si concentra in primo luogo sugli impatti idrologici dei cambiamenti climatici, con il calcolo delle soglie di flusso del fiume Brahmaputra e l’inquadramento dei problemi relativi alla gestione delle sue acque, per poi passare a una valutazione integrata della vulnerabilità e del rischio del sistema socio-ecologico che ci interagisce, con una particolare attenzione allo sviluppo di approcci operativi nel contesto di paesi in via di sviluppo. La valutazione è stata condotta nel contesto del Basso bacino del fiume Brahmaputra (LBRB).

Firma dello studente

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