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# Flooding in Dhaka, Bangladesh, and the challenge of climate change

The country of Bangladesh is located in the Ganges-Brahmaputra-Meghna river delta, and faces multiple natural hazards, in particular flooding, and other challenges such as sea-level rise and a growing population. Dhaka, the capital of Bangladesh with a population of over 17 million people, is among the top five coastal cities most vulnerable to climate change, with over 30 % of the population living in slums. Effective disaster mitigation and adaptation requires an understanding how hazards such as flooding impact the population, e.g. in terms of mortality. If this link is understood, appropriate measures can be undertaken to assist the exponentially growing population in aquiring effective coping mechanisms.

This thesis contributes to the understanding of the behavior of extreme water levels and their links to mortality by assessing the past and current situation in Dhaka. We hypothesize that water levels have changed in frequency, magnitude and duration during the past century, and that extreme water levels lead to an increase in mortality. We also believe that the impacts of climate change on flooding and thus livelihoods in a complex delta can not be treated isolated from other challenges of global change, and illustrate this by setting up a conceptual socio-hydrological causal network that assesses the interactions of natural and anthropogenic processes in a holistic way.

We first analyzed daily water levels of the past 100 years in order to detect potential shifts in extremes. We also employ the enhanced Driving force - Pressure - State - Impact - Response framework compiled with an extensive literature review to explore the complex interactions between the hydrological system under climate change and anthropogenic impacts due to e.g. the construction of dams as well as a growing population.

Our analysis suggests that water levels have indeed changed over the course of the past century. While the magnitude and duration of average flood events decreased, the frequency of extreme flood events has increased. Low water levels have also changed, with a significant decrease in the annual minimum water level most noticeable when we compare the time periods 1909 - 1939 and 1979 - 2009.

The constructed socio-hydrological framework confirms that both natural and anthropogenic processes and their two-way feedbacks need to be included in a climate change impact assessment. The conceptual framework can put these impacts into perspective, allowing policy makers to know where available resources can be used effectively to increase resilience and reduce vulnerability.

Climate change takes place over long stretches of time and thus enable the population of Bangladesh to adapt slowly. Resources such as social capital, which is one of the main tools for slum dwellers to be able to cope with flooding can be altered over time, and as such the system can be considered overall stable and resilient. However, transboundary water sharing issues during the dry season and other implications resulting from dam structures such as Farakka Barrage complicate a prognosis on how the rapidly growing population will be affected in the 21st century. This is particularly important in connection with our previous findings, which suggest that the Greater Dhaka population already experience a significant increase in mortality during droughts. Climate change can thus be seen as an anthropogenic amplification of the socio-hydrological challenges already faced by Bangladesh today.

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# Chapter 1

# Introduction

> *"We are nature's laboratory on disasters. We don't have volcanoes. But any other natural disaster you think of, we have it."*

Ainun Nishat
*International Union for Conservation of Nature, Dhaka, Bangladesh*

Climate change is expected to impact the hydrological cycle due to both increased temperatures, leading to changes in snow and ice regimes, and shifts in the precipitation distribution (Arnell, 1999; IPCC, 2013). Especially shifts in hydrological extremes leading to floods and droughts can have devastating economic and social effects such as loss of land, crops, or livestock, an increase in diseases, or even death (Hijioka et al., 2014).

In a changing climate, extreme floods may increase (Milly et al., 2002), aggravating the situation for millions of people (Few, 2003), in particular in South Asian coastal cities. The OECD report (Nicholls, R.J. et al., 2007) places Dhaka, the capital of Bangladesh, among the top five coastal cities most vulnerable to climate change. Dhaka is currently threatened by natural hazards such as earthquakes, tropical cyclones and - on an almost annual basis - flooding (GAR, 2009, 2011). The effects of some of these threats can be counter-acted in part by improved disaster risk reduction measures, but economic risk exposure is nevertheless expected to rise with the strongly growing assets in developing regions, in particular during the next two decades (Patt et al., 2010). In addition, despite a comparatively low fertility rate of 2.2 children per woman, the population of Dhaka has increased from roughly 12 million inhabitants in 2000 to 16.8 million in 2015 (United Nations, 2007) and to even larger numbers by the end of the century due to urban migration and the large proportion of young adults expected to become parents within the next years. Due to economic growth and growing population alone, the people of Dhaka already experience an increase in risk due to flooding. Any impact of climate change on flooding is therefore important for the future of the citizens of Dhaka, whether the effect is positive through a reduction in flooding, or negative by aggravating the current flood situation (Alam and Rabbani, 2007).

## 1.1 Current situation

### 1.1.1 Flooding and its impact on the livelihood in Dhaka City

Flooding in Dhaka is quantified by the exceedance of pre-determined danger levels at water level measurement stations operated by the Bangladesh Water Development Board. Flooding in the megacity is largely impacted by the close proximity to the confluence of the Ganges and Brahmaputra rivers upstream, as well as the conjunction with the Meghna river further downstream (Figure 1.1). The risk of flooding is aggravated through rapid urbanization and concurrent encroachment on retention areas, as well as malfunctions of both the natural and man-made drainage system. Particularly devastating flood years include the flooding of 2007, as well as the flood of 2004, during which over 30 million people were homeless in Bangladesh, with over 40 % of Dhaka inundated. Water logging and drainage congestion enhance river flooding and its detrimental effect, which is being addressed with regulations governing the use of polyethylene shopping bags (banned in 2002, Reazuddin and Team (2006)), but still poses a problem throughout Dhaka. Many of Dhaka's residents, in particular slum dwellers residing in so-called informal settlements, inhabit flood-prone areas, and only the western part of the city is currently protected by an embankment. If the embanked areas do flood, insufficient sleuces and pumps as well as water logging causes the water to stagnate and drain even slower than in the unembanked areas of Dhaka. Stagnant bodies of water cause several problems and lead to a further reduction of the limited financial and material assets and resources available to the urban poor. Thus, inundation usually affects the poor more strongly, creating a social inequity (Brouwer et al., 2007).

Dhaka's livelihood is in great parts comprised of informal systems such as the brick industry and slum dwellers. The brick fields are situated on the outskirts of Dhaka City, in close proximity to flood-prone areas as this aids the very traditional production process by providing both sand, water, and easy access to waterway transportation (Aßheuer, 2014). Likewise, slum settlements, which house roughly 30 % of Dhaka's population, are largely not recognized officially by the government. Their construction is therefore not regulated and tends to occupy flood-prone areas. Although particularly slum dwellers have seemed to adapt to flooding (Aßheuer et al., 2013), the question arises how possible changes in future flooding may affect these informal systems. Of interest are flood magnitude, duration as well as frequency and the on-set of flooding and the length of the flood season.

### 1.1.2 Impact of water levels on health and mortality

Risks of flooding include both short- and long-term health risks such as gastrointestinal diseases, an increase in vector-borne diseases, psychological effects, and possibly death (Alderman et al., 2012; Lowe et al., 2013). Both the flood of 2004 and 2007 led to faecal contamination of drinking water sources in Dhaka due to drainage congestion problems (Sirajul Islam et al., 2007; Islam et al., 2010). Because the three most devastating floods


**Figure 1.1:** Map of study area, showing the Ganges, Brahmaputra and Meghna river systems as well as the location of the water level station in Dhaka ■. • represent the respective discharge stations, Farakka Barrage is located in the west on the border between India and Bangladesh.

occurred within the past 25 years, a general increase in extreme events is perceived (Alam and Rabbani, 2007; Mirza, 2011; Khalequzzaman, M.D., 1994).

Low water levels are also coming into focus as the groundwater level in Dhaka has receded in past years (Hoque et al., 2007), with low river levels further depleting the available water resources. Aside from hardships for the day-to-day life, droughts also lead to health-related risks. Dey et al. (2012) found that in Northwestern Bangladesh, droughts lead to increased levels of gastrointestinal diseases as well as dysentery compared to normal years.

Both floods and droughts not only have a negative effect on health, but can also impact the mortality of the exposed population, as substantiated already for floods in Asian countries by Jonkman (2005). Hashimoto et al. (2011) used a numerical 2D flood simulation model to estimate flood-related health risks for Dhaka, and found a connection between maximum inundation depth and mortality. On a global scale, Alderman et al. (2012) reviewed 35 epidemiological studies and found that mortality can increase up to 50 % in the first year after an extreme flood. Heavy flooding is assumed to increase mortality both through direct and indirect effects (Ahern et al., 2005; Du et al., 2010). Direct effects include accidents with power lines and drowning, which are concurrent with the flooding (i.e. do not exhibit a time lag). Indirect effects however, can lead to a higher morbidity due to e.g. gastrointestinal diseases (Sirajul Islam et al., 2007), and could increase mortality with a time lag.

### 1.1.3 Climate change in Bangladesh

Numerous reports from large organizations such as the Food and Agriculture Organization of the United Nations, the Urban Climate Research Network, the OECD and the World Bank identify climate change as one of the greatest challenges not just for Dhaka, but for all of Bangladesh over the course of the 21st century (Chowdhury, 2001; Nicholls, R.J. et al., 2007; Aquastat, 2011; Rosenzweig et al., 2015), with Inman (2009) even referring to Bangladesh as the “ground zero of climate change”. IPCC (2013) and Hijioka et al. (2014) in particular provide an extensive overview of the physical components of climate change in South Asia including a focus on possible impacts, adaptation and vulnerability. These reports often concentrate on Bangladesh’s major natural hazards likely to be affected by climate change, such as flooding and sea-level rise, and agree that climate change will generally worsen the situation in Bangladesh during the coming years.

Studies focusing especially on extreme water levels in Bangladesh range from studies on the Ganges, Brahmaputra and Meghna catchments to more region-specific approaches. Hirabayashi et al. (2013) found significant decreases in the return period of a 100 year flood event by 2071 - 2100 under the RCP8.5 scenario for both the Ganges and Brahmaputra from a study of 11 global climate models (GCMs) selected from the CMIP5. Using 12 GCMs in a discharge-weighted ensemble model, Gain et al. (2011) detected that in the lower Brahmaputra catchment the magnitude of extremely low flows will increase, while on the other hand their results project a significant increase in peak flow at Bahadurabad station (the main discharge station of the Bramaputra, see Figure 1.1). They presume this effect is mainly due to an increase in monsoon discharge resulting from a later onset of the monsoon (Mirza et al., 2003; Immerzeel et al., 2010; Immerzeel and Bierkens, 2013). Masood et al. (2015) also sees increases in both precipitation and runoff, particularly in the Meghna catchment, while Whitehead et al. (2015) finds prolonged periods of droughts.

Although these studies generally agree on slight to significant changes in discharge patterns, they are based on regional and global climate models (e.g. Coupled Model Intercomparison Project CMIP5 models, Taylor et al. (2012)) that often have difficulty in adequately representing Indian Summer monsoon dynamics (Immerzeel and Bierkens, 2010; Annamalai and Sperber, 2016), even when applying statistical post-processing (Dobler and Ahrens, 2008, 2010). River routing schemes are also typically not included in global climate models, or fail to reproduce accurate annual cycles, let alone peak discharges, in part due to a lack of information on the depth and width of river channels (Bierkens, 2015). While the climate model output could be used to drive a dynamical hydrological model, this also proves difficult for large catchments such as the GBM. The larger a river basin becomes, the more difficult it is to obtain and sustain a data network of sufficient quality to calibrate and validate a hydrological model. In the GBM, the problem of obtaining sufficient observational data is especially true for the Himalayas (Mirza et al., 2003; Immerzeel, 2008; Immerzeel et al., 2010; Immerzeel and Bierkens, 2013) and for variables such as soil moisture and evapotranspiration (Masood et al., 2015). In addition, if at all included, anthropogenic processes in these models are often limited to simple parameterizations of e.g. water extraction for irrigation purposes, while international water sharing or reservoir management are currently not incorporated in climate change projections or modelling studies (Bierkens, 2015).

Because of these constraints, classical climate and hydrological modelling approaches fail to represent the complex and often non-linear feedbacks between the natural and the anthropogenic system (Sivapalan et al., 2011; Bierkens, 2015). However, according to Niemeijer and de Groot (2008a) the identification of processes important for a particular research problem, location or question is only possible when the overall complexity of a system is acknowledged and understood. A climate change model that focuses on mainly the natural processes is thus not suitable for a region as complex as Bangladesh, and a cross-thematic approach that includes processes not only across all compartments of the soil-vegetation-atmosphere system, but also incorporates anthropogenic processes is needed (Wagener et al., 2010; Gill and Malamud, 2014, 2016). Studying water levels under climate change can not be accomplished without taking into account processes such as sea-level rise, the building of (international) dams, or increases of freshwater demand due to a growing population.

### 1.1.4 The need for a socio-hydrological framework

The need for a coupling of the anthropogenic and the hydrological system to adequately describe the complex feedbacks and dynamics across spatial and temporal scales can be addressed by the recently emerged field of socio-hydrology (Sivapalan et al., 2011; Di Baldassarre et al., 2015; Troy et al., 2015; Wesselink et al., 2017). Initiatives such as the IAHS Panta Rhei hydrological decade, which covers the period from 2013 to 2022 and puts a primary focus on change in hydrology and society, stress the importance of a socio-hydrological perspective (Wagener et al., 2010; Montanari et al., 2013).

Current approaches on studying the impact of climate change on water resources in Bangladesh largely rely on one-way causal chains without feedbacks (Gill and Malamud, 2014, 2016). For example, when studying the resilience of coastal communities to climate change, Amoako Johnson et al. (2016) describes a two-way feedback between salinity and shrimp farming, but does not extend the research to include other factors impacting salinity (Mirza, 1997; Vineis et al., 2011). Including two-way feedbacks between the human and water system is a key component of a socio-hydrological approach (Sivapalan et al., 2014).

Attributing certain implications to climate change is difficult without acknowledging the complexity of socio-hydrological interactions. Inman (2009) describe that farmers living along the coast have migrated further inland because a growing brackish zone due to rising sea levels has led to an increase in salinification, negatively affecting crop yield. These households are labelled as “climate refugees”, but the extension of the brackish zone cannot be attributed to rising sea levels alone: the construction of dams further upstream reduces flows which in turn allows the sea water to reach further inland (Mirza, 1997, 1998; Gain and Giupponi, 2014). Rabbani et al. (2010) also stress that policy actions to address the impact of climate change in Bangladesh must be based on a comprehensive framework assessing both social and environmental interactions across all time scales. Despite the large number of reports and studies conducted on the impacts of climate change in Bangladesh, a comprehensive socio-hydrological framework has to our knowledge not yet been set up. Such a framework can aid in showcasing socio-hydrological aspects that are currently barely being focused on by researchers and policy makers in general. For example, when attempting to mitigate the impact of natural processes on mortality, the focus in Bangladesh has mostly been on cyclones, tornadoes and flooding (Paul, 1998; Alam and Collins, 2010; Paul et al., 2010; Aßheuer et al., 2013). Disaster management was succesful in reducing the deaths, particularly those related to cyclones, but little has been done to mitigate the effects of precipitation and temperature on mortality (Burkart et al., 2011a,b, 2014a,b; Burkart and Kinney, 2016, 2017).

## 1.2 Scientific objectives

Because of the links between environmental factors and mortality, climate change is expected to impact mortality (Patz et al., 2005). Since Dhaka is at risk to a large variety of natural hazards, disaster mitigation and adaptation requires an understanding whether hazards such as flooding are linked to an increase in mortality. If this link is understood, appropriate measures can be undertaken to assist the growing population in aquiring effective coping mechanisms. This thesis aims to contribute to the understanding of the behavior of extreme water levels and their links to mortality by providing an assessment of the past and current situation in Dhaka. We hypothesize that water levels have changed in frequency, magnitude and duration during the past century, and that extreme water levels lead to an increase in mortality.

To be able to study how these water levels may change in the future, we provide a conceptual framework to assess the interactions of hydrological processes with the natural environment which accounts for societal impacts in a holistic way. By focusing more closely on those processes most important within Bangladesh and the Ganges-Brahmaputra-Meghna delta, as well as their implications on both the country-wide and individual level, we can not only assess the importance of flooding compared to other processes, but also identify the areas where the country is most vulnerable. Impacts of climate change can be put into perspective, allowing policy makers to know where available resources can be used most effectively to increase resilience and reduce vulnerability.

Chapter 2 introduces the physical geography of Bangladesh and flooding in the Ganges-Brahmaputra-Meghna catchment, followed by a description of the data utilized in this thesis in Chapter 3.1. We focus on rare - but particularly high-risk - events using extreme-value theory described along with other methods applied included in Chapter 3.2. In Chapter 4, we present an overview on observed water levels during the past 100 years and study the connection between flooding and mortality in Dhaka. Chapter 5 compares potential impacts of climate change on hydrology in view of the range of additional challenges faced by Bangladesh, before combined results are discussed in Chapter 6. All figures (see List of Figures, p. VII) were created from respective data, unless otherwise noted.

# Chapter 2

# Socio-economy, climate and hydrology of Bangladesh

This section provides a brief overview of the basic geographical features of Bangladesh, in particular with respect to the Ganges, Brahmaputra and Meghna rivers. Where appropriate, information is also given on the entire Ganges - Brahmaputra - Meghna catchment. Chapter A.1 and A.2 include further details, in particular on the Indian Summer monsoon and the El Niño Southern Oscillation (ENSO).

Bangladesh is located in South Asia and shares land borders with Myanmar (about 300 km) and the majority with India (about 4100 km). The coast line along the Bay of Bengal, which is difficult to estimate due to its deltaic nature, is between 580 km and 710 km long, with one-third of the country classified as coastal (Central Intelligence Agency, 2013; Rabbani et al., 2010). Compared to its neighbors, Bangladesh is a rather small country with 145,000 km$^2$ (Myanmar: 676,578 km$^2$, India: 3,287,263 km$^2$). The country extends about 800 km from north to south, and about 400 km from west to east. The mostly flat topography of Bangladesh (Figure 1.1 has a mean elevation of about 58 m, with 80 % of the country being a deltaic flood plain which lies no more than 10 m above mean sea level. Higher elevations are solely found in the northern highlands and the south-eastern Chittagong hill tracts, where the country's highest elevation is located at Saka Haphong (1052 m).

The deltaic landscape is largely shaped by the countless rivers of the Ganges - Brahmaputra - Meghna (GBM) system (Figure 2.1, more details in Section 2.3). The combined annual runoff from the GBM rivers into the Bay of Bengal of over 1,200 million m$^3$ leads to regular flooding, covering on average 20 % of the land surface (Figure 2.6, Mirza (1997, 1998)). The highly dynamical landscape is also prone to river avulsions; in 1762 parts of the Brahmaputra shifted 150 km westward after an earthquake, while the long coast line makes the country susceptible to increasng sea levels (Höfer and Messerli, 2006; Brammer, 2012; Pethick and Orford, 2013; Brammer, 2014).

The Ganges, Brahmaputra and Meghna combined form one of the largest tidal deltaic regions in the world, transporting up to $10^6$ metric tons of sediment largely comprised of fine sand, silt and clay through the lower Meghna estuary into the Bay of Bengal

(Datta and Subramanian, 1997; Islam et al., 1999; Haque et al., 2016). These sediments are vital to the fertility of the alluvial soils, and also lead to a net accretion despite frequent land loss due to river bank erosion. The sediments transported within the GBM are also the major contributor to the Bengal Fan, the world's largest submarine fan which extends up to 3000 km long into the Bay of Bengal (Curray et al., 2002).

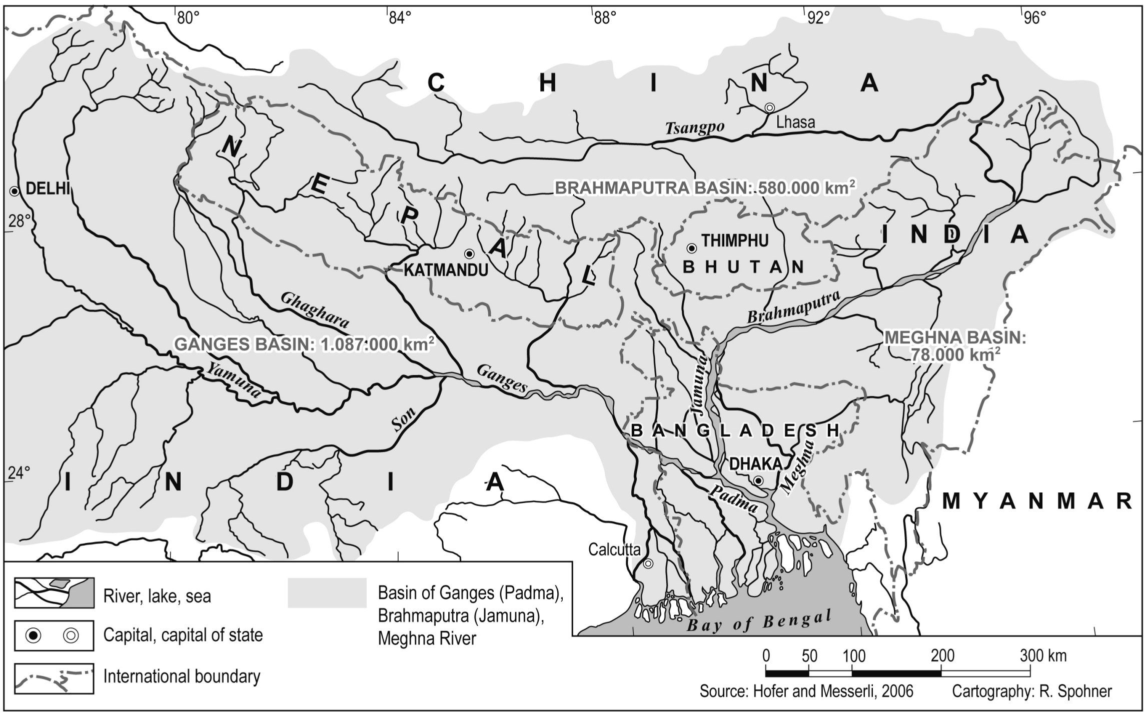


**Figure 2.1:** Location of Bangladesh and catchment area of the Ganges, Brahmaputra, and Meghna rivers; Figure from Aßheuer et al. (2013).

In addition to flooding, Bangladesh regularly faces other natural hazards such as extreme temperatures, droughts, hail storms and tropical cyclones (Alam and Dominey-Howes, 2014b,a; Burkart and Kinney, 2017; Cecil and Blankenship, 2012). Due to its critical tectonic position on the junction of the greater Indian, Burma and Eurasian plates which interact in the Bengal Basin it also lies at risk of major earthquakes (Steckler et al., 2008; Alam and Dominey-Howes, 2016).

## 2.1 Socio-economic aspects of global change

Formerly Eastern Pakistan, the People's Republic of Bangladesh formed after a civil war in 1971. Bangladesh is home to the world's ninth largest population of about 160 million people, and is expected to have a population of over 200 million by 2030 despite its comparatively low birth rate of 2.2 children per woman (United Nations, 2007).

The nominal Gross Domestic Product (GDP) in 2016 was estimated to be about 228 billion USD (International Monetary Fund, 2016), ranking 34 out of 229 when compared globally (Central Intelligence Agency, 2013). About half of the GDP is generated through services, with industry and agriculture composing about 30 % and 15 %, respectively. About 65 % of Bangladeshis are employed in the latter sector, with rice and fish being one of the key export products in addition to garments, leather, and jute (Yu et al., 2010). With an average annual economic growth of about 6 %, the country reached lower-middle income status in 2015, which translates to a gross national income (GNI) per capita above $1026 and below $4035. Simultaneously, the poverty headcount ratio, or percent of population below the national poverty line of $1.90 per day, has decreased from 44.2 % in 1991 to 18.5 % in 2010 (World Bank, 2017).

Bangladesh has seen a steady decrease in its rural population from 95 % in 1960 to 66 % in 2015 (World Bank, 2017). As a result, the country has several cities growing in population, such as Khulna (1 million) and Chittagong (4.5 million), with the largest being the capital Dhaka (17.5 million). The megacity lies about 200 km inland south of the confluence of the Ganges and Brahmaputra river and is surrounded by four smaller rivers (Figure 2.2). Flooding is a regular event, which impacts in particular the slum dwellers of Dhaka (estimated up to 30 % of the population) as slums are often located in the flood-prone areas. Due to continuing urban migration, Dhaka is expected to grow about 3 % per year, reaching close to 30 million people by 2030 (UN-Habitat, 2016), with the slum settlements expected to annually increase by more than 10 % during the coming years (Aßheuer et al., 2013).

## 2.2 Climate of Bangladesh

Bangladesh is located in a tropical monsoon climate. The Indian Summer monsoon is primarily driven by a strong land-ocean thermal contrast caused by differential heating of the land surface area in relation to the ocean, and results in three distinct seasons: mild winters (ONDJF), hot, humid pre-monsoon summers (MAMJ), and a humid and rainy monsoon season (JJAS) (Höfer and Messerli, 2006; Islam et al., 2005). Detailed information on the monsoon can be found in Chapter A.1.1.

In most of Bangladesh, the highest average temperatures are reached by April, with little variation in mean daily temperature until October (Figure 2.3). Average daytime summer temperatures range between 20 and 30 °C, with minimum temperatures increasing steadily during the monsoon season. The highest maximum daily temperature of 45.1 °C was recorded on May 19th, 1972 in Rajshahi. The coldest temperatures are usually recorded in January, with average daily temperatures between 16 - 20 °C during the day and seldom below 10 °C at night. The lowest minimum daily temperature recorded was 1.1 °C on February 3rd, 1905 in Rangpur (World Meteorological Organization, 2017).

90 % of all discharge flowing through Bangladesh is due to precipitation falling outside of the country. Precipitation in the GBM basin is largely convective precipitation with some orographic rainfall due to the Himalayas. Amounts vary greatly during the year, and there is a distinct dry period from December to March. About 60 - 70 % percent of the annual total precipitates during the Indian Summer monsoon season (JJAS), with a sharp increase following its onset (Immerzeel, 2008).

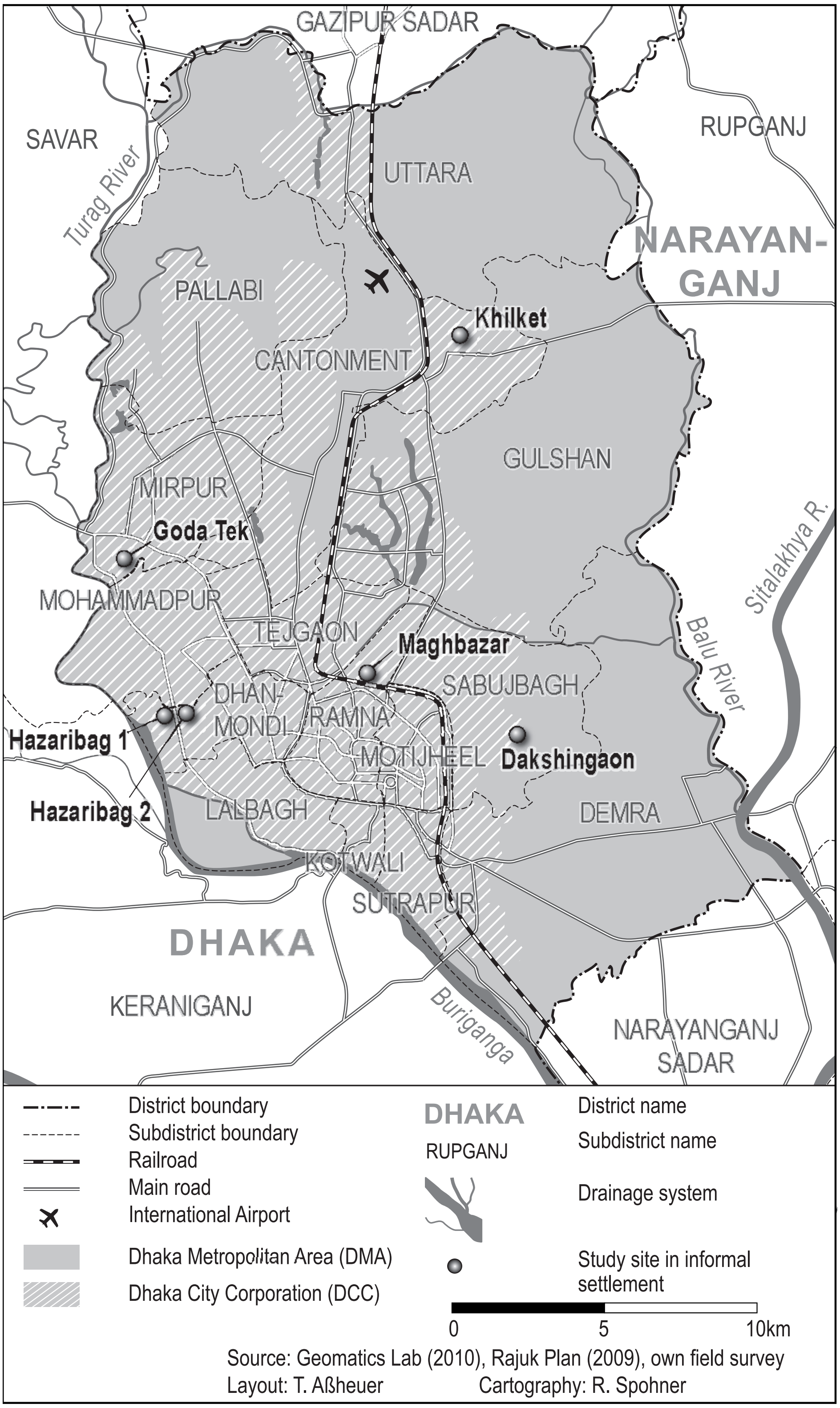


**Figure 2.2:** The city of Dhaka with selected slums that were visited in a field survey by Aßheuer et al. (2013); Figure from Aßheuer et al. (2013).

The southeastern coast of Bangladesh is first to experience the arrival of humid air masses from the Bay of Bengal, which marks the onset of the Indian Summer monsoon, with a mean arrival date of June 2nd. During the following two weeks, the system moves to the north where the flow is deflected westward by the Meghalayas, and continues on to reach northwestern Bangladesh, where the mean arrival date is June 15th (Ahmed and Karmakar, 1993). In mid-July, the summer monsoon is in full force across the GBM catchment as the pressure gradient between land and ocean becomes strongest. The monsoon has usually lost its intensity by the end of September (Höfer and Messerli, 2006; Islam et al., 2005; Rafiuddin et al., 2010). This movement of the Indian Summer monsoon reflects itself in the average annual rainfall across the Ganges basin, which varies from 2290 mm on the eastern end to 760 mm in the west (Gain and Giupponi, 2014). The Brahmaputra basin also shows varying amounts, with annual averages ranging between 734 mm in the Tibetean Plateau, which is shadowed by the Himalayas, to 2354 mm in the flood plains (Immerzeel, 2008).

In Bangladesh, the annual precipitation amount averages to $\sim$ 2300 mm, with most precipitation usually occuring between 21 to 9 BST (Bangladesh Standard Time) and a morning maximum at 6 BST (Islam et al., 2005). December and January rarely see any significant precipitation amounts; 90 % of the precipitation falls between April and September. Figure 2.3 shows the average monthly precipitation values along with the mean, maximum and minimum temperatures recorded at five climate stations (see also Chapter 3.1.1). The wettest region in Bangladesh is found near Teknaf on the south-eastern coast, where the monsoon initially hits Bangladesh and combined with orographic rainfall due to the Chittagong Hill tracts causes annual sums of over 3500 mm. Higher precipitation sums are also found in the northeastern region close to Srimongal and the Meghalayas. The lowest amounts are recorded in the far northwestern regions close to Rangpur, where annual precipitation amounts only reach about 1350 mm.

Precipitation outside of the monsoon season is much lower and mainly caused by heavy thunderstorms during the pre-monsoon season, accompanied by hail storms. The Bangladesh Meteorological Department classifies these storms as a major hazard for Bangladesh; they are among the strongest in the world (Cecil and Blankenship, 2012). The heaviest hailstone recorded worldwide weighed 1.02 kg and was found on April 14, 1986 near Khulna (World Meteorological Organization, 2017). Other pre-moonson hazards include tornados, such as the single tornado in the Manikganj district to the west of Dhaka which killed over 1000 people on April 26, 1989 (World Meteorological Organization, 2017). In addition, up to three tropical cyclones make landfall along the coast of Bangladesh each year during the post-monsoon months October and November (Alam and Dominey-Howes, 2014a).

## 2.3 Rivers in the Ganges-Brahmaputra-Meghna delta

The Ganges-Brahmaputra-Meghna basin covers parts of India, Nepal, China, Bhutan and Bangladesh, extending over more than 1.6 million km$^2$ (Figure 2.1) and is thus the third-largest river system in the world (Chowdhury and Ward, 2004). The three rivers

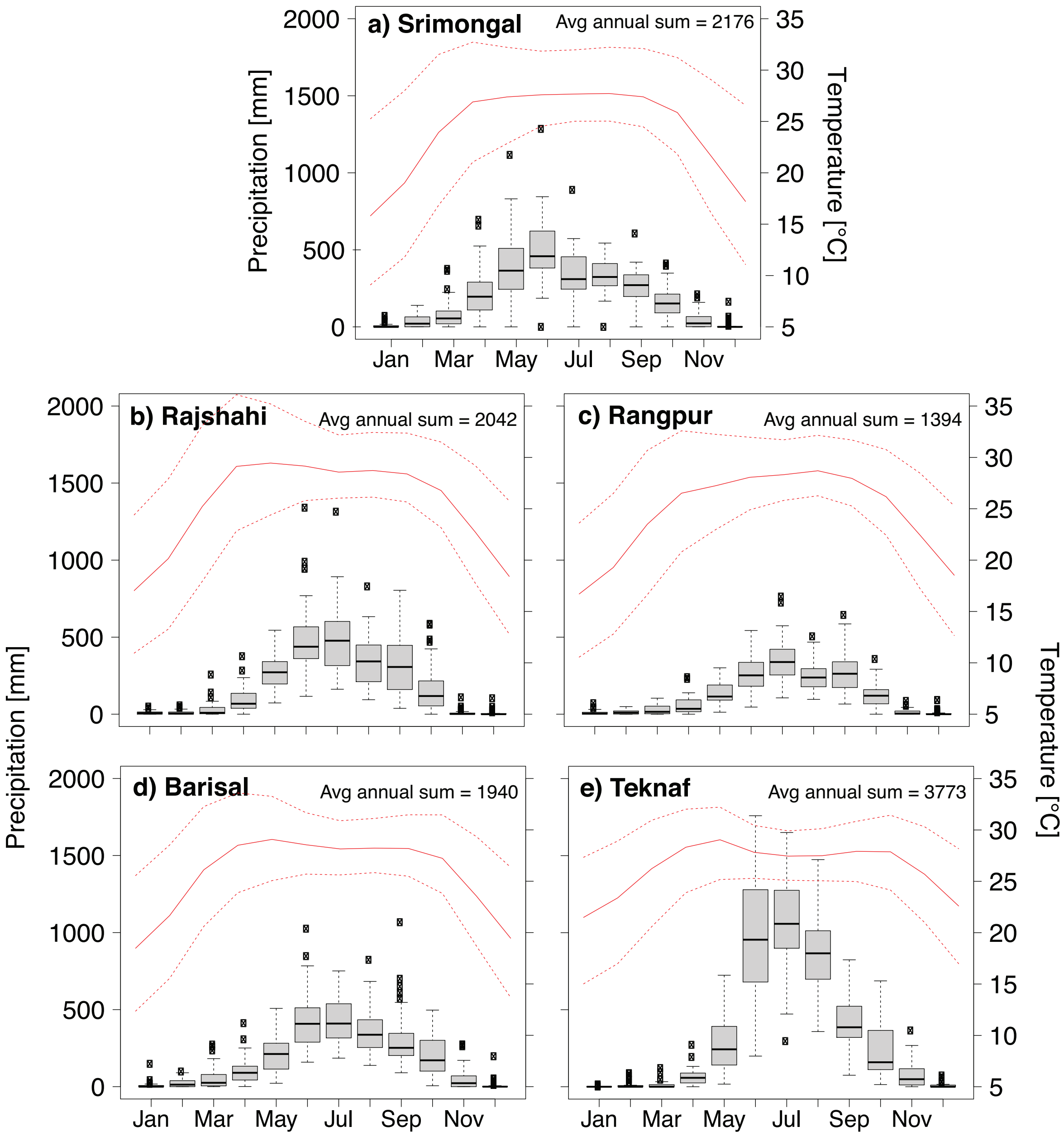


**Figure 2.3:** Boxplots of monthly precipitation values as well as the average, minimum and maximum monthly temperatures at five climate stations in Bangladesh based on data for 1948 - 2007, see Figure 3.1 for the location of the stations.

join in Bangladesh and drain into the Bay of Bengal, but 90 % of the discharge results from precipitation outside Bangladesh. About 80 % of Bangladeshis live in the GBM basin.

The Ganges river originates in the Indian state of Uttarakhand and turns southeast through the Gangetic Plain in Northern India before crossing into Bangladesh shortly after Farakka Barrage, reaching a total length of 2,510 km (see Section 2.3.1). Only 4 % of the Ganges catchment is within Bangladesh, but it affects more than 35 million Bangladeshis who live in the Southern Gangatic plains and depend on the river for mainly agricultural reasons (Swain, 1996). In Bangladesh, the Ganges delta is also home to several rare species such as *Platanista gangetica* (Ganges River dolphin) or *Panthera tigris tigris* (Bengal tiger), and supplies the Sundarban mangrove forests with fresh water (Gain and Giupponi, 2014).

The Brahmaputra originates as the river Tsangpo ("Purifier") in the Tibetian Plateau from the Chemayungdung Glacier, and continues southeast through China along the Himalayan belt before entering northeastern India. From there, it flows southwest until it enters northern Bangladesh at Bahadurabad, continuing on as the Jamuna and merging with the Ganges in the flood plain about 80 km west of Dhaka (Immerzeel, 2008). With a total length of ∼2,900 km and an average discharge of 20,670 $m^3/s$, it is both the longest and largest in terms of flow of the three rivers (see Table 2.1). The total sediment load is comparable to that of the Ganges (Subramanian and Ramanathan, 1996).

The Meghna river is created by the junction of the Surma and Kushiyara rivers close to the border of Bangladesh and comparatively short (∼280 km), but accounts for 43 % of the GBM catchment in Bangladesh (Aquastat, 2011). The tributaries originate in the Meghalaya hill tracts, which include record-holder rain gauge stations such as Mawsynram with an annual average of 11,872 mm (World Meteorological Organization, 2017). Regularly occuring flash floods make a noticeable impact further downstream where the Meghna joins the Padma at Chandpur. During the flood season, it can reach widths of up to 11 km, and it plays an important role in transporting sediments through the Lower Meghna estuary (Haque et al., 2016).

The flow regime in all three rivers is determined largely by Indian Summer Monsoon, including contributions from snowmelt from the Himalayas in particular for the upper reaches of the Ganges and Brahmaputra (Chowdhury and Ward, 2004; Immerzeel, 2008; Jian et al., 2009). The hydrological year thus runs from April 1st until March 31st, with a distinct flood season in the monsoon months (JJAS) and a pronounced low flow in the drier months (DJFM, Figure 2.4). The flow of the Brahmaputra rises earlier than the Ganges due to the earlier onset of the monsoon in the east, and usually peaks one month before the Ganges reaches its high flow in the months of August and September (Höfer and Messerli, 2006).

The Ganges and Brahmaputra have seen both sudden and more gradual river avulsions. During the flood season, short-term shifts in river channels frequently create islands and bars, called *chars*. Vegetated chars, which are extremely vulnerable to flooding and erosion, play an important role for the livelihood up to 600,000 people who mainly rely on agriculture, fishing and rearing livestock (Sarker et al., 2003). Larger avulsions

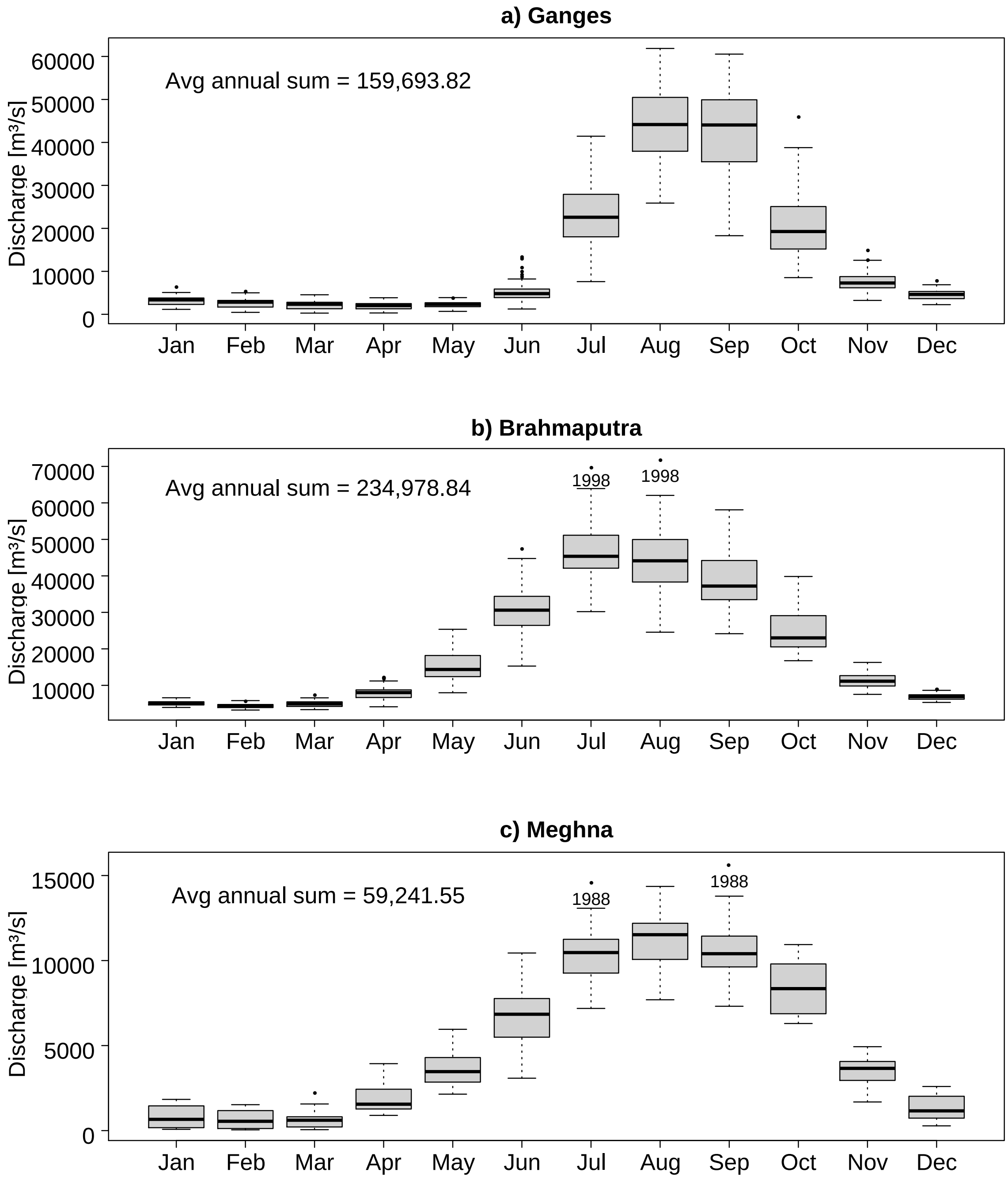


**Figure 2.4:** Boxplots of average monthly discharge of the a) Ganges, b) Brahmaputra and c) Meghna rivers based on data from 1953 - 2009 (Chapter 3.1.2). Outliers in the flood season are labeled with the year of occurrence.

**Table 2.1:** Statistics for the Ganges-Brahmaputra-Meghna basin from Aquastat (2011) and Gain and Giupponi (2014). Discharge statistics are for daily discharge (see Figure 2.4 for monthly discharge) and based on data from the Global Runoff Data Centre GRDC (Koblenz, Germany) and the Bangladesh Water Development Board BWDB (Dhaka, Bangladesh, see Chapter 3.1). Estimates for sediment load found in literature vary (Subramanian and Ramanathan, 1996; Islam et al., 1999; Akter et al., 2015).

| | Ganges | Brahmaputra | Meghna |
|---|---|---|---|
| Total catchment size [$km^2$] | 1,087,000 | 580,000 | 78,000 |
| Catchment size in Bangladesh [$km^2$] | 45,548 (4%) | 39,100 (7 %) | 35,000 (43 %) |
| Percent of Bangladesh | 37 % | 27 % | 24 % |
| River length [km] | 2,510 | 2,900 | 264 |
| Average discharge [$m^3/s$] | 13,541 | 20,670 | 5,400 |
| Maximum discharge [$m^3/s$] | 75,469 (Sept 1998) | 97,902 (Aug 1988) | 17,667 (Sep 1988) |
| Minimum discharge [$m^3/s$] | 183 (Mar 1997) | 2,466 (Apr 1962) | 0 (Feb 1983,84,86) |
| Sediment load [$10^6$ tonnes per year] | 316 to 660 | 402 to 721 | 10 to 25 |

can occur during or after severe flood events. Following the flood of 1787, the Tista river, which was then one of the main Ganges tributaries in Bangladesh, changed its course eastward to the channel of the present-day Brahmaputra. In the same year, the Brahmaputra itself began gradually shifting westward towards its present-day channel from its original course as a tributary of the Meghna (Höfer and Messerli, 2006). Due to the high population density in Bangladesh, a present-day shift would affect the livelihoods of millions.

### 2.3.1 Farakka Barrage

The GBM basin contains several large dams and hydropower facilities. The largest such structure directly affecting Bangladesh is Farakka Barrage, located on the Indian border with Bangladesh. Construction started in 1961, with the 2,245 m long dam beginning operating in 1975 to ensure continuing navigability of the Bhagirathi-Hoogly river system that connects the Ganges to the port of Kolkata. This flow diversion poses several socio-ecological issues affecting approximately 35 million Bangladeshis in the lower Ganges basin (Swain, 1996; Gain and Giupponi, 2014).

The construction of Farakka Barrage led to a significant decrease of dry season flow of up to 50 % (Figure 2.5). While this agrees with the findings of several authors (Mirza, 1997, 1998; Gain and Giupponi, 2014), studies disagree on the dam's impact during the flood season, with our analysis showing no significant change (Figure not shown). Section 5.1.4 and A.3.4 for a more extensive discussion on the role of Farakka Barrage.

About 20 % of Bangladesh is inundated on average each year (Figure 2.6). These floods play an important role in agriculture by fertilizing the alluvial soils. However, the country also regularly experiences severe dry years, and has been prone to extreme floods that can cover up to 70 % of the country. Both dry and wet years have a

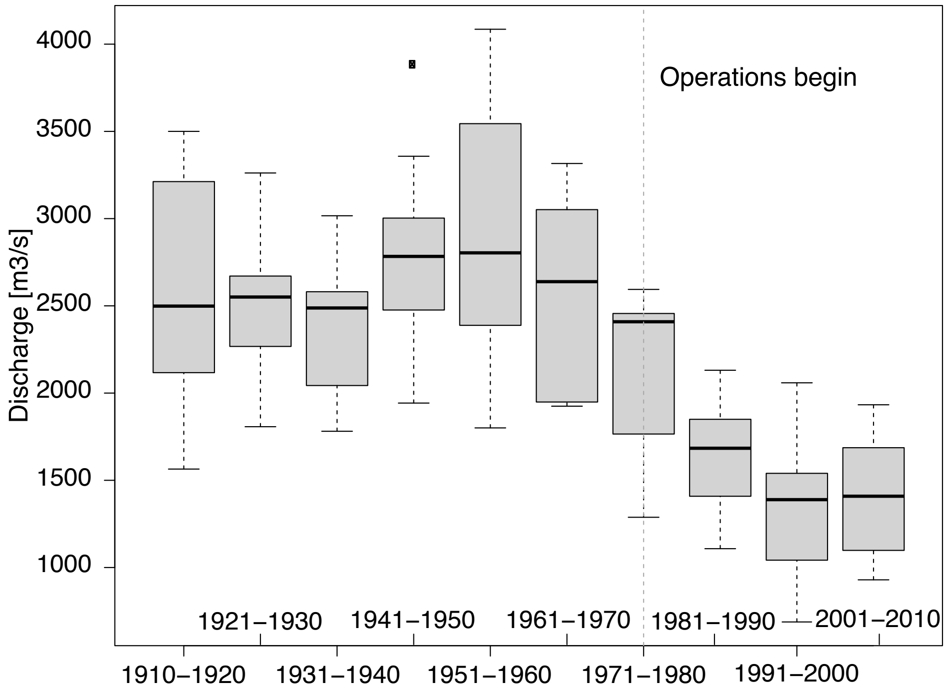


**Figure 2.5:** Boxplots of average dry season flow (JFMAM) of the Ganges at Hardinge Bridge station (Bangladesh), located downstream from Farakka Barrage. Averages are per decade and based on data from 1910 - 2010 (Chapter 3.1.2).

tremendous impact on the livelihoods of millions of Bangladeshis (Khalequzzaman, M.D., 1994; Mirza, 1997, 1998; Höfer and Messerli, 2006; Gain and Giupponi, 2014).

### 2.3.2 Low flow

Natural causes for low flow are e.g. reduced precipitation during a year of weak summer monsoon, increased evapotranspiration and reduced water storage (Smakhtin, 2001). For the Ganges and Brahmaputra, colder temperatures in the upper regions of the catchments can result in less melt water, so particularly cold years can also contribute to lower than usual flows. Anthropogenic factors such as irrigation, extreme groundwater pumping and Farakka Barrage exacerbate the situation (Höfer and Messerli, 2006; Mirza, 1998).

The months of regular low flow are JFM (Figure 2.4), which coincides with the dry season of Bangladesh (Figure 2.3). Years with minimal flooding include the year of 1978 (Höfer and Messerli, 2006), during which very little rainfall was recorded in Bangladesh in the months of August and September. While the Upper Ganges catchment experienced strong flooding, potential runoff was extremely low in the Brahmaputra and Meghna catchments. Combined with the low precipitation, the flooded areas were thus located solely in the western part of Bangladesh, with only 7.6 % of the country flooded as opposed to the average of 20.8 % (Figure 2.6, Höfer and Messerli (2006)).

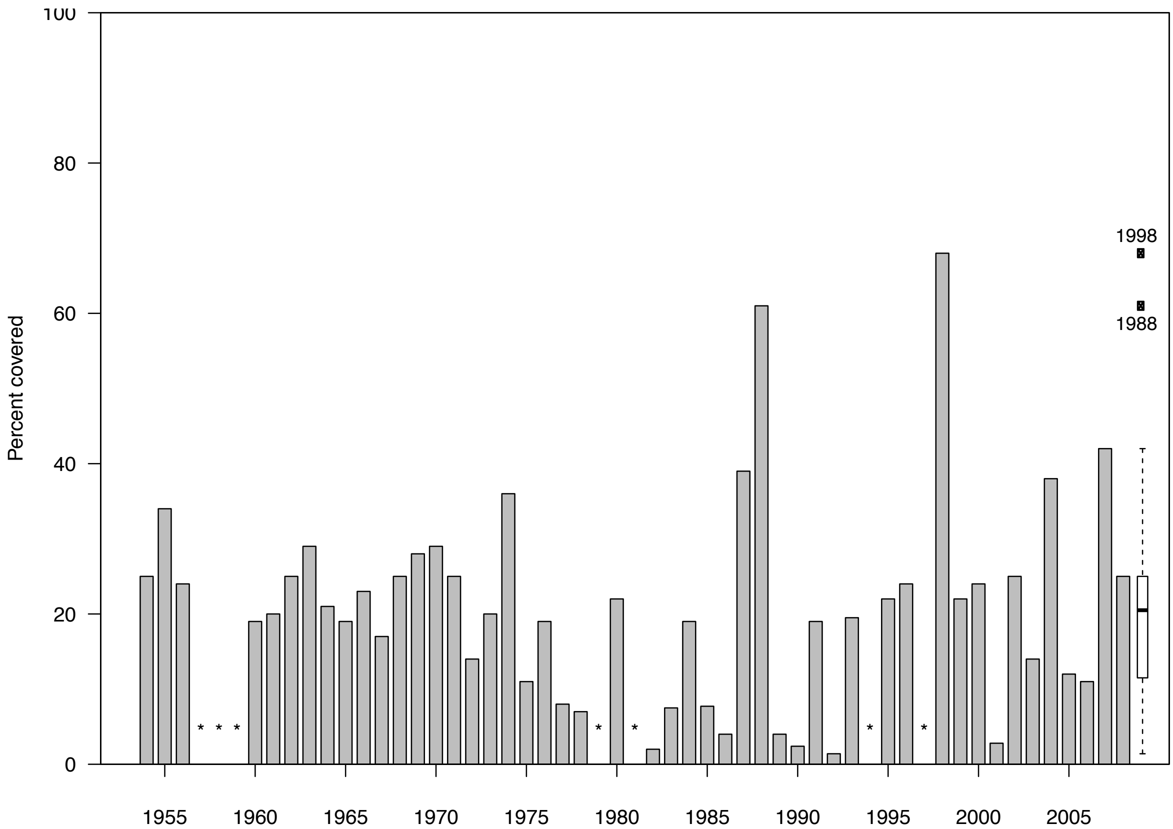


**Figure 2.6:** Average annual area inundated in Bangladesh in % land surface area based on data from 1954 - 2008. Stars indicate years with missing data. The last bar shows a boxplot indicating the mean and interquartile range over the entire period, with outliers labeled with the year of occurrence.

### 2.3.3 High flow

The Ganges, Brahmaputra and Meghna rivers are all mainly driven by monsoonal precipitation, thus floods occur largely in the monsoon season between June and September (Figure 2.4). While average floods typically inundate about 20 % of the country each year, extreme floods such as the event of 1998 can inundate over 65 % of the country (Figure 2.6). Single extreme rainfall events cause flash-flooding in the Meghna basin, but are excluded from further analysis due to scarce sub-daily data availability.

Flooding in the GBM delta is affected by a combination of different factors, ranging from hydrometeorological conditions such as the magnitude and frequency of precipitation, the synchronization of discharge peaks in the GBM rivers to soil conditions and evaporation in the basin as well as sea level rise at the river mouth outflow. El Niño Southern Oscillation (ENSO) events can also strongly contribute to extreme flood events via their influence on the Indian Summer monsoon (Chapter A.1.1, Mirza (2003b, 2011)). Anthropogenic influences also play a role via dams, irrigation, and the alteration of river channels so natural drainage areas are no longer available (Khalequzzaman, M.D., 1994; Höfer and Messerli, 2006). Despite wide-spread public belief that deforestation in the Himalayas is a major contributing factor to flooding in the GBM delta, Höfer and Messerli (2006) extensively analyzed these highland-lowland interactions and strongly disagree with this claim.

Major floods in Bangladesh seem to be mainly driven by the Brahmaputra, with the Ganges and Meghna playing secondary roles (Höfer and Messerli, 2006; Mirza, 2011). Because the three most devastating floods occurred within the past 25 years, a general increase in extreme events is perceived, which is discussed further in Chapter 4 (Khalequzzaman, M.D., 1994; Mirza, 2011).

One such extreme flood event occured in 1988. A first flood period occurred between mid-April and mid-May in eastern and north-eastern Bangladesh. Two main rainfall periods, one in early July and one in late August, with exceptionally strong rainfall in the Meghalayas, could be the reason for the second and third peaks in Meghna and Brahmaputra flows. The Ganges catchment did not see significantly higher-than-normal rainfall amounts, but exceptional snow and glacial melt is a possible reason for the high discharge amounts that combined with that of the Brahmaputra and Meghna on August 23rd. This in combination with a high groundwater table, in particular under the confluence of the GBM, caused nation-wide inundation of $\sim 63$ % well until mid-September (Höfer and Messerli, 2006; Khalequzzaman, M.D., 1994).

The flood of 1998 inundated $\sim 65$ % of the country for up to 67 days, with depths reaching over three metres in some regions (Höfer and Messerli, 2006; Khalequzzaman, M.D., 1994). Following a dry pre-monsoon and early monsoon period, significantly above-average rainfall occured in Bangladesh and the Meghalayas from July 5th until September 6th. This very humid monsoon is attributed to a La Niña event. After a particularly strong precipiation period from August 31st until September 6th, all three rivers reached their annual peak discharges between September 7th - 9th. Especially the regions around the confluence of the three rivers were flooded due to the backwater effects, with high tides worsening the situation (Höfer and Messerli, 2006).

# Chapter 3

# Data and methods

This chapter provides an overview of the meteorological and hydrological data as well as the methods used in the following chapters.

## 3.1 Data

Observations for meteorological as well as hydrological variables in Bangladesh are available up to 100 years as detailed below. The two main sources for data used in this study, the Bangladesh Meteorological Department (BMD) and the Bangladesh Water Development Board (BWDB), provide homogeneous and quality-controlled data. Where appropriate we treated for missing values using neighbouring stations.

### 3.1.1 Temperature and precipitation

With data sets available from local partners at the BMD as well as the German Weather Service, our final data set was based on daily rain gauge measurements at 33 stations covering Bangladesh for 60 years (1948 - 2007). The same data set also contains other variables such as daily mean, minimum and maximum temperature. Less than 5 % of all values are missing for most stations. A principle component analysis using the precipitation data for the pre-monsoon and monsoon season reveals five precipitation subregions, with regional differences generally much smaller than seasonal differences (Figure 3.1).

### 3.1.2 Hydrological data

Daily discharge data was obtained from the Global Runoff Data Centre (GRDC) as well as the Bangladesh Water Development Board (BWDB) for the Ganges, Brahmaputra and Meghna rivers. The available time periods for each of the stations as well as basic statistics on e.g. average daily flow or annual minimum and maximum discharges are

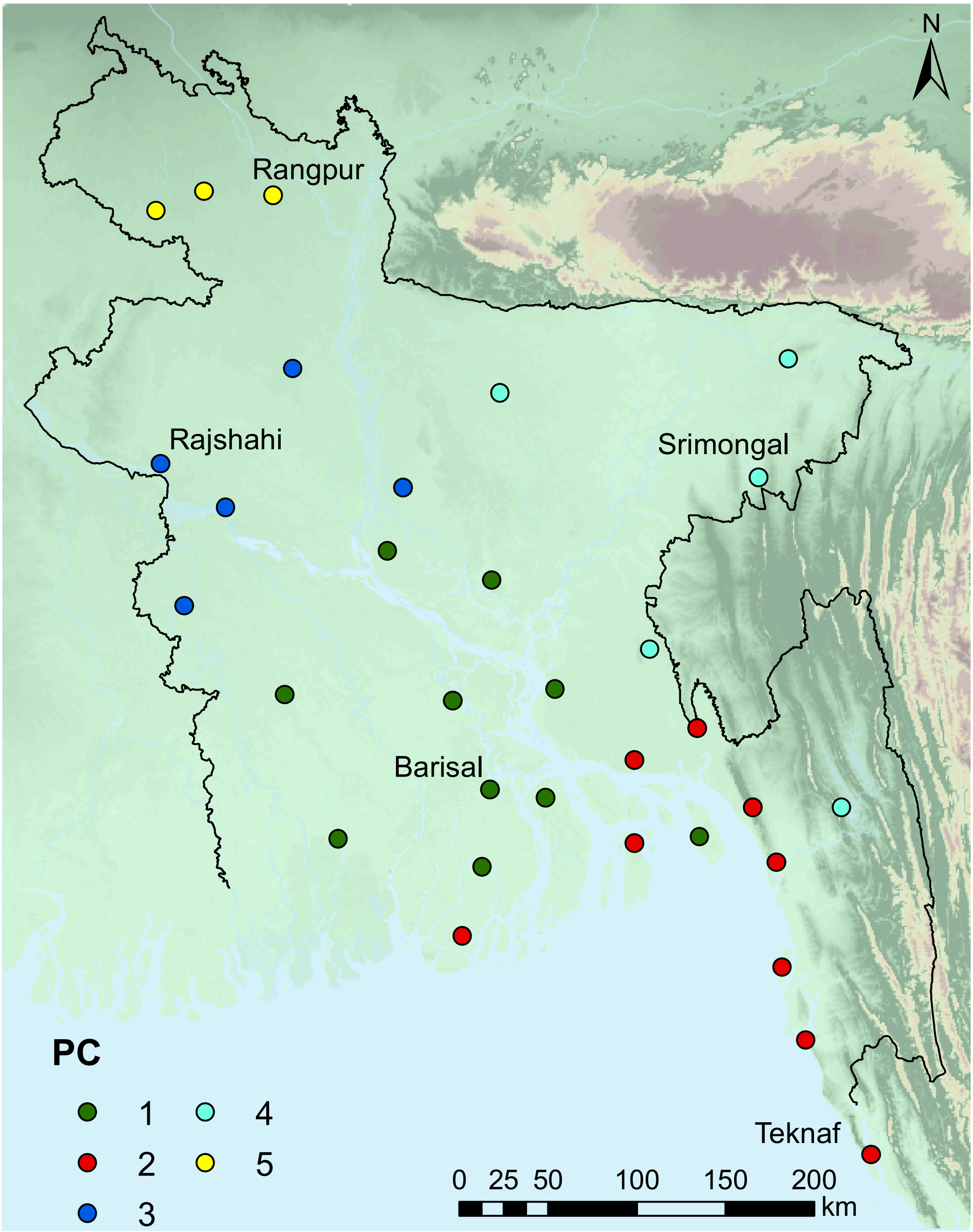


**Figure 3.1:** Location of the 33 climate stations in Bangladesh and the precipitation regime during the pre-monsoon and monsoon season derived from a principle component analysis for the years 1948 - 2007. The station names indicate the principal stations.

listed in Table 2.1. The chosen stations all have a consistent data set with few missing values, especially during the flood season between June and September.

Daily water level data is provided by the Bangladesh Water Development Board for four stations surrounding the city of Dhaka (Figure 2.2). The water level is measured daily, with values given both for low and high tides. Since this study focuses on flooding, the high tide data set is used unless specified otherwise. Table 3.1 lists the duration and percent missing values for the time series, with Dhaka (SW42) having the longest time series beginning in April 1909. All four time series $wl_i, i = SW42, SW179, SW299, SW302$ are available for at least 50 years, although some stations are prone to gaps, especially Demra (SW179). Even though the stations are located on different rivers surrounding Dhaka, these rivers lie within 30 km of each other and are interconnected. Therefore, while the stations exhibit slight differences in mean, standard deviation and number of days above danger level, these are rather small. Indeed, the correlation between all four stations is $r_{Pearson} = 0.98$ or higher for all combinations. As shown in Figure 3.2, the residuals obtained by subtracting the annual cycle from the original time series are also correlated strongly. Since the trend analysis following in Chapter 4 requires a long time series with as few gaps as possible, the high correlation between the stations is used to impute missing values for one of the time series using the information collected at the three neighbouring stations. Figure 4.6 shows the results of a logistic regression between one station being above the danger level depending on the water level of another station for each pair of stations. It follows that once the danger level (gray line) is exceeded at Dhaka (SW42), the probability of the other three stations also being above danger level is above 85 %. The time series of Dhaka (SW42) is therefore chosen as the time series to impute.

**Table 3.1:** Description of water level data for the four stations surrounding Dhaka city. The parenthesis in the second column show values for the imputed data set.

| | Dhaka (SW42) | Dhaka (SW42) | Demra (SW179) | Tongi (SW299) | Mirpur (SW302) |
|---|---|---|---|---|---|
| Duration | Apr 1909 to Nov 2009 | Jan 1953 to Nov 2009 | Apr 1952 to Nov 2009 | Apr 1960 to Nov 2009 | Jan 1953 to Nov 2009 |
| Percent missing | 11.5 % | 14.1 % (2.4 %) | 19.8 % | 7.1 % | 7.1 % |
| Mean [m] | 3.03 | 3.06 (3.03) | 3.20 | 3.15 | 3.25 |
| Stdev [m] | 1.48 | 1.43 (1.45) | 1.45 | 1.62 | 1.55 |
| Danger level [m] | 6.00 | 6.00 | 5.75 | 6.08 | 5.94 |
| Average NOD | 6.0 | 6.4 (6.7) | 12.0 | 10.6 | 19.1 |

The missing values are estimated based on a combination of the mean annual cycle of station Dhaka (SW42) and a linear regression between the residuals of the stations (see Chapter 3.2.1). The following steps describe the method in more detail:

- Time series $wl_i, i = SW42, SW179, SW299, SW302$ are smoothed by moving averages and detrended. The annual cycle is then estimated from the mean of all observations for every day per year over the entire period. Subtracting this from the original time series leads to the residuals $wl_i^{obs,res}$. The strong correlation

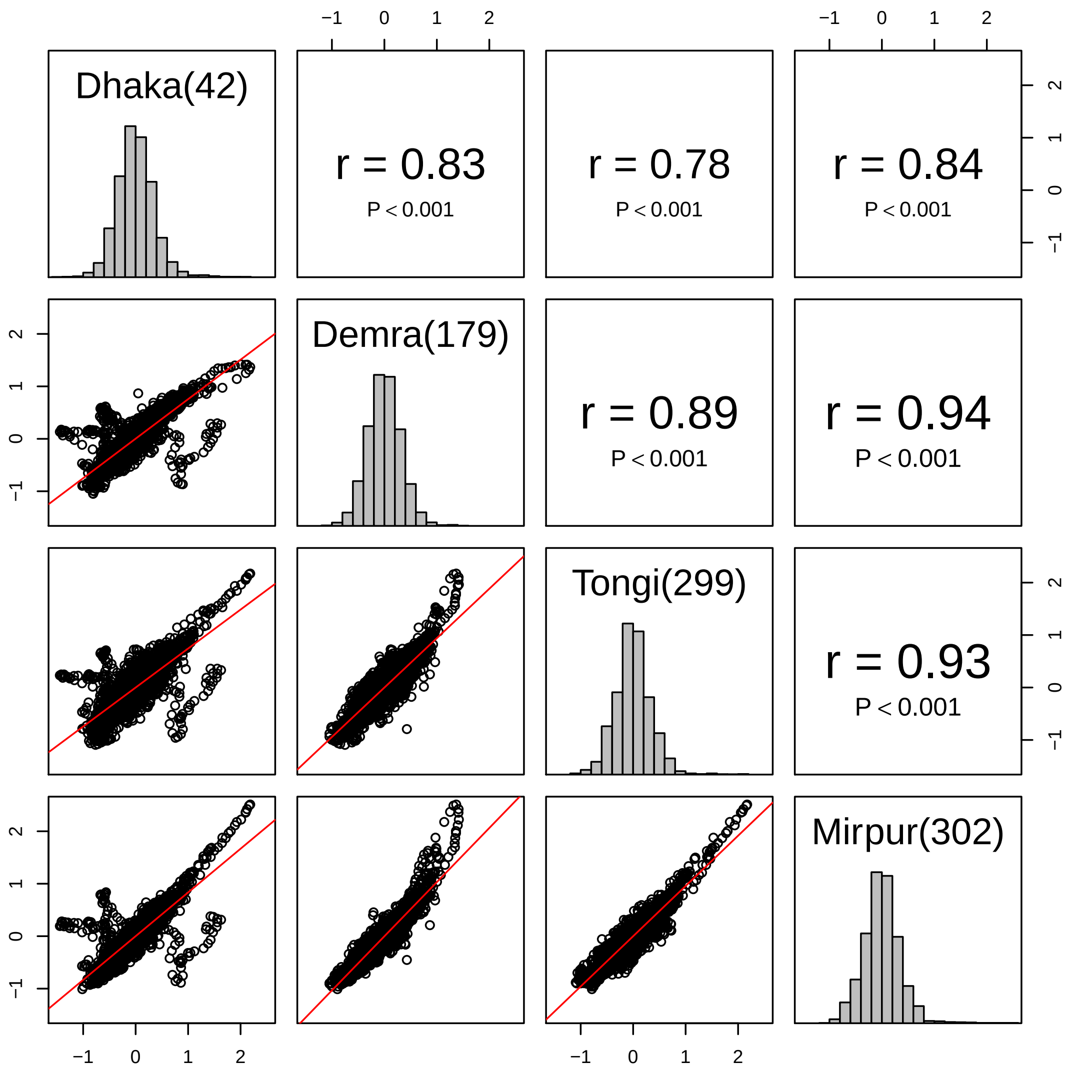


**Figure 3.2:** Correlation between the residuals [m] of the four water level stations surrounding Dhaka. The diagonal shows histograms for the individual stations, the panels below the diagonal depict the scatterdiagram of paired stations with a linear regression line drawn. The explained variance, Pearson's correlation coefficient as well as the corresponding p-value are shown in the panels above the diagonal. All correlations are significant at the 0.001 level.

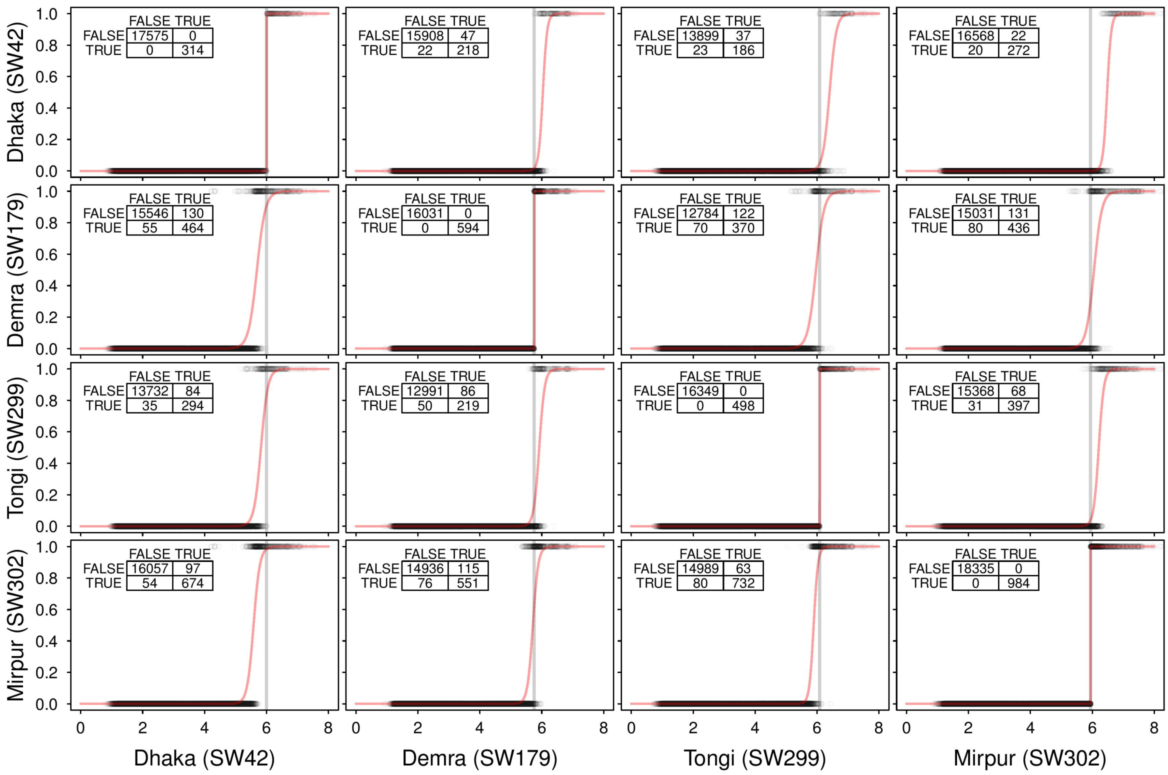


**Figure 3.3:** Logistic regression for four water level stations in Dhaka to treat missing data (1953 - 2007).

between the stations also exists between the residuals, as can be seen in Figure 3.2.

- A linear regression model $wl_{SW42}^{obs,res} = \beta wl_{SW302}^{obs,res} + \epsilon$ is set up between the residuals of Dhaka (SW42) and the station with the strongest correlation in the anomalies, Mirpur (SW302).

- The model fit (reaching an adjusted $r^2 = 0.78$) is then used to predict the residuals $wl_{SW42}^{mod,res}$ for those days with missing values at station Dhaka (SW42).

- The imputed time series for Dhaka (SW42) $wl_{SW42,imp}$ is obtained by filling the missing values of $wl_{SW42}$ by adding $wl_{SW42}^{mod,res}$ to the temporally corresponding seasonal cycle component.

In this way, the missing data for the water level station Dhaka for the time period 1953 - 2009 could be decreased from 14 % to 2 %. The chosen imputation method adequately reconstructs the time series, as the mean and variance differ only slightly (Table 3.1. A two sample t-test does not reject the null hypothesis $H_0$ of equal means ($p$ = 0.15), while a F test on the variances of the observed and imputed time series for Dhaka (SW42) can not reject the null hypothesis $H_0$ that the variances are equal ($p$ = 0.14). The differences between both the mean and the variance of the original and imputed data set are therefore not significantly larger than zero. For further validation, all residuals of Mirpur (SW302) are used to predict the entire time series of Dhaka (SW42) $wl_{val}$. The RMSE is then computed by $RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(wl_{obs} - wl_{val})^2} = 0.20m$. The low RMSE value also shows that the method is suitable when imputing missing values to create a longer data set with fewer gaps.

### 3.1.3 Mortality data

Mortality data for the Dhaka Statistical Metropolitan Area was obtained from the Bangladesh Bureau of Statistics (BBS) for January 2003 - December 2007. The data lists fatalities per day, and stems from the Sample Vital Registration System (SVRS). The SVRS is conducted by the BBS by splitting the population group into 1,000 primary sample units (PSUs). Each PSU consists of about 250 households who are in turn comprised of an average of 4.7 household members. The system not only records information on the infrastructure of the households, but also vital population statistics including mortality. 80 PSUs lie in Greater Dhaka, with a total of 16,024 households actively participating during the chosen time frame. Since September 2002, the SVRS relies on a dual recording system for it's statistics: all data is collected both by a local member located within the PSU, as well as by a BBS official every three months. In case of discrepancies between the two data sets, a BBS official revisits the site to obtain the correct information and two surveys are then compared to ensure high quality of data. Once discrepancies between the two data sets are found, the official revisits the site to obtain the correct information (Bangladesh Bureau of Statistics (BBS), 2008). The survey discloses the date of death, age and sex of the deceased, as well as a cause of death. However, the latter is not medically certified. We excluded maternity-related deaths, leading to a total of 5,770 death counts included in our analysis. Further information regarding this data set can be found in Burkart et al. (2011a, 2014b) and Thiele-Eich et al. (2015).

## 3.2 Methods

In the subsequent chapters, a variety of methods was used to study hydrological processes in Bangladesh. Exploring relationships between two or more variables initially requires an exploratory data analysis to check for e.g. the type of variable, shape of their distributions, and associations with other variables. This is followed by a four-step model fitting procedure, namely model specification, parameter estimation, model validation and finally statistical inference. The following subsections present these four steps for generalized linear models (GLM), of which a subset are used to study trends in time series data (Chapter 3.1 and 4). An introduction to distributed lag non-linear models used to examine the connection between extreme water levels and mortality (Chapter 4) as well as extreme value theory applied in Chapter 4 follows. The eDPSIR framework used for Chapter 5 is described in Section 3.2.4.

### 3.2.1 Generalized linear models

In the following, we describe the four-step model fitting procedure for generalized linear models, which allow to specify a model with response variables that follow different distributions using different link functions that serve as a transformation of the response variable. The following is largely based on Nelder and Wedderburn (1972) and Dobson and Barnett (2008).

#### Model specification

Since our focus is on the connection of a single response variable $Y$ to several explanatory variables, presenting an univariate model is sufficient. We assume that the observed variables $y_1, y_2, ...y_n$ are realiziations of the random variables $Y_1, Y_2, ..., Y_n$ with a probability distribution belonging to the exponential family of distributions

$$f(y;\theta,\phi) = \exp\left\{\frac{y\theta - b(\theta)}{a(\theta)} + c(y,\phi)\right\} \tag{3.1}$$

where $a, b$ and $c$ are known functions associated with the distribution of the response. The paramerters $\theta$ and $\phi$ are called the *canonical* parameter and the *dispersion* parameter, respectively. The expectation $E(Y)$ can be linked by the function $g(\cdot)$ to a linear combination of the explanatory variables $x_1, x_2, ..., x_n$ through an equation of the general form

$$g(E(Y)) = \beta_0 + \beta_1 x_1 + \cdots + \beta_p x_p. \tag{3.2}$$

We use general linear models as well as logistic regression and describe these in further detail below.

**General linear models** Generalized linear models (GLMs) are an extension of the general linear model used for linear regression. This special case arrives if the response variable on hand follows a normal distribution with expectation $\mu$,

$$Y \sim N(\mu, \sigma^2) \tag{3.3}$$
$$E(Y) = \mu \tag{3.4}$$
$$g(\mu) = \mu. \tag{3.5}$$

The canonical link funciton $g(\cdot)$ is the identical function. Thus the linear predictor, i.e. the right hand side of (3.2), can be interpreted on the scale of the response.

**Logistic regression** Logistic regression is a non-linear transformation of linear regression used for binary responses, e.g. whether or not a certain threshold is crossed. The relationship between a variable and its response can be described by defining a binary random variable as

$$Z = \begin{cases} 1 \text{ if the outcome is a } \textit{success} \\ 0 \text{ if the outcome is a } \textit{failure} \end{cases} \tag{3.6}$$

with $Pr(Z = 1) = \pi$ and $Pr(Z = 0) = 1 - \pi$, with $Z$ following the Bernoulli distribution, also a member of the exponential family,

$$Z \sim Bern(\pi) \tag{3.7}$$

$$E(Z) = \pi \tag{3.8}$$

$$g(\pi) = \text{logit}(\pi) = \log\left(\frac{\pi}{1-\pi}\right). \tag{3.9}$$

Here the logit function serves as link between the expectation $\pi$ and the linear predictor. Thus, the right hand side of (3.2) has to be interpreted on the logit scale.

### Parameter estimation

To arrive at the parameter estimates $\hat{\beta}_j$ of parameters $\beta_j$ maximum likelihood estimation (MLE) is applied as described in the following.

The likelihood function $L(\boldsymbol{\beta}; \boldsymbol{y})$[1] returns the likelihood depending on the parameter vector $\boldsymbol{\beta} = [\beta_0, \beta_1, ..., \beta_p]^T$ from the parameter space $\Omega$ based on the fixed random vector $\boldsymbol{y} = [Y_1, ..., Y_n]^T$. $\hat{\boldsymbol{\beta}}$ is the value that maximizes the likelihood function

$$L(\hat{\boldsymbol{\beta}}; \boldsymbol{y}) \geq L(\boldsymbol{\beta}; \boldsymbol{y}) \text{ for all } \boldsymbol{\beta} \text{ in } \Omega. \tag{3.10}$$

As the logarithmic function is monotonic, $\hat{\boldsymbol{\beta}}$ also maximizes the log-likelihood function $l(\boldsymbol{\beta}; \boldsymbol{y}) = \log L(\boldsymbol{\beta}; \boldsymbol{y})$:

$$l(\hat{\boldsymbol{\beta}}; \boldsymbol{y}) \geq l(\boldsymbol{\beta}; \boldsymbol{y}) \text{ for all } \boldsymbol{\beta} \text{ in } \Omega. \tag{3.11}$$

The latter is easier to handle both analytically and numerically. $\hat{\boldsymbol{\beta}}$ is obtained by solving for the differentials of the log-likelihood equation

$$\frac{\partial l(\boldsymbol{\beta}; \boldsymbol{y})}{\partial \beta_j} = 0 \text{ for each element } j = 0, 1, \ldots, p. \tag{3.12}$$

The optimization is performed by using the Fisher scoring algorithm as implemented in the `glm` function in R.

[1] Note that this is algebraically identical to the joint probability density function $f(\boldsymbol{y}; \boldsymbol{\beta})$ of the $Y_i$'s, but here $\boldsymbol{\beta}$ are fixed while the random variables $\boldsymbol{y}$ vary.

As $\hat{\boldsymbol{\beta}}$ depends on the random variable $\boldsymbol{y}$, it is random itself and satisfies several properties such as consistency, which states that

$$P(\lim_{n\to\infty} \hat{\boldsymbol{\theta}} = \theta) = 1, \text{ with } \theta \text{ the true parameter} . \tag{3.13}$$

Other properties include asympotic normality, efficiency or sufficiency and are described in further detail in Dobson and Barnett (2008).

### Model validation

**Diagnostics for the linear models** For a model as specified in Sect. 3.2.1 that adequately represents the data, *standardized residuals* should be approximately normally distributed and independent from each other as well as unrelated to the explanatory variables. In addition, the variance of errors should remain constant over time, or *homoscedastic*.

For the linear model the standardized residuals are formulated as

$$r_i = \frac{y_i - \hat{\mu}_i}{\hat{\sigma}}. \tag{3.14}$$

The first can be verified using graphical techniques such as normal probability plots, where residuals are plotted in ranked order against their expected values assuming these are also normally distributed. The plot should show an approximately straight line, with departures indicating departures from normality, and are useful to detect outliers. Independence can be checked by analyzing residual autocorrelations or a residual time series plot, with e.g. steadily increasing residuals calling for more complex model set ups. By plotting the standardized residuals against individual explanatory variables, any emerging patterns indicate the need for an alternative model set up.

Also note that given the observations follow the normal distribution, minimizing the sum of squared residuals $\sum(y_i - \hat{\mu}_i)^2$ is identical to maximizing the log-likelihood in Equation (3.11) (Nelder and Wedderburn, 1972).

**Bootstrap** Hydrological time series, e.g. observed flood events, often exhibit a positive autocorrelation. If this autocorrelation still remains in the residuals the assumption of uncorrelated errors is not fulfilled. This leads to an underestimation of error for the estimated parameters (Arlot and Celisse, 2009). To handle this problem, a bootstrap is performed by choosing a value $x_i$, leaving out a window of length $l/2$ on both sides, where $l$ is the value at which the acf is no longer dominant. The glm is then set up on the remaining values, and used to predict from $x_i$. This process is repeated by a sufficient high number, i.e. 500 times and provides a more robust estimate of the error.

**Cross-validation** In addition *cross-validation* is used to check model prediction performance and to detect problems such as overfitting or finding particularly influential observations. Rather than using the entire available data set to set up the model, the data is split into a training and a testing set. The parameters of the model are then estimated from the training data set, with the testing set used for predictions (Arlot and Celisse, 2009).

In a k-fold cross-validation, the data is split into $k$ blocks of equal length, with each block used once as the testing set. The average error over all k testing sets is then reported as the cross validation statistic. In the case of highly autocorrelated variables which violate the independecy assumption, thus leading to an underestimation of the model error, LOOCV is adapted by not only choosing LOO as the test set, but also including values from a window of a length similar to the lag at which the autocorrelation becomes negligible. For further details, see Arlot and Celisse (2009).

### Statistical inference and model interpretation

**Hypothesis tests** The estimated parameters $\hat{\beta}$ are subject to sampling variations. The $\alpha$% confidence interval of the estimated population parameter describes the range in which *true* parameter lies with probability $\alpha$%.

Confidence intervals for the estimated parameter/gof statistic can be obtained by *bootstrapping* (Efron and Tibshirani, 1994). Steps for this procedure include resampling the data set $n$ times with replacement, calculating the parameter and thereby retrieving a sampling distribution for the parameter or test statistic in question. 95 % confidence intervals are then the range between 2.5 percentile and 97.5 percentile.

Hypothesis tests are used to infer how well a set of candidate models fit the data. For this, a goodness of fit statistic $G$ is required on which a hypothesis test can then be conducted. The steps of such a test are

- specifying a simple model $M_0$ (corresponds to null hypothesis $H_0$), which is a special case of a more general model $M_1$ (corresponds to alternative hypothesis $H_1$),
- fitting both models and calculating $G_0$ and $G_1$,
- using the difference $G_1 - G_0$ or the ratio $G_1/G_0$ to compare the two fits, and
- testing $H_0 : G_1 = G_0$ against $H_1 : G_1 \neq G_0$ using the sampling distribution of the difference or the ratio. In the present studies the sampling distribution are commonly assessed by bootstrapping.

If $H_0$ cannot be rejected, the simpler model $M_0$ is retained on the grounds of parsimony (Sober, Elliott, 1981).

**Goodness of fit measures** Several goodness of fit measures exist such as the coefficient of determination, which includes the ratio of the model error to the variance of the dependant variable and is written e.g. for linear models as

$$R^2 = 1 - \frac{\sum(y_i - \hat{\mu}_i)^2}{\sum(y_i - \bar{y})^2} \tag{3.15}$$

$R^2$ thus describes how well the model explains the variation of the data. In a simple linear regression $R^2$ is equivalent to the squared Pearson correlation coefficient between the reponse $y$ and the predictor $x$. Although it is easy to interpret, $R^2$ increases as the number of model parameters increase, which makes adjustments to Equation (3.15) necessary for models with large parameters with respect to the sample size. Per the Wherry formula (Yin and Fan, 2001)

$$R^2_{adj} = 1 - (1 - R^2)\frac{n-1}{n-p-1}. \tag{3.16}$$

As the sample size $n$ increases or the number of parameters $p$ decreases, the difference between $R^2$ and $R^2_{adj}$ becomes smaller.

For a logistic regression, the deviance

$$D = -2\sum_{i=1}^{n} (y_i \log(\hat{\pi}_i) + (1 - y_i)\log(1 - \hat{\pi}_i)) \tag{3.17}$$

can be used to assess the goodness of fit and testing hypothesis, with $y_i$ the observed "successes" and "failures", and $\hat{\pi}_i$ the fitted values (Dobson and Barnett, 2008).

In addition to goodness of fit measures and cross validation procedures as described in Section 3.2.1, different model selection criteria can be used such as the Akaike Information Criterion AIC or the Bayesian Information Criterion BIC (Akaike, 1973; Burnham and Anderson, 1973).

When comparing several candidate models for a certain data set, the Akaike Information Criterion AIC estimates the models' prediction performance relative to each other and aims at finding the model with the best predictions. For $n \gg p^2$ ,

$$AIC = -2l(\hat{\boldsymbol{\theta}}; \boldsymbol{y}) + 2p, \tag{3.18}$$

with $p$ the number of parameters.

If $n \gg p$, the AIC can be corrected for finite sample size (Burnham and Anderson, 1973). For univariate linear models with normally-distributed residuals,

$$AICc = AIC + \frac{2p(p+1)}{n-p-1}, \tag{3.19}$$

which converges to AIC as $n$ increases.

Choosing the lowest AIC calculated from all candidate models $M_i$ is equivalent to minimizing the information loss between $M_i$ and the true model (which is in practice unknown and not assumed to be included in the candidate model set). However, minimizing the AIC provides no information on whether or not the chosen model is of high quality. AIC can also be used to compare two models which are not nested, as long as the models were constructed on the same data. This is not the same for the likelihood ratio test, which only works on nested models.

The Bayesian information criterion BIC is derived with the aim of selecting the true model, which is assumed to be included among the candidate models $M_i$. The BIC is formulated similar to the AIC as

$$BIC = -2l(\hat{\boldsymbol{\theta}}; \boldsymbol{y}) + \log(n) \cdot p, \tag{3.20}$$

with $p$ the number of observations. It has a larger penalty term than the AIC resulting in simpler models being chosen when using the BIC. Note that Stone (1977) showed that leave-one-out CV and AIC are asymptotically identical, as are k-fold CV and BIC (with the k folds carefully chosen).

While the above methods can be used to compare which of several models is a better fit, the interpretation of the model should rely on the magnitude of the parameters and the associated confidence in the parameter estimation.

### 3.2.2 Distributed lag non-linear models

Generalizing GLMs to include non-linear cases leads to generalized additive models (GAM, Hastie and Tibshirani, 1990) of the form

$$g(E(Y)) = \beta_0 + f_1(x_1) + f_2(x_2) + \cdots + f_m(x_m), \tag{3.21}$$

where $f_i(x_i)$ are smooth functions, i.e. have continuous derivatives up to a certain order, of the predictors $x_i$. A GAM is therefore a generalization of a GLM, which in turn is a generalization of a general linear model or simple linear regression.

Setting up a model which relates extreme water levels and mortality requires taking into account a time lagged exposure-response relationship as the effects of extreme water levels can both be noticed directly, e.g. via drowning, as well as after a certain period of time, e.g. via a disease. The effect on mortality measured at any given time can however usually not be ascribed to a single environmental expose, but rather for multiple exposure events, i.e. multiple days of flooding. Distributed lag models are a form of GAM based on a regression equation in which the current dependent variable, or increase in risk $s(x,t)$, is predicted based on both current as well as previous values of the explanatory variable over the period $\Delta t = [t_0, t_1]$, with $t_0$ and $t_1$ the first and last time step of relevant exposures:

$$s(x,t) = \int_{t_0}^{t_1} x_u \cdot w(t-u)du. \tag{3.22}$$

The weighting function $w(t-u)$ assigns weights to previous exposures to represent their individual effect on the dependent variable. The model in Equation (3.22) can be rephrased to express the risk along lag $l \in [l_0, L]$, with $L - l_0 = t_1 - t_0$:

$$s(x,t) = \int_{l_0}^{L} x_{t-l} \cdot w(l)dl \approx \sum_{l=l_0}^{L} x_{t-l} \cdot w(l). \tag{3.23}$$

The weighting function $w(l)$ is called the *lag-response* function. These equations do not yet take into account the temporal dimension in the exposure-response relationship. Gasparrini (2014) describes how this can be achieved with distributed lag non-linear models (DLNMs), an approach originally stemming from time series analysis (Armstrong, 2006). Here, a function $s(x,t)$ describes this relationship by taking into account the exposure history of $x$ at times $t$ in the *exposure-response* function $f(x)$ as well as the lag $l \in [l_0, L]$ in the lag-response function $w(l)$:

$$s(x,t) = \int_{l_0}^{L} f(x_{t-l}) \cdot w(l)dl \approx \sum_{l=l_0}^{L} f(x_{t-l}) \cdot w(l). \tag{3.24}$$

As $f(x) \cdot w(l)$ can usually not be expressed through a linear combination, this would result in nonlinear parameters and thus require optimization routines. While this is at best inconvenient, Equation (3.24) further assumes independency between $f(x)$ and $w(l)$, for which the exposure-response relationship needs to be identical at each lag $l$, as well as equall response-lag relationship for each $x$. This requirement is not conducive to our study, where independency cannot be guaranteed. To relax this premise, $s(x,t)$ can be expressed by defining a *cross-basis* $s(x,t)$ as the bidimensional functional space in which $f \cdot w(x_{t-l}, l)$ specifies the combined relationships along the predictor $x$ and the lag dimenson $l$:

$$s(x,t) = \int_{l_0}^{L} f \cdot w(x_{t-l}, l)dl \approx \sum_{l=l_0}^{L} f \cdot w(x_{t-l}, l). \tag{3.25}$$

The tensor product expresses the *exposure-lag-response* function $f \cdot w(x_{t-l}, l)$ as a linear combination of variables and parameters. The algebraic notation of this tensor product is described in further detail in Gasparrini (2014), but most importantly, the DLNM model specification relies only on the choice for functions $f(x)$ and $w(l)$, e.g. splines, step-wise functions, etc. Previous knowledge regarding i.e. a range of possible time lags can be incorporated through the choice of specific functions and constraints. The estimation of the $v_x \times v_l$ parameters $\boldsymbol{\eta}$ is then conducted with standard regression models. While tests for constrained models (lag-response, exposure-response) as well as confidence intervals are available, a more general hypothesis testing procedure for DLNMs is still under development as the two null hypotheses $H_0 : f(x) = x$ and $H_0 : w(l) = c$ are not independent from one another (Gasparrini, 2014). To still be able to select the best model, a simulation study by Gasparrini (2014) found that a AIC-based selection tends to slight overfitting, but still outperform the much stronger underfitting apparent when using the BIC, perhaps due to the stronger penalty inherent in the latter criterion.

### 3.2.3 Block maxima approach - Extreme value theory

To study rare events such as heavy flooding, extreme value theory is used in estimating the probability of such an extreme event occurring. Of the different approaches described in Coles (2001), block maxima can be chosen for the representation of annual minima and maxima and is detailed below.

We use the generalized extreme value (GEV) family of distributions to model the distribution of the annual maxima/minima of a variable, assuming that the elements of the time series are independent and identically distributed and that they have a common distribution function F (Coles, 2001). Distributions of the GEV family are described by the location parameter $\mu$, the scale parameter $\sigma$, and the shape parameter $\xi$ of the form:

$$F(x;\mu,\sigma,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} \tag{3.26}$$

defined on $\{x : 1+\xi(\frac{x-\mu}{\sigma}) > 0\}$, where $-\infty < \mu < \infty$, $\sigma > 0$ and $-\infty < \xi < \infty$. The GEV is a combination of the following three families, which are distinguished via $\xi$:

- $\xi = 0$ Gumbel type, light upper tail
- $\xi > 0$ Fréchet type, heavy upper tail
- $\xi < 0$ Weibull type, bounded upper tail

To estimate the parameters of the GEV distribution for annual minima, the variable $x_1, ..., x_m$ need to be converted to $-x_1, ..., -x_m$, with $\mu = -\mu$. Estimates were performed using the R package "ismev" (Original S functions written by Janet E. Heffernan with R port and R documentation provided by Alec G. Stephenson., 2016) using the MLE method to estimate the parameters of the distribution. Statistics of the distribution such as the mean can then be computed by:

$$E(z) = \begin{cases} \mu + \sigma\frac{\Gamma(1-\xi)-1}{\xi} & \text{if } \xi \neq 0, \xi < 1, \\ \mu + \sigma\,\gamma & \text{if } \xi = 0, \\ \infty & \text{if } \xi \geq 1, \end{cases} \tag{3.27}$$

where $\gamma$ is the Euler-Mascheroni constant. For a return period $\frac{1}{p}$, the return level $z_p$ and the associated return level plot can be obtained from inverting Equation (3.26) and setting $y_p = -\log(1-p)$:

$$z_p = \begin{cases} \mu - \frac{\sigma}{\xi}[1 - y_p^{-\sigma}] & \text{for } \xi \neq 0, \\ \mu - \sigma \ \log \ y_p & \text{for } \sigma = 0. \end{cases} \tag{3.28}$$

The model and uncertainty of estimated parameters is validated by bootstrapping (Efron and Tibshirani, 1994). When comparing changes in GEV over time, the GEV is fit using covariates for $\mu$, $\sigma$ and $\xi$. The different fits for the two time series are then examined using the $\chi^2(df)$ distributed deviance to compare the log-likelihood ratio of the two:

$$D = 2(nllh_0 - nllh_{alt}), \tag{3.29}$$

with $nllh_0$ the negative log-likelihood of the GEV fitted to the whole data set, and $nllh_{alt}$ that from including a step-wise trend for $\mu$ and $\sigma$ as a covariate.

### 3.2.4 The enhanced Driving force - Pressure - State - Impact - Response framework

We use the enhanced Driving force - Pressure - State - Impact - Response (eDPSIR) framework described in Niemeijer and de Groot (2008a) and Niemeijer and de Groot (2008b) to visualize and thus contribute to a deeper understanding of the complex interactions between socio-hydrological processes in Bangladesh. The eDPSIR approach suggests creating a causal network, which provides a formal structure for the selection of key indicators and allows for two-way feedbacks, which is not possible in simpler causal chains.

The eDPSIR framework is flexible in respect to the degree of completeness and the detail required, which both largely depend on the specified research question and application (Niemeijer and de Groot, 2008a). This also ensures that interactions on different spatio-temporal scales often evident in socio-hydrological processes can be included (Sivapalan and Blöschl, 2015). Niemeijer and de Groot (2008b) lists five steps to formally construct a causal network per the eDPSIR framework:

- Step 1: Broadly define the domain of interest
- Step 2: Determine boundary conditions
- Step 3: Determine the boundaries of the system
- Step 4: Identification of abstract indicators of the main factors and processes
- Step 5: Iteratively mapping the indicators in a direction graph

Relevant socio-hydrological indicators to include in Step 4 and especially Step 5 are collected based on an extensive literature review (see also Chapter A.1, A.2, A.3 and A.4).

Indicators can be either abstract or concrete enough to measure and observe (i.e. water level), and can be more detailed for some processes than others, with the amount of detail dependant on the research question at hand. After identifying indicators to be included in the framework, Patrício et al. (2016) stresses the importance of quantifying and specifying the nature of the interactions between indicators.

For the direction graph, Niemeijer and de Groot (2008a) suggests organizing the indicators as environmental or societal indicators and indicators at the pressure interface, with subcategories for e.g. environmental compartments. Along with key nodes, the pressure interface is one of two fundamental elements of the direction graph, and corresponds to those indicators that exert pressure on the environment (in our case e.g. climate change). Key nodes usually have an above-average number of arrows, and can be classified as (Niemeijer and de Groot, 2008a):

**Root nodes** More outgoing arrows.

**Central nodes** Both higher-than-average incoming and outgoing arrows.

**End-of-chain nodes** More incoming arrows.

The causal network can then be used for indicator selection to study specific research questions using the following steps (Niemeijer and de Groot, 2008b):

- Define the research question:
  - Determine the kind of available information.
  - Determine the scale at which to work.
  - Determine where in the eDPSIR network the focus lies.
  - Determine whether an environment, or human-centered perspective is required.
- Identify key nodes in the causal network and explore relevant sections of the causal network in more detail.
- Select the best concrete indicators for the selected nodes.

### 3.2.5 Software

The main programming language and statistical software used for our work is R, which offers a variety of statistical methods as well as graphing devices.

A combination of functions from the base system and externally supplied packages were needed to conduct our study:

- *zoo* for time series analysis (Zeileis and Grothendieck, 2005)
- *glm* function for the set-up of the generalized linear models (R Core Team, 2015)
- *dnlm* for the distributed nonlinear lag models (Gasparrini, 2011)
- *ismev* for GEV and GPD approach (Original S functions written by Janet E. Heffernan with R port and R documentation provided by Alec G. Stephenson., 2016)

# Chapter 4

# Water levels in the megacity Dhaka

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To understand the behavior of flooding and its links to factors such as mortality in the future, an assessment of the past and current situation in Dhaka is necessary. Our research provides an overview on the past 100 years of flooding in Dhaka and its possible links to mortality. In particular, we focus on rare but particularly high-risk events using extreme-value theory.

To assess the frequency, magnitude and duration of flooding in Dhaka during the last 100 years, the water level data set was used at all four stations to count the number of days exceeding the danger level. The danger levels for the four stations are 6, 5.75, 6.08 and 5.94 m for Dhaka (SW42), Demra (SW179), Tongi (SW299) and Mirpur (SW302), respectively (see also Table 3.1).

Changes in frequency, magnitude and duration of flooding in Dhaka during the last 100 years are presented. Possible trends are discussed, as well as the relationship to mortality in the greater Dhaka area.

## 4.1 Assessment of historic changes in frequency, magnitude and duration of water levels

Inititally, the time series for the four water level stations are studied. Since the time series are highly autocorrelated up to lags of 30 days or more, all gaps smaller than 30 days are filled in using linear interpolation for years where peak values were not missing. Years which still had more than 10 % missing values were excluded. Then, a quantile regression (Chapter 3.2) is performed to see how the time series changes over time with respect to different quantiles such as the 1st, 2nd or 3rd quartile. Figures 4.1 and 4.2 show that at all stations, the lower quantiles including the median remain the same or increase slightly, with the higher quantiles showing either no change or decreasing slightly over time.

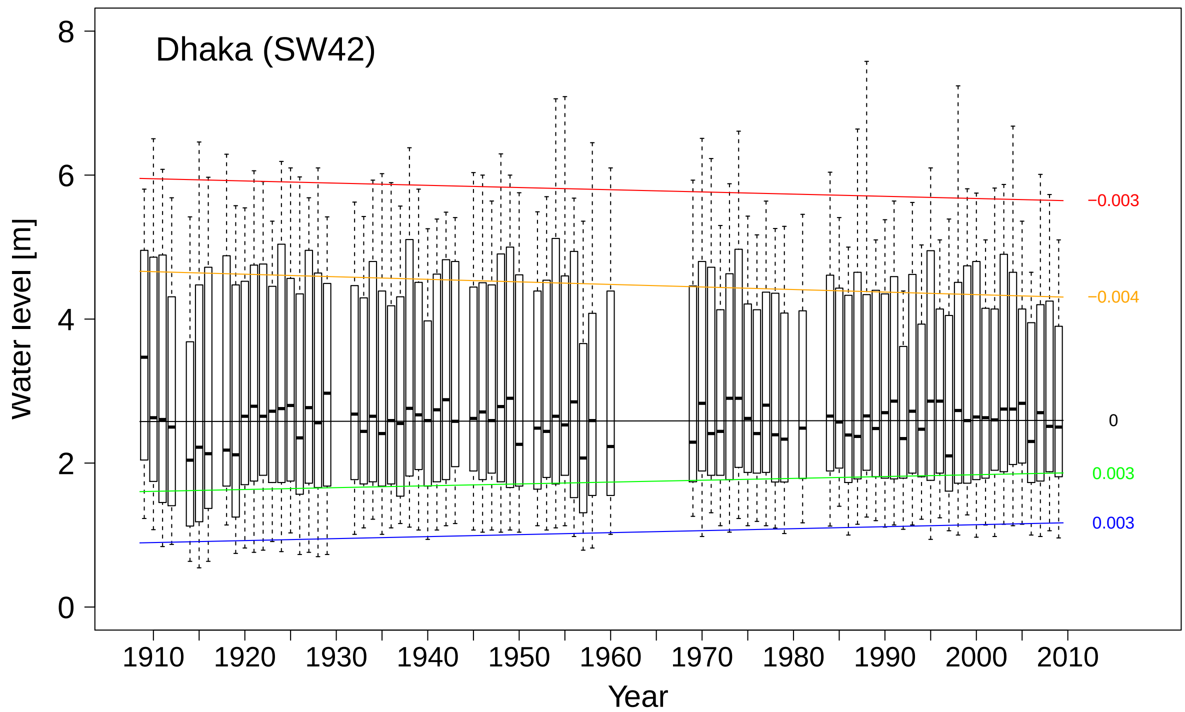


**Figure 4.1:** Annual boxplots for water level station Dhaka (SW42) for the years 1909 - 2009. Regression lines are drawn through the upper and lower extremes (red and blue), as well as the 1st, 2nd and 3rd quartile (green, black and orange, respectively). The slopes of the regression lines are printed on the right [m/year].

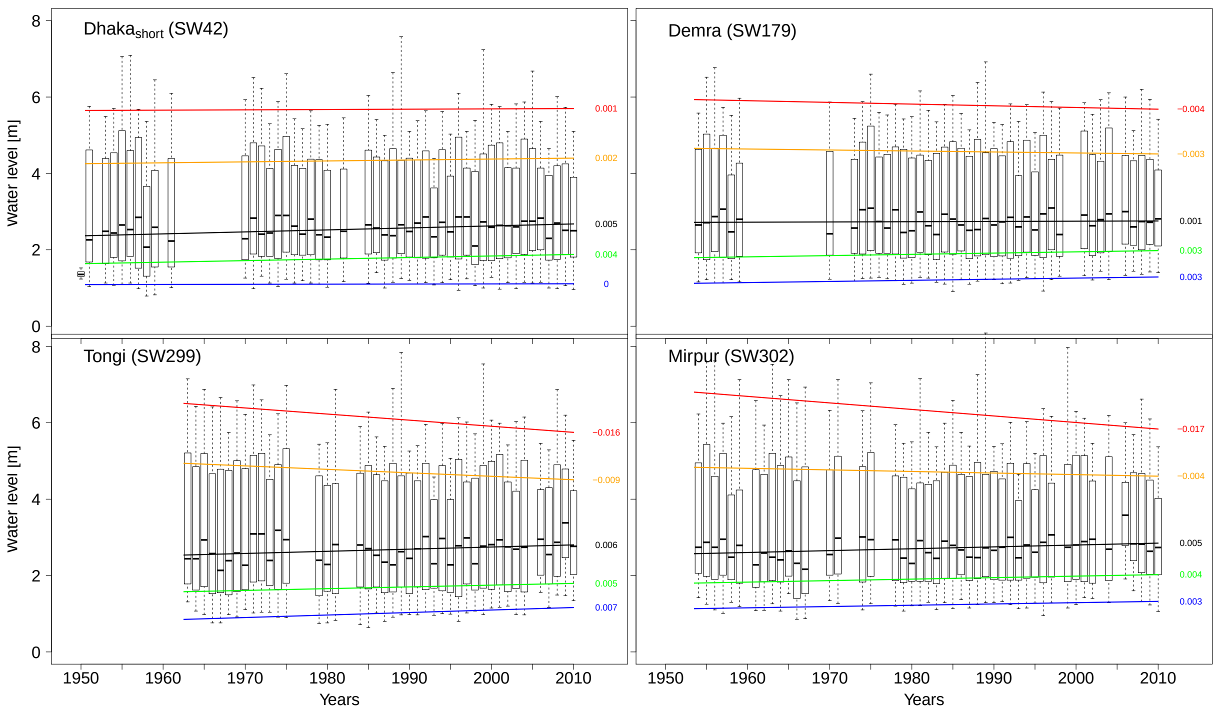


**Figure 4.2:** Annual boxplots for the four water level stations surrounding Dhaka for the years 1950 - 2009. Regression lines are drawn through the upper and lower extremes (red and blue), as well as the 1st, 2nd and 3rd quartile (green, black and orange, respectively). The slopes of the regression lines are printed on the right [m/year].

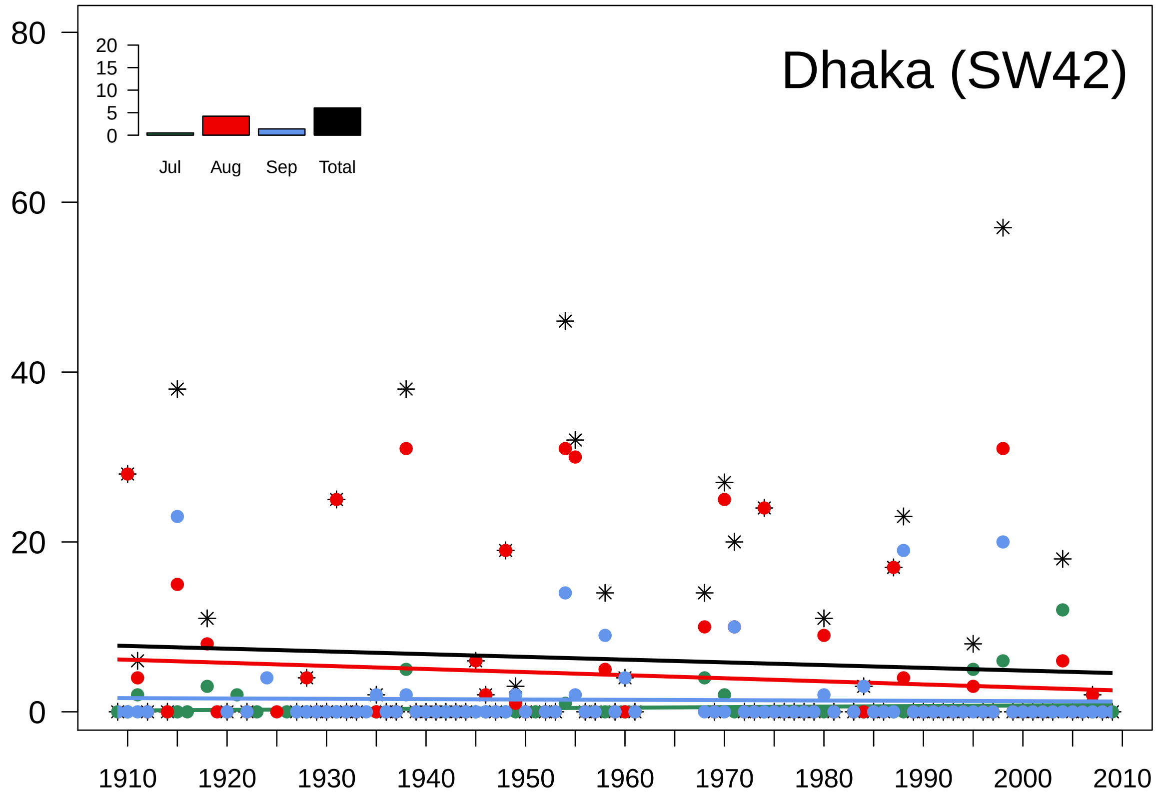


**Figure 4.3:** Number of days above danger level $NOD_{dl}$ for Dhaka (SW42) for the years 1909 - 2009. Black asterix denote the annual $NOD_{dl}$, dots the monthly $NOD_{dl}$ for July (green), August (red) and September (blue). Trend lines are drawn using linear regression. The barplot in the top left corner show the average $NOD_{dl}$ per month and year.

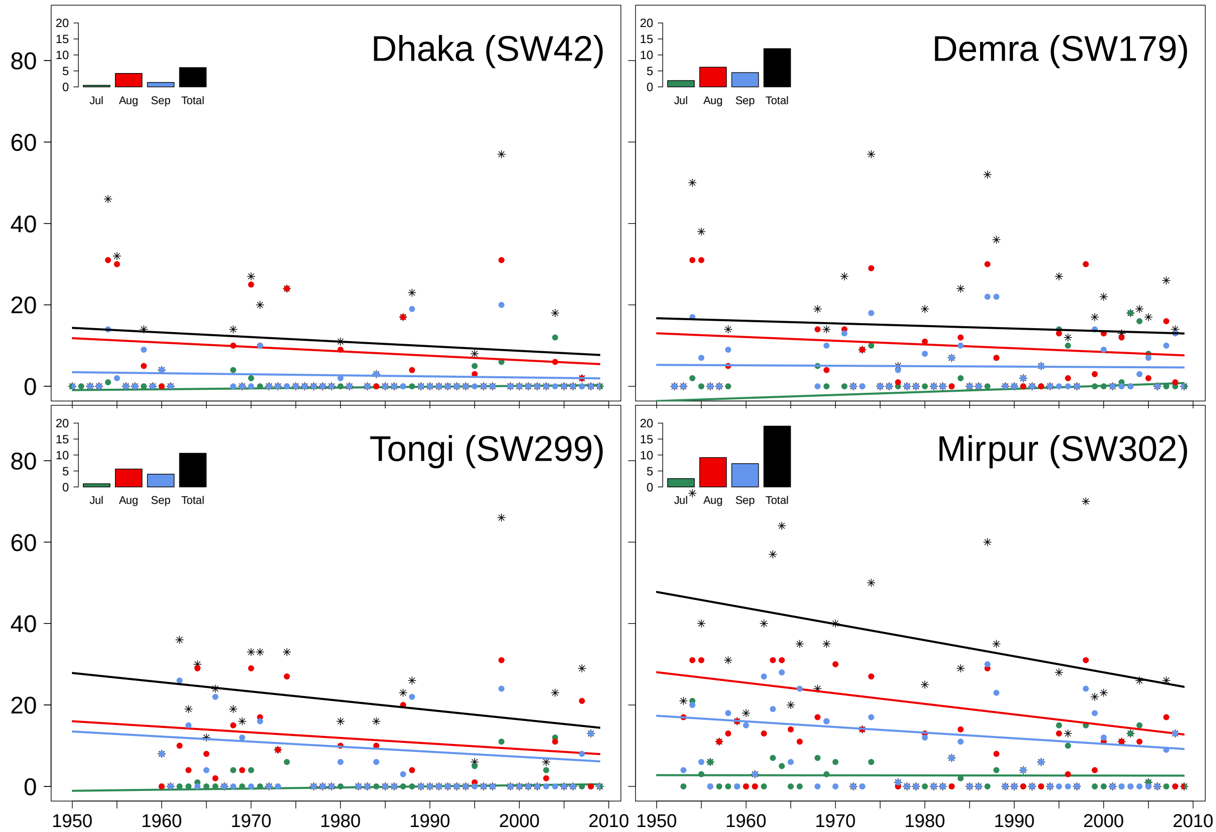


**Figure 4.4:** Number of days above danger level $NOD_{dl}$ for four water level stations surrounding Dhaka for the years 1950 - 2009. Black asterix denote the annual $NOD_{dl}$, dots the monthly $NOD_{dl}$ for July (green), August (red) and September (blue). Trend lines are drawn using linear regression. Barplots in the top left show the average $NOD_{dl}$ per month and year.

Figures 4.3 and 4.4 show the number of days above danger level $NOD_{dl}$ for all four water level stations in Dhaka covering differing time periods from 1909-2009, with the average $NOD_{dl}$ in the upper left corner. With the exception of station Tongi (SW299), all days above danger level were found to be in the months between July and September with a maxima in August, concurring with the monsoon season in Bangladesh. For Tongi (SW299), eight days were counted above danger level in October, but were excluded from the analysis because of the low total count, and because they were quite evenly distributed over the time period (1960, 1970, 1984, 1987). Excluding years with more than 10 % missing values, the danger level is exceeded in 34 % (Dhaka (SW42)), 31 % ($Dhaka_{short}$ (SW42), 55 % (Demra (SW179), 47 % (Tongi (SW299)), and 72 % (Mirpur (SW302)) of the years. Mirpur (SW302) is above DL most frequently, with the annual $NOD_{dl}$ being almost twice to three times as high as at other stations.Both the annual total as well as the average monthly $NOD_{dl}$ are similar for the two time periods for Dhaka (SW42). Since this water level station has been in operation for over 100 years, the similarity between both time series indicates that the water level data for the first half is reliable (see also Chapter 3.1.2).
Both the annual as well as the monthly $NOD_{dl}$ were then examined for trends using the Mann–Kendall test. The annual number of days above danger level is found to significantly decrease at Tongi (SW299) and Mirpur (SW302) (Table 4.1). This decrease can largely be attributed to the significant decrease in $NOD_{dl}$ in August and September. Water levels at station $Dhaka_{short}$ (SW42) also exhibit a slightly negative trend in September, significant at the 0.10 level. For Demra (SW179) as well as the long time series of Dhaka (SW42), no statistically significant trend is found.

**Table 4.1:** Kendall's $\tau$ for the Mann-Kendall trend test for $NOD_{dl}$. **Bold** values denote trends significant at the 0.10 level, * denotes trends significant at the 0.05 level.

| | Dhaka (SW42) | $Dhaka_{short}$(SW42) | Demra(SW179) | Tongi(SW299) | Mirpur(SW302) |
|---|---|---|---|---|---|
| Jul | -0.028 | 0.014 | 0.156 | 0.028 | -0.055 |
| Aug | -0.093 | -0.118 | -0.042 | **-0.204** | **-0.281*** |
| Sep | -0.058 | **-0.184** | 0.015 | **-0.204** | **-0.194** |
| Annual | -0.090 | -0.132 | 0.037 | **-0.223*** | **-0.220*** |

The similar trends in number of days above danger level $NOD_{dl}$ are consistent with the close proximity of the stations (Figure 2.2) and also documented by the significant correlations of $r_{Pearson} = 0.80$ or higher between the stations (Figure 4.5). While Mirpur (SW302) is almost always above DL when any of the other stations record a $NOD_{dl}$ (Figure 4.5, lowest row), this is not the case for Dhaka (SW42).

A logistic regression (Chapter 3.2.1) was performed to model the probability of one station being above DL depending on the water level of the other station. Figure 4.6 indicates that once Dhaka (SW42) exceeds the danger level, it is highly likely with $p > 0.9$ that the other three stations will also have crossed their respective danger levels. On the other hand, if the DL is crossed at Mirpur (SW302), the probability of any other station also recording a $NOD_{dl}$ is very low. This concurs with the findings from Figure 4.4, where Mirpur (SW302) has by far the greatest annual $NOD_{dl}$.

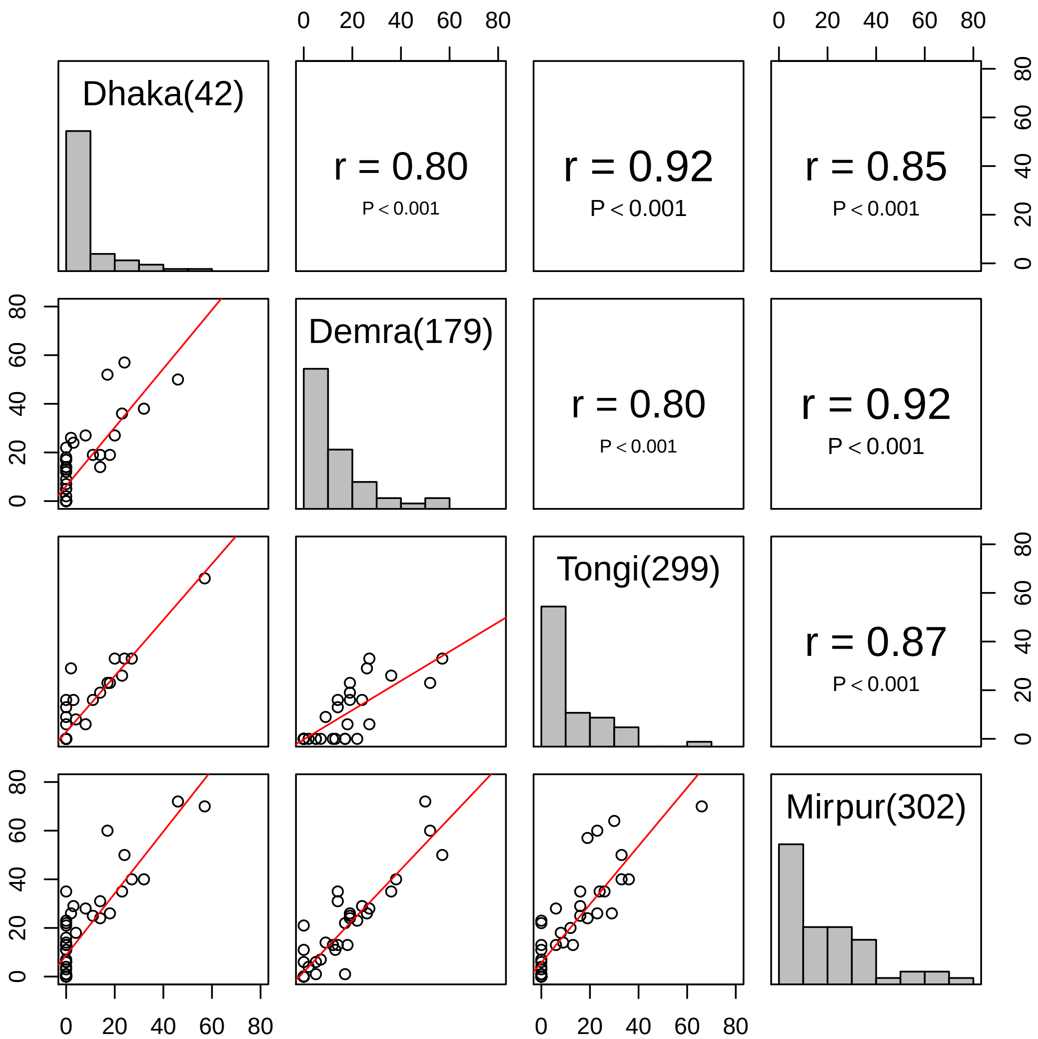


**Figure 4.5:** Correlation between the $NOD_{dl}$ of the four water level stations surrounding Dhaka. The diagonal shows histograms for $NOD_{dl}$ at the individual stations. The panels below the diagonal depict the scatterdiagram of paired stations with a linear regression line drawn. The explained variance, Pearson's correlation coefficient as well as the corresponding p-value are shown in the panels above the diagonal. All correlations are significant at the 0.001 level.

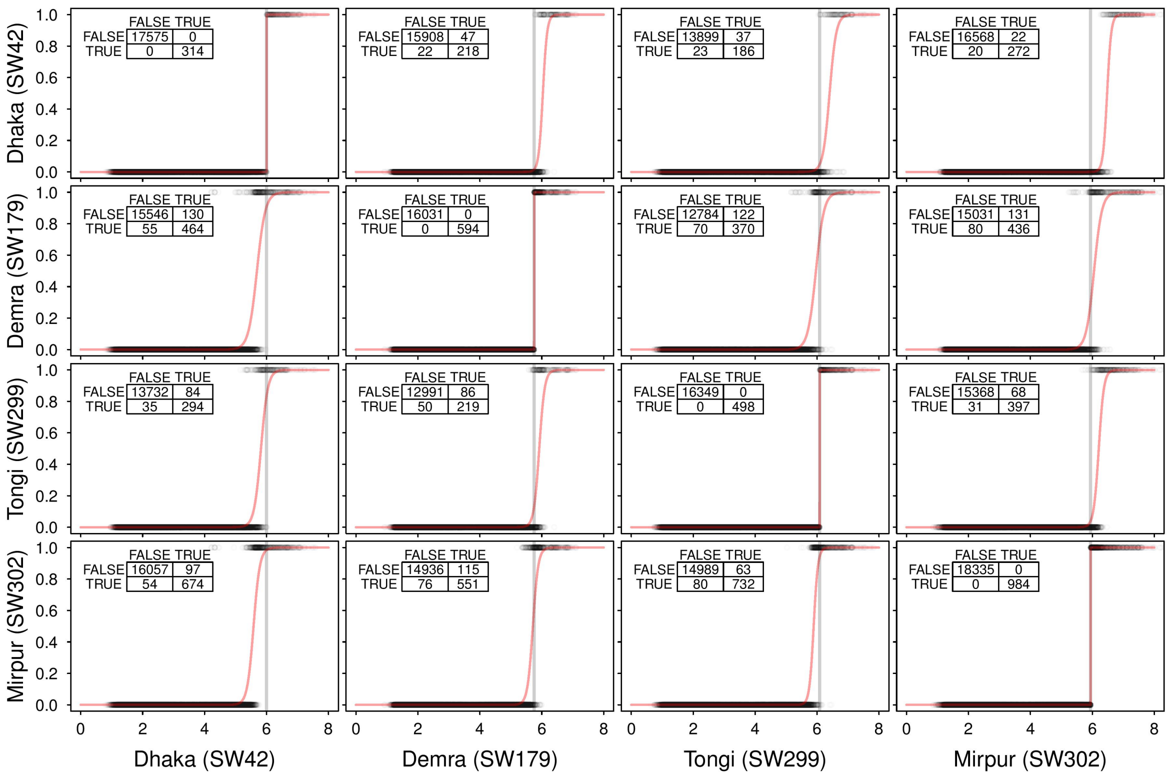


**Figure 4.6:** Logistic regression modelling of the probability of one station being above danger level depending on the water levels of the other stations. Light gray lines are the respective danger levels for the stations. Contingency tables describing the model fit are included in the top left corner.

In addition to the monthly and annual $NOD_{dl}$, the duration of flooding above danger level is also of interest. Figures 4.7 and 4.8 show the duration of flood events, defined as consecutive days at or above danger level for each of the stations. If two flood events are separated by only six days recording below danger level, they are considered as one continuous event. This is only relevant for eight events at stations Dhaka (SW42), Demra (SW179) and Mirpur (SW302). For Dhaka (SW42), 32 events were counted between 1909 - 2009, with an average duration of 16.3 days. While no significant trend in flood duration was found for the past 100 years (Mann-Kendall trend test, $p = 0.300$), a slight decrease of 1.2 days/10 years is evident for $\text{Dhaka}_{\text{short}}$ (SW42) (Figure 4.8, $p = 0.117$). For the other three stations, this decrease is more significant, with Demra (SW179) having the strongest decrease of 3.5 days/10 years ($p < 0.05$).

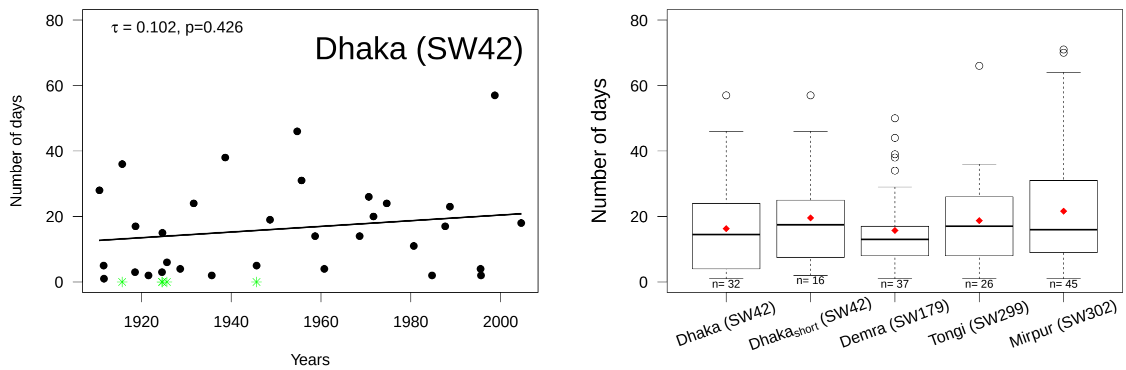


**Figure 4.7:** Duration of flooding in Dhaka for 1909 - 2009. Years in which two flood events were counted as one are marked by green stars. The right hand side shows a boxplot (whiskers at 1.5 IQR) with n the total number of events. Red diamonds denote the mean duration.

As seen from Figures 4.1 and 4.2, the trend in annual maximum water levels is slightly negative. To see if there is a trend in the variance of the maximum water level, i.e. if the extremes - when they do occur - become more extreme over time, the running variance is calculated using the maximum water levels for each year from Dhaka (SW42). Those years with more than 15 days with missing values were neglected (13 years, see red points). Then, the running variance is calculated with a window of 20 years. Figure 4.9 shows this running variance for the years 1909 - 2009 with uncertainty bounds given by the standard error. The green lines, which stand for significant differences between the two time periods (F test, $p < 0.05$), indicate that the variance increases by about a factor of five between 1918 - 1934 and 1969 - 1998.

This suggests that indeed the decrease of magnitude in annual maximum water levels does not contradict the observed increase in the most extreme events. To study this in more detail, the parameters of a generalized extreme value distribution (Chapter 3.2.3) are estimated from the annual maximum water level for both 1909 - 1939 and 1979 - 2009. Since $\xi$ is not significantly different from zero in both cases, both can be considered Gumbel distributions. A deviance test (Chapter 3.2.3) reveals a significant

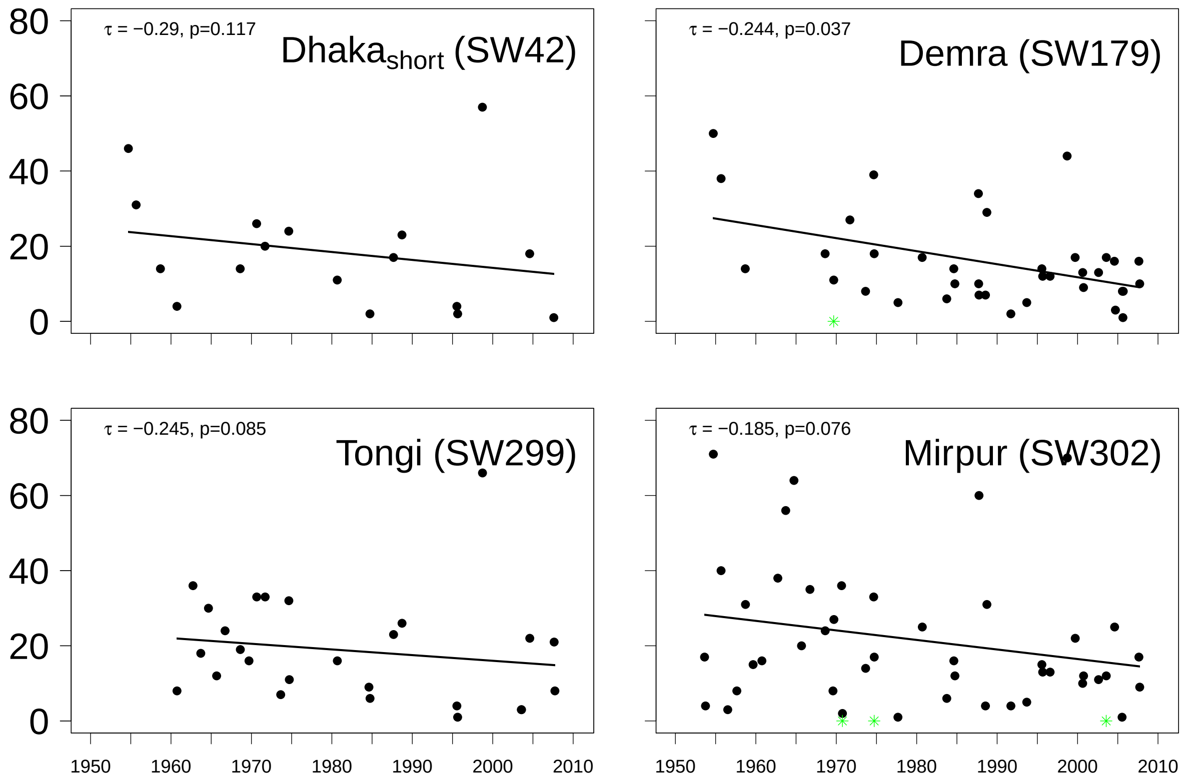


**Figure 4.8:** Duration of flooding at the four water level stations for 1950 - 2009. Kendall's $\tau$ from the Mann-Kendall trend test and the corresponding p-value are also shown. Years in which two flood events were counted as one are marked by green stars.

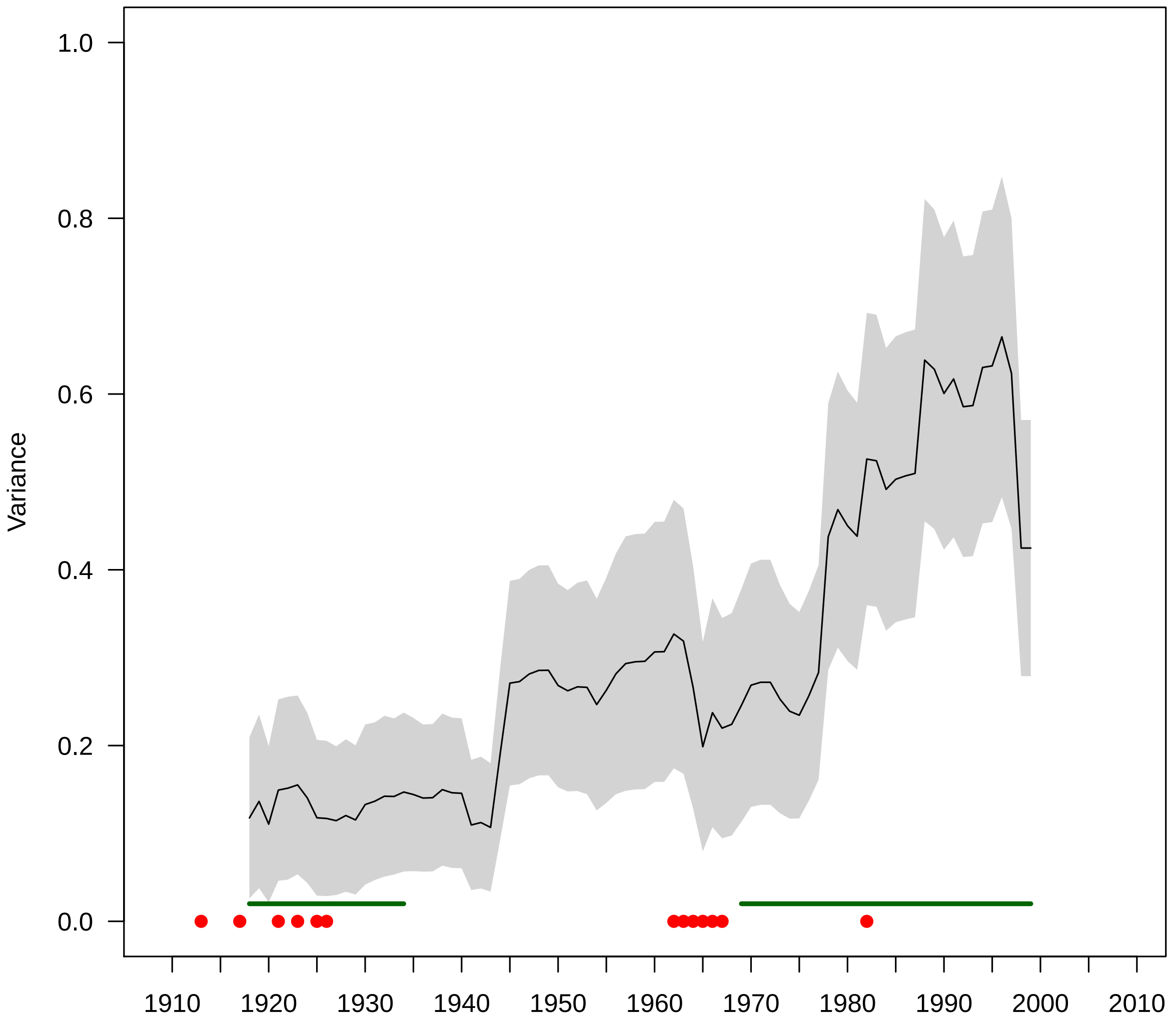


**Figure 4.9:** Running variance for the annual maximum water level in Dhaka. Red dots are missing years, green lines denote two time periods which have significantly different values from another (F test, $p < 0.05$).

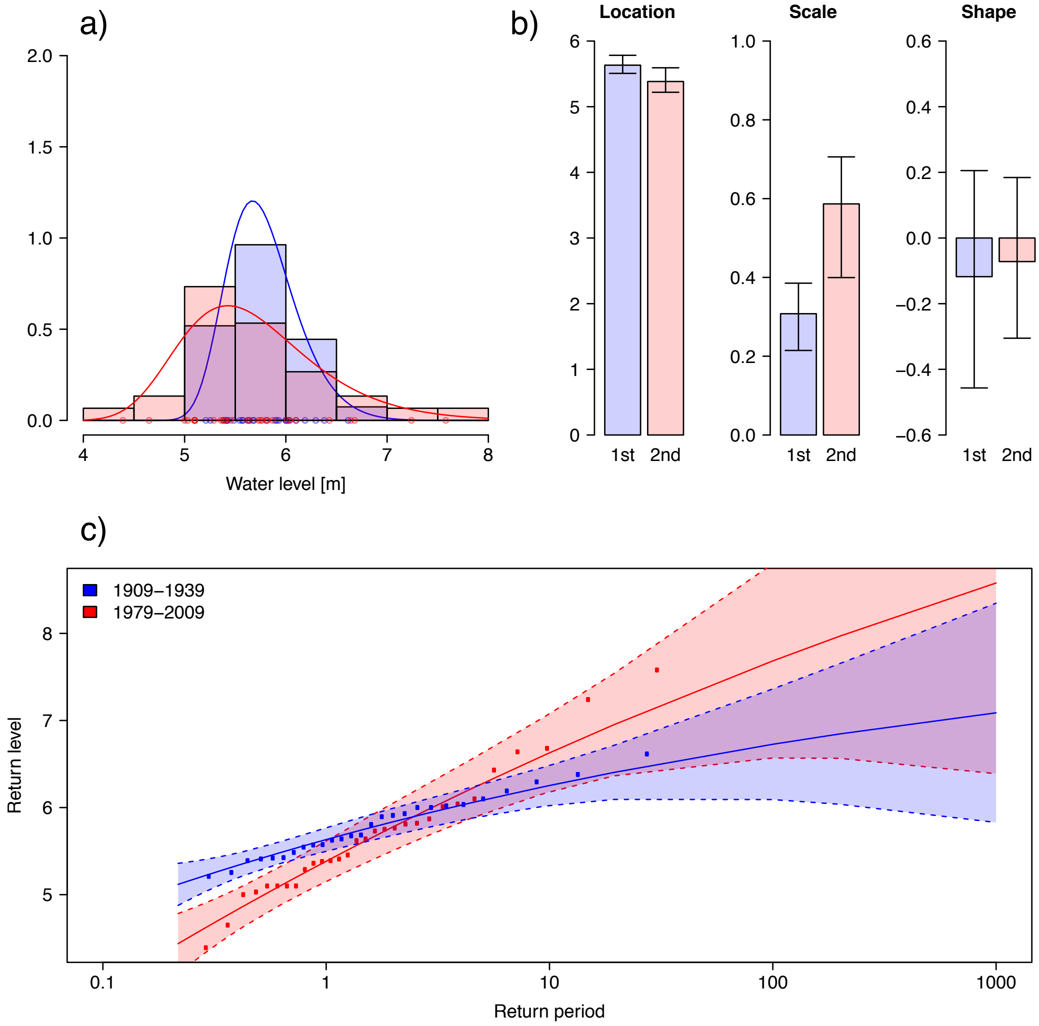


**Figure 4.10:** a) shows the GEV distributions fitted to annual maximum water levels for 1909 - 1939 (blue) and 1979 - 2009 (red), estimated parameters location $\mu$, scale $\sigma$ and shape $\xi$ are shown in b). Error bars depict 95 % confidence intervals obtained from non-parametric bootstrapping (R=500). Return level plots with 95 % confidence intervals are shown in c).

change over time in the Gumbel distribution once a step-wise trend is introduced for $\mu$ and $\sigma$ as a covariate ($D = 14.92, df = 2, p < 0.001$). From the comparison of both distributions in Figure 4.10 it follows that while indeed the location parameter $\mu$ decreases at the 0.10 significance level, corresponding to the decrease in magnitude for the expected annual maxima from 5.78 m to 5.68 m, the scale parameter $\sigma$ increases at the 0.05 significance level, which stands for a heavier tail or an increase in the more extreme events. From the return level plot, it follows that annual maximum water levels above 5.9 m have a lower return period during the second time period than compared to the first, thereby having a higher chance of occuring in a given year. For example, while a water level of 6.25 m has a return period of 10 years during the first time period, the return period decreases to 4.8 years during 1979 - 2009. The water level with a 10-year return period is now 6 % higher at 6.63 m.

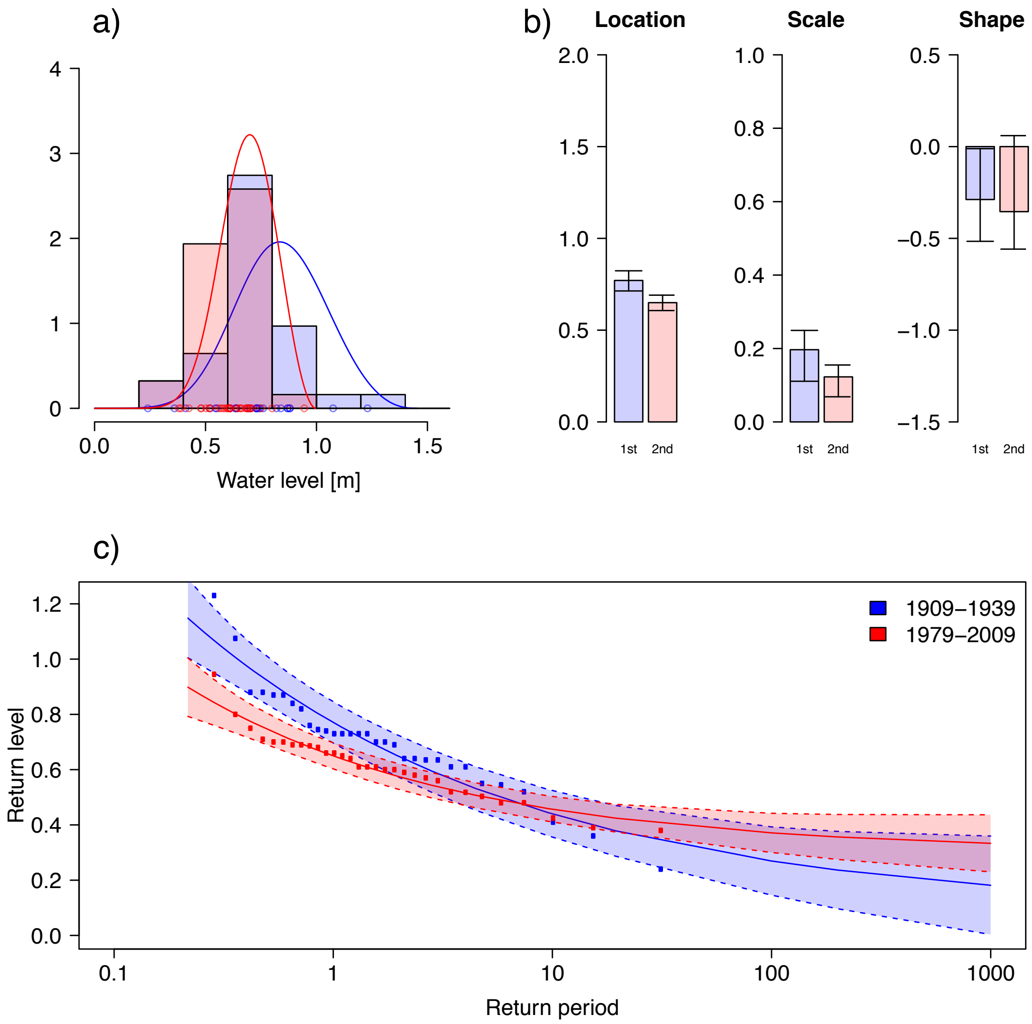


**Figure 4.11:** a) shows the GEV distributions fitted to annual minimum water levels for 1909 - 1939 (blue) and 1979 - 2009 (red), estimated parameters location $\mu$, scale $\sigma$ and shape $\xi$ are shown in b). Error bars depict 95 % confidence intervals obtained from non-parametric bootstrapping (R = 500). Return level plots with 95 % confidence intervals are shown in c).

As seen from Figure 4.1, annual minimum water levels seem to slightly increase over the past century. To see if there is a trend in the variance of the minimum water level, i.e. if the extremes - when they do occur - become more extreme over time, the parameters of a generalized extreme value distribution are estimated from the annual minimum water level for both 1909 - 1939 and 1979 - 2009. The shape parameter $\xi$ is significantly below zero in both cases (at 0.05 for first period, 0.10 for second), reflecting the Weibull distribution applied to minimum time series. From the comparison of both distributions in Figure 4.11 it follows that contrary to the regression line above, the location parameter $\mu$ decreases at the 0.05 significance level, corresponding to a decrease in magnitude for the expected annual minima from 0.71 m to 0.61 m, while the scale parameter $\sigma$ does not change. From the return level plot, it follows that all return periods of minimum water levels below the average annual minimum (return period = 1) have significantly lower return levels during the second time period than compared to the first, thereby a higher chance of occurring in a given year. The water level with a 1-year return period in the first period now has a return period of 0.5 years. For water levels above a return period of 1, no significant change can be found, which indicates that the extreme minimum water levels do not increase in frequency or magnitude.

Overall, while the magnitude and duration of average flood events in Dhaka have decreased over time, the frequency of the most extreme flood events has increased. The magnitude of extremely low flows has also decreased significantly over the past century.

## 4.2 Mortality during floods of 2004 and 2007

Here, individual extreme hydrological events are studied to see if an impact on mortality can be detected. During the time period of available mortality data (2003 - 2007), two major flood events occurred in 2004 and 2007. Extreme drought events, which would be registered for water levels around 0.55 m (Figure 4.11), were not included in this time frame.

### 4.2.1 Flood event of 2004

Heavy rainfalls during the beginning of July over large parts of the Ganges, Brahmaputra and Meghna catchments, accumulating over 300 mm in less than 7 days, resulted in heavy flooding throughout up to 50 % of the country. Figure 4.12 demonstrates the elevated water levels in Dhaka surpassing the danger level of 6 m during most of July, with up to 40 % of the capital being inundated. In September, a second flood peak can be seen due to a localized monsoon depression with heavy precipitation, bringing the total mortality count to 730 (Mirza, 2011). The mortality distribution shows the typical seasonal pattern with the highest levels occurring during winter, the lowest during the monsoon, and a secondary maximum during the pre-monsoon (although variations are less pronounced than during other years). During and after the flood event of 2004, mortality shows a clear trough with rather little noise in the daily mortality data.

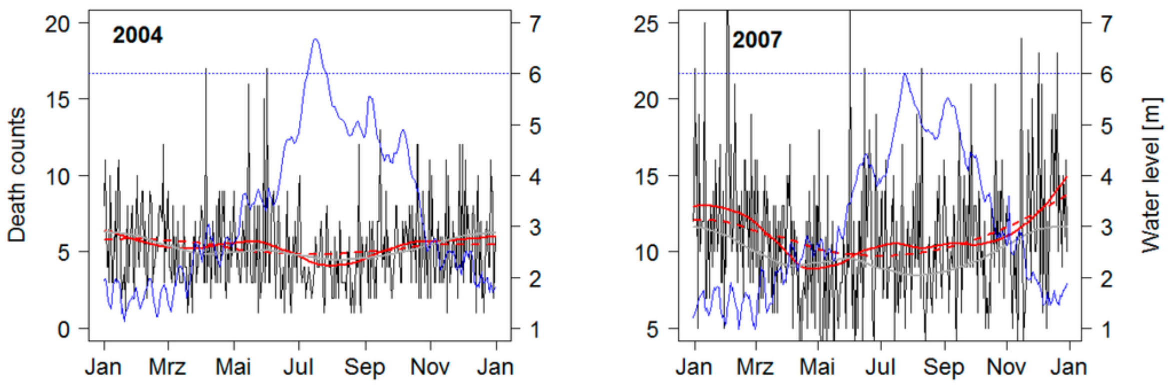


**Figure 4.12:** Time series plots of water level in Dhaka (blue) and daily deaths in flooded zilas in 2004 and 2007 (black). Red solid line displays loess smoothed values using an $\alpha$ of 0.1, the dashed red lines displays loess smoothed values using an $\alpha$ of 0.25. The gray line represents the average mortality from 2003 - 2007.

### 4.2.2 Flood event of 2007

In 2007, excess rainfall in the Brahmaputra and Meghna catchments resulted in the first pronounced water level peak in the middle of July, with a second peak following and at the beginning of September. A total of 49 Zilas were affected with 55 % of all roads flooded. While the water level station located in Dhaka did not cross the BWDB prescribed danger level of 6 m, the greater Dhaka area was considered as heavily flooded, with a total mortality count of 649 attributed to flooding (Disaster Management Bureau, 2007). Generally, seasonal variations in mortality are more pronounced in 2007 compared to other years and the annual mortality level is above average. During the monsoon, mortality is elevated and does not decline as usually after the secondary premonsoon peak. Several short-term peaks in daily mortality counts can be observed. However, these peaks do not exceed the general noise level.

## 4.3 Connection of flooding in Dhaka with mortality

Contour plots demonstrate variations in RR at low and high water levels, whilst in between (at water levels of approximately 2.5 to 5.5 m), few variations in RR can be observed (Figure 4.13). At lower water levels (between water levels of 1.0 and 2.5 m) there is a varying pattern with increasing as well as decreasing mortality over the 30 days period. At a high water level of above 6 m, we observed a small decrease in mortality at lags of 0 to 3 days followed by an increase in mortality between lags of 6 and 17 days. However, few of the effects depicted in the contour plots were significant. In Figure 4.14, the association between water level and mortality is displayed for selected lag periods (mostly significant lag periods were included in this figure). At lag 7, there is a significant increase in mortality with decreasing water level below 3 m, highlighting an adverse effect of low water levels (or drought). With growing lag period this "drought effect" diminishes and at lag 21 days there is a significant increase in mortality with increasing water levels up to approximately 3 m. At a lag of 28 days, the relationship between water level and mortality changes again and mortality increases with decreasing water level, i.e. a drought effect. However, this finding is only significant on a 90 % level. For a lag period of 7 and 14 days we observed a minimal increase in mortality with increasing water level above the median. This increase is, however, not significant. In Figure 4.15, the relative risk of all-cause mortality along lags is displayed for selected water levels. Again, these outputs underline the relevance of low levels and their effect on mortality. At a water level of 1 m we observed an increase in mortality up to a lag of 7 days. After 7 days, mortality decreases and reaches its lowest point at a lag of approximately 23 days before it starts rising again. At water level 2.5 m, mortality decreases slowly but significantly up to a lag of 21 days after which it starts rising again.

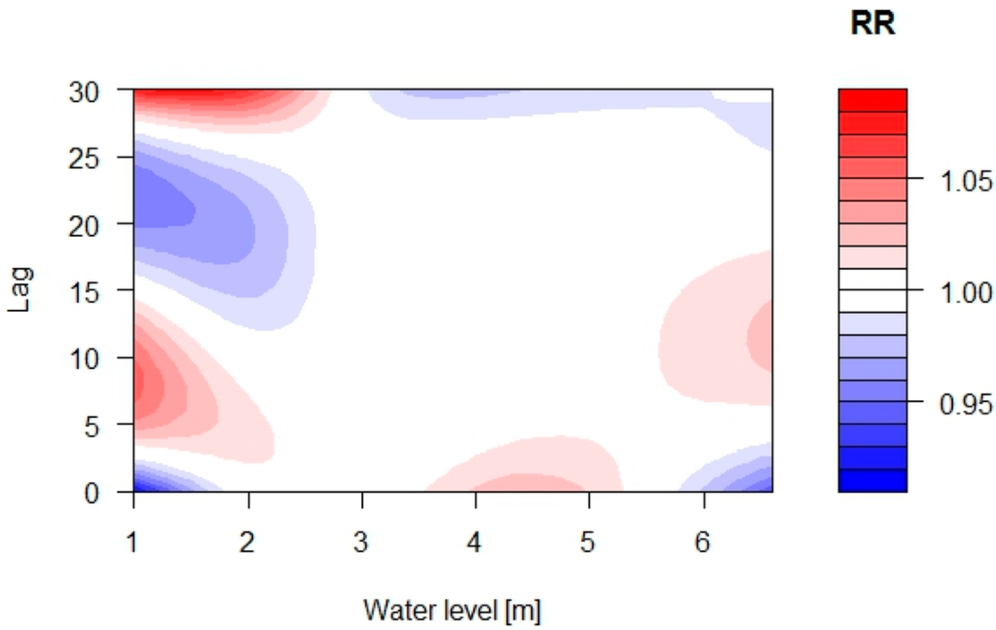


**Figure 4.13:** Contour plot of the relative risk (RR) of all-cause mortality along water level and lags, with reference to the median water level using a distributed lag non-linear model.

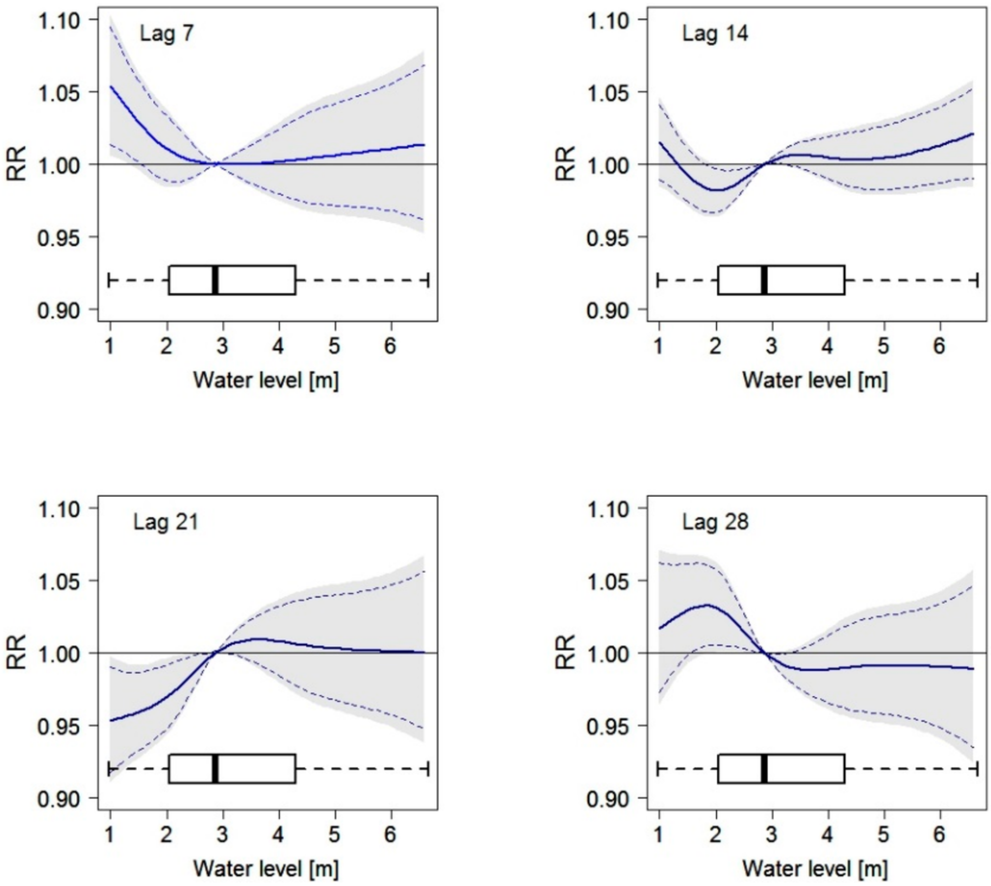


**Figure 4.14:** Relationship between the daily number of deaths and the water level in Dhaka for a lag period of 7, 14, 21 and 28 days using a distributed lag non-linear model. Curves are adjusted for trend, season, and day of the month. Grey areas display upper and lower 95 % confidence intervals; dashed lines display upper and lower 90 % confidence intervals. Boxplots for the water level distribution are included at the bottom of each plot.

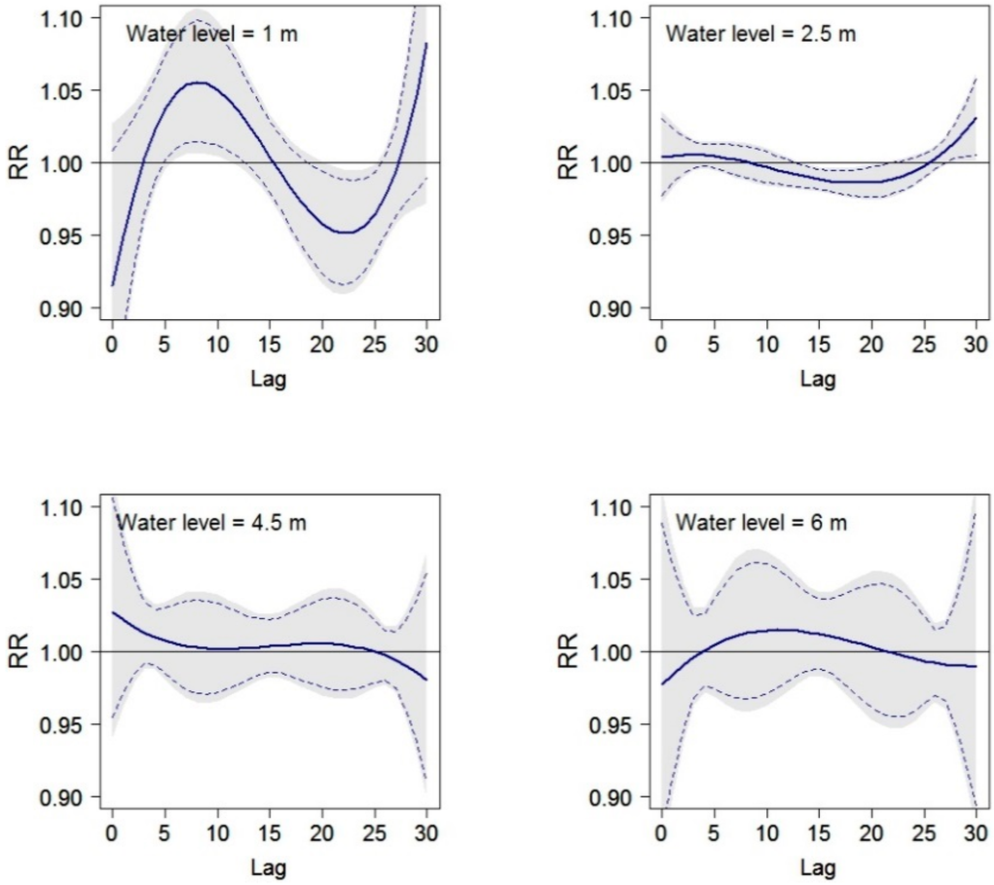


**Figure 4.15:** Plots of the relative risk of all-cause mortality at water levels of 1.0 m, 2.5 m, 4.5 m and 6.0 m along lags, with reference at the median water level using distributed lag non-linear models. Outputs are adjusted for trend, season, and day of the week. Grey areas display upper and lower 95 % confidence intervals; dashed lines display 90 % upper and lower 95 % confidence intervals.

# Chapter 5

# A socio-hydrological framework for Bangladesh

In Chapter 4 we found a connection between low water levels and mortality rates. Whether or not climate change will further strenghten or even amplify this relationship and how this might affect the growing population of Bangladesh is a very important question, but in a country as geographically diverse as Bangladesh, attributing tendencies to climate change can be problematic, as the direct effects of climate change can sometimes not be distinguished from other anthropogenic impacts. We use the enhanced Driving force - Pressure - State - Impact - Response (eDPSIR) framework described in Chapter 3.2.4 to visualize and contribute to a deeper understanding of the complex interactions between natural and anthropogenic processes in Bangladesh (Niemeijer and de Groot, 2008a,b).

The eDPSIR framework is flexible in respect to the degree of completeness and the detail required, which both largely depend on the specified research question and application (Niemeijer and de Groot, 2008a). The framework also ensures that interactions on different spatio-temporal scales often evident in socio-hydrological processes can be included (Sivapalan and Blöschl, 2015). In accordance with Niemeijer and de Groot (2008b), we construct the causal network using the following five steps:

- *Step 1: Broadly define the domain of interest*
  Natural and anthropogenic processes - including natural hazards and technical failures - impacting hydrology in Bangladesh.
- *Step 2: Determine boundary conditions*
  Socio-hydrological processes in the monsoon-driven climate of Bangladesh.
- *Step 3: Determine the boundaries of the system*
  The system considered is the country of Bangladesh and dominant socio-hydrological processes in the GBM catchment.
- *Step 4: Identification of abstract indicators of the main factors and processes*
  A selection of the main indicators relating to socio-hydrological processes in Bangladesh are listed in Table 5.1.

- *Step 5: Iteratively mapping the indicators in a direction graph*
  The connections between the indicators for natural and anthropogenic processes, including natural hazards and technical failures, is provided in a direction graph (Figure 5.1).

With this causal network, we provide a frame of reference for the work conducted in previous chapters, while also highlighting additional indicators that need to be considered for further studies. In the following sections, the identification of abstract indicators (Table 5.1, Step 4) as well as the visualization of the conceptual framework in a direction graph (Figure 5.1, Step 5) will be presented and discussed.

## 5.1 Key indicators for socio-hydrological processes in Bangladesh

The indicators included in the overview of socio-hydrological processes in Bangladesh (Figure 5.1 and Table 5.1 ) were collected through an extensive literature review, and are detailed for purposes of brevity in Chapter A.1, A.2, A.3 and A.4. This includes the specification and quantification of the nature of the feedbacks between the indicators, which can have a multitude of implications, both on a broader, country-wide level as well as on an individual level (see A.5.1 and A.5.2).

A selection of key indicators presented in Table 5.1 is discussed in more detail in Sections 5.1.1 to 5.1.5. From the visualization of the causal network describing socio-hydrological process interactions in Bangladesh (Figure 5.1), we learn that most indicators are highly interconnected. No indicator is without any interactions, and there are numerous connections across both the natural and anthropogenic system, including several two-way feedbacks. An average of $4.8 \pm 3.1$ arrows enter each indicator, with an average of $4.9 \pm 2.6$ leaving. We consider indicators with $\geq 7$ interactions as key nodes, which we differentiate according to the relation between incoming and outgoing arrows:

**Root nodes** *More outgoing arrows, i.e. high impact, low feedback*
Precipitation. Extreme temperatures. Cyclones. Earthquakes. Coastal flooding. Population growth. Urbanization. Climate change. Dam construction.

**Central nodes** *Both higher-than-average incoming and outgoing arrows, i.e. highly interacting nodes*
Discharge. Sedimentation. Sea level. Salinity. Subsidence. Flood. Freshwater availability. Crops. Dam breakage.

**End-of-chain nodes** *More incoming arrows, i.e. impacted by many other indicators*
Vegetation. Agroforestry. All implications.

A selection of these key nodes and related interactions are presented in Table 5.1 and the following sections.

**Table 5.1:** A selection of indicators included in the causal network describing socio-hydrological processes in Bangladesh sorted according to Driving force - Pressure - State - Impact - Response.

| **Driving force** | Climate change | | Population growth | | Higher health standards | International dam construction | Shrinking space of democracy |
|---|---|---|---|---|---|---|---|
| **Pressure** | Sea level rise | Shift in precipitation regime | Higher demand of fresh water supply, groundwater pumping | Increased demand for food | Improve freshwater quality | Farakka Barrage | Limited urban ground |
| **State** | Advance of brackish water zone inland | Prolonged dry season | Decrease of groundwater table depth below cities | Growth of shrimp farming industry | Increased amount of deep wells | Change in Ganges discharge | Urban poor dwell on 0.5 % of Dhakas area |
| **Impact** | Increased salinity in above- and below-ground water supply<br><br>Reduction of freshwater availability | Less precipitation during brick making season | Land subsidence | Increased salinity in above-ground water supply in coastal region<br><br>→ Hypertension due to increased dietary salt intake | Freshwater with lower risk of spreading communicable diseases | Decrease of flow in dry season | Limited freshwater<br><br>Increased exposure to water stress |
| **Response** | De-salinification | Productivity of brick field industry increases | Deep aquifer pumping | De-salinification | Arsenic contamination at 1/5 of the wells | Ecosystem Changes, Political tension, Migration | High expenses for daily water supply<br><br>Stress on livelihood and morbidity |

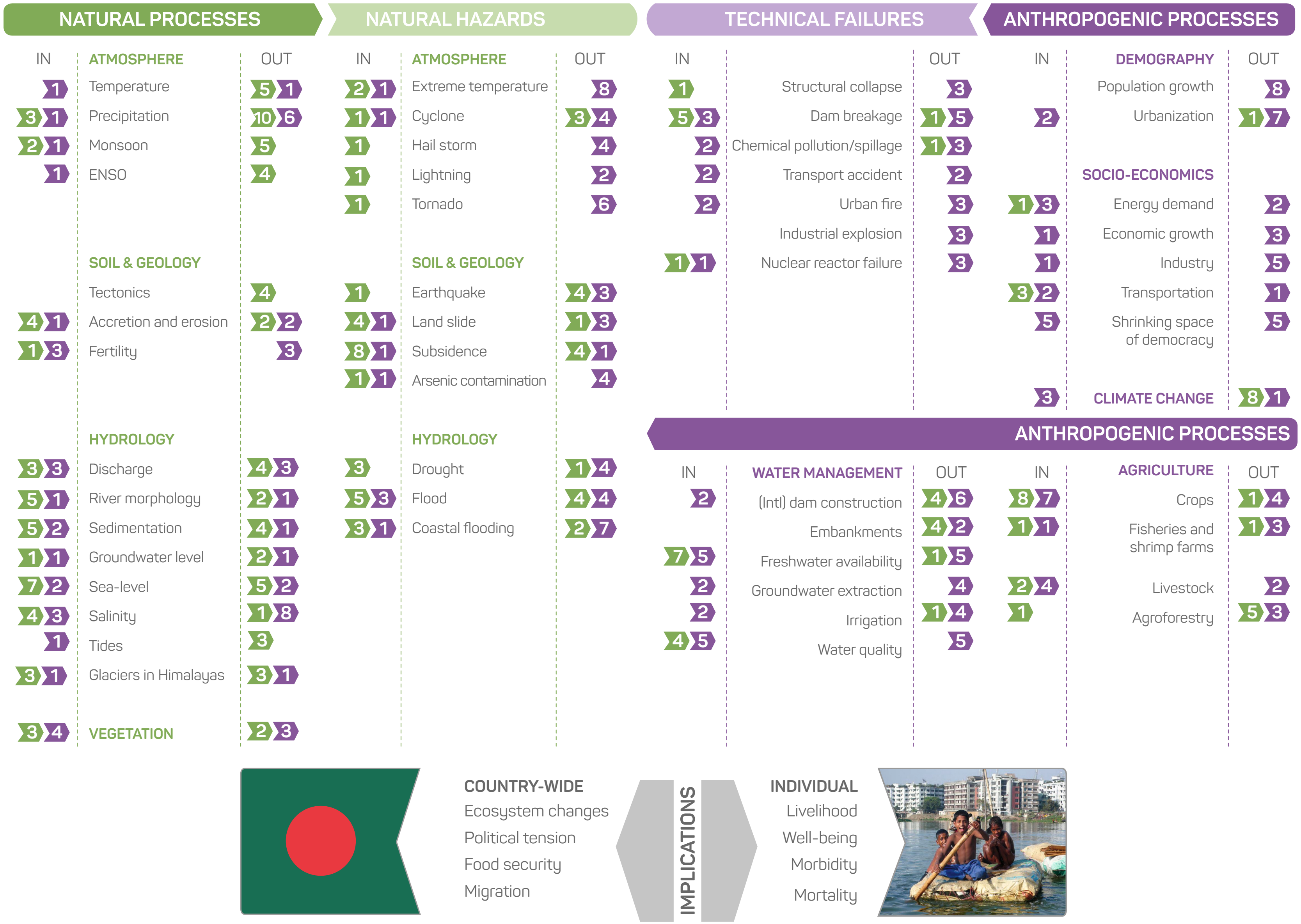


**Figure 5.1:** Natural and anthropogenic indicators important to the socio-hydrology of Bangladesh. Due to the large number of feedbacks, we chose to display the total number of in- and outgoing arrows for both natural (green) and anthropogenic (purple) interactions. Implications on the country-wide and individual level are included in the purple arrows.

Several of these key nodes and their interactions with other indicators will be discussed in the following.

### 5.1.1 Driving force: climate change

A changing climate impacts almost all natural processes including natural hazards in Bangladesh (Figure 5.1.1, see also Section 1.1.3), with pressure resulting from e.g. sea level rise and changes in the precipitation regime (Inman, 2009; IPCC, 2013). By highlighting the 1st and 2nd degree impacts of climate change in Figure 5.1.1, it becomes clear that climate change is connected to almost all aspects of the causal network, with two examples detailed in the following.

**Sea level rise** Relative mean sea levels have increased between 2.8 and 8.8 mm/year, with sea levels at high tide impacted more strongly by about 15.9 and 17.2 mm/year (Rabbani et al., 2010; Pethick and Orford, 2013). As a result, the brackish water zone moves further inland and leads to increased salinity in above- and below ground water, thus impacting freshwater availability (Inman, 2009; Brammer, 2014). This in turn enhances hypertension due to an increased dietary salt intake as well as having adverse effects to the rice farms in the vicinity (Mirza, 1998; Khan et al., 2008; Vineis et al., 2011). A possible response includes desalinifaction treatments through e.g. agroforestry, or the construction of embankments (Hasan and Alam, 2006; Brammer, 2014).

**Changes in precipitation regime** The IPCC (2013) and Gain et al. (2011) expect that a later onset in the monsoon will shift the precipitation regime in the GBM catchment, likely leading to a prolonged dry season. This directly impacts the brick making industry, an industry prominent in Bangladesh which relies solely on the months of the dry season for the creation of an estimated 17 billion bricks each year (Braun and Aßheuer, 2011; Aßheuer et al., 2013; Aßheuer, 2014). An extension of the dry season would thus increase the productivity of the brick fields.

### 5.1.2 Driving force: population growth

Despite a comparatively low birth rate of 2.2 children per woman, Bangladesh is expected to see an increase in population of 218 million by 2050 (United Nations, 2007; Streatfield and Karar, 2008). This population growth serves as the driving force for several socio-hydrological interactions in Bangladesh, two of which are water demand and food supply.

**Water demand** A growing population automatically requires more freshwater. In urban areas such as Dhaka, which have seen large population growth through urbanization and nationwide migration, groundwater pumping has put pressure on the system

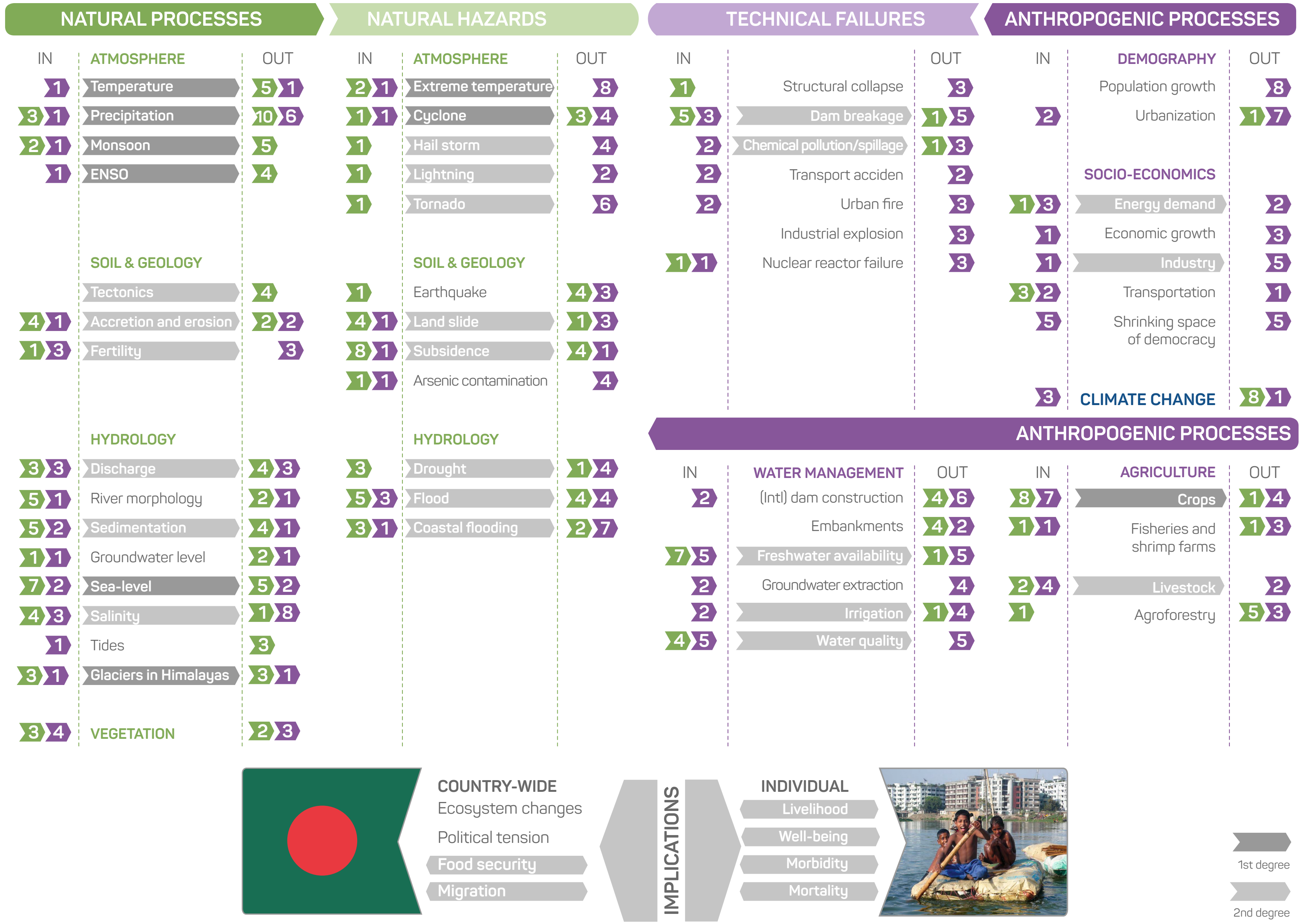


**Figure 5.2:** Interactions resulting from climate change. The 9 indicators directly impacted by climate change are highlighted in dark gray (1st degree), those indicators in turn impact more indicators highlighted in light gray (2nd degree).

as the groundwater table depth beneath the city has decreased at an average rate of 2 m per year since 1986 (Akther et al., 2009; Haque et al., 2013). This increased groundwater extraction contributes to the continuing land subsidence varying between -1.1 mm/year and 43.8 mm/year, in particular in the larger urban areas (Syvitski et al., 2009; Brown and Nicholls, 2015). Reducing the subsidence can be achieved by resorting to deep aquifer pumpig, more efficient use of available resources, as well as enabling sufficient aquifer recharge through water management.

**Food supply** An increased demand for food, in particular in the nation's large cities and megacity Dhaka has led to the growth of the shrimp farming industry by 20 - 30 % annually since the 1990s, making up more than 2.5 % of the global shrimp production (Rahman et al., 2013). The accelerated and at times unregulated growth of the industry has led to farm land being converted to shrimp cultivation grounds by increasing the salinity, which in turn increased the salinity in the above-ground water supply (Haque, 2006; Rahman et al., 2013) and thus has led e.g. to a noticeable rise in reported cases of hypertension due to a higher intake of dietary salt (Vineis et al., 2011). To lower the effects of salinity on the population, efforts have been undertaken to regulate the shrimp industry and thus limit the intrusion of saline water, mitigating the effects through an increased use of rain water harvest technology, or desalinification through e.g. agroforestry (Hasan and Alam, 2006; Rahman et al., 2013).

### 5.1.3 Driving force: higher health standards

Until the 1980s, rain-fed ponds on the surface were the main source of drinking water, but often contaminated with pathogens. Higher health standards, in particular the goal to reduce infant mortality from diarrheal diseases via an increase of piped water supplies led to an increase in the amount of deep wells being dug (Acharyya et al., 2000; Sivapalan et al., 2011), especially in the northern parts of the country. Indeed, the improved quality in freshwater initially lowered the risk of spreading communicable diseases, and infant mortality has been decreasing. However, due to geological processes, the ground is naturally contaminated with arsen, with 20 % of the wells showing arsenic values above the permitted value of 50 ppb (Uddin and Huda, 2011). Since the detection of arsenic contamination in 1993, efforts from the government as well as organizations such as WHO, UNICEF and national NGOs have led to regulations before drilling new wells, de-contamination of the affected wells and raising awareness in the population. Still, up to 80 million people are considered to be affected by arsenic.

### 5.1.4 Driving force: international dam construction

Because of heavy siltation in the port of Kolkata, the Indian government began constructing a dam on the border between India and Bangladesh to divert 40,000 $m^3/s$ from the Ganges into the Bhagirathi-Hoogly river system (feeder canal to Kolkata).

The construction on Farakka barrage began in 1961, with operations starting in April 1975 (see also extensive discussions in Chapter 2.3.1 and A.3.4). In Bangladesh, this resulted in changes in the discharge of the Ganges further downstream, with a particularly noteable reduction of up to 50 % in the dry season (Figure 2.5, Mirza (1997, 1998); Gain and Giupponi (2014)). The decrease in extreme minimum water levels (Chapter 4) could also be due to Farakka Barrage. The reduction of flow in turn led, among other things, to an increase in salinity (Mirza, 1997; Inman, 2009) and the following implications:

**Ecosystem changes** - variations in the balance between freshwater and salt water threatens the ecosystem downstream of Farakka barrage, such as the Sundarbans. The breeding and survival of fish, shrimp and other animals such as the Bengal tiger is also tied to the extension of the brackish water zone (Inman, 2009; Gain and Giupponi, 2014).

**Political tension and migration** - the construction of Farakka Barrage affects the livelihood of about 35 million people who dwell in the lower Ganges basin (Swain, 1996; Gain and Giupponi, 2014). Several attempts have been made to politically formalize treaties to regulate the flow of water, particularly in the dry season (Mirza, 1997, 1998). The various success of these efforts has caused political tension between India and Bangladesh. Migration away from the coast, where an increase in salinity has led to a multitude of problems, is also attributed to Farakka Barrage (Adel, 2002; Inman, 2009).

The impact of both national and international dam construction is not just limited to the above effects. An extensive list of the involved socio-hydrological processes and their complex feedbacks is provided in Chapter A.3.4 and included in Figure 5.3.

### 5.1.5 Driving force: shrinking space of democracy

Shrinking space of democracy is a term referring to current developments in Bangladesh that reduce the democratic rights of the people, such as the introduction of new laws curtailing the freedom of speech and increasing arrests of journalists (Ahmad, 2015; Amnesty International, 2017). Additional laws endanger people to be arrested for more than ten years if they criticize the so called founder of the nation (the assassinated father of the current Prime Minister) or if they are perceived to endanger public order through e.g. posts in social media. New projects of foreign-funded non-governmental organizations (NGOs) are under strict - and to some extent arbitrary - control of the government (see also Chapter A.3.2; Bergman (2016); Rahman and Ahmad (2016)). This especially impacts the urban poor: because of limited urban ground, in particular in Dhaka which is surrounded by four rivers (Figure 2.2), the urban poor usually have too little space. While government officials have previously agreed on allowing the urban poor to dwell in 5 % of the city, they currently inhabit only about 0.5 %. The areas were these slum settlements are currently located usually have limited freshwater available and are exposed to water stress due to their location (Figure 2.2). This leads

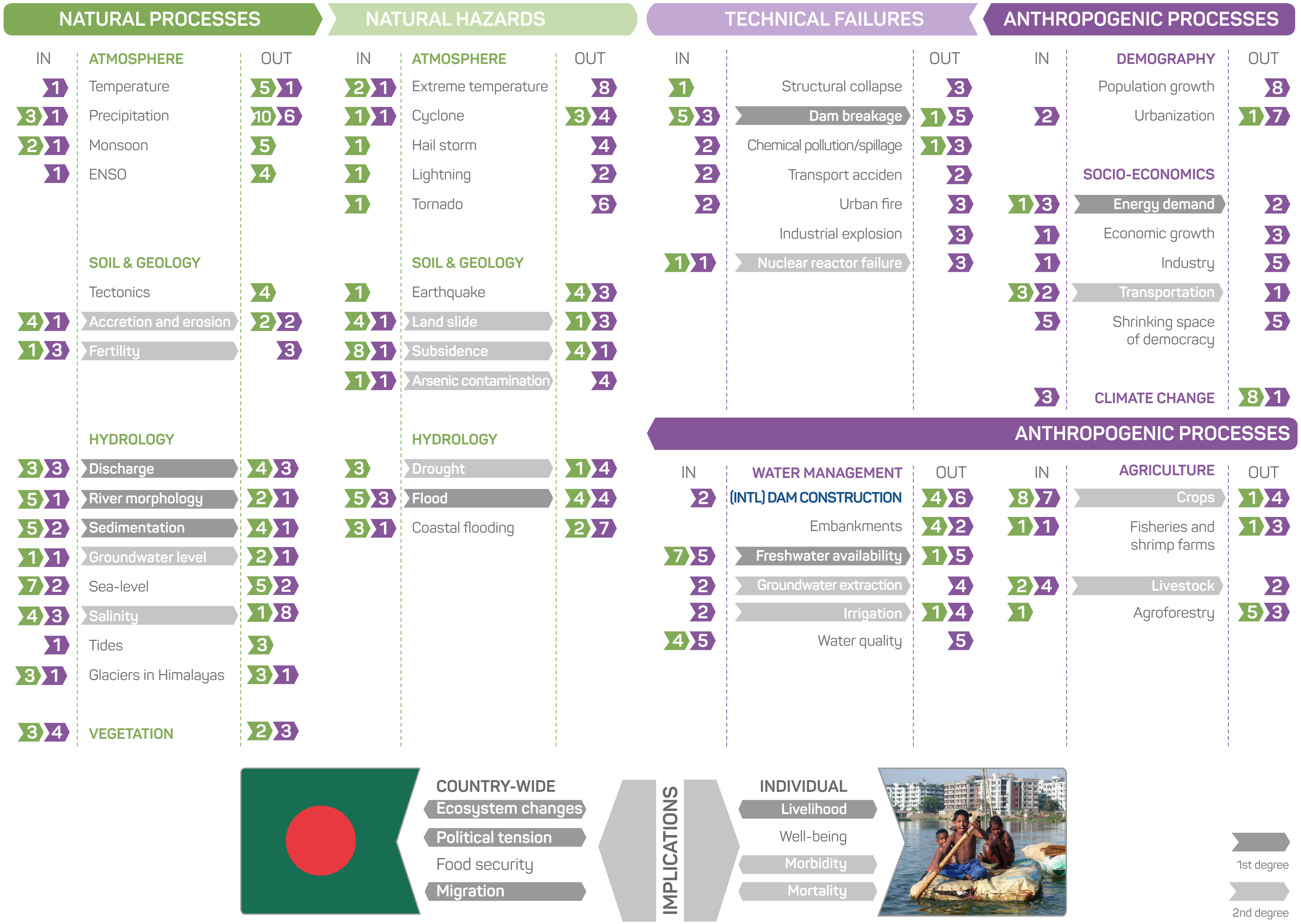


**Figure 5.3:** Interactions resulting from dam construction. The 11 indicators directly impacted by dam construction are highlighted in dark gray (1st degree), those indicators in turn impact more indicators highlighted in light gray (2nd degree).

to high expenses for daily water supply and an increased stress on the livelihood and morbidity of the slum dwellers, who also often lack the financial capital to adequately deal with varying water supplies (Aßheuer, 2014). Enabling access to freshwater, which is currently withheld from the majority of the poor people in Dhaka, would allow the population to realize their high resilience potential. By refusing this Right to Water (inter)national governments actively prevent the people from utilizing their resilient structures (Keck and Etzold, 2013).

## 5.2 An application of the framework: studying mortality

The overall mortality rate is low, with Bangladesh placing 179 out of 226 countries worldwide (Central Intelligence Agency, 2013). The mortality rate for adult females (males) per 1000 adults was 104.08 (149.25) in 2015 (India: 141.53 (213.44), Germany: 51.72 (94.65)[1]; United Nations Population Division (2017)). In recent years, Nahar et al. (2015) detected an overall shift in cause of death from communicable diseases to noncommunicable diseases, with a particular rise in violent deaths as the primary cause among teenage girls. We propose that the causal network can be applied to study key indicators affecting mortality and thus develop specific interventions to further decrease the mortality rate.

We present a sketch of how a possible application of the framework could look like:

- *Define the research question:*

  What are the key processes responsible for the comparatively high adult mortality rate in Bangladesh?

  - *Determine the kind of available information.* Mortality data is available from institutions such as the Bangladesh Bureau of Statistics or the Bangladesh Road Transport Authority, as well as scientific literature in particular for natural hazards, while death rates from technical failures are mainly available through various news reports.
  - *Determine the scale at which to work.* Nation-wide.
  - *Determine where in the eDPSIR framework the focus lies.* On processes directly affecting mortality, as well as first-order links to morbidity.
  - *Determine whether an environment, or human-centered perspective is required.* A human-centered perspective is required when studying the reduction of mortality rate.

- *Identify key nodes in the causal network and explore relevant sections of the causal network in more detail.* Mortality is a root node as not only precipitation and salinity lead to an increased mortality (Burkart et al., 2011a; Vineis et al., 2011),

[1] Numbers for Germany from 2013

but all natural hazards and technical failures can lead to a higher mortality rate (see Section A.2 and Section A.4). For relevant sections of the causal network, see Figure 5.4, which shows all indicators impacting mortality in the 1st and 2nd degree.

- *Select the best concrete indicators for the selected nodes.* Natural hazards and technical failures.

When attempting to mitigate the impact of natural processes on mortality, the focus in Bangladesh has mostly been on cyclones, tornadoes and flooding (Paul, 1998; Alam and Collins, 2010; Paul et al., 2010; Aßheuer et al., 2013). The number of deaths due to cyclones has significantly decreased since early warning systems have been introduced following the wake of the 1991 cyclone (>138,000 lives lost, Alam and Collins (2010)). Death counts in the two recent flood events of 2004 and 2007 are also lower compared to those of the previous three extreme flood events (3,680 in 1987, 2,379 in 1988, and 1,050 in 1998 Mirza (2011)). This absence of high water level effects on mortality could indicate an adequate adaptation to such events as discussed in Aßheuer et al. (2013).

While disaster management was successful in reducing the mortality rate, little has been done to mitigate the effects of precipitation, temperature, and extremely low water levels on mortality (Burkart et al., 2011a,b, 2014a,b; Thiele-Eich et al., 2015; Burkart and Kinney, 2016, 2017). In addition, from Figure 5.4, we see that both natural and anthropogenic processes influence mortality, with recent technical failures such as the structural collapse of a textile factory in Dhaka in April 2016 causing over 1,100 deaths. Dhaka also has a particular high transport accident rate, with the Bangladesh Road Transport Authority reporting 2,376 fatalities and 1,958 injuries for 2015 (Maniruzzaman and Mitra, 2005; Bangladesh Police, 2017).

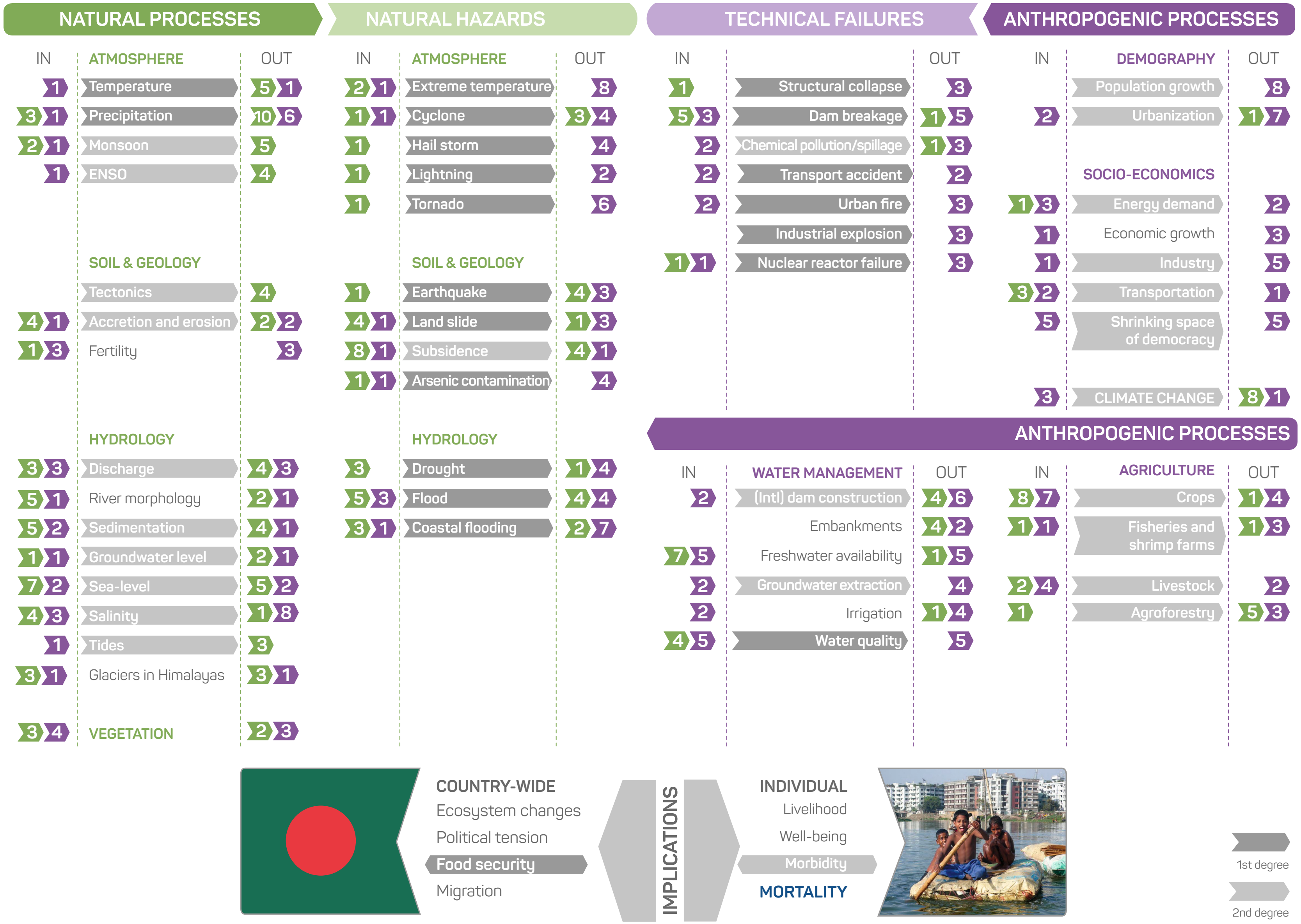


**Figure 5.4:** Indicators impacting mortality. The 21 indicators directly impacting mortality are highlighted in dark gray (1st degree), those indicators connected to the former are highlighted in light gray (2nd degree).

# Chapter 6

# Discussing flooding in the context of climate change

In the following, we will discuss the results from Chapter 4 and 5 and give an outlook on future research.

### Water levels and their connection to mortality

We hypothesized that water levels have changed in frequency, magnitude and duration during the past century, and that mortality increases with or follows extreme water levels. Our analysis suggests that water levels have indeed changed over the course of the past century. While the magnitude and duration of average flood events decreased, the frequency of extreme flood events has increased. Low water levels have also changed, with a significant decrease in the annual minimum water level most noticeable when we compare the time periods 1909 - 1939 and 1979 - 2009. A rise in mortality following extreme floods could not be substantiated, but an increase in relative risk of death was found as water levels decrease.

Our results concerning trends in flooding seem to be at variance with the results from Mirza et al. (2001), who did not find any consistent changes in peak discharge for the Ganges, Brahmaputra and Meghna using mean-based statistics. Since the discharges of this three-river system should be related, although not directly, to changes in Dhakas water levels, this discrepancy requires some thought. Concurring with Mirza et al. (2001), we did not find an increase in mean extreme event indicators. The average annual maximum water level even slightly decreased ($p < 0.10$). However, the estimated GEV distribution for the second half of the century shows a more frequent occurrence of extreme events, suggesting that there is in fact a change in the variance of extreme events: when extreme events do occur, they become more extreme. Such a tendency cannot easily be detected from quantile regression or test statistics based on the data mean as applied by Mirza et al. (2001).

While extreme events were seen to increase in magnitude and frequency, flood duration did not show any significant change. This is an important and somewhat positive finding as Aßheuer (2014) found a significant link between the number of days with high water levels and negative impacts on households located in informal settlements. An increase in damages due to flooding is therefore not likely due to an increase in flood duration, but perhaps more due to an increased exposure of the population and their assets (Patt et al., 2010).

Trends in low water levels have previously not been studied for Dhaka. Alam and Rabbani (2007) found no change in annual average precipitation in daily rainfall data for Dhaka from 1971 to 2005, while the number of days without precipitation did increase. Since a positive relation between days without precipitation and low water levels seems physically reasonable, their results concur with our results that indicate tha the annual minimum water level has decreased over time.

We assumed that flooding could result in direct deaths through e.g. drowning, or could have indirect effects leading to an overload or breakdown of infrastructures, ultimately resulting in an increase of death rates. The spread of pathogens due to stagnating water bodies and the increase of water-borne diseases, as well as a reduced access to health care and medical facilities, could contribute to a higher number of deaths. Milojevic et al. (2012) reported a significant impact of flooding on respiratory diseases for up to 6 months after a flood event, but did not see any effects on gastrointestinal diseases or mortality when studying health effects in rural Bangladesh. Our results also show that high water levels have no or only a weak relationship with mortality for the urban area of Dhaka.

Death counts in the two recent flood events of 2004 and 2007 are lower compared to those of the previous three extreme flood events (3,680 in 1987, 2,379 in 1988, and 1,050 in 1998; Mirza (2011)). This absence of high water level effects on mortality could indicate an adequate adaptation to such events as discussed in Aßheuer et al. (2013). This is in line with Ashley and Ashley (2009), who studied flood fatalities in the United States and found that behavior during floods was a risk factor for mortality. Flood policy makers are recommended to target specific groups and educate about the dangers of floods. With the much more frequent exposure of the Bangladeshi population to this natural hazard, the decline in mortality in recent years could in fact be due to a more educated and adapted community.

Less focus has been placed on the implications of droughts on mortality, in particular for an urban area. This study highlights a possible negative effect of low water levels and drought on mortality in Bangladesh. Explanations for this might be stagnating bodies of water or a general lack of dilution of freshwater and sewage systems, leading to contamination and the spread of pathogens (Hashizume et al., 2007; Zhang et al., 2007). In studies conducted in Bengal, the first outbreak of cholera in the year was associated with low precipitation and low river discharge. High precipitation and peak streamflow of rivers during the monsoon was associated with the second peak during the monsoon (Akanda et al., 2009; Hashizume et al., 2009).

Hydrological effects, in particular those of low water levels, on mortality in this urban setting are of utmost importance when assessing the implications of climate change on the growing urban population in greater Dhaka. In this respect, we consider our approach as highly beneficial to assess the complex association between effect and response, and to better understand temporal displacement of mortality and harvesting.

While the hydrological monitoring network of the Bangladesh Water Development Board provides an extensive spatial coverage for the region, the daily water level time series has several years of missing values which could not be imputed from neighboring stations particularly for the years before 1953. Although the direct contribution of individual factors to past floods is difficult to measure, they certainly cause uncertainty in the assessment of trends in water level. Khalequzzaman, M.D. (1994) names changes in riverbed characteristics such as siltation or external changes such as human interference with canals or the filling in of river channels to gain more accessible land for housing as possible factors in the creation of floods. Factors such as sea-level rise, subsidence, compaction of sediments in the enormous river delta, and a sinking groundwater table underneath Dhaka all cause changes in land elevation, which are not taken into account in our trend analysis of historic water levels due to insufficient data. Satellite measurements could be used to indicate how strong elevation changes were in past years, but the coverage is insufficient for the past 100 years. The water level data could also be impacted directly as the Buriganga River contributes to recharging the Dupi Tila aquifer below Dhaka (Morris et al., 2003).

A longer span of mortality data would also be beneficial, as high water level values may have an effect without these showing as significant, possibly due to the low number of death counts in the greater Dhaka area and the overall survey sample size. Problems could also occur due to uncertainty in the registration of flood-related deaths and their exact location, as proposed by Milojevic et al. (2011), who studied medium-term impacts of flooding on mortality in the UK. Even using their extensive data set of mortality registrations for 1993 - 2006 linked to over 300 flood events, they found a counter-intuitive decrease in mortality the year after flooding, which could in part be due to uncertainty regarding the place of residence when registering death counts.

Burkart et al. (2011a) analyzed seasonality of all-cause and cause-specific mortality, which was generally lower during summer and the rainy season, and peaked during the cold season. With regard to diarrheal mortality, a secondary peak at the end of the rainy season could be observed in rural areas and areas with a low socioeconomic status, but variations were at the limit of detection and significance. Droughts or low water levels typically occur during the cold season when mortality is high. As it is difficult to separate the effects of water level and temperature on mortality, it is possible that we have not sufficiently adjusted for season. Our observed effect could then in part be due to cold temperature effects, but it is also possible that part of the cold effect found in Burkart et al. (2011b) is, in fact, a drought effect.

Our results nevertheless give an indication for several actions to assist the population of Dhaka in increasing their adaptive capacity (Hess et al., 2012; Faisal et al., 2003) to natural hazards. While the Flood Forecast and Warning Center already provides accurate information and timely warnings regarding flood events, this network should be further developed to also include information regarding drought so the population, planning authorities and decision makers can adequately prepare. NGOs and international relief organizations should not focus mainly on the catastrophe management following extreme flood events and heat waves, but consider the impact of droughts and cold spells on mortality when preparing for natural disasters in the region.

Habiba et al. (2014) studied drought adaptation measures of farmers in Northwestern Bangladesh and found that e.g., the provision of drought-tolerant crops or the establishment of community health care services would assist the community in coping with droughts. We propose extending these studies to include a focus on an urban setting, where the depleted groundwater table is an issue that can possibly exacerbate low river levels.

Structural as well as non-structural measures also need to be implemented to assist the population in coping with extreme events (Faisal et al., 2003). During the flood of 2004, 2 million city residents had limited access to drinking water as their supplies were contaminated, resulting in over 100,000 reported diarrhea cases in Dhaka alone (Alam and Rabbani, 2007; Sirajul Islam et al., 2007). This was due in large parts to submerged pumps operated by the Dhaka Water and Sewerage Authority. While the overall death count was low compared to previous flood events, it is nevertheless important that the pump and sleuce system is well-prepared to deal with an increase in extreme flood events, even though the average annual flooding may decrease. This holds particularly true since the population of Dhaka is expected to grow in future years, leaving more people affected by flooding. Despite this population growth, it is still important to ensure that flood plains and embankments are accessible and not filled up to create land. Additional measures could include the dredging of rivers (Khalequzzaman, M.D., 1994).

Finally, a closer look at climate change and its impact on water levels in Dhaka is vital to adequately prepare the population for the expected changes until the end of the century. Using climate scenarios from four global climate models as input to the river modeling system MIKE11-GIS, Mirza (2011) estimated that the mean flooded area is expected to increase by 29 % for 0 to 2 °C of warming. While it is not yet feasible to derive urban water levels directly from global climate model or even regional climate model output, a closer look should be taken into downscaling methods connecting model output to urban water models such as MIKE URBAN to assess future impact of climate change on extreme water levels in Dhaka.

To discuss the question of how flooding in both the city of Dhaka and the country of Bangladesh will be impacted by climate change, we set up a socio-hydrological framework in Chapter 5, which will be discussed in the following.

### Socio-hydrological feedbacks

In Chapter 5 we set up and visualized a conceptual framework to comprehend the complexity of the socio-hydrological challenges faced by Bangladesh. The framework proved useful in providing both a holistic overview as well as allowing a more detailed study of certain cause-effect-response links. The importance of including both natural and anthropogenic processes is stressed as almost all indicators in Figure 5.1 show interactions with both compartments.

Using one flexible framework to combine diverse natural processes occuring in Bangladesh's hillslopes, coastal areas, fluvial and glacial systems with e.g. demographic and socioeconomic processes, while also including their intricate connections, allows for the identification of both positive and negative feedbacks. We agree with Patrício et al. (2016) that the eDPSIR approach is a useful tool in identifying key cause-effect-response links in complex environmental systems, and believe that the framework can successfully be used to study the functioning of individual system components, which is vital in setting up socio-hydrological models to predict the impact of climate change (Wagener et al., 2010).

When addressing challenges of both climate and global change in Bangladesh, reports such as Chowdhury (2001); Nicholls, R.J. et al. (2007); GAR (2009) and GAR (2011) tend to focus mostly on natural hazards. While the "hazardousness" of Bangladesh can undoubtedly be confirmed from our framework (Gill and Malamud, 2014), we also show that it is important to include a focus on anthropogenic processes such as the construction of dams. The reduction of dry season discharge through Farakka Barrage is certainly not a natural hazard, but affects the livelihood of millions of people and cannot be ignored. We thus agree with Gill and Malamud (2014) and Gill and Malamud (2016) that natural hazard risk assessment needs to consider the effect of human interactions as these can have drastic implications for the system.

Several key nodes were identified from Figure 5.1 (Chapter 5.1). In particular the central nodes have been extensively studied, especially the connection between subsidence, sea level rise and salinity (Hoque and Alam, 1997; Syvitski et al., 2009; Rabbani et al., 2010; Pethick and Orford, 2013; Brammer, 2014; Schiermeier, 2014), as well as precipitation and its importance to flooding and freshwater availability (Immerzeel, 2008; Immerzeel et al., 2010; Immerzeel and Bierkens, 2012, 2013). While research on flooding usually at least also includes a focus on the construction of dams (Mirza, 1997, 1998; Mirza et al., 2001; Mirza, 2003a,b; Mirza et al., 2003; Höfer and Messerli, 2006; Jian et al., 2009; Immerzeel and Bierkens, 2013; Gain and Giupponi, 2014), sedimentation is treated in a more isolated manner despite the numerous interactions with other variables such as soil fertility, accretion and erosion (Brammer, 2012; Pelletier et al., 2015). While a certain prognosis can be made on precipitation, sea level rise and flooding from earth system models, other aspects such as salinity and sedimentation are currently not adequately incorporated in earth system models. As these are key aspects impacting the livelihoods of millions of people, this further underlines the need for more socio-hydrological modelling approaches when analyzing the complex interactions in the GBM delta (Sivapalan et al., 2011; Bierkens, 2015; Pelletier et al., 2015).

We also detect feedback loops such as e.g. the increase in shrimp farming in areas with high salinity content, which in turn leads to an even stronger salinification of coastal areas (Amoako Johnson et al., 2016). While these two-way feedback loops are crucial to the understanding of natural and anthropogenic processes, in particular in the context of climate change, they are also not included sufficiently in models (Di Baldassarre et al., 2015; Pelletier et al., 2015).

In addition to pinpointing areas in which earth system models should be developed further, the framework can also aid in showcasing socio-hydrological aspects that are currently barely being focused on by researchers and policy makers. For example, when attempting to mitigate the impact of natural hazards on mortality, the focus in Bangladesh currently lies mostly on cyclones, tornadoes and flooding (Paul, 1998; Alam and Collins, 2010; Paul et al., 2010; Aßheuer et al., 2013). From Chapter 4 and 5.2, it becomes clear that droughts - though not a key node in Figure 5.1 - have a significant impact on mortality rate. While the population has developed sufficient coping mechanisms to recurring floods, these are not yet in place for more rarely occuring drought events. The lack of focus in this area by researchers and NGOs working in disaster management is problematic, more so as we can see from Figure 5.1 that droughts are connected to several key nodes such as freshwater availability and a lower discharge due to the construction of dams, and are thus far from an isolated problem (Immerzeel and Bierkens, 2012; Gain and Giupponi, 2014).

### Identifying tipping points

The socio-hydrological framework includes several non-linear interactions between indicators, which respond at a variable rate to the driving forces. Two-way feedbacks could gradually amplify the forcing, and/or could include tipping points, a threshold marking abrupt changes in the forcing-response relationship that could lead to sudden and perhaps irreversible system transitions (Pelletier et al., 2015). For Bangladesh, we identified several tipping points e.g. sinking deltas as a natural and e.g. political conflict as an anthropogenic tipping point.

**Natural tipping point - sinking deltas** Subsidence is one of the central nodes identified in Chapter 5, with Syvitski et al. (2009) naming the oceans global volume, aggradation, sediment compaction, and vertical movements resulting from plate tectonics and other geophysical processes as the four main factors in determining a delta's elevation above sea level. As the ocean volume is likely to expand due to climate change (IPCC, 2013), and Bangladesh also experiences increasing compaction with e.g. increases in groundwater extraction (Brown and Nicholls, 2015) and reduced aggradation due to e.g. the construction of dams and embankments (Gain and Giupponi, 2014), the GBM delta is at risk from increasing subsidence and thus rising relative mean sea levels, more coastal flooding, and higher salinity. The latter are all key nodes in the socio-hydrological framework, stressing the importance of a holistic approach to highlight the relationship of key processes in the GBM delta. Furthermore, Syvitski et al. (2009) describe the sinking of a delta as a non-linear process that can reach a certain threshold after which the subsidence is no longer reversible. This has already occured in the delta of the Indus River in Pakistan, which has shrunk by 90 % of its original size and runs dry close to 140 days of the year, displacing up to a million people.

**Anthropogenic tipping point - political conflict** A tipping point could also occur due to political tension, which refers both to intra-national conflicts, e.g. the Chittagong Hill Tract conflict due to building of Kaptai Dam, which displaced over

100,000 members of the ethnic group of the Chawa (Parveen and Faisal, 2002), as well as international tension, e.g. due to water sharing issues resulting from the construction of Farrakka barrage. Over the years, several attempts have been made to formalize the sharing of water in the dry season, with schedules suggesting to alternate flow every two weeks while supplying a minimum flow of 35,000 $m^3/s$ to Bangladesh. The impacts resulting from the construction of Farraka Barrage, in particular in the dry season, are extensively discussed in Chapters 2.3.1, 5.1.4 and A.3.4. Already, political tension is seen as a result of these impacts, largely due to the minimum flow not being met in every year (Mirza, 1997). If political tension remains unadressed, livelihoods and well-being of individuals will be more and more affected, and could - in a worst-case scenario - eventually lead the system to armed conflict, certainly a tipping point from which the system could not easily revert to its original state (Houghton et al., 2010; Buntgen et al., 2011; Schleussner et al., 2016).

**The challenge of climate change**

While it is noteworthy that Bangladesh contributes comparatively little to global climate change in terms of $CO_2$ emissions, there is overwhelming agreement that Bangladesh and the GBM delta are likely to be severely impacted by climate change. A particular focus in constructing this framework was thus placed on addressing the overall challenge of climate change to ensure that policy makers know where available resources can be used most effectively to increase resilience and reduce vulnerability.

To answer the question how climate change will impact flooding in Bangladesh, and especially the slum dwellers in Dhaka, it is important to not only take into account the direct effects of the changing climate on flooding, but also their interactions with other indicators in the framework. While a prognosis on flooding currently remains difficult to quantify down to exact numbers due to large uncertainties in climate models, possible changes such as increases in the duration, magnitude or frequencies of flooding will likely take place over long stretches of time. This enables the population to adapt slowly. Resources such as social capital, which is one of the main tools for the slum dwellers in Dhaka to be able to cope with flooding, can be altered over time (Aßheuer et al., 2013; Aßheuer, 2014), and as such the system can be considered overall stable and resilient. This is also evident in the missing connection between extreme flooding and mortality (Chapter 4).

However, changes to the system such as the construction of Farraka Barrage may severly impact the current capacity to cope. We showed that since operations began in 1974/1975, the hydrological characteristics of the river downstream have been changed (Chapter 2.3.1, Swain (1996); Mirza (1998); Gain and Giupponi (2014)). While the effect is also present during the flood season, this holds especially true for the dry season, which has a wide number of implications both on the country-wide as well as the individual level. With dam construction having more interactions than climate change (11 vs 9, Figure 5.1) we strongly agree with Gain and Giupponi (2014); Whitehead et al. (2015) who name the construction of dams as one of the major causes of anthropogenically induced hydrological alterations.

Planned projects such as the Indian River Linking Project, which calls for the construction of a similar dam on the Brahmaputra before it enters Bangladesh, are thus of particular concern (Doshi, 2016). In addition, China is planning to build its own dam further upstream. With 90 % of the river discharge draining through Bangladesh falling as precipitation outside of Bangladesh and droughts expected to increase in the future (Whitehead et al., 2015), these structures are bound to impact the livelihood of the millions of people living in the GBM delta. Treaties to share the water of the Ganges across the border have already proven largely ineffective for Farakka Barrage with only two countries involved (Mirza, 1998; Gain and Giupponi, 2014). The situation along the Brahmaputra, with two countries planning on retaining water along their respective borders before the river enters Bangladesh, is likely to be even more complicated. Both India and China also have to adapt to the challenges posed by a growing population and climate change, and are not likely to refrain from building the dams. A slum dweller in Dhaka can be expected to have the resources to cope with i.e. an increase in flood duration of 5 days by 2100 (Aßheuer et al., 2013; Aßheuer, 2014), but how the geopolitical decision making of the neighbouring countries will impact the livelihoods is completely unclear. We also find that while climate change mostly interacts with natural processes in Figure 5.1.1, these are in turn connected to anthropogenic processes affecting the entire framework. A slow rise in absolute sea level by itself is negligible compared to the pressure put on e.g. freshwater availability and food supply by a rapidly growing population (Brammer, 2014). Personal interviews with slum dwellers confirm that the urban poor in particular face many short-termed challenges such as e.g. food security, educating their children, or finding employment, and perceive these as a much greater risk than climate change. Climate change can thus be seen as an anthropogenic amplification of the socio-hydrological challenges faced by Bangladesh.

Both the urban and rural poor are a particularly vulnerable subset of the population. While the continuing economic growth has helped reduce the population living below the poverty line by increasing financial capital, they are usually affected more strongly by hardships such as salinization and water logging than more affluent members of the community, creating a social inequity (Brouwer et al., 2007; Amoako Johnson et al., 2016). In particular poor women and children are often disproportionally affected by impacts on e.g. food security (Mirza, 2011). The urban poor currently face a shrinking space of democracy, which increases the vulnerability by e.g. forcing slum dwellers to build their homes in flood-prone areas by refusing them the right to urban space (Chapter 5.1.5). In extreme cases, the lack of workers' rights in the textile industry is thought to be responsible for the high death toll after a structural collapse in April 2016, as workers' concerns were not taken serious and building codes were violated (The Guardian, 2013; Than, 2013).

#### Using the framework to identify and aid in creating effective solutions

The link between environmental and anthropogenic dimensions is of great importance to successful policy and decision making, and aids in creating effective solutions (Niemeijer and de Groot, 2008b; Rabbani et al., 2010). An example for the country's capabilities to execute effective disaster risk management is the large-scale investment into infrastructure such as shelters and embankments to protect the population from cyclones (Yu et al., 2010). However, while this has been successful in reducing the number of deaths related to cyclones, these embankments in turn impacted e.g. coastal sediment transport, affecting soil fertility and thus crop yield (Hossain et al., 2008; Schiermeier, 2014; Pelletier et al., 2015). Larger projects such as the Bangladesh Delta Plan could build on and expand the presented socio-hydrological framework to carefully evaluate possible impacts (Rabbani et al., 2010).

Creating more resilient communities today simultaneously prepares them for the unavoidable challenge of future climate change. The socio-hydrological framework has the potential to address the challenges from avoidable feedback cycles such as an increased salinity and reduction in freshwater in coastal areas through unregulated shrimp farming. Freshwater supply could be increased through rainwater harvesting, recycling waste water and increasing water productivity through educating communities, or through the installment of flexible embankments that allow flooding during the monsoon season but keeps out saline water during the dry season (Schiermeier, 2014). On the other hand, projects suggesting the diversion of water from the Ganges to increase freshwater availability in the dry season (Brammer, 2013, 2014) seems questionable with the multitude of implications from dam construction (Figure 5.3).

To address drivers of poverty in the GBM delta, which include salinization, water logging, employment, education and access to roads, focusing on other issues such as improving the population's capacity to learn or self-organize rather than on the capacity to cope with the long-term effects of climate change are also of importance (Amoako Johnson et al., 2016). Successful implementation of capacity building measures could be vital to enable the slum dwellers to move from simply "getting by" to "getting ahead" (Aßheuer et al., 2013; Aßheuer, 2014). Most importantly, we agree with Rabbani et al. (2010) and Aßheuer (2014) that these solutions should not be offered from the outside, but should be developed in close cooperation with affected communities as well as through empowering researchers at national universities.

**Future research**

The goal of setting up a socio-hydrological framework was to show that the impacts of climate change on flooding and thus livelihoods in Bangladesh can not be treated isolated and by utilizing a causal chain approach, but rather that both natural and anthropogenic processes and their two-way feedbacks need to be included. While this can be confirmed from the extensive overview provided in Figure 5.1, certain aspects could certainly be elaborated on and adapted depending on the research question. For example, a study focusing on ecosystem changes needs to include naturally occuring fauna such as the Bengal tiger, which is currently missing from the framework.

Depending on the goal or research question, a stronger focus also needs to be placed on the quantification of the indicator interaction (Patrício et al., 2016). The impact of e.g. precipitation and subsidence is weak and negligible on certain spatial scales (Steckler et al., 2010), but important if the goal of a study is to assess the likelihood of the entire delta sinking in the next 100 years (Syvitski et al., 2009; Steckler et al., 2010). Discussing the different processes responsible for adult mortality also is not possible without quantifying the increase in death rate from each of the individual interactions.

Especially for the links coming from climate change, links may have different levels of certainty, which is important when communicating the results to policy makers. For some interactions, such as the connection between ENSO with monsoon precipitation, scientific literature disagrees on the nature of the interaction, which is currently not evident from Figure 5.1. Temporal information important for studying short-term effects such as the amount of freshwater available over the course of a dry season, or long-term effects from e.g. climate change, as well as non-linear link interaction is also not clearly distinguished (Pelletier et al., 2015).

When discussing impacts on the human system, Patrício et al. (2016) criticize the eDPSIR approach for its over-simplification of environmental problems, especially in that different eDPSIR components are being treated as mutually exclusive. They suggest using the Drivers - Activities - Pressures - State (change) - Impacts (on human welfare) - Response (using Measures) or DAPSI(W)R(M) framework, an extension of the eDPSIR that includes e.g. activities in the framework in an attempt to more clearly distinguish between driving forces and pressures while also placing a stronger focus on human welfare (Scharin et al., 2016).

The eDPSIR framework currently treats hazards as discreet and independent events, and neglects the possibility of spatiotemporal co-occurrence. Instead of including natural hazards in a single hazard approach, the framework in Figure 5.1 could be combined with a multihazard framework as proposed by Gill and Malamud (2014, 2016), which would allow the inclusion of a hazard cascade, where primary hazards trigger the onset of a secondary hazard. An example for such a compound event is the occurrence of a major flood immediately after an earthquake in 1787, which also led to a 150 km westward shift in the flow of the Brahmaputra (Höfer and Messerli, 2006; Khalequzzaman, M.D., 1994). Should a similar event occur today, this would impact millions of people due to the high population density. For Bangladesh, a multihazard framework is also of importance as Gill and Malamud (2016) identify flooding as a particularly vulnerable secondary hazard, meaning that it is likely that primary hazards such as earthquakes, tsunamis, land slides, subsidence, storms or extreme temperatures - all of which occur regularly in the GBM delta - could increase the probability of a flood event occuring.

Gill and Malamud (2014) propose that a complete multihazard methodology should contain the following four aspects:

**Hazard identification and comparison** The identification and valid comparison of all identified individual hazards, relevant to a given spatial region.

**Hazard interactions** The identification and characterisation of all possible interactions between identified hazards.

**Hazard coincidence** An investigation into the impacts of two or more hazards coinciding spatially and/or temporally, such that the hazard potential and/or vulnerability may differ from the sum of its parts.

**Dynamic vulnerability** An understanding of how one, or a series of hazards, will impact upon the vulnerability and resilience of a community, thus changing the overall future risk to a location or community.

While we do identify and compare hazards and their interactions in Figure 5.1 and Chapters 5, A.1, A.2, A.3 and A.4, we are currently not focusing on hazard coincidence and dynamic vulnerability of the community. We suggest that a multihazard expansion of our framework would greatly benefit the documentation, understanding and attribution of compound events, which is essential to modelling how these events will be affected by climate change.

The availability of high-quality observational data on relevant temporal and spatial scales for both natural and anthropogenic processes is another necessity, in particular for those indicators identified as key nodes such as precipitation, salinity and freshwater availability (Elsner et al., 2008; Cash et al., 2008; Annamalai and Sperber, 2016; Masood et al., 2015). This is important both to monitor for possible changes in e.g. mortality rate, as well as to reduce uncertainty in modelling physical relationships such as e.g. monsoon dynamics (Immerzeel and Bierkens, 2010; Simmer et al., 2015; Annamalai and Sperber, 2016). Such observations are key to improving earth system models used in global climate modelling approaches. Rather than quantifying climate change impacts in an isolated manner, implementing the observed feedbacks between climate, hydrology and society can advance earth system models to provide climate change scenarios including the anthropogenic amplification of existing socio-hydrological challenges.

# Appendix A

# Indicators included in enhanced Driving force - Pressure - State - Impact - Response framework

This chapter provides a more extensive discussion of the indicators included in the socio-hydrological framework (Figure 5.1), and lists all indicator interactions including applicable references using the following scheme:

*Interacts with:* $\rightarrow$
Outgoing arrows in Figure 5.1.
*Impacted by:*$\leftarrow$
Incoming arrows in Figure 5.1.

## A.1 Indicators for natural processes

The relevant natural indicators contributing to sociohydrological processes in Bangladesh can be separated into four compartments: the atmosphere, the soil and ground, hydrology and vegetation. Effects of other intra-annual atmospheric circulations such as the Indian Ocean Dipole (IDO), Quasi Biennial Oscillation (QBO) or the Madden-Julian-Oscillation (MJO) are not described here, but can be found in e.g. Meehl and Arblaster (2002) and Ahmed et al. (2016).

### A.1.1 Atmosphere

In the following, key atmospheric variables and observed trends relevant to hydrological processes in Bangladesh are listed.

**Temperature** For a description of the temperature regime in Bangladesh, see Chapter 2.2. Temperature is a key component of cold spells, heat waves and droughts as well as glacial melt and determining the growth of crops and vegetation, while temperature differences between the flood plains in Bangladesh and the Tibetian Plateau are thought to influence the strength of the Indian Summer monsoon (Liu and Chen, 2000; Immerzeel, 2008; Wassmann et al., 2009a,b). This temperature difference is expected to amplify, as seasonal temperatures are expected to increase between 2000 and 2100, with stronger changes on the Tibetian Plateau. Likewise, global warming is also evident within the GBM catchment, with both mean and extreme temperatures increasing in past observations and future projections (IPCC, 2013). This change in temperature is believed to impact crop yields, in particular for rice (Wassmann et al., 2009a,b).

*Interacts with:* →
Monsoon. Glacial melt. Vegetation. Extreme temperatures. Droughts. Crops.
*Impacted by:*←
Climate change.

**Precipitation** For a description of the precipitation regime in Bangladesh, see Chapter 2.2 and Islam et al. (2005); Islam and Islam (2006) and Rafiuddin et al. (2010). Single precipitation events can be driven by cyclones or hail storms, while the amount of annual precipitation is largely determined by the strength of the Indian Summer monsoon (Immerzeel, 2008).

Precipitation is a key driver for many hydrological processes in Bangladesh, in particular discharge (Chowdhury and Ward, 2004; Jian et al., 2009) and thus droughts and flooding. In addition, annual loading of water during the monsoon season through increased precipitation and subsequent unloading lead to vertical elastic deformation of up to 6 cm over the entire GBM delta (Steckler et al., 2010). During the dry and pre-monsoon season, brick manufacturing can be impacted by heavy precipitation events (Aßheuer, 2014). Precipitation also influences sedimentation, salinity, glacial melt, vegetation and crop yield (Mirza, 1998; Vineis et al., 2011; Tao and Zhang, 2013; Pelletier et al., 2015; Zhao et al., 2016). Heavy rains have led to land slides and dam breakages (Ahasan et al., 2013). Burkart and Kinney (2016) describe the connection between precipitation and mortality for seasons, age and gender; they found that e.g. low but ongoing amounts of precipitation during the dry season can result in an increase in mortality in the elderly. During the rainy season, heavy amounts of precipitation cause a rise in infectious disease mortality (Burkart et al., 2014b), but also seems to mitigate heat stress (Burkart and Kinney, 2016).

Because of it's connection to hydrological processes Bangladesh, the impact of climate change on precipitation in Bangladesh is of great interest. In the following, we briefly discuss past trends and future projections for precipitation. The assessment of past trends in precipitation across a catchment as large and climatically diverse as the GBM is difficult as sufficient observational records are lacking (IPCC, 2013). Furthermore, the choice of precipitation products such as the Climate Prediction Center Merged Analysis of Precipitation (CMAP) or the Climate Anomaly Monitoring System (CAMS) largely determine the outcome of trend analyses, with products disagreeing especially for the region of Bangladesh (Cash et al., 2008). Existing attempts using observations include Mirza et al. (1998), who provides an overview of trends based on data from the 16 meteorological subdivisions within the GBM catchment; Gain and Giupponi (2014), who found no trends in annual precipitation in the Ganges basin between 1964 - 2005; Immerzeel (2008) who likewise found no significant trends in annual precipitation for the period of 1900 - 2002 in the Brahmaputra basin.

For Bangladesh, station data cover most of the country from the 1950s onward. By assessing data from 17 stations for 1958 - 2007, Shahid (2010) detected significant increases in country-wide average annual and pre-monsoon rainfall, with an overall increase in wet months and a decrease in dry months. Mirza et al. (1998) confirms the results for the areas of the Ganges, Brahmaputra and Meghna catchment inside Bangladesh.

Future estimates of rainfall for Bangladesh and the entire GBM catchment come with large uncertainties as climate models still experience difficulties in capturing an adequate representation of the Indian Summer monsoon (Immerzeel et al., 2010), but IPCC (2013) project significant increases in both mean and extreme precipitation during the monsoon season, with light rain events decreasing. Immerzeel (2008) also finds seasonal increases in precipitation between 2000 to 2100 for the Brahmaputra basin, in particular for the monsoon season.

*Interacts with:* →
Discharge. Sedimentation. Salinity. Glacial melt. Vegetation. Extreme heat. Land slides. Subsidence. Droughts. Floods. Industry. Freshwater availability. Crops. Dam breakage. Morbidity. Mortality.
*Impacted by:*←
Monsoon. ENSO. Cyclones. Climate change.

**Monsoon** The Indian Summer or South Asian monsoon is a highly complex circulation system resulting from differential heating of land and water over the Indian subcontinent. By mid-June, humid air masses arrive along the southeastern coast of Bangladesh, marking the onset of the monsoon, the key driver for summer precipitation in Bangladesh. Moving to the northwest in the coming weeks, the summer monsoon is in full force across the GBM catchment as the pressure gradient between land and ocean becomes strongest by mid-July. Up to 70 % of Bangladesh's total annual precipitation falls during the monsoon, which usually loses its intensity by the end of September (Höfer and Messerli, 2006; Immerzeel, 2008). In addition, annual loading of water during the monsoon season through increased precipitation and flooding and subsequent unloading lead to vertical elastic deformation of up to 6 cm over the entire GBM delta (Steckler et al., 2010). Further information on the Indian summer monsoon, e.g. regarding its connection to glacial melt, hail storms or lightning, can be found in e.g. (Höfer and Messerli, 2006; Webster et al., 1998; Scherler et al., 2011; Zhao et al., 2014; Annamalai and Sperber, 2016).

The monsoon undergoes intraseasonal oscillations as well as interannual variations, (Lawrence et al., 2001; Fujinami et al., 2011), and its strength is significantly related to air temperature differences between the flood plains in Bangladesh and the Tibetian Plateau (TP) as well as the snow cover on the TP (Li et al., 1996; Liu and Yanai, 2001; Immerzeel, 2008; Immerzeel and Bierkens, 2010). The monsoon over the Indian subcontinent is also affected by El Niño Southern Oscillation, with El Niño years generally resulting in weaker monsoons as convection is surpressed over South Asia (Webster et al., 1998; Kumar, 1999; Singh et al., 2001). For Bangladesh, Ahasan et al. (1993) found that the overall variability of precipitation in Bangladesh remains largely unaffected, but more extreme events occur during ENSO years.

Immerzeel et al. (2010), Immerzeel and Bierkens (2010), Saha et al. (2014), and Annamalai and Sperber (2016) describe difficulties in assessing climate change impacts on monsoon systems, as climate models experience difficulties in correctly representing their complex dynamical features. For example, the majority of the climate models used for the Coupled Model Intercomparison Project (CMIP5) has not been able to capture the overall weakening of the monsoon in the years since 1950, (Saha et al., 2014) while Sharmila et al. (2015) found regional inconsistencies in the spatial patterns among 20 CMIP5 models. Models did agree on an intensification of the frequency and strength of extremely wet and dry years under RCP8.5, with a decrease in number of wet days (Sharmila et al., 2015). Regional climate model simulations found the weakening of the past to continue into the 21st century, as well as a delayed onset by several days (Ashfaq et al., 2009).

*Interacts with:* →
Precipitation. Glacial melt. Hail storms. Lightning. Subsidence.
*Impacted by:*←
Temperature. ENSO. Climate Change.

**ENSO** During the El Niño phase of the El Niño Southern Oscillation (ENSO), the Bay of Bengal and adjoining regions are dominated by high pressure anomalies, with low pressure anomalies prevailing during La Niña years (Singh et al., 2001). El Niño (La Niña) events are thought to be connected to a weak (strong) monsoon and thus lower (higher) precipitation amounts (Kumar, 1999). Singh et al. (2001) detected an increase in monsoon precipitation during La Niña years for the Meghna basin, resulting in increased discharge and a mean tide level that is 5 cm higher in August compared to an El Niño year. A co-occurrence of ENSO and IOD events showed severe anomalies for droughts and floods, indicating that precipitation is indeed impacted by ENSO (Ahmed et al., 2016). However, in recent years the impact of ENSO on monsoon precipitation is not as clear. Immerzeel (2008) and Fujinami et al. (2011) could not confirm that ENSO plays an important role in explaining monsoon precipitation. Cash et al. (2008) found that the choice of precipitation data product can determine the apparent relationship between rainfall and ENSO, while Kumar (1999); Kumar et al. (2006) suggest that a midlatitude continental warming trend has enhanced the land-ocean thermal gradient beneficial to a strong monsoon event, so that monsoon rainfall rates stay high despite a strong ENSO event. Elsner et al. (2008) suggests that El Niño conditions may be relevant to the formation of cyclones. The impacts of climate change on the different characteristics of ENSO are detailed in Yeh et al. (2009), with the expected shift in El Niño from the eastern Pacific to the central Pacific likely to have an impact on the Indian Summer monsoon.

*Interacts with:* →
Precipitation. Monsoon. Sea level. Cyclones.
*Impacted by:*←
Climate change.

### A.1.2 Soil and geology

Processes concerning the soil, in particular in the diverse and complex coastal region of Bangladesh, as well as geological characteristics of Bangladesh, are extensively described in Moslehuddin et al. (1997); Brammer (2012, 2013, 2014); Emran et al. (2017). Brief descriptions of the most important aspects with respect to hydrological processes and their key interactions are given below.

**Tectonics** The greater Indian and Eurasian Plate meet with the Burma Arc in the Bengal Basin, thus Bangladesh is situated in a critical tectonic position with tectonic motions in the region uncertain and thus a largely unknown seismic hazard. For an extensive review of the tectonics in the Bengal Basin and its contribution to the creation of the delta as well as the distribution of sediments throughout Bangladesh, see e.g. Johnson and Alam (1991); Kuehl et al. (2011). The active subduction zone resulting from the Indian plate moving under the Burma Arc contributes to subsidence and changes of relative mean sea level in the region, while various fault lines make Bangladesh prone to earthquakes (Steckler et al., 2008, 2016).

*Interacts with:* →
Sedimentation. Sea level. Earthquakes. Subsidence.

**Accretion and erosion** Accretion and erosion refer to the growth and loss of land, particularly along the coastline, coastal islands and rivers, and is often a cyclic process in the highly dynamic coastal region of Bangladesh. Satellite imagery combined with ground truthing and water level measurements indicate constant changes in Bangladesh's surface area. Accretion and erosion are affected by the slope of the banks (steep - erosion, gentle - accretion), sea level and tidal pressure (high - erosion, low - accretion), and the material composition of banks (loose - erosion, compact - accretion). (Rabbani et al., 2010; Brammer, 2014; Emran et al., 2017)

Accretion and erosion rates vary throughout Bangladesh, but are especially pronounced in the Meghna estuary (eastern region in Figure A.1). By comparing Landsat images from 1984 and 2007, Brammer (2013) found that the estuary had a net growth of 19.6 $km^2$ per year, or 451 $km^2$ in total. Accretion is mainly dependant on the sediment loads carried by the Ganges, Brahmaputra and Meghna, and is thus also influenced by dams being built further upstream (Haque et al.

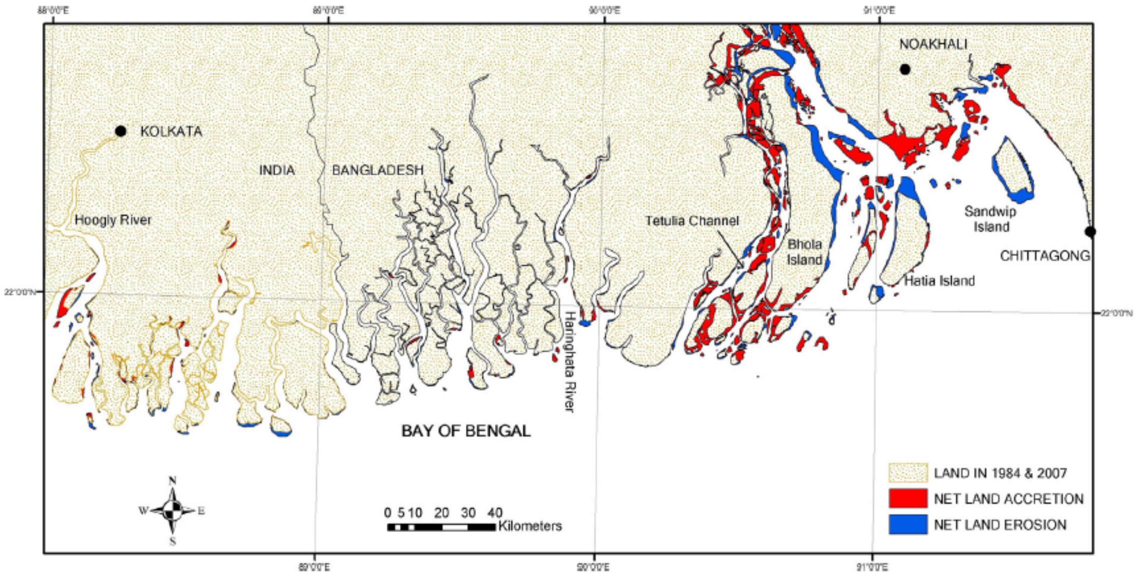


**Figure A.1:** Gains and losses of land on the Brahmaputra-Ganges-Meghna delta front between 1984 - 2007, from Brammer (2012).

(2016), see also Chapter 2.3). Accretion is aided by an increased focus on agroforestry, as mangroves can assist in stabilizing land (Hasan and Alam, 2006).

Despite a net gain, several areas have lost significant amounts of land because of erosion. For example, Sandwip Island has lost a net 24 $km^2$ in land in the past 30 years, which has led to increased migration from the coast line and river banks further inland as households - often farmers - need to move to sustain their livelihoods (Brammer, 2014; Emran et al., 2017).

*Interacts with:* →
River morphology. Sea level. Migration. Livelihoods.
*Impacted by:*←
River morphology. Sedimentation. Sea level. Tides. Agroforestry.

**Fertility** Soil fertility is a vital factor in determining the sustainable use of land for agricultural purposes. It describes the ability of the soil to supply plants with sufficient nutrients and thus directly influences agricultural yields (Rahman and Parkinson, 2007). Soil organic carbon, available nitrogen, and the concentration of phosporus and potassium are soil fertility parameters described extensively for Bangladesh by Rahman and Parkinson (2007); Moslehuddin et al. (1997). Soil fertility varies throughout Bangladesh (Ali et al., 1997), with upland soils low in organic matter and deficient in nitrogen whereas the flood plains generally show fertile soils. Agroforestry and educational efforts in sustainable agricultural practices in Bangladesh have shown to positively impact fertility (Hasan and Alam, 2006). With increasing depletion of soil organic matter throughout Bangladesh, Ali et al. (1997), Moslehuddin et al. (1997), Hossain (2001) and Rahman and Parkinson (2007) stress the need for conservation measures to ensure a continuing acceptable fertility status in coming years.

*Interacts with:* →
Crops. Food security. Livelihood.
*Impacted by:*←
Floods. Crops. Agroforestry. Chemical pollution and spillage.

### A.1.3 Hydrology

An overview of the hydrology of Bangladesh is also given in Chapter 2.3.

**Discharge** See Table 2.1, Figure 2.4 and Chapter 2.3 for details.

*Interacts with:* →
Groundwater level. Salinity. Droughts. Floods. Transportation. Freshwater availability. Nuclear reactor failure.
*Impacted by:*←
Precipitation. Sea level. Glacial melt. Dam construction. Irrigation. Dam breakage.

**River morphology** Morphological variables of river channels include bankfull width, channel slope, and meander length (Bjerklie, 2007). These variables are influenced by the size, composition and availability of sediments, as well as vegetation along the slopes and obstructions further upstream (Mugade and Sapkale, 2015). River aggradation or degradation, the process of raising or lowering the river bed plays a role in relative sea level.

Bangladesh has highly dynamic rivers, with short-term shifts in river channels creating *chars* that affect the livelihood of up to 600,000 people (Sarker et al., 2003). Larger avulsions can cause the river channel to shift several kilometers, such as the 150 km westward shift of the Brahmaputra after an earthquake in 1762 (Höfer and Messerli, 2006; Brammer, 2012, 2014).

*Interacts with:* →
Accretion and Erosion. Sea level. Livelihoods.
*Impacted by:*←
Accretion and Erosion. Vegetation. Sedimentation. Earthquake. Floods. Dam construction.

**Sedimentation** Combined, the Ganges, Brahmaputra and Meghna carry between 728 and 1,506 $10^6$ tons of sediments through Bangladesh (see also Chapter 2.3). Pelletier et al. (2015) found sediment yield increasing with precipitation and decreasing with increasing vegetation growth. The amount of sediments is vital to soil fertility, river morphology and accretion, with its distribution throughout the delta also depending on glacial melt and past tectonic movement (Kuehl et al., 2011; Struck et al., 2015). Areas with high amounts of sedimentation such as behind embankments experience problems due to water logging and fewer useable waterways for transportation (Hoque and Alam, 1997; Mahmuduzzaman et al., 2014). Dams such as Farakka barrage have been attributed with reducing sedimentation (Gain and Giupponi, 2014), with reduced sediments accelerating the sinking of deltas Syvitski et al. (2009). Sediments also play a role in arsenic contamination (Acharyya et al., 2000).

*Interacts with:* →
River morphology. Accretion. Subsidence. Arsenic contamination. Transportation.
*Impacted by:*←
Precipitation. Vegetation. Tectonics. Erosion. Glacial melt. Dams. Embankments.

**Groundwater level** The groundwater level varies throughout the GBM delta, with sinking groundwater tables tied to the degree of subsidence (Syvitski et al., 2009). A high groundwater level can in turn exacerbate flooding (Höfer and Messerli, 2006; Khalequzzaman, M.D., 1994). Aquifer recharge, which increases the groundwater level, depends on discharge and groundwater pumping (Hoque et al., 2007). In the city of Dhaka, an overall decrease of the groundwater table depth of an average rate of 2 m per year has been observed since 1986 (Akther et al., 2009; Haque et al., 2013).

*Interacts with:* →
Subsidence. Floods. Freshwater availability.
*Impacted by:*←
Discharge. Groundwater extraction.

**Sea level** Absolute sea levels through a variety of global processes, including thermal expansion, changes in ocean salinity, and melting ice sheets and glaciers. In the Bay of Bengal, sea levels are impacted by ENSO during monsoon season (Singh et al., 2001; Moon et al., 2015) and have a backwater effect on discharge and can thus worsen flooding (Mahmuduzzaman et al., 2014). Relative mean sea levels are impacted by river aggradation and degradation (Pelletier et al., 2015), tides (Pethick and Orford, 2013), and changes in elevation of land, e.g. because of tectonic movement and subsidence (Syvitski et al., 2009; Wada et al., 2012; Konikow, 2011), or glacial isostatic adjustment, which lowers the apparent sea level rise by 0.3 mm per year (Douglas and Peltier, 2002). Pethick and Orford (2013) stress that observing and analyzing relative mean sea levels underestimates the rise in high water levels, and suggests the effective sea level rise (ESLR), which focuses on trends in high tide maxima, which have increased due to estuary channels being constricted by the construction of embankments. ESLRs in the Bay of Bengal have increased between 2.8 and 8.8 mm/year, with high water levels impacted more strongly by about 15.9 and 17.2 mm/year (Rabbani et al., 2010; Pethick and Orford, 2013).

Rising sea levels increase salinity in coastal areas (Schiermeier, 2014), and cause increased erosion and coastal flooding. Rabbani et al. (2010); IPCC (2013) and Alam and Uddin (2013) state that a 45 cm sea level rise could dislocate about 35 million people from coastal areas by 2050. Changing coast lines could also cause border disputes and political tension (Houghton et al., 2010). Globally, absolute sea levels are expected to rise due to global warming, with Pfeffer et al. (2008)

estimating a total sea level rise between 0.8 to 2 m by 2100 as physically possible and plausible. Glacial melt is also expected to play a role in increasing sea levels.

*Interacts with:* →
Erosion. Discharge. Salinity. Floods. Coastal flooding. Migration. Livelihood.
*Impacted by:*←
ENSO. Tectonics. Accretion. River morphology. Tides. Glacial melt. Subsidence. Climate change. Embankments.

**Salinity** Salinity refers to the saline content of land and water in the coastal areas of Bangladesh. Over 1 million hectar of cultivated land (about 70 %) are considered to be saline to a varying degree (Rahman et al., 2013). Salinitzation of agricultural lands, freshwater ponds, canals and rivers is caused by salt water intrusion due to tides or coastal flooding, as well as upward movement of saline groundwater during the dry season (Haque, 2006; Brammer, 2014; Mahmuduzzaman et al., 2014). Precipitation, discharge, sea level rise and increasing extraction of freshwater through groundwater pumping are further factors determining the degree of salinity (Mirza, 1998; Vineis et al., 2011). Shrimp farming requires a certain amount of salinity, but the recent unregulated expansion of shrimp farms has led to previously cultivatable land being converted to saline soils, a process which is difficult to reverse (Amoako Johnson et al., 2016). Increased salinity of drinking water not only create problems for deltaic crops, livestock and ecosystems (Haque, 2006; Wassmann et al., 2009b; Rabbani et al., 2010), but can also cause hypertension and other health-related issues in humans (Khan et al., 2008; Vineis et al., 2011). Agroforestry could be beneficial in reducing salinity content of soils and water (Hasan and Alam, 2006).

*Interacts with:* →
Vegetation. Freshwater availability. Water quality. Crops. Shrimp farming. Livestock. Ecosystems. Livelihood. Morbidity.
*Impacted by:*←
Precipitation. Discharge. Sea level. Coastal flooding. Groundwater extraction. Shrimp farming. Agroforestry.

**Tides** Tidal fluctuations in water levels can be observed as far as 400 km inland, with a typical amplitude of semi-diurnal tidal fluctuations of e.g. 60 cm in the Meghna river 30 km east of Dhaka (Lobitz et al., 2000; Han and Webster, 2001). The mean tide level also varies by about 1 m within a 14 - day neap-spring tide cycle, as well as throughout the year, reaching its peak during the monsoon season (Singh et al., 2001). Tidal ranges are about 2 - 3 m for southwestern Bangladesh, and increase to 2.5 - 4 m in Chittagong. The strength of the tides impact accretion and erosion (Emran et al., 2017), can worsen flooding and are important to relative sea level (Pethick and Orford, 2013). Embankments influence tidal range, which has increased due to the estuary channels being constricted by embankments (Pethick and Orford, 2013).

*Interacts with:* →
Accretion and Erosion. Sea level. Floods.

*Impacted by:*←
Embankments.

**Glaciers in GBM catchment** The GBM catchment includes over 25.000 km$^2$ of glaciers in the Himalayas, particularly in the Tibetian Plateau (Immerzeel et al., 2010). Even though the runoff regimes of both the Ganges and the Brahmaputra are driven by monsoon precipitation, meltwater from these glaciers seasonally contributes to the flow of especially the Brahmaputra river (3.1 % glaciated area), and to a lesser extent also to the Ganges (1.0 % glaciated area) (Immerzeel, 2008; Immerzeel et al., 2010; Lutz et al., 2014). The mass balance of glaciers in the Himalayas is thus of concern when assessing hydrological processes in Bangladesh (Kehrwald et al., 2008). For a detailed description of glaciers, including their spatial variation throughout the Himalayas, see Shi and Liu (2000) and Maussion et al. (2014).

Glaciers in the GBM catchment retreat or have a negative mass balance either because of less accumulation through reduced snow fall or increased melting, evaporation and sublimation in the zone of ablation e.g. due to higher temperatures (Rupper and Roe, 2008). Studying temperatures on the Tibetian Plateau between 1955 and 1996, Liu and Chen (2000) found an increase in annual mean temperature of 0.16 °C per decade, and an increase in 0.32 °C per decade for the winter mean. Seasonal snow cover in the Himalayan and Tibetian region has decreased by 30 % between 1966 and 2001, with the rate of decrease largest at lower elevations (Rikiishi and Nakasato, 2006). In accordance, glacial retreat has been observed throughout the Himalayas, in particular along the northern Himalayas, with up to 80 % of glaciers in western China retreating during the past 50 years (Ding et al., 2006). Furthermore, the rate of glacial retreat in Asia has been accelerating (Hijioka et al., 2014).

Several studies have attempted to assess how climate change might impact glaciers in the Himalaya, e.g. due to changes in meteorological parameters such as precipitation and temperature, as well as the effects this would have on water resources and ecosystems in the region (Xu et al., 2009; Bolch et al., 2012). While IPCC (2013) projected a decrease of glacial surface area from 500,000 to 100,000 km$^2$ between 1995 and 2030, Scherler et al. (2011) considers this an overestimation as heavily debris-covered glaciers retreat much slower than initially assumed. Regardless, both Scherler et al. (2011) and Zhao et al. (2014) found that by 2050, more than 65% of the monsoon-driven glaciers in the Himalaya will have retreated, thus initially contributing more meltwater to the catchment and contributing between 3.6 - 9.2 mm to sea level rise (Zhao et al., 2014, 2016). However, with continuing decrease, the amount of meltwater over time will also decrease, which in turn impacts the sediment load at the headwaters of the Ganges and Brahmaputra (Hijioka et al., 2014; Struck et al., 2015). For the period 2046 - 2065 and the IPCC4 A1B scenario, Immerzeel et al. (2010) found a reduction in flow in upstream parts of Ganges (17.6 %) and Brahmaputra (19.6 %) despite increased precipitation.

While glaciers certainly have an impact on hydrological processes further downstream, a prognosis on the development of the glaciers in the Himalayas is difficult and comes with large uncertainties. Climate models have difficulties in correctly representing one of the key contributors to glacial volume loss, namely precipitation, as the monsoon circulation is often not captured correctly (Immerzeel et al., 2010; Lutz et al., 2013; Hijioka et al., 2014; Zhao et al., 2016). Nevertheless, the expected changes in glaciers due to climate change are an important component when evaluating future water resources in Bangladesh, in particular as they can in turn contribute to rising sea levels (Bolch et al., 2012; Chen et al., 2013).

*Interacts with:* →
Sedimentation. Discharge. Sea level. Freshwater availability.
*Impacted by:*←
Temperature. Precipitation. Monsoon. Climate change.

### A.1.4 Vegetation

Vegetation in Bangladesh consists mainly of bamboo and rattan in the lower hills of Chittagong, swampy vegetation and jungles in the central part of the country, and cultivated plants and fruit in the northern plains. The Sundarbans covering 6,017 $km^2$ in the southern part of the Ganges delta are one of the largest mangrove forests worldwide, and have been a UNESCO heritage site since 1997 (Iftekhar and Saenger, 2008).

Despite covering a comparatively small area in Bangladesh, the Sundarban mangroves are a carbon sink with a large carbon storage potential and play an important role in carbon cycling (Alongi, 2014). Organic-rich soils account for up to 98 % carbon storage in mangrove forests, while mangroves also provide nutrients for fish spawning grounds (Donato et al., 2011).

In metropolitan areas, vegetation contributes to urban green spaces and plays an important role in the urban ecosystem, e.g. through cleaning the air and reduction of noise (Byomkesh et al., 2012). Green spaces have also been connected directly to the well-being of Dhaka's inhabitants (Gruebner et al., 2012). However, due to rapid urbanization and migration in recent years, green spaces have shrunk significantly in recent years. Dewan and Yamaguchi (2008) found that in the 1960s, close to 80 % of all land was non-urban, but that this number was reduced to 40 % by 2005 .

*Interacts with:* →
River morphology. Sedimentation. Ecosystem. Livelihood. Well-being.
*Impacted by:* ←
Precipitation. Temperature. Salinity. Urbanization. Freshwater supply. Crops. Agroforestry.

## A.2 Natural hazards

### A.2.1 Atmospheric

**Extreme temperatures** Extremely hot temperatures or heat waves impact energy demand due to increased cooling, freshwater supply, water quality, crop production, livestock, morbidity and mortality (Zuo et al., 2015). Urban areas often see an increased summer mortality peak due to cardiovascular problems experienced due to high temperatures (Burkart et al., 2011a,b). As the population is not adjusted to a colder climate and thus often not adequately equipped with clothing and housing, temperatures below 10 °C can already cause respiratory diseases despite the comparatively mild winters. This increase in morbidity ultimately contributes to an increased mortality due to the lack of access to medicine and primary care. Thus, colder periods have an even stronger connection to excess mortality (Burkart et al., 2014a; Burkart and Kinney, 2017). Effects due to both extremely low and high temperatures are more noticeable among children and especially the elderly (Burkart et al., 2011b).

While maximum daily temperatures are expected to increase in the future, cold days have decreased over the past years, and the impact of cold temperatures may lessen even further with future climate change (IPCC, 2013).

*Interacts with:* →
Energy demand. Freshwater availability. Water quality. Crops. Livestock. Well-being. Morbidity. Mortality.
*Impacted by:*←
Temperature. Precipitation. Climate Change.

**Cyclones** The cyclone season in Bangladesh is mainly in the pre-monsoon (AM) and post-monsoon season (ON), with 0 to 3 events each year (Alam and Dominey-Howes, 2014a). Most cyclones hitting Bangladesh originate in the Bay of Bengal and the Indian Ocean. While cyclones hit all along the coast, the highest number of landfalls occurs near Chittagong (Alam and Dominey-Howes, 2014a). Although robust trend assessments are difficult due to data constraints, Hijioka et al. (2014) did not find significant trends in the number of tropical cyclones making landfall. Additional information can be found in a review compiled by Alam and Dominey-Howes (2014a) covering 304 cyclone events in Bangladesh between 1000 and 2009.

Peterson and Mehta (1981) presumed that periods with particularly intense cyclonic activity correlate to periods with reduced tornado activity, but this is to be verified by further studies. On the other hand, cyclones often result in storm surges, such as during the 1985 Bhola tropical cyclone, which raised water levels by up to 3 m all throughout the Bay of Bengal (Alam and Dominey-Howes, 2014a).

As cyclones move further inland, millions of people are affected. The category 4-5 cyclone Sidr formed in the Bay of Bengal on November 11th, 2007, before making land-fall in southwestern Bangladesh on November 15th and dissipating on November 16th. Sidr affected over 6 million people by destroying 0.35 million ha of cropland, damaging 0.9 million and destroying 0.3 million homes. Livelihoods of over 500,000 people were disrupted as employment ceased and income generating-assets such as rikshas were destroyed, with numerous households deciding to migrate inland (Kartiki, 2011). The destruction of water treatment plants and freshwater pipes caused a shortage of drinking water (Rabbani et al., 2010).

Unusually high fatality rates such as during the 1991 cyclone (>138,000 lives lost) have resulted from cyclones in the past (Alam and Collins, 2010), with a conservative estimate from Alam and Dominey-Howes (2014b) attributing over 16 million deaths to 71 tropical cyclones in the Bay of Bengal between 1484 and 2009. Alam and Collins (2010) names several factors as responsible: storm surges are amplified to exceptionally high levels due to the physical characteristics of the continental shelf, with the funnel-shaped coast further amplifying storm surges as they reach the low-lying coastal areas (As-Salek, 1998). Early-warning systems and shelters were also not readily available in the past (Alam and Collins, 2010), although significant improvements have been made in the years since 1991, after which the number of cyclone related deaths rapidly decreased, with cyclone Sidr causing 3,000 fatalities in 2007 (Rabbani et al., 2010; Paul et al., 2010; Alam and Dominey-Howes, 2014a).

Due to the variety of factors contributing to the genesis and intensification of tropical cyclones, estimating the impact of climate change is difficult. While SSTs are expected to increase in the region, a possible connection between increasing SSTs and intensification of tropical cyclones seems debatable in the Bay of Bengal (see Alam and Dominey-Howes (2014a) for an extensive discussion), with Elsner et al. (2008) suggesting that other factors such as changes in the region of origin and El Niño conditions may be more relevant.

*Interacts with:* →
Precipitation. Tornadoes. Coastal flooding. Migration. Livelihoods. Morbidity. Mortality.
*Impacted by:*←
ENSO. Climate change.

**Hail storms** Heavy hailstorms are also noteworthy for Bangladesh, which usually occur during the months of April to June, accompanying the heavy thunderstorms in the pre-monsoon season (Cecil and Blankenship, 2012). Bangladesh also holds the record for the heaviest hailstone weighing 1.02 kg, which was found on April 14, 1986 near Khulna (World Meteorological Organization, 2017). Hail storms not only damage crops and buildings, but also result in loss of life, as e.g. the hail storm in April 1986 caused a ferry to capsize, leaving over 100 people dead and many injured (UN Department of Humanitarian Affairs, 1986).

*Interacts with:* →
Crops. Livelihood. Morbidity. Mortality.
*Impacted by:*←
Monsoon.

**Lightning** Bangladesh has a comparatively high lightning rate, with 20 - 30 strikes per $km^2$ per year for most parts of Bangladesh. Lightning strikes occur throughout the year, but peak during the pre-monsoon (MAMJ) months, as does the fatality rate (Gomes et al., 2006, 2012; Holle, 2008). Despite presumed underreporting especially in the rural areas, the lightning fatality rate is higher than in more developed countries, with 100 to 200 fatalities each year (Gomes et al., 2006). A single storm event in May 2016 tallied over 65 people killed from lightning strikes in just four days (Pokharel, 2016).

*Interacts with:* →
Morbidity. Mortality.
*Impacted by:*←
Monsoon.

**Tornadoes** Tornadoes are most likely in the afternoon and evening in early April during severe local convective storms (Yamane et al., 2013), with the most violent tornadoes occuring in a small area in central Bangladesh. Peterson and Mehta (1981) presume that periods with particularly intense tornado activity correlate with periods of reduced cyclonic activity. Tornadoes damage crops, livestock, buildings (Paul, 1998), impact the mental health of the population (Choudhury et al., 2006) and cause high fatalities, especially among the elderly (Sugimoto et al., 2011). On April 26, 1989, a single tornado in the Manikganj district to the west of Dhaka killed over 1,000 people, the deadliest tornado on record (World Meteorological Organization, 2017); another tornado on May 13, 1996 destroyed 30,000 homes (70 - 90 % of standing structures) in over 90 villages in north-central Bangladesh, killing over 700 people (Kunii et al., 1996; Paul, 1998).

*Interacts with:* →
Crops. Livestock. Livelihood. Well-being. Morbidity. Mortality.
*Impacted by:*←
Cyclones.

### A.2.2 Land

**Earthquake** Alam and Dominey-Howes (2016) catalogued about 562 earthquakes between 810BC and 2012 in Bangladesh and the Bay of Bengal area, based on both felt intensities as well as instrumentally recorded events (from January 1st, 1900 onward). The last major earthquake was the 1762 Arakan earthquake, during which Chittagong sank several meters, numerous tsunamis were triggered, and over 500 people were killed (Alam and Dominey-Howes, 2014b; Steckler et al., 2016).

Both Cummins (2007) and Steckler et al. (2016) describe the Ganges-Brahmaputra Delta as a still highly tectonic active region, with 13 to 17 mm/year plate convergence along a locked megathrust fault (or >5.5 m since 1762). This leads them to expect the next earthquake to reach a magnitude of 8 to 9 on the Richter scale. Since population has drastically increased since 1762, this would impact over 140 million people living within 100 km of the locked megathrust.

*Interacts with:* →
River morphology. Land slides. Subsidence. Coastal flooding. Livelihood. Morbidity. Mortality.
*Impacted by:*←
Tectonics.

**Land slide** Land slides in Bangladesh occur predominantly in the hilly areas such as the southeastern Chittagong hill tracts, especially during the monsoon season following heavy rains or following floods. Due to their unpredictable nature, they often not only result in erosion of up to 10,000 tons per $km^2$ per year, but also in loss of homes as well as causing severe injuries and casualties (Karim and Haider, 1991). On June 11th, 2007, more than one-third of Chittagong was flooded due to high tidal water and unusually heavy rains intensified by a storm on June 10th, with more than 425 mm of rainfall recorded in 24 hours. Resulting flash floods caused mud slides in the deforested hills near Chittagong, leaving more than 150 injured and at least 130 dead (Ahasan et al., 2013).

*Interacts with:* →
Erosion. Livelihood. Morbidity. Mortality.
*Impacted by:*←
Precipitation. Erosion. Earthquakes. Floods. Agroforestry.

**Subsidence** Subsidence is a drop in land elevation, usually occuring gradually over time and rarely through sudden ground collapses. The net subsidence rate is determined by a complex interaction between tectonics, compaction, sedimentation and anthropogenic causes (Syvitski et al., 2009), and is described extensively in a literature review for the GBM delta by Brown and Nicholls (2015), as well as by numerous authors such as Hoque and Alam (1997), Steckler et al. (2008), Steckler et al. (2010), Higgins et al. (2014) and Brammer (2014). Net subsidence rates vary both temporally and spatially throughout Bangladesh's coastal regions between -1.1 mm/year to 43.8 mm/year, with a mean rate of 5.6 mm/year and a median rate of 2.9 mm/year. Higher rates are often found locally in urban areas due to e.g. groundwater abstraction (Brown and Nicholls, 2015). In addition, annual loading of water during the monsoon season through increased precipitation and flooding and subsequent unloading lead to seasonal vertical elastic deformation of up to 6 cm over the entire GBM delta (Steckler et al., 2010).

According to Brammer (2014), subsidence in Bangladesh is largely due to tectonic movements in the region and aggravated by the various troughs, folds and fault lines in the basin (Hoque and Alam, 1997; Steckler et al., 2008). For example, in the eastern half of the delta, the subsidence rate of 1 to 12 mm/year is thought to mainly be due to tectonic loading (Steckler et al., 2010). Using Interferometric Synthetic Aperture Radar (InSAR) and ground-based GPS measurements , Higgins et al. (2014) produced a spatial map of observed subsidence rates between 2007 and 2011. Subsidence rates for Dhaka ranged between 0 to over 10 mm/year, the highest rates from 0 to over 18 mm/year were found in southwestern Bangladesh, an area with more readily compacting organic-rich soil. In 1762, an earthquake is estimated to have dropped the land near Chittagong by several meters (Schiermeier, 2014).

Subsidence can be due to e.g. reduced precipitation leading to drying and compacting of sediments (natural compaction), while anthropogenic processes include e.g. groundwater extraction or embankments and polders (Syvitski et al., 2009; Konikow, 2011; Wada et al., 2012). Tectonic uplifting, as well as aggradation through sedimentation counteract subsidence to a certain extent (Hoque and Alam, 1997; Higgins et al., 2014).

Because of subsidence, relative sea level increases, resulting in an increased vulnerability to high tides, coastal flooding and storm surges. Other implications include salinification, land loss, and water logging due to slower drainage (Higgins et al., 2014; Schmidt, 2015). When subsidence occurs in urban areas, sudden structural collapses can occur, particularly when building codes have not been met (see Section A.4).

Syvitski et al. (2009) classified the Ganges-Brahmaputra-Meghna Delta as a delta in peril, meaning that the reduction in aggradation due to reduced sediment flow plus accelerated compaction, partly due to major groundwater extraction, currently overwhelms the estimated rate of sea level rise. With increasing subsidence, the delta is at risk of collapsing, and would be unable to return to its natural state (as seen in the Indus delta).

*Interacts with:* →
Erosion. Sea level. Salinity. Coastal flooding. Structural collapse.
*Impacted by:*←
Precipitation. Monsoon. Tectonics. Aggradation. Sedimentation. Groundwater level. Floods. Earthquakes. Groundwater extraction.

**Arsenic contamination** In 1993, it was discovered that Bangladesh's soils are naturally contaminated with arsenic (Acharyya et al., 2000), partly aided by the sediment structure which makes the soil particularly susceptible to contamination due to the increased surface to mass ratio (Datta and Subramanian, 1997). The contamination of the soil is reflected in the contamination of groundwater, which is pumped to the surface in particular during the dry season for individual freshwater use and irrigation. Using the contaminated groundwater for irrigation is problematic both for the well-being and morbidity of the population, as well as for agriculture such as rice paddies (van Geen et al., 2006; Brammer, 2009). In Bangladesh, up to 40 million people in the southern delta of the GBM catchment use tube wells with arsenic levels over the permissible level of 50 ppb (Uddin and Huda, 2011). The increased extraction of groundwater and the use of phosphate fertilizer may have aided the release of arsenic from sediments (Acharyya et al., 2000).

Uddin and Huda (2011) lists several impacts to individuals due to chronic arsenic exposure, ranging from cardiovascular effects to cognitive impairment and an increased risk of cancer. Infant morbiditiy and mortality also increase with arsenic exposure during pregnancy, usually via drinking water.

*Interacts with:* →
Water quality. Crops. Morbidity. Mortality.

*Impacted by:*←
Sedimentation. Groundwater extraction.

### A.2.3 Hydrological

**Droughts** Droughts are mainly due to a combination of factors such as decreased precipitation and lower discharges. See Chapter 2.3.2 for detailed information.

*Interacts with:* →
Vegetation. Freshwater availability. Transportation. Morbidity. Mortality.
*Impacted by:*←
Precipitation. Temperature. Discharge.

**Floods** Around 20 % of the country is flooded on average each year, fertilitzing the soil through nutrient-rich alluvial deposits. See Chapter 2.3.3 for detailed information.

*Interacts with:* →
Fertility. River morphology. Land slides. Subsidence. Freshwater availability. Dam breakage. Morbidity. Mortality.
*Impacted by:*←
Precipitation. Discharge. Groundwater level. Sea level. Tides. Urbanization. Dam construction. Agroforestry.

**Coastal flooding** Coastal flooding is mostly due to storm surges and tsunamis. Storm surges resulting from cyclones can raise water levels by up to 3 m, flooding the low-lying coastal areas (Karim and Mimura, 2008; Alam and Dominey-Howes, 2014b). Alam et al. (2012) provides a review of a total of 135 tsunami events in the northeast Indian Ocean, with the most recent tsunami having occurred simultaneously during the flood of 1988 (Khalequzzaman, M.D., 1994). Cummins (2007) and Alam et al. (2012) consider it very likely that the Bay of Bengal has a high potential for tsunami-triggering earthquakes in future years.

Coastal flooding can reduce crop yields and impact freshwater availability, such as following the storm surge during Cyclone Sidr, which contaminated over 6,000 ponds with saline water, reducing the available freshwater and increasing the salinity of both water and land during the following months (Rabbani et al., 2010; Mahmuduzzaman et al., 2014). Depending on the severity of flooding, households are left homeless, which can sometimes lead to migration (Red Cross, 2001). With increasing subsidence, coastal flooding will worsen (Higgins et al., 2014; Schmidt, 2015), although the construction of embankments can lessen the effects to a certain extent (Pethick and Orford, 2013).

*Interacts with:* →
Sea level. Salinity. Freshwater availability. Livestock. Dam breakage. Livelihoods. Migration. Morbidity. Mortality.
*Impacted by:*←
Cyclones. Earthquakes. Subsidence. Dam breakage.

## A.3 Indicators for anthropogenic processes

### A.3.1 Demography

**Population growth** Despite a comparatively low birth rate of 2.2 children per woman, Bangladesh is expected to see an increase in population of 218 million by 2050 (United Nations, 2007; Streatfield and Karar, 2008). The continuous growth of the population impacts the transportation and agricultural sector, urbanization, freshwater supply, water quality, and energy demand (Faisal and Parveen, 2004; Haque et al., 2013; Gain and Giupponi, 2014).

*Interacts with:* →
Urbanization. Energy demand. Transportation. Freshwater supply. Water quality. Crops. Shrimp farming. Livestock.

**Urbanization** Urban growth in cities such as Dhaka, which has rapidly increased in population from an estimated 12 million in 2000 to 16.8 million in just 15 years, is largely attributed to the migration from rural areas, as well as economig growth (United Nations, 2007; Dewan and Yamaguchi, 2008; Rabbani et al., 2010). Urbanization causes several urban development issues such as increasing traffic jams and accidents, urban fires, reduced water quality through an increase in untreated waste water, increased flooding through water logging, the reduction of living areas for the urban poor, as well as increased violence due to socio-economic pressures. (Rana, 2011; Haque et al., 2013; Gain and Giupponi, 2014) In addition, urbanization and economic growth with associated increases in per capita income can cause dietary changes in form of a “livestock revolution” (Delgado, 2003).

*Interacts with:* →
Flooding. Transportation. Transportation accidents. Shrinking space of democracy. Water quality. Livestock. Urban fires. Political tension.
*Impacted by:*←
Population growth. Migration.

### A.3.2 Socio-economics

**Energy demand** Overall, 60 % of the population has access to electricity in Bangladesh (90 % in urban areas, 50 % in rural areas). Currently, electricity is largely produced using fossil fuels, and more than able to cover the needed amount (53 billion kWh production vs 46 billion kWh consumption in 2014). Hydropower is generated at Kaptai Dam, where 5 % of the country’s electricity is produced (Parveen and Faisal, 2002). A nuclear facility is currently planned 160 km northwest of Dhaka (World Nuclear Association, 2017). Key drivers regulating energy demand are industrial processes as well as personal consumption, which can increase e.g. during a heat wave.

*Interacts with:* →
Dam construction. Nuclear reactor failure.
*Impacted by:*←
Extreme temperatures. Population growth. Industry. Dam construction.

**Economic growth** While Bangladesh is currently considered a developing country with a lower-middle-income economy, Bangladesh's economy is also expected to grow tremendously during the 21st century. Economic growth is beneficial to the industry sector, while associated increases in per capita income can cause dietary changes in form of a "livestock revolution" (Delgado, 2003).

*Interacts with:* →
Industry. Livestock. Livelihoods.
*Impacted by:*←
Industry.

**Industry** The main sectors of industry are the production of garments and leather, with more than 80 % of total exports coming from the textile sector (Central Intelligence Agency, 2013). Dhaka also has a thriving brick industry (Aßheuer et al., 2013). The water quality in the vicinity of factories and especially tanneries is often negatively affected due to untreated waste water being released into the rivers. The continuing growth of the industry sector, which is tied directly to the overall economic growth, will initially require more energy and freshwater consumption before more sustainable production methods are implemented.

*Interacts with:* →
Water quality. Energy demand. Freshwater supply. Economic growth. Chemical pollution and spillage.
*Impacted by:*←
Economic growth.

**Transportation** The transportation network in Bangladesh contains of 2,460 km railways, 8,370 km of waterways, which are reduced to about 5,200 km in the dry season, and 21,269 km of roads, of which over 90 % are unpaved (Central Intelligence Agency, 2013). Urbanization has led to increasing traffic congestion, particularly in Dhaka, with a high rate of transport accidents Maniruzzaman and Mitra (2005); Bangladesh Police (2017). Increased sedimentation can make waterways unfeasible for transportation (Hoque and Alam, 1997; Mahmuduzzaman et al., 2014).

*Interacts with:* →
Transportation accidents.
*Impacted by:*←
Discharge. Sedimentation. Drought. Population growth. Urbanization.

**Shrinking space of democracy** Shrinking space of democracy is a term referring to current developments in Bangladesh that reduce the democratic rights of the people, such as the introduction of new laws curtailing the freedom of speech and increasing arrests of journalists (Ahmad, 2015; Amnesty International, 2017).

Additional laws endanger people to be arrested for more than ten years if they criticize the so called founder of the nation (the assassinated father of the current Prime Minister) or if they are perceived to endanger public order through e.g. posts in social media. New projects of foreign-funded non-governmental organizations (NGOs) are under strict - and to some extent arbitrary - control of the government (see also Chapter A.3.2; Bergman (2016); Rahman and Ahmad (2016)). This especially impacts the urban poor, who are more and more refused certain rights. E.g. in urban areas through the reduction of available living areas due to urbanization, no regulated and safe access to freshwater, the violating of building codes, displacement of entire communities due to the construction of dams, or workers' rights being withheld all prevent the people from utilizing their resilient structures and creating a sustainable livelihood (Parveen and Faisal, 2002; Keck and Etzold, 2013; Hackenbroch, 2013; Aßheuer, 2014).

*Interacts with:* →
Political tension. Livelihoods. Well-being. Morbidity. Mortality.
*Impacted by:*←
Urbanization. Freshwater availability. Dam construction. Structural collapse. Urban fires.

### A.3.3 Climate change

Global warming due to an increasing $CO_2$ concentration in the atmosphere has impacts on many processes in Bangladesh. For a detailed description, see Chapter 1.1.3 or reports such as Nicholls, R.J. et al. (2007); IPCC (2013) and Hijioka et al. (2014). Increases in energy demand and industrial growth, as well as deforestation of mangroves are processes contributing to global climate change through an increase in $CO_2$ (Donato et al., 2011; IPCC, 2013; Hijioka et al., 2014), while increasing $CO_2$ concentrations in the atmosphere could lead to higher crop yields (Faisal and Parveen, 2004; Tao and Zhang, 2013).

*Interacts with:* →
Temperature. Precipitation. Monsoon. ENSO. Sea level. Glacial melt. Extreme temperatures. Cyclones. Crops.
*Impacted by:*←
Energy demand. Industry. Agroforestry.

### A.3.4 Water management

**Dam construction** Within Bangladesh, Kaptai Dam was constructed to meet increasing demands on freshwater supply and electricity, 5 % of which is generated through hydropower (Central Intelligence Agency, 2013; Parveen and Faisal, 2002). International dam construction at e.g. Farraka Barrage on the Indian border has several reasons, see more in Chapter 2.3.1 and 5.1.4, as well as Figure 2.5. Smaller dams are constructed as flood prevention, or to increase freshwater supply e.g. for irrigation purposes. Despite water sharing agreements with

India, dry season discharge and groundwater levels have decreased further downstream from Farakka Barrage (Mirza, 1997, 1998; Adel, 2002; Gain and Giupponi, 2014). Dams also reduce available sedimentation, impact river morphology, and can cause severe flooding in case of dam breachment (Syvitski et al., 2009). Both Farakka Barrage and Kaptai Dam have resulted in ecosystem changes further downstream in the Sundarbans, political tension, migration and have impacted livelihoods (Parveen and Faisal, 2002; Mirza, 1997, 1998; Inman, 2009; Gain and Giupponi, 2014).

*Interacts with:* →
Sedimentation. River morphology. Discharge. Floods. Energy supply. Dam breakage. Ecosystem changes. Political tension. Migration. Livelihood.
*Impacted by:*←
Energy demand. Freshwater availability.

**Embankments** Embankments and levees have been constructed in the coastal region of Bangladesh to protect the area from coastal flooding and increase the land area available for crops (Hoque and Alam, 1997; Inman, 2009). Embankments influence sea levels and tidal ranges through changes in the estuary channels (Pethick and Orford, 2013), but also prevent sedimentation from entering the protected area, which leads to uncompensated subsidence and the accompanying problems of water logging and drainage congestion (Hoque and Alam, 1997; Schmidt, 2015).

*Interacts with:* →
Sedimentation. Sea level. Tides. Coastal flooding. Crops. Dam breakage.

**Freshwater availability** Freshwater is supplied through precipitation, discharge, glacial melt, groundwater pumping and reservoirs built through the construction of dams (Gain and Giupponi, 2014; Gain and Wada, 2014). About 15 % of the population lack access to freshwater sources (Central Intelligence Agency, 2013; Rabbani et al., 2010). Supply is affected through increasing salinity and coastal flooding (Haque, 2006; Wassmann et al., 2009b; Rabbani et al., 2010), as well as a extreme temperatures, growing population, urbanization, the textile industry and extensive irrigation (Hijioka et al., 2014; Zuo et al., 2015). Despite an abundance of water in the flood season, water is scarce in the dry season, which can amplify droughts and have negative effects on crops, livestock and morbidity (Gain and Wada, 2014). An extensive assessment of future freshwater availability in the Brahmaputra basin is supplied by Gain and Wada (2014).

*Interacts with:* →
Droughts. Groundwater extraction. Irrigation. Crops. Livestock. Morbidity.
*Impacted by:*←
Precipitation. Discharge. Groundwater level. Salinity. Glacial melt. Extreme temperatures. Coastal flooding. Population growth. Industry. Shrinking space of democracy. Dam construction. Groundwater extraction.

**Groundwater extraction** Because freshwater demand currently exceeds the supply in urban areas, groundwater pumping has led to a decrease of groundwater levels at an average rate of 2 m per year (Akther et al., 2009; Hoque et al., 2007; Haque et al., 2013), and an increase in salinity in coastal areas (Mirza, 1998; Vineis et al., 2011). In rural areas, the increased extraction of groundwater for irrigation set free arsenic from sediments in deeper layers, reducing the water quality (Acharyya et al., 2000). Subsidence of land due to increased groundwater depletion (Wada et al., 2012; Konikow, 2011). Groundwater depletion could be counteracted by increasing freshwater supply through reservoir storage via the construction of dams, waste water treatment and rainwater harvesting.

*Interacts with:* →
Groundwater level. Subsidence. Arsenic contamination. Freshwater availability.
*Impacted by:*←
Freshwater availability. Irrigation.

**Irrigation** Irrigation for agricultural purposes, especially for rice during the dry season, is among the main water uses in Bangladesh, and thus important to agricultural productivity and food security (Shahid, 2011). Irrigation also allows for crop diversification, which is important for food security.

*Interacts with:* →
Discharge. Groundwater extraction. Crops. Food security. Morbidity.
*Impacted by:*←
Freshwater availability. Crops.

**Water quality** Water quality is affected by waste water from industry and households, as well as chemical pollution and spillage, with population growth and urbanization causing a decline in quality over past years particularly for Dhaka (Haque et al., 2013). Extreme temperatures, salinity, the increasing use of fertilizers to compensate for a reduction of soil fertility, and arsenic contamination also impact water quality (Haque, 2006; van Geen et al., 2006; Brammer, 2009, 2014; Zuo et al., 2015). Access to clean water is important to ecosystems, crops, livestock and human health. While e.g. contaminated water sources due to flooding lead to the outbreak of communicable diseases (Sirajul Islam et al., 2007; Islam et al., 2010), irrigation with arsenic contaminated water increases morbidity and is detrimental to rice paddies (van Geen et al., 2006; Brammer, 2009).

*Interacts with:* →
Crops. Livestock. Ecosystem change. Morbidity. Mortality.
*Impacted by:*←
Salinity. Extreme temperatures. Arsenic contamination. Floods. Population growth. Urbanization. Industry. Crops. Chemical pollution and spillage.

### A.3.5 Agriculture

While agriculture contributes only about 15 % to the nation's GDP, 65 % of Bangladeshis are employed in the sector, with rice and fish being one of the key export products (Yu et al., 2010).

**Crops** The main crop currently grown in Bangladesh is rice, covering about 80 % of the total cropped area. The country is self-sufficient for rice and consumes an estimated 30 million tons per year (Ricepedia, 2014), but perceives a decline in productivity due to decreasing soil fertility (Hossain, 2001; Hossain et al., 2005). Factors impacting rice yields are salinification, changes in growing season due to atmospheric changes such as increasing precipitation, temperature or $CO_2$ levels, and extreme temperatures (Rahman and Parkinson, 2007; Wassmann et al., 2009a,b; Tao and Zhang, 2013). During the pre-monsoon season, crops are also at risk from destruction through hail and tornadoes(Paul, 1998; Cecil and Blankenship, 2012), while during the dry season arsenic contaminated water used for the irrigation of rice paddies can also impact crop production (van Geen et al., 2006; Brammer, 2009). In coastal regions, embankments are often necessary to create or protect land for the purpose of agriculture (Hoque and Alam, 1997). Unsustainable farming practices have led to increased chemical pollution and have been detrimental to soil fertility (Rasul and Thapa, 2004).

*Interacts with:* →
Fertility. Irrigation. Water quality. Chemical pollution. Food security.
*Impacted by:*←
Precipitation. Temperature. Fertility. Salinity. Extreme temperatures. Hail storms. Tornadoes. Arsenic contamination. Population growth. Embankments. Freshwater supply. Irrigation. Water quality. Climate change. Dam breakage.

**Fisheries and shrimp farms** About 80 % of the population's daily animal protein intake comes from fish, with fisheries and shrimp farms contributing over 3.5 % to Bangladesh's GDP (Ali, 1999). A growing population has created a larger demand for food, and especially pond-based shrimp farming has increased over the last years (Streatfield and Karar, 2008). The shrimp farms require the conversion of freshwater ponds to brackish water to create a suitable habitat for shrimp cultivation, and thus prove a successful adaptation to increasing sea levels and associated salinity intrusion (Amoako Johnson et al., 2016). However, in particular the unregulated establishment of a growing number of shrimp farms by destroying embankments has intensified the salinification of both water and farm land in coastal areas, causing a decline in rice yield as well as loss of livestock and mangrove degradation (Haque, 2006; Paul and Vogl, 2011; Rahman et al., 2013; Mahmuduzzaman et al., 2014; Amoako Johnson et al., 2016)

*Interacts with:* →
Salinity. Dam breakage. Ecosystem changes. Food security.
*Impacted by:*←
Salinity. Population growth.

**Livestock** Poultry, cattle, goats and sheep are the main livestock in Bangladesh. Most livestock is raised by landless and small farmers (74 % of cattle, 82.5 % of goats and sheep, and 82.7 % of poultry), although commercial production has increased in recent years (Huque and Sarker, 2014). Urbanization and economic growth with associated increases in per capita income can cause dietary changes in form of a"livestock revolution" (Delgado, 2003), where diets change to include larger proportions of livestock-related products such as eggs, meat and dairy. Although this effect has not yet been detected (Pica-Ciamarra and Otte, 2011), this could impact the livestock production in the future. Extreme temperatures, increasing salinity and reduced water quality can negatively impact livestock production as morbidity is increased (Haque, 2006; Rabbani et al., 2010; Zuo et al., 2015).

*Interacts with:* →
Freshwater availability. Food security.
*Impacted by:*←
Salinity. Extreme temperatures. Population growth. Urbanization. Economic growth. Water quality.

**Agroforestry** Agroforestry refers to both deforestation and the planting of trees such as orchards or mangroves, which could aid in increasing fertility, reducing salinity and increasing accretion (Hasan and Alam, 2006) as well as allowing the creation of sustainable livelihoods for the rural population (Nath et al., 2005; Rahman, 2011).

Deforestation in the hilltracts of Chittagong is thought to contribute to increased land slides and flooding (Nath et al., 2005), although Höfer and Messerli (2006) could not confirm this in the case of the Himalayas. Deforestation of mangroves would release a large amount of carbon (Donato et al., 2011).

*Interacts with:* →
Accretion. Fertility. Salinity. Land slides. Flooding. Climate change. Ecosystem change. Livelihoods.
*Impacted by:*←
Salinity.

## A.4 Technical failures

Technical failures per the classification used in Gill and Malamud (2014) that have occured or are likely to occur in coming years in Bangladesh are listed in the following. Sources are mainly technical reports and news reports.

**Structural collapse** Building collapses are unfortunately not uncommon in Bangladesh, particularly in the larger cities such as Dhaka. In April 2016, Rana Plaza collapsed, wounding almost 2,500 and killing over 1,100 people, mainly workers fom the four garment factories housed in the building (BBC, 2013). Subsequent investigations found that the building was built in an area that is assumed to not having been drained properly, while up to four floors were added illegally, thus violating construction codes. Heavy vibrating machinery in combination with insufficient steel reinforcements in the concrete is another reason for the collapse. Notably, the workers had noticed the cracks in walls and pillars the day before the collapse, but were forced to return to work when the factory owners reopened on the next day (The Guardian, 2013; Than, 2013).

*Interacts with:* $\rightarrow$
Shrinking space of democracy. Morbidity. Mortality.
*Impacted by:*$\leftarrow$
Subsidence.

**Dam breakage** Dams and embankments are often not designed to withstand extreme floods and are thus at risk of breaking at an already perilous time (World Wide Fund For Nature, 2001). During floods and cyclones, which are accompanied by heavy coastal flooding, embankments are often destroyed or breached (Hossain et al., 2008; Alam and Dominey-Howes, 2014a). The increase of shrimp farming has also led to an increased destruction of embankments to allow saline water to enter previously protected areas (Amoako Johnson et al., 2016).These breakages often leave entire villages inundated, which not only lead to huge financial losses, but also cause migration and urbanization particularly among the poor who see little chance in building up their homes again (Hossain et al., 2008). Livelihoods of farmers are endangered if they lose their harvest, such as after the Paknar Haor dam breach in Sunamganj in April 2017. Excessive rain and an unusally early flash flood caused the dam breach, which resulted in an estimated loss of 0.5 million tons of rice and 1276 tons of fish due to changes in oxygen levels (Bangla Mirror, 2017).

Emergency releases of water at upstream dams to prevent dam breakage are also an issue, with political tension added when the dams are located outside of Bangladesh. In September 2000, four dams in India were not able to withstand severe flooding - the subsequently released water caused an unnaturally sudden and high flood peak downstream in Western Bangladesh (World Wide Fund For Nature, 2001). Up to 2000 causalities were reported, partly because this area is usually not flooded and residents were thus not equipped with the resources to cope with this sudden threat (Red Cross, 2001).

*Interacts with:* $\rightarrow$
Floods. Coastal flooding. Crops. Ecosystems. Migration. Political tension. Livelihoods.
*Impacted by:*$\leftarrow$
Precipitation. Discharge. Floods. Coastal flooding. Dam construction. Shrimp farming.

**Chemical pollution and spillage** Chemical pollution is a widespread problem in Bangladesh, in particular close to industrial centers (Matin, 1995; Saha et al., 2009). This includes pollution through untreated waste water and spillages such as the ammonia gas leak in Chittagong on August 22nd, 2016 which affected up to 200 and hospitalized 50 people (Hussain, 2016; Chittagong Bureau, 2016). Particular problematic are textile industry and tanneries, many of which save on utility costs by dumping waste water directly into the rivers without removing textile dyes and other garment treatment chemicals. These factories are located in the outer skirts of Dhaka and often directly near the slum settlements of the urban poor (Yardley, 2013). Intense agricultural practices and population density are expected to aggravate chemical pollution over the coming years (Datta and

Subramanian, 1997).

The risk of chemical contamination is amplified due to the soil characteristics in Bangladesh according to Datta and Subramanian (1997). The sediments in the GBM delta are solely made up of fine sand, silt and clay. The small sediment size (and thus large surface-to-mass ratios) and mineral composition result in a high potential for chemical adsorptive reactions.

*Interacts with:* →
Fertility. Water quality. Ecosystem changes. Morbidity.
*Impacted by:*←
Crops. Textile industry.

**Transport accident** Bangladesh has one of the highest road accident fatality rates worldwide, with 60 deaths per 10,000 motor vehicles per year reported by Maniruzzaman and Mitra (2005), most of which are transport accidents related to minivans and busses as there is little car ownership outside of Dhaka. 20 % of all cases occur in Dhaka, with overall numbers likely to be higher as Maniruzzaman and Mitra (2005) also consider the reporting system faulty. In recent years, the Bangladesh Road Transport Authority has reported a decline in total number of accidents, yet still 2,376 fatalities and 1,958 injuries were reported for 2015, with the high number of fatalities likely due to the high number of pedestrians involved (up to 50 % of all accidents) (Maniruzzaman and Mitra, 2005; Bangladesh Police, 2017).

*Interacts with:* →
Morbidity. Mortality.
*Impacted by:* ←
Urbanization. Transportation.

**Urban fire** Fires are a hazard particularly noteable in the densely populated urban spaces, which can also cause industrial explosions. Together with structural collapses, urban fires have killed at least 1,800 Bangladeshi garment workers between 2005 and 2013 (The Guardian, 2013). One such fire broke out on the ground floor of the Tazreen factory in outer Dhaka in November 2012, injuring over 200 and killing at least 117 workers. Reasons for the fire named in subsequent investigations are an electrical short circuit, the high death toll is also a direct result of blocked escape routes and faulty fire alarm routines. The building's fire safety certificate had expired in July 2012 (BBC, 2013).

*Interacts with:* →
Industrial explosions. Morbidity. Mortality.
*Impacted by:*←
Urbanization. Shrinking space of democracy.

**Industrial explosion** An industrial explosion refers to an industrial accident that directly results from technical malfunction, negligence or incompetent use. At least two major industrial explosions have taken place between September 2016 and April 2017 alone. In Dhaka, boiler explosions and a subsequent fire left 50 workers severely injured and an additional 40 workers dead at the packaging factory Tampaco Foils Ltd in September 2016 (Gazipur Correspondent, 2016). A boiler explosion at a rice mill injured 28 and killed 1 worker in Dinajpur in April 2017 (Sunny, 2017).

*Interacts with:* →
Urban fires. Morbidity. Mortality.

**Nuclear reactor failure** Bangladesh does not yet have a nuclear power plant, but has continuously been pursuing plans since 1963 to construct the Rooppur Nuclear Power Plant with two nuclear reactors 160 km northwest of Dhaka. Site work started in October 2013 and was largely completed in April 2016, with construction of the first Rooppur nuclear unit expected to begin in August 2017 (World Nuclear Association, 2017). Concerns are voiced about the decrease in dry season flow of the Ganges river due to Farakka barrage, as vast amounts of water will be required for the cooling of the nuclear reactors. The water used to cool the reactors is also returned to the Ganges, thus increasing the temperature of the water downstream of the plant, causing ecosystem changes. In addition, the plant is located near three active earthquake fault lines. Because the plant is being built in a densely populated region, a nuclear reactor failure would impact up to 3.5 million people living in a 30 km radius (Islam, 2015). Nuclear reactor failure is thus a problem that could occur in coming years.

*Interacts with:* →
Ecosystem changes. Morbidity. Mortality.
*Impacted by:*←
Discharge. Energy demand.

## A.5 Implications

The various processes in the natural and anthropogenic system have a number of implications, which we discuss on the country-wide as well as the individual level. Of course, the implications themselves interact: an increase in morbidity is also likely to impact mortality, just as migration or political tension can have a detrimental effect on the well-being of an individual. Implications are counted in the purple arrows of Figure 5.1.

### A.5.1 Country-wide implications

Our assessment focuses on four main impacts on the regional to national scale that can be related to hydrological processes in Bangladesh:

**Ecosystem changes** Changes in ecosystems such as the Sundarbans, the mangrove forests in southwestern Bangladesh, can be observed through studying ecological indicators such as the growth of algae or the thriving of fish species (Dale and Beyeler, 2001; Rabbani et al., 2010; Gain and Giupponi, 2014).

**Political tension** Current international political tension relating to hydrological processes in the region is due to e.g. marine boundary disputes and water sharing issues on the Ganges river (Mirza, 1998; Gain and Giupponi, 2014). National political tension is ongoing due to e.g the construction of Kaptai Dam in the Chittagong Hill tracts, which displaced over 100,000 people from mostly ethnic communities (Parveen and Faisal, 2002).

**Food security** Food security plays a central role in risk assessment studies for the GBM delta, in particular for poor women and children (Faisal and Parveen, 2004; Mirza, 2011; Keck and Etzold, 2013; Hijioka et al., 2014). Currently, Bangladesh is one of the most efficient regions world-wide in terms of people fed per ton produced (Cassidy et al., 2013). Regardless, Rabbani et al. (2010) states that more than 27 % of the population in South Asia currently lacks access to adequate food supplies. In addition, the country is not yet self-sufficient and has larger imports than exports (Yu et al., 2010).

**Migration** Bangladesh has a net migration rate of -3.1 migrant(s) per 1,000 population (2016 est., (Central Intelligence Agency, 2013)). Nation-wide movement is observed both seasonally in seeking labor, as well as continuously directed from coastal regions to cities inland, with coastal erosion and salinification named as key reasons to permanently move a household (Inman, 2009; Kartiki, 2011).

### A.5.2 Individual implications

Impacts on the individual level occur in the following four categories.

**Livelihood** The livelihood of an individual and the corresponding household is composed of five assets as postulated by and described in Chambers and Conway (1991), DfID (1999) and Krantz (2001) :

- *Human capital* includes the knowledge, skill set, ability to work as well as physical and psychological health (see sections on Well-being, Morbidity and Mortality below).
- *Natural capital* refers to renewable and non-renewable resources naturally available from the environment, e.g. water, air, soil, oil and metals, and is the basis of any production.
- *Financial capital* is comprised of the financial resources available or accessible to a household, including economic assets such as cash, savings and access to credit programs.
- *Physical capital* refers to materials, machinery and infrastructure.
- *Social capital* has varying definitions across disciplines, we understand it as the ability of actors to secure benefits by virtue of membership in social networks or other social structures (Portes, 1998).

The more capital is available to an individual or their household, the more they are likely to withstand adverse effects from processes such as natural hazards (Aßheuer et al., 2013; Bebbington, 1999).

**Well-being** The constitution of the WHO states that "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." Well-being thus describes both the physical and psychological state of well-being, and is a vital aspect of overall health (Gruebner et al., 2012; WHO, 1946).

**Morbidity** Morbidity refers to an illness or an abnormal condition or quality such as a disability resulting from any cause (Ezzati et al., 2004).

**Mortality** In certain cases, natural and anthropogenic processes can directly be attributed as the cause of death. The number of deaths in a population is measured by the mortality rate (Burkart et al., 2011a).

# Bibliography


Acharyya, S. K., S. Lahiri, B. C. Raymahashay, and A. Bhowmik, 2000: Arsenic toxicity of groundwater in parts of the Bengal basin in India and Bangladesh: The role of Quaternary stratigraphy and Holocene sea-level fluctuation. *Environmental Geology*, **39**, 1127–1137, doi:10.1007/s002540000107.

Adel, M. M., 2002: Man-made climatic changes in the Ganges basin. *International Journal of Climatology*, **22**, 993–1016, doi:10.1002/joc.732.

Ahasan, M. N., M. A. M. Chowdhary, and D. Quadir, 1993: Variability and Trends of Summer Monsoon Rainfall over Bangladesh. *Journal of Hydrology and Meteorology*, **7**, 1–17, doi:10.3126/jhm.v7i1.5612.

Ahasan, M. N., M. A. M. Chowdhury, and D. A. Quadir, 2013: Simulation of a heavy rainfall event of 11 June 2007 over Chittagong, Bangladesh using MM5 model. *MAUSAM*, **64**, 405–416.

Ahern, M., R. S. Kovats, P. Wilkinson, R. Few, and F. Matthies, 2005: Global health impacts of floods: Epidemiologic evidence. *Epidemiologic Reviews*, **27**, 36–46, doi:10.1093/epirev/mxi004.

Ahmad, F., 2015: Restrictions on freedom of expression. *Daily Star*.
URL `http://www.thedailystar.net/law-our-rights/restrictions-freedom-expression-152341 [2017/06/15]`

Ahmed, M. K., M. S. Alam, A. H. M. Youduf, and M. M. Islam, 2016: A long-term trend in precipitation of different spatial regions of Bangladesh and its teleconnections with El Nino Southern Oscillation and Indian Ocean Dipole. *Theoretical and Applied Climatology*, 1–14, doi:10.1007/s00704-016-1765-2.

Ahmed, R. and S. Karmakar, 1993: Arrival and withdrawal dates of the summer monsoon in bangladesh. *International Journal of Climatology*, **13**, 727–740, doi:10.1002/joc.3370130703.

Akaike, H., 1973: Information theory and an extension of the maximum likelihood principle. *2nd International Symposium on Information Theory*, Akademiai Kiado, Tsahkadsor, Armenia, USSR, 267–281.

Akanda, A. S., A. S. Jutla, and S. Islam, 2009: Dual peak cholera transmission in bengal delta: A hydroclimatological explanation. *Geophysical Research Letters*, **36**.

Akter, J., M. H. Sarker, I. Popescu, and D. Roelvink, 2015: Evolution of the Bengal Delta and Its Prevailing Processes. *Journal of Coastal Research*, **32**, 1212–1226.

Akther, H., M. Ahmed, and K. Rasheed, 2009: Spatial and Temporal Analysis of Groundwater Level Fluctuation in Dhaka City, Bangladesh. *Bangladesh. Asian Journal of Earth Sciences*, **2**, 49–57.

Alam, E. and A. E. Collins, 2010: Cyclone disaster vulnerability and response experiences in coastal Bangladesh. *Disasters*, **34**, 931–954, doi:10.1111/j.1467-7717.2010.01176.x.

Alam, E. and D. Dominey-Howes, 2014a: A new catalogue of tropical cyclones of the northern Bay of Bengal and the distribution and effects of selected land-falling events in Bangladesh. *International Journal of Climatology*, **35**, 801–835, doi:10.1002/joc.4035.

— 2014b: An analysis of the AD1762 earthquake and tsunami in SE Bangladesh. *Natural Hazards*, **70**, 903–933, doi:10.1007/s11069-013-0841-5.

— 2016: A catalogue of earthquakes between 810BC and 2012 for the Bay of Bengal. *Natural Hazards*, **81**, 2031–2102, doi:10.1007/s11069-016-2174-7.

Alam, E., D. Dominey-Howes, C. Chagué-Goff, and J. Goff, 2012: Tsunamis of the northeast Indian Ocean with a particular focus on the Bay of Bengal region-A synthesis and review. *Earth-Science Reviews*, **114**, 175–193, doi:10.1016/j.earscirev.2012.05.002.

Alam, M. and M. G. Rabbani, 2007: Vulnerabilities and responses to climate change for Dhaka. *Environment and Urbanization*, **19**, 81–97, doi:10.1177/0956247807076911.

Alam, S. M. and K. Uddin, 2013: A Study of Morphological Changes in the Coastal Areas and Offshore Islands of Bangladesh Using Remote Sensing. *American Journal of Geographic Information System*, **2**, 15–18, doi:10.5923/j.aj gis.20130201.03.

Alderman, K., L. R. Turner, and S. Tong, 2012: Floods and human health: a systematic review. *Environment international*, **47**, 37–47, doi:10.1016/j.envint.2012.06.003.

Ali, M., S. Saheed, D. Kubota, T. Masunaga, and T. Wakatsuki, 1997: Soil degradation during the period 1961-1995 in Bangladesh. Part 2. Selected chemical characters . *Soil Science and Plant Nutrition*, **43**, 879–890.

Ali, M. Y., 1999: Fish Resources Vulnerability and Adaptation to Climate Change in Bangladesh. *Vulnerability and Adaptation to Climate Change for Bangladesh*, Springer Netherlands, Dordrecht, 113–124.

Alongi, D. M., 2014: Carbon Cycling and Storage in Mangrove Forests. *Annual Review of Marine Science*, **6**, 195–219, doi:10.1146/annurev-marine-010213-135020.

Amnesty International, 2017: Caught between fear and repression: Attacks on freedom of expression in Bangladesh. Index: Asa 13/6114/2017, Amnesty International, London, UK.

Amoako Johnson, F., C. W. Hutton, D. Hornby, A. N. Lázár, and A. Mukhopadhyay, 2016: Is shrimp farming a successful adaptation to salinity intrusion? A geospatial associative analysis of poverty in the populous GangesBrahmaputraMeghna Delta of Bangladesh. *Sustainability Science*, **11**, 423–439, doi:10.1007/s11625-016-0356-6.

Annamalai, H. and K. R. Sperber, 2016: South Asian Summer Monsoon Variability in a Changing Climate. *The Monsoons and Climate Change*, Springer International Publishing, 25–46.

Aquastat, 2011: Ganges-Brahmaputra-Meghna Basin: Water Report 37. Regional Report, Food and Agriculture Organization of the United Nations.

Arlot, S. and A. Celisse, 2009: A survey of cross-validation procedures for model selection. **4**, 40–79, doi:10.1214/09-SS054.

Armstrong, B., 2006: Models for the Relationship Between Ambient Temperature and Daily Mortality. *Epidemiology*, **17**, 624–631.

Arnell, N. W., 1999: Climate change and global water resources. *Glob. Environ. Chang.*, **9**, S31–S49.

As-Salek, J. A., 1998: Coastal Trapping and Funneling Effects on Storm Surges in the Meghna Estuary in Relation to Cyclones Hitting NoakhaliCox's Bazar Coast of Bangladesh. *Journal of Physical Oceanography*, **28**, 227–249.

Ashfaq, M., Y. Shi, W. Tung, Trapp, R.J., X. Gao, Pal, J.S., and Diffenbaugh, N.S., 2009: Suppression of south Asian summer monsoon precipitation in the 21st century. *Geophysical Research Letters*, **36**, L01704, doi:10.1029/2008GL036500.

Ashley, S. T. and W. S. Ashley, 2009: Flood Fatalities in the United States.

Aßheuer, T., 2014: *Klimawandel und Resilienz in Bangladesch. Die Bewaeltigung von Ueberschwemmungen in den Slums von Dhaka*. Ph.D. thesis, Stuttgart, Germany.

Aßheuer, T., I. Thiele-Eich, and B. Braun, 2013: Coping with the impacts of severe flood events in dhaka's slums - the role of social capital. *Erdkunde*, **67**, 21–35.

Bangla Mirror, 2017: Paknar Haor Dam breaches in Sunamganj, new areas inundated. *Bangla Mirror*, http://www.banglamirrornews.com/2017/04/paknar-haor-dam-breaches-in-sunamganj-new-areas-inundated/ [2017/06/07].

Bangladesh Police, 2017: Statistics of Accident and Casualties. *Bangladesh Road Transport Authority (BRTA)*, http://www.brta.gov.bd/newsite/en/statistics-of-accident-casualties/ [2017/06/07].

BBC, 2013: Bangladesh clothing factory hit by deadly fire. *BBC News*, http://www.bbc.com/news/world-asia-24453165 [2017/03/27].

BBC, 2013: Bangladesh Dhaka building collapse leaves 87 dead. *BBC News*, http://www.bbc.com/news/world-asia-22275597 [2017/03/27].

Bebbington, A., 1999: Capitals and Capabilities: A Framework for Analyzing Peasant Viability, Rural Livelihoods and Poverty. *World Development*, **27**, 2021 – 2044.

Bergman, D., 2016: Concerns raised over new Bangladesh NGO law. *Aljazeera*. URL `http://www.aljazeera.com/news/2016/10/concerns-raised-bangladesh-ngo-law-161020121856969.html [2017/06/15]`

Bierkens, M. F. P., 2015: Global hydrology 2015: State, trends, and directions. *Water Resources Research*, **51**, 4923–4947, doi:10.1002/2015WR017173.

Bjerklie, D. M., 2007: Estimating the bankfull velocity and discharge for rivers using remotely sensed river morphology information. *Journal of Hydrology*, **341**, 144–155, doi:10.1016/j.jhydrol.2007.04.011.

Bolch, T., A. Kulkarni, A. Kääb, C. Huggel, F. Paul, J. Cogley, H. Frey, J. Kargel, K. Fujita, M. Scheel, S. Bajracharya, and M. Stoffel, 2012: The state and fate of Himalayan glaciers. *Science*, **336**, 310–314.

Brammer, H., 2009: Mitigation of arsenic contamination in irrigated paddy soils in South and South-east Asia. *Environment International*, **35**, 856–863, doi:10.1016/j.envint.2009.02.008.

— 2012: *The Physical Geography of Bangladesh*. University Press Ltd., Dhaka, Bangladesh.

— 2013: *Climate Change, Sea-level Rise and Development in Bangladesh*. University Press Ltd., Dhaka, Bangladesh.

— 2014: Bangladesh's dynamic coastal regions and sea-level rise. *Climate Risk Management*, **1**, 51–62, doi:10.1016/j.crm.2013.10.001.

Braun, B. and T. Aßheuer, 2011: Floods in megacity environments: vulnerability and coping strategies of slum dwellers in Dhaka, Bangladesh. *Natural Hazards*, **58**, 771–787, doi:10.1007/s11069-011-9752-5.

Brouwer, R., S. Akter, L. Brander, and E. Haque, 2007: Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Analysis*, **27**, 316–826.

Brown, S. and R. Nicholls, 2015: Subsidence and human influences in mega deltas: The case of the Ganges-Brahmaputra-Meghna. *Science of The Total Environment*, **527**, 362–374, doi:10.1016/j.scitotenv.2015.04.124.

Buntgen, U., W. Tegel, K. Nicolussi, M. McCormick, D. Frank, V. Trouet, J. O. Kaplan, F. Herzig, K.-U. Heussner, H. Wanner, J. Luterbacher, and J. Esper, 2011: 2500 Years of European Climate Variability and Human Susceptibility. *Science*, **331**, 578–582, doi:10.1126/science.1197175.

Burkart, K., S. Breitner, A. Schneider, M. M. H. Khan, A. Krämer, and W. Endlicher, 2014a: An analysis of heat effects in different subpopulations of Bangladesh. *International Journal of Biometeorology*, **58**, 227–37, doi:10.1007/s00484-013-0668-5.

Burkart, K., M. H. Khan, A. Krämer, S. Breitner, A. Schneider, and W. R. Endlicher, 2011a: Seasonal variations of all-cause and cause-specific mortality by age, gender, and socioeconomic condition in urban and rural areas of bangladesh. *Int J Equity Health*, **10**, 32.

Burkart, K., M. M. H. Khan, A. Schneider, S. Breitner, M. Langner, A. Krämer, and W. Endlicher, 2014b: The effects of season and meteorology on human mortality in tropical climates: a systematic review. *Transactions of The Royal Society of Tropical Medicine and Hygiene*, **108**, 393–401, doi:10.1093/trstmh/tru055.

Burkart, K. and P. Kinney, 2016: Is precipitation a predictor of mortality in Bangladesh? A multi-stratified analysis in a South Asian monsoon climate. *Science of The Total Environment*, **553**, 458–465, doi:10.1016/j.scitotenv.2016.01.206.

Burkart, K. and P. L. Kinney, 2017: What drives cold-related excess mortality in a south Asian tropical monsoon climate? Season vs. temperatures and diurnal temperature changes. *International Journal of Biometeorology*, **61**, 1073–1080, doi:10.1007/s00484-016-1287-8.

Burkart, K., A. Schneider, S. Breitner, M. H. Khan, A. Krämer, and W. Endlicher, 2011b: The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. *Environmental Pollution*, **159**, 2035–2043.

Burnham, K. and D. Anderson, 1973: Model Selection and Multimodel Interference. *A Practical Information-Theoretic Approach*, Springer.

Byomkesh, T., N. Nakagoshi, and A. M. Dewan, 2012: Urbanization and green space dynamics in Greater Dhaka, Bangladesh. *Landscape and Ecological Engineering*, **8**, 45–58, doi:10.1007/s11355-010-0147-7.

Cash, B., Rodó Xavier, Kinter James, Fennessy Michael, and B. Doty, 2008: Differing Estimates of Observed Bangladesh Summer Rainfall. *Journal of Hydrometeorology*, **9**, 1106–1114.

Cassidy, E. S., P. C. West, J. S. Gerber, and J. A. Foley, 2013: Redefining agricultural yields: from tonnes to people nourished per hectare. *Environmental Research Letters*, **8**, 034015.

Cecil, D. J. and C. B. Blankenship, 2012: Toward a global climatology of severe hailstorms as estimated by satellite passive microwave imagers. *Journal of Climate*, **25**, 687–703, doi:10.1175/JCLI-D-11-00130.1.

Central Intelligence Agency, 2013: The World Factbook 2013-14. `https://www.cia.gov/library/publications/the-world-factbook/index.html`, online; Accessed: 20 February 2017.

Chambers, R. and G. Conway, 1991: Sustainable rural livelihoods : practical concepts for the 21st century. *IDS Discussion Paper*, **296**, 29.

Chen, J. L., C. R. Wilson, and B. D. Tapley, 2013: Contribution of ice sheet and mountain glacier melt to recent sea level rise. *Nature Geoscience*, **6**, 549 – 552.

Chittagong Bureau, 2016: 43 hospitalised after Chittagong fertiliser factory gas leak; probe teams formed. *bdnews24.com*, http://bdnews24.com/bangladesh/2016/08/23/43-hospitalised-after-chittagong-fertiliser-factory-gas-leak-probe-teams-formed [2017/06/06].

Choudhury, W. A., F. A. Quraishi, and Z. Haque, 2006: Mental health and psychosocial aspects of disaster preparedness in Bangladesh. *International Review of Psychiatry*, **18**, 529–535, doi:10.1080/09540260601037896.

Chowdhury, M. R. and N. Ward, 2004: Hydro-meteorological variability in the greater Ganges-Brahmaputra-Meghna Basins. *International Journal of Climatology*, **24**, 1495–1508, doi:DOI: 10.1002/joc.1076.

Chowdhury, S., 2001: Bangladesh Climate Change and Sustainable Development. Technical Report 21104, South Asia Rural Development Unit of the World Bank.

Coles, S., 2001: *An Introduction to Statistical Modeling of Extreme Values*, Springer.

Cummins, P. R., 2007: The potential for giant tsunamigenic earthquakes in the northern Bay of Bengal. *Nature*, **449**, 75–78, doi:10.1038/nature06088.

Curray, J. R., F. J. Emmel, and D. G. Moore, 2002: The Bengal Fan: morphology, geometry, stratigraphy, history and processes. *Marine and Petroleum Geology*, **19**, 1191–1223, doi:10.1016/s0264-8172(03)00035-7.

Dale, V. H. and S. C. Beyeler, 2001: Challenges in the development and use of ecological indicators. *Ecological Indicators*, **1**, 3–10, doi:10.1016/S1470-160X(01)00003-6.

Datta, D. K. and V. Subramanian, 1997: Texture and mineralogy of sediments from the ganges-brahmaputra-meghna river system in the bengal basin, bangladesh and their environmental implications. *Environmental Geology*, **30**, 181–188, doi:10.1007/s002540050145.

Delgado, C. L., 2003: Rising consumption of meat and milk in developing countries has created a new food revolution. *The Journal of Nutrition*, **133**, 3907S–3910S.

Dewan, A. M. and Y. Yamaguchi, 2008: Effect of Land Cover Changes on Flooding: Example from Greater Dhaka of Bangladesh. *International Journal of Geoinformatics*, **4**.

Dey, N., M. Alam, A. Sajjan, M. Bhuiyan, L. Ghose, Y. Ibaraki, and F. Karim, 2012: Assessing Environmental and Health Impact of Drought in the Northwest Bangladesh. *Journal of Environmental Science and Natural Resources*, **4**, 89–97, doi:10.3329/jesnr.v4i2.10141.

DfID, D. f. I. D., 1999: Sustainable Livelihoods Guidance Sheets Framework Introduction Vulnerability Transforming. *Context*, 26, doi:10.1002/smj.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, K. Yan, L. Brandimarte, and G. Blöschl, 2015: Debates - Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes.

Ding, Y., S. Liu, J. Li, and D. Shangguan, 2006: The retreat of glaciers in response to recent climate warming in western China. *Annals of Glaciology*, **43**, 97–105, doi:10.3189/172756406781812005.

Disaster Management Bureau, 2007: Flood Report 2007. Executive summary, Ministry of Food and Disaster Management For Government of the Peoples Republic of Bangladesh with the assistance of comprehensive Disaster Management Programme (CDMP). Available online: http://www.ddm.gov.bd/ (accessed on 21 Januray 2015).

Dobler, A. and B. Ahrens, 2008: Precipitation by a regional climate model and bias correction in Europe and South Asia. *Meteorologische Zeitschrift*, **17**, 499–509.

— 2010: Analysis of the Indian summer monsoon system in the regional climate model COSMO-CLM. *Journal of Geophysical Research*, **115**, 1–12, doi:10.1029/2009JD013497.

Dobson, A. and A. Barnett, 2008: *An Introduction to Generalized Linear Models*, CRC Press, Taylor and Francis Group.

Donato, D., B. Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, and M. Kanninen, 2011: Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, **4**, 293–297, doi:10.1038/ngeo1123.

Doshi, V., 2016: India set to start massive project to divert ganges and brahmaputra rivers. *The Guardian*.
URL `https://www.theguardian.com/global-development/2016/may/18/india-set-to-start-massive-project-to-divert-ganges-and-brahmaputra-rivers [2017/06/24]`

Douglas, B. C. and W. R. Peltier, 2002: The Puzzle of Global Sea-Level Rise. *Physics Today*, **55**, 35, doi:10.1063/1.1472392.

Du, W., G. J. FitzGerald, M. Clark, and X.-Y. Hou, 2010: Health impacts of floods. *Prehospital and Disaster Medicine*, **25**, 265–272, doi:10.1017/S1049023X00008141.

Efron, B. and R. Tibshirani, 1994: *An introduction to the bootstrap*. CRC press.

Elsner, J. B., J. P. Kossin, and T. H. Jagger, 2008: The increasing intensity of the strongest tropical cyclones. *Nature*, **455**, 92–95, doi:10.1038/nature07234.

Emran, A., A. M. Rob, and H. M. Kabir, 2017: Coastline change and erosion-accretion evolution of the sandwip island, bangladesh. *International Journal of Applied Geospatial Research*, **8**, doi:DOI: 10.4018/IJAGR.2017040103.

Ezzati, M., A. Lopez, A. Rodgers, and C. Murray, 2004: Comparative Quantification of Health Risks: Global and Regional Burden of Disease Due to Selected Major Risk Factors. Technical report, World Health Organization, Geneva.

Faisal, I., M. Kabir, and A. Nishat, 2003: The disastrous flood of 1998 and long term mitigation strategies for Dhaka City. *Flood Problem and Management in South Asia*, Springer, 85–99.

Faisal, I. M. and S. Parveen, 2004: Food Security in the Face of Climate Change, Population Growth, and Resource Constraints: Implications for Bangladesh. *Environmental Management*, **34**, 487–498, doi:10.1007/s00267-003-3066-7.

Few, R., 2003: Flooding, vulnerability and coping strategies: local responses to a global threat. *Progress in Development Studies*, **3**, 43–58, doi:10.1191/1464993403ps049ra.

Fujinami, H., D. Hatsuzuka, T. Yasunari, T. Hayashi, T. Terao, F. Murata, M. Kiguchi, Y. Yamane, J. Matsumoto, M. N. Islam, and A. Habib, 2011: Characteristic intraseasonal oscillation of rainfall and its effect on interannual variability over Bangladesh during boreal summer. *International Journal of Climatology*, **31**, 1192–1204, doi:10.1002/joc.2146.

Gain, A. K. and C. Giupponi, 2014: Impact of the Farakka Dam on thresholds of the hydrologic: Flow regime in the Lower Ganges River Basin (Bangladesh). *Water (Switzerland)*, **6**, 2501–2518, doi:10.3390/w6082501.

Gain, A. K., W. W. Immerzeel, F. C. Sperna Weiland, and M. F. P. Bierkens, 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**, 1537–1545, doi:10.5194/hess-15-1537-2011.

Gain, A. K. and Y. Wada, 2014: Assessment of Future Water Scarcity at Different Spatial and Temporal Scales of the Brahmaputra River Basin. *Water Resources Management*, **28**, 999–1012, doi:10.1007/s11269-014-0530-5.

GAR, 2009: Global Assessment Report on Disaster Risk Reduction 2009. Risk and Poverty in a Changing Climate. Technical report, United Nations International Strategy for Disaster Reduction Secretariat (UNISDR).

— 2011: Global Assessment Report on Disaster Risk Reduction 2011. Revealing Risk, Redefining Development. Technical report, United Nations Publication.

Gasparrini, A., 2011: Distributed lag linear and non-linear models in R: the package dlnm. *Journal of Statistical Software*, **43**, 1–20.

— 2014: Modeling exposure-lag-response associations with distributed lag non-linear models. *Statistics in Medicine*, **33**, 881–899, doi:10.1002/sim.5963.

Gazipur Correspondent, 2016: Explosion of gas line booster, not boiler, caused Tampaco fire, Titas now suspects. *bdnews24.com*, http://bdnews24.com/bangladesh/2016/09/20/explosion-of-gas-line-booster-not-boiler-caused-tampaco-fire-titas-now-suspects [2017/06/07].

Gill, J. C. and B. D. Malamud, 2014: Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics*, **52**, 680–722, doi:10.1002/2013RG000445, 2013RG000445.

— 2016: Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. *Earth System Dynamics*, **7**, 659–679, doi:10.5194/esd-7-659-2016.

Gomes, C., M. Ahmed, F. Hussain, and K. R. Abeysinghe, 2006: Lightning accidents and awareness in South Asia: Experience in Sri Lanka and Bangladesh. *International Conference on Lightning Protection, Kanazawa*, 1–4.

Gomes, C., M. Ahmed, and D. Zele, 2012: Lightning related fish mortality: Case study From Bangladesh. *International Conference on Lightning Protection, Vienna*, 1–4, doi:10.1109/ICLP.2012.6344259.

Gruebner, O., M. M. H. Khan, S. Lautenbach, D. Müller, A. Krämer, T. Lakes, and P. Hostert, 2012: Mental health in the slums of Dhaka - a geoepidemiological study. *BMC public health*, **12**, 177, doi:10.1186/1471-2458-12-177.

Habiba, U., R. Shaw, and Y. Takeuchi, 2014: Farmers adaptive practices for drought risk reduction in the northwest region of bangladesh. *Natural Hazards*, **72**, 337–359.

Hackenbroch, K., 2013: Negotiating public space for livelihoods: about risks, uncertainty and power in the urban poor's life. *Erdkunde*.

Han, W. and P. J. Webster, 2001: Forcing Mechanismy of Sea Level Interannual Variability in the Bay of Bengal. *Journal of Physical Oceanography*, **32**, 216–239.

Haque, A., Sumaiya, and M. Rahman, 2016: Flow Distribution and Sediment Transport Mechanism in the Estuarine Systems of Ganges-Brahmaputra-Meghna Delta. *International Journal of Environmental Science and Development*, **7**, 22–30, doi:10.7763/IJESD.2016.V7.735.

Haque, S. A., 2006: Salinity problems and crop production in coastal regions of Bangladesh. *Pak. J. Bot*, **38**, 1359–1365.

Haque, S. J., S.-i. Onodera, and Y. Shimizu, 2013: An overview of the effects of urbanization on the quantity and quality of groundwater in South Asian megacities. *Limnology*, **14**, 135–145, doi:10.1007/s10201-012-0392-6.

Hasan, M. K. and A. K. M. A. Alam, 2006: Land Degradation Situation in Bangladesh and Role of Agroforestry. *Journal of Agriculture and Rural Development*, **4**, 19–25, doi:10.3329/jard.v4i1.763.

Hashimoto, M., T. Suetsugi, K. Sunada, and ICRE, 2011: Study on the flood simulation techniques for estimation of health risk in Dhaka city, Bangladesh. *AGU Fall Meeting Abstracts*, H1370.

Hashizume, M., B. Armstrong, S. Hajat, Y. Wagatsuma, A. S. Faruque, T. Hayashi, and D. A. Sack, 2007: Association between climate variability and hospital visits for non-cholera diarrhoea in Bangladesh: effects and vulnerable groups. *International Journal of Epidemiology*, **36**, 1030–1037.

Hashizume, M., Y. Wagatsuma, A. S. Faruque, T. Hayashi, and B. Armstrong, 2009: Climatic components of seasonal variation in cholera incidence. *Epidemiology*, **20**, S153.

Hastie, T. and R. Tibshirani, 1990: *Generalized Additive Models*, Chapman & Hall, London.

Hess, J. J., J. Z. McDowell, and G. Luber, 2012: Integrating climate change adaptation into public health practice: using adaptive management to increase adaptive capacity and build resilience. *Environmental Health Perspectives*, **120**, 171.

Higgins, S. A., I. Overeem, M. S. Steckler, J. P. M. Syvitski, L. Seeber, and S. H. Akhter, 2014: InSAR measurements of compaction and subsidence in the Ganges-Brahmaputra Delta, Bangladesh. *Journal of Geophysical Research: Earth Surface*, **119**, 1768–1781, doi:10.1002/2014JF003117.

Hijioka, Y., E. Lin, J. Pereira, R. Corlett, X. Cui, G. Insarov, R. Lasco, E. Lindgren, and A. Surjan, 2014: Asia. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L. White, eds., Cambridge, United Kingdom and New York, NY, USA, 1327–1370.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae, 2013: Global flood risk under climate change. *Nature Climate Change*, **3**, 816–821, doi:10.1038/nclimate1911.

Höfer, T. and B. Messerli, 2006: *Floods in Bangladesh: History, Dynamics and Rethinking the Role of the Himalayas*. United Nations University Press.

Holle, R. L., 2008: Annual rates of lightning fatalities by country. *International Lightning Detection Conference, Tucson, Arizona*, 2–14.

Hoque, M. and M. Alam, 1997: Subsidence in the lower deltaic areas of Bangladesh. *Marine Geodesy*, **20**, 105–120, doi:10.1080/01490419709388098.

Hoque, M. A., M. M. Hoque, and K. M. Ahmed, 2007: Declining groundwater level and aquifer dewatering in Dhaka metropolitan area, Bangladesh: causes and quantification. *Hydrogeology Journal*, **15**, 1523–1534, doi:10.1007/s10040-007-0226-5.

Hossain, M., 2001: Farmer's view on soil organic matter depletion and its management in bangladesh. *Nutrient Cycling in Agroecosystems*, **61**, 197–204.

Hossain, M., S. White, S. Elahi, N. Sultana, M. Choudhury, Q. Alam, J. Rother, and J. Gaunt, 2005: The efficiency of nitrogen fertiliser for rice in Bangladeshi farmers' fields. *Field Crops Research*, **93**, 94–107, doi:10.1016/j.fcr.2004.09.017.

Hossain, Z., Z. Islam, and T. Sakai, 2008: An Investigation on Failure of Embankments in Bangladesh. *Sixth International Conference on Case Histories in Geotechnical Engineering*, **4**.

Houghton, K. J., A. T. Vafeidis, B. Neumann, and A. Proelss, 2010: Maritime boundaries in a rising sea. *Nature Geoscience*, **3**, 813–816, doi:10.1038/ngeo1029.

Huque, K. and N. Sarker, 2014: Feeds and feeding of livestock in Bangladesh: performance, constraints and options forward. *Bangladesh Journal of Animal Science*, **43**, 1–10.

Hussain, A., 2016: Chittagong Gas Leak: Probe finds gross negligence. *Dhaka Tribune*, http://www.dhakatribune.com/bangladesh/2016/08/29/chittagong-gas-leak-probe-finds-gross-negligence/ [2017/06/06].

Iftekhar, M. S. and P. Saenger, 2008: Vegetation dynamics in the bangladesh sundarbans mangroves: a review of forest inventories. *Wetlands Ecology and Management*, **16**, 291–312, doi:10.1007/s11273-007-9063-5.

Immerzeel, F., W. W. Pellicciotti and M. F. P. Bierkens, 2013: Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, **6**, 742–745, doi:10.1038/ngeo1896.

Immerzeel, W., 2008: Historical trends and future predictions of climate variability in the Brahmaputra basin. *International Journal of Climatology*, **28**, 243–254, doi:10.1002/joc.1528.

Immerzeel, W. W. and M. F. P. Bierkens, 2010: Seasonal prediction of monsoon rainfall in three Asian river basins: The importance of snow cover on the Tibetan Plateau. *International Journal of Climatology*, **30**, 1835–1842, doi:10.1002/joc.2033.

— 2012: Asia's water balance. *Nature Geoscience*, **5**, 841–842, doi:10.1038/ngeo1643.

Immerzeel, W. W., L. P. H. van Beek, and M. F. P. Bierkens, 2010: Climate change will affect the Asian water towers. *Science (New York, N.Y.)*, **328**, 1382–5, doi:10.1126/science.1183188.

Inman, M., 2009: Where warming hits hard. *Nature Reports Climate Change*, 18–21, doi:10.1038/climate.2009.3.

International Monetary Fund, 2016: IMF DataMapper. `http://www.imf.org/external/datamapper`, online; Accessed: 20 February 2017.

IPCC, 2013: *Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Islam, A., A. Haque, and S. Bala, 2010: Hydrologic characteristics of floods in Ganges-Brahmaputra-Meghna (GBM) delta. *Natural Hazards*, **54**, 797–811, doi:10.1007/s11069-010-9504-y.

Islam, A. K. M. S. and M. N. Islam, 2006: Rainfall Estimation Over Bangladesh Using Remote Sensing Data. Technical Report June, Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka.

Islam, M. N., T. Terao, H. Uyeda, T. Hayashi, and K. Kikuchi, 2005: Spatial and Temporal Variations of Precipitation in and around Bangladesh. *Journal of the Meteorological Society of Japan*, **83**, 21–39.

Islam, M. R., S. F. Begum, Y. Yamaguchi, and K. Ogawa, 1999: The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation. *Hydrological Processes*, **13**, 2907–2923.

Islam, R., 2015: Water shortages pose risks to Bangladesh's first nuclear plant. *The Third Pole*, https://www.thethirdpole.net/2015/06/05/water-shortages-pose-risks-to-bangladeshs-first-nuclear-plant [2017/06/06].

Jian, J., P. J. Webster, and C. D. Hoyos, 2009: Large-scale controls on Ganges and Brahmaputra river discharge on intraseasonal and seasonal time-scales. *Quarterly Journal of the Royal Meteorological Society*, **135**, 353–370, doi:10.1002/qj.

Johnson, S. and A. Alam, 1991: Sedimentation and Tectonics of the Sylhet Trough, Bangladesh. *Geological Society of America Bulletin*, **103**, 1513–1527.

Jonkman, S., 2005: Global perspectives on loss of human life caused by floods. *Natural Hazards*, **34**, 151–175, doi:10.1007/s11069-004-8891-3.

Karim, M. F. and M. J. Haider, 1991: Erosional hazards of Chittagong city, Bangladesh. Proceedings of RTPESA5: Workshop on Soil Erosion and Debris Flow Control, UNDP- Regional Training Programme on Erosion and Sedimentation for Asia (RTPESA, Yogyakarta, Indonesia.

Karim, M. F. and N. Mimura, 2008: Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. *Global Environmental Change*, **18**, 490–500, doi:10.1016/j.gloenvcha.2008.05.002.

Kartiki, K., 2011: Climate change and migration: a case study from rural Bangladesh. *Gender & Development*, **19**, 23–38.

Keck, M. and B. Etzold, 2013: Resilience refused wasted potentials for improving food security in Dhaka. *Erdkunde*, **67**, 75–91, doi:10.3112/erdkunde.2013.01.07.

Kehrwald, N. M., L. G. Thompson, Y. Tandong, E. Mosley-Thompson, U. Schotterer, V. Alfimov, J. Beer, J. Eikenberg, and M. E. Davis, 2008: Mass loss on Himalayan glacier endangers water resources. *Geophysical Research Letters*, **35**, L22503, doi:10.1029/2008GL035556.

Khalequzzaman, M.D., 1994: Recent Floods in Bangladesh : Possible Causes and Solutions. *Natural Hazards*, **9**, 65–80, doi:10.1007/BF00662591.

Khan, A., S. K. Mojumder, S. Kovats, and P. Vineis, 2008: Saline contamination of drinking water in Bangladesh. *The Lancet*, **371**, 385, doi:10.1016/S0140-6736(08)60197-X.

Konikow, L. F., 2011: Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters*, **38**, 1–5, doi:10.1029/2011GL048604.

Krantz, L., 2001: The sustainable livelihood approach to poverty reduction. *Division for Policy and Socio-Economic Analysis*, 44.

Kuehl, S., M. Allison, S. Goodbred, and H. Kudrass, 2011: The Ganges- Brahmaputra Delta. *River Deltas- Concepts, Models, and Examples*, L. Giosan and J. Bhattacharya, eds., Society for Sedimentary Geology, 413–434.

Kumar, K., B. Rajagopalan, M. Hoerling, G. Bates, and M. Cane, 2006: Unraveling the Mystery of Indian Monsoon Failure During El Nino. *Science*, **314**, doi:10.1126/science.1131152.

Kumar, K. K., 1999: On the Weakening Relationship Between the Indian Monsoon and ENSO. *Science*, **284**, 2156–2159, doi:10.1126/science.284.5423.2156.

Kunii, O., T. Kunori, K. Takahashi, M. Kaneda, and N. Fuke, 1996: Health impact of 1996 tornado in Bangladesh. *Lancet*, **348**, 757, doi:10.1016/S0140-6736(05)65669-3.

Lawrence, D. M., P. J. Webster, D. M. Lawrence, and P. J. Webster, 2001: Interannual Variations of the Intraseasonal Oscillation in the South Asian Summer Monsoon Region. *Journal of Climate*, **14**, 2910–2922.

Li, C., M. Yanai, C. Li, and M. Yanai, 1996: The Onset and Interannual Variability of the Asian Summer Monsoon in Relation to LandSea Thermal Contrast. *Journal of Climate*, **9**, 358–375.

Liu, X. and B. Chen, 2000: Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology*, **20**, 1729–1742.

Liu, X. and M. Yanai, 2001: Relationship between the Indian monsoon rainfall and the tropospheric temperature over the Eurasian continent. *Quarterly Journal of the Royal Meteorological Society*, **127**, 909–937, doi:10.1002/qj.49712757311.

Lobitz, B., L. Beck, A. Huq, B. Wood, G. Fuchs, A. S. G. Faruque, and R. Colwell, 2000: Climate and infectious disease: Use of remote sensing for detection of Vibrio cholerae by indirect measurement. *Proceedings of the National Academy of Sciences*, **97**, 1438–1443.

Lowe, D., K. L. Ebi, and B. Forsberg, 2013: Factors increasing vulnerability to health effects before, during and after floods. *International Journal of Environmental Research and Public Health*, **10**, 7015–67, doi:10.3390/ijerph10127015.

Lutz, A. F., W. W. Immerzeel, A. Gobiet, F. Pellicciotti, and M. F. P. Bierkens, 2013: Comparison of climate change signals in CMIP3 and CMIP5 multi-model ensembles and implications for Central Asian glaciers. *Hydrology and Earth System Sciences*, **17**, 3661–3677, doi:10.5194/hess-17-3661-2013.

Lutz, A. F., W. W. Immerzeel, A. B. Shrestha, and M. F. P. Bierkens, 2014: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, **4**, 587–592, doi:10.1038/nclimate2237.

Mahmuduzzaman, M., Z. U. Ahmed, A. K. M. Nuruzzaman, and F. R. S. Ahmed, 2014: Causes of Salinity Intrusion in Coastal Belt of Bangladesh. *International Journal of Plant Research*, **4**, 8–13, doi:10.5923/s.plant.201401.02.

Maniruzzaman, K. and R. Mitra, 2005: Road Accidents in Bangladesh. *IATSS Research*, **29**, 71–73, doi: 10.1016/S0386-1112(14)60136-9.

Masood, M., F. Yeh, N. Hanasaki, and K. Takeuchi, 2015: Model study of the impacts of future climate change on the hydrology of Ganges - Brahmaputra - Meghna basin. *Hydrol. Earth Syst. Sci*, **19**, 747–770, doi:10.5194/hess-19-747-2015.

Matin, M. A., 1995: Environmental pollution and its control in Bangladesh. *Trends in Analytical Chemistry*, **14**, 468–473, doi: 10.1016/0165-9936(95)90807-Y.

Maussion, F., D. Scherer, T. Mölg, E. Collier, J. Curio, and R. Finkelnburg, 2014: Precipitation seasonality and variability over the Tibetan Plateau as resolved by the high Asia reanalysis. *Journal of Climate*, **27**, 1910–1927, doi:10.1175/JCLI-D-13-00282.1.

Meehl, G. A. and J. M. Arblaster, 2002: Indian Monsoon GCM Sensitivity Experiments Testing Tropospheric Biennial Oscillation Transition Conditions. *Journal of Climate*, **15**, 923–944.

Milly, P. C. D., R. T. Wetherald, K. a. Dunne, and T. L. Delworth, 2002: Increasing risk of great floods in a changing climate. *Nature*, **415**, 514–7, doi:10.1038/415514a.

Milojevic, A., B. Armstrong, M. Hashizume, K. McAllister, A. Faruque, M. Yunus, P. Kim Streatfield, K. Moji, and P. Wilkinson, 2012: Health effects of flooding in rural bangladesh. *Epidemiology*, **23**, 107–115, doi:10.1097/EDE.0b013e31823ac606.

Milojevic, A., B. Armstrong, S. Kovats, B. Butler, E. Hayes, G. Leonardi, V. Murray, and P. Wilkinson, 2011: Long-term effects of flooding on mortality in england and wales, 1994-2005: controlled interrupted time-series analysis. *Environ Health*, **10**, 11.

Mirza, M., 2011: Climate change, flooding in South Asia and implications. *Regional Environmental Change*, **11**, 95–107.

Mirza, M. M. Q., 1997: Hydrological changes in the Ganges system in Bangladesh in the post-Farakka period. *Hydrological Sciences*, **42**, 613–632, doi:10.1080/02626669709492062.

— 1998: Diversion of the ganges water at farakka and its effects on salinity in bangladesh. *Environmental Management*, **22**, 711–722, doi:10.1007/s002679900141.

— 2003a: The Choice of Stage-Discharge Relationship for the Ganges and Brahmaputra Rivers in Bangladesh. *Nordic Hydrology*, **34**, 321–342.

— 2003b: Three recent extreme floods in Bangladesh: A hydro-meteorological analysis. *Natural Hazards*, **28**, 35–64, doi:10.1023/A:1021169731325.

Mirza, M. M. Q., R. A. Warrick, and N. J. Ericksen, 2003: The Implications of Climate Change on Floods of the Ganges, Brahmaputra and Meghna Rivers in Bangladesh. *Climatic Change*, **57**, 287–318.

Mirza, M. Q., R. A. Warrick, N. J. Ericksen, and G. J. Kenny, 1998: Trends and persistence in precipitation in the Ganges , Brahmaputra and Meghna river basins. *Hydrological Sciences-Journal- des Sciences Hydrologiques*, **43**.

Mirza, R. A., M Monirul Qaderand Warrick, N. J. Ericksen, and G. J. Kenny, 2001: Are floods getting worse in the Ganges, Brahmaputra and Meghna basins? *Global Environmental Change Part B: Environmental Hazards*, **3**, 37–48, doi:10.1016/S1464-2867(01)00019-5.

Montanari, A., G. Young, H. Savenije, D. Hughes, T. Wagener, L. Ren, D. Koutsoyiannis, C. Cudennec, E. Toth, S. Grimaldi, G. Blschl, M. Sivapalan, K. Beven, H. Gupta, M. Hipsey, B. Schaefli, B. Arheimer, E. Boegh, S. Schymanski, G. D. Baldassarre, B. Yu, P. Hubert, Y. Huang, A. Schumann, D. Post, V. Srinivasan, C. Harman, S. Thompson, M. Rogger, A. Viglione, H. McMillan, G. Characklis, Z. Pang, and V. Belyaev, 2013: panta rhei - everything flows: Change in hydrology and society - the iahs scientific decade 2013 - 2022. *Hydrological Sciences Journal*, **58**, 1256–1275, doi:10.1080/02626667.2013.809088.

Moon, J.-H., Y. T. Song, and H. Lee, 2015: PDO and ENSO modulations intensified decadal sea level variability in the tropical Pacific. *Journal of Geophysical Research: Oceans*, **120**, 8229–8237, doi:10.1002/2015JC011139.

Morris, B. L., A. A. Seddique, and K. M. Ahmed, 2003: Response of the Dupi Tila aquifer to intensive pumping in Dhaka, Bangladesh. *Hydrogeology Journal*, **11**, 496–503.

Moslehuddin, A., S. Laizoo, and K. Egashira, 1997: Fertility status of bangladesh soils - a review. *Journal of the Faculty of Agriculture Kyushu University*, **41**, 257–267.

Mugade, U. R. and J. B. Sapkale, 2015: Influence of Aggradation and Degradation on River Channels : A Review. *International Journal of Engineering and Technical Research*, **3**, 209–212.

Nahar, Q., S. E. Arifeen, K. Jamil, and P. K. Streatfield, 2015: Causes of adult female deaths in Bangladesh: findings from two National Surveys. *BMC Public Health*, **15**, 911.

Nath, T. K., M. Inoue, and H. Myant, 2005: Small-scale agroforestry for upland community development: a case study from chittagong hill tracts, bangladesh. *Journal of Forest Research*, **10**, 443–452, doi:10.1007/s10310-005-0171-x.

Nelder, J. and R. Wedderburn, 1972: Generalized linear models. *Journal of the Royal Statistical Society, Series A*, **135**, 370–384.

Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Château, and R. Muir-Wood, 2007: Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates. Environment Working Papers No. 1, Organisation for Economic Co-operation and Development.

Niemeijer, D. and R. S. de Groot, 2008a: A conceptual framework for selecting environmental indicator sets. *Ecological Indicators*, **8**, 14 – 25, doi:http://dx.doi.org/10.1016/j.ecolind.2006.11.012.

— 2008b: Framing environmental indicators: moving from causal chains to causal networks. *Environment, Development and Sustainability*, **10**, 89–106, doi:10.1007/s10668-006-9040-9.

Original S functions written by Janet E. Heffernan with R port and R documentation provided by Alec G. Stephenson., 2016: *ismev: An Introduction to Statistical Modeling of Extreme Values*. R package version 1.41.
URL `https://CRAN.R-project.org/package=ismev`

Parveen, S. and I. M. Faisal, 2002: People versus Power: The Geopolitics of Kaptai Dam in Bangladesh. *International Journal of Water Resources Development*, **18**, 197–208, doi:10.1080/07900620220121756.

Patrício, J., M. Elliott, K. Mazik, K.-N. Papadopoulou, and C. J. Smith, 2016: DPSIR - Two Decades of Trying to Develop a Unifying Framework for Marine Environmental Management? *Frontiers in Marine Science*, **3**, 1–14, doi:10.3389/fmars.2016.00177.

Patt, A. G., M. Tadross, P. Nussbaumer, K. Asante, M. Metzger, J. Rafael, A. Goujon, and G. Brundrit, 2010: Estimating least-developed countries vulnerability to climate-related extreme events over the next 50 years. *Proceedings of the National Academy of Sciences*, **107**, 1333–1337, doi:10.1073/pnas.0910253107.

Patz, J. A., D. Campbell-Lendrum, T. Holloway, and J. A. Foley, 2005: Impact of regional climate change on human health. *Nature*, **438**, 310–7, doi:10.1038/nature04188.

Paul, B. G. and C. R. Vogl, 2011: Impacts of shrimp farming in Bangladesh: Challenges and alternatives. *Ocean and Coastal Management*, **54**, 201–211, doi:10.1016/j.ocecoaman.2010.12.001.

Paul, B. K., 1998: Coping with the 1996 Tornado in Tangail, Bangladesh: An Analysis of Field Data. *The Professional Geographer*, **50**, 287–301, doi:10.1111/0033-0124.00121.

Paul, B. K., H. Rashid, M. S. Islam, and L. M. Hunt, 2010: Cyclone evacuation in Bangladesh: Tropical cyclones Gorky (1991) vs. Sidr (2007). *Environmental Hazards*, **9**, 89–101, doi:10.3763/ehaz.2010.SI04.

Pelletier, J. D., B. Murray, J. L. Pierce, P. R. Bierman, D. D. Breshears, B. T. Crosby, M. Ellis, E. Foufoula-Georgiou, A. M. Heimsath, C. Houser, N. Lancaster, M. Marani, D. J. Merritts, L. J. Moore, J. L. Pederson, M. J. Poulos, T. M. Rittenour, J. C. Rowland, P. Ruggiero, D. J. Ward, A. D. Wickert, and E. M. Yager, 2015: Earth's Future Forecasting the response of Earth's surface to future climatic and land use changes : A review of methods and research needs Earth's Future. *Earth Future*, **3**, 220–251, doi:10.1002/2014EF000290.Received.

Peterson, R. E. and K. C. Mehta, 1981: Climatology of tornadoes of India and Bangladesh. *Archives for Meteorology, Geophysics, and Bioclimatology Series B*, **29**, 345–356, doi:10.1007/BF02263310.

Pethick, J. and J. D. Orford, 2013: Rapid rise in effective sea-level in southwest Bangladesh: Its causes and contemporary rates. *Global and Planetary Change*, **111**, 237–245, doi:10.1016/j.gloplacha.2013.09.019.

Pfeffer, W. T., J. T. Harper, and S. O'Neel, 2008: Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science (New York, N.Y.)*, **321**, 1340–3, doi:10.1126/science.1159099.

Pica-Ciamarra, U. and J. Otte, 2011: The Livestock Revolution: rhetoric and reality. *Outlook on Agriculture*, 1–23.

Pokharel, S., 2016: Lightning strikes kill 65 people in four days in Bangladesh. *CNN*, Available online: http://www.ddm.gov.bd/ (accessed on 13 June 2017).

Portes, A., 1998: Social capital: Its origins and applications in modern sociology. *Annual Review of Sociology*, **24**.

R Core Team, 2015: *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.
URL `https://www.R-project.org/`

Rabbani, G., A. Rahman, and N. Islam, 2010: Climate Change and Sea Level Rise: Issues and Challenges for Coastal Communities in the Indian Ocean Region Golam. *Coastal Zones and Climate Change*, D. Michel and A. Pandya, eds., The Henry L. Stimson Center, 17–29.

Rafiuddin, M., H. Uyeda, and M. N. Islam, 2010: Characteristics of monsoon precipitation systems in and around Bangladesh. *International Journal of Climatology*, **30**, doi:10.1002/joc.1949.

Rahman, M. M., V. R. Giedraitis, L. S. Lieberman, M. T. Akhtar, and V. Taminskien, 2013: Shrimp Cultivation with Water Salinity in Bangladesh: The Implications of an Ecological Model. *Universal Journal of Public Health*, **1**, 131–142, doi:10.13189/ujph.2013.010313.

Rahman, S., 2011: *Cost benefit and livelihood impacts of agroforestry in Bangladesh: Impacts of agroforestry in Bangladesh — Center for International Forestry Research*. Lambert Academic Publishing, Saarbruecken, 172 pp.

Rahman, S. and T. Ahmad, 2016: Bangladesh: Controversial New Law Regulating Work and Activities of Foreign NGOs. *Law Library of Congress*.

Rahman, S. and R. Parkinson, 2007: Productivity and soil fertility relationships in rice production systems, Bangladesh. *Agricultural Systems*, **92**, 318–333, doi:10.1016/j.agsy.2006.04.001.

Rana, M. M. P., 2011: Urbanization and sustainability: challenges and strategies for sustainable urban development in Bangladesh. *Environment, Development and Sustainability*, **13**, 237–256, doi:10.1007/s10668-010-9258-4.

Rasul, G. and G. B. Thapa, 2004: Sustainability of ecological and conventional agricultural systems in Bangladesh: an assessment based on environmental, economic and social perspectives. *Agricultural Systems*, **79**, 327–351, doi:10.1016/S0308-521X(03)00090-8.

Reazuddin and Team, 2006: Report: Banning Polyethylene Shopping Bags: A Step Forward to Promoting Environmentally Sustainable Development in Bangladesh. Technical report, Bangladesh Centre for Advanced Studiest, Dhaka, Bangladesh.

Red Cross, 2001: Bangladesh: Floods 2000 - Final Report. *International Federation of Red Cross and Red Crescent Societies*, **10**.

Ricepedia, 2014: Bangladesh. Basic Statistics. *Research Program on Rice. Global Rice Science Partnership*, Available online: ricepedia.org/bangladesh (accessed on 13 June 2017).

Rikiishi, K. and H. Nakasato, 2006: Height dependence of the tendency for reduction in seasonal snow cover in the Himalaya and the Tibetan Plateau region, 1966-2001. *Annals of Glaciology*, **43**, 369–377, doi:10.3189/172756406781811989.

Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrothra, S. Shakal, T. Bowman, and S. Ali Ibrahim, 2015: ARC3.2. Climate Change and Cities. Second Assessment Report of the Urban Climate Change Research Network. Summary for city leaders., Urban Climate Research Network.

Rupper, S. and G. Roe, 2008: Glacier changes and regional climate: A mass and energy balance approach. *Journal of Climate*, **21**, 5384–5401, doi:10.1175/2008JCLI2219.1.

Saha, A., S. Ghosh, A. S. Sahana, and E. P. Rao, 2014: Failure of CMIP5 climate models in simulating post-1950 decreasing trend of Indian monsoon. *Geophysical Research Letters*, **41**, 7323–7330, doi:10.1002/2014GL061573.

Saha, M. L., M. Khan, M. Ali, and S. Hoque, 2009: Bacterial load and chemical pollution level of the River Buriganga, Dhaka, Bangladesh. *Bangladesh Journal of Botany*, **38**, 87–91, doi: 10.3329/bjb.v38i1.5128.

Sarker, M. H., I. Huque, M. Alam, and R. Koudstaal, 2003: Rivers, chars and char dwellers of bangladesh. *International Journal of River Basin Management*, **1**, 61–80, doi:10.1080/15715124.2003.9635193.

Scharin, H., S. Ericsdotter, M. Elliott, R. K. Turner, S. Niiranen, T. Blenckner, K. Hyytiäinen, L. Ahlvik, H. Ahtiainen, J. Artell, L. Hasselström, T. Söderqvist, and J. Rockström, 2016: Processes for the sustainable stewardship of marine environments. *Ecological Economics*, **128**, 55–67, doi:10.1016/j.ecolecon.2016.04.010.

Scherler, D., B. Bookhagen, and M. R. Strecker, 2011: Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience*, **4**, 156–159, doi:10.1038/ngeo1068.

Schiermeier, Q., 2014: Holding back the tide. *Nature*, **508**, 164–166, doi:10.1136/bmj.297.6652.853.

Schleussner, C.-F., J. F. Donges, R. V. Donner, and H. J. Schellnhuber, 2016: Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proceedings of the National Academy of Sciences*, doi:10.1073/pnas.1601611113.

Schmidt, C. W., 2015: Delta subsidence: An imminent threat to coastal populations. *Environmental Health Perspectives*, **123**, A204–A209, doi:10.1289/ehp.123-A204.

Shahid, S., 2010: Rainfall variability and the trends of wet and dry periods in Bangladesh. *International Journal of Climatology*, **30**, 2299–2313, doi:10.1002/joc.2053.

— 2011: Impact of climate change on irrigation water demand of dry season Boro rice in northwest Bangladesh. *Climatic Change*, **105**, 433–453, doi:10.1007/s10584-010-9895-5.

Sharmila, S., S. Joseph, A. Sahai, S. Abhilash, and R. Chattopadhyay, 2015: Future projection of Indian summer monsoon variability under climate change scenario: An assessment from CMIP5 climate models. *Global and Planetary Change*, **124**, 62–78, doi:10.1016/j.gloplacha.2014.11.004.

Shi, Y. and S. Liu, 2000: Estimation on the response of glaciers in China to the global warming in the 21st century. *Chinese Science Bulletin*, **45**, 668–672, doi:10.1007/BF02886048.

Simmer, C., I. Thiele-Eich, M. Masbou, W. Amelung, H. Bogena, S. Crewell, B. Diekkrger, F. Ewert, H.-J. H. Franssen, J. A. Huisman, A. Kemna, N. Klitzsch, S. Kollet, M. Langensiepen, U. Lhnert, A. S. M. M. Rahman, U. Rascher, K. Schneider, J. Schween, Y. Shao, P. Shrestha, M. Stiebler, M. Sulis, J. Vanderborght, H. Vereecken, J. van der Kruk, G. Waldhoff, and T. Zerenner, 2015: Monitoring and modeling the terrestrial system from pores to catchments: The transregional collaborative research center on patterns in the soil-vegetation-atmosphere system. *Bulletin of the American Meteorological Society*, **96**, 1765–1787, doi:10.1175/BAMS-D-13-00134.1.

Singh, O., T. M. A. Khan, T. S. Murty, and M. S. Rahman, 2001: Sea Level Changes Along Bangladesh Coast in Relation to the Southern Oscillation Phenomenon. *Marine Geodesy*, **24**, 65–72, doi:10.1080/01490410120192.

Sirajul Islam, M., A. Brooks, M. S. Kabir, I. K. Jahid, M. Shafiqul Islam, D. Goswami, G. B. Nair, C. Larson, W. Yukiko, and S. Luby, 2007: Faecal contamination of drinking water sources of Dhaka city during the 2004 flood in Bangladesh and use of disinfectants for water treatment. *Journal of Applied Microbiology*, **103**, 80–7, doi:10.1111/j.1365-2672.2006.03234.x.

Sivapalan, M. and G. Blöschl, 2015: Time scale interactions and the coevolution of humans and water. *Water Resources Research*, **51**, 6988–7022, doi:10.1002/2015WR017896.

Sivapalan, M., M. Konar, V. Srinivasan, A. Chhatre, A. Wutich, C. A. Scott, and J. L. Wescoat, 2014: Earth' s Future Socio-hydrology : Use-inspired water sustainability science for the Anthropocene Earth' s Future. *Earth's Future*, **2**, 225–230.

Sivapalan, M., H. H. G. Savenije, and G. Blöschl, 2011: Socio-hydrology: A new science of people and water. *Hydrological Processes*, doi:10.1002/hyp.8426.

Smakhtin, V., 2001: Low flow hydrology: a review. *Journal of Hydrology*, **240**, 147 – 186, doi:10.1016/S0022-1694(00)00340-1.

Sober, Elliott, 1981: The principle of parsimony. *The British Journal for the Philosophy of Science*, **32**, 145–156.

Steckler, M. S., S. H. Akhter, and L. Seeber, 2008: Collision of the Ganges?Brahmaputra Delta with the Burma Arc: Implications for earthquake hazard. *Earth and Planetary Science Letters*, **273**, 367–378, doi:10.1016/j.epsl.2008.07.009.

Steckler, M. S., D. R. Mondal, S. H. Akhter, L. Seeber, L. Feng, J. Gale, E. M. Hill, and M. Howe, 2016: Locked and loading megathrust linked to active subduction beneath the indo-burman ranges. *Nature Geoscience*, **9**, 615–618, doi:10.1038/ngeo2760.

Steckler, M. S., S. L. Nooner, S. H. Akhter, S. K. Chowdhury, S. Bettadpur, L. Seeber, and M. G. Kogan, 2010: Modeling Earth deformation from monsoonal flooding in Bangladesh using hydrographic, GPS, and Gravity Recovery and Climate Experiment (GRACE) data. *Journal of Geophysical Research*, **115**, B08407, doi:10.1029/2009JB007018.

Stone, M., 1977: An asymptotic equivalence of choice of model by cross-validation and Akaike's criterion. *Journal of the Royal Statistical Society B*, **39**, 44–47.

Streatfield, P. K. and Z. A. Karar, 2008: Population challenges for Bangladesh in the coming decades. *Journal of Health, Population, and Nutrition*, **26**, 261–72.

Struck, M., C. Andermann, N. Hovius, O. Korup, J. M. Turowski, R. Bista, H. P. Pandit, and R. K. Dahal, 2015: Monsoonal hillslope processes determine grain size-specific suspended sediment fluxes in a trans-Himalayan river. *Geophysical Research Letters*, **42**, 2302–2308, doi:10.1002/2015GL063360.

Subramanian, V. and A. L. Ramanathan, 1996: *Nature of Sediment Load in the Ganges-Brahmaputra River Systems in India*, Springer Netherlands, Dordrecht. 151–168.

Sugimoto, J. D., A. B. Labrique, S. Ahmad, M. Rashid, A. A. Shamim, B. Ullah, R. D. Klemm, P. Christian, and K. P. West, 2011: Epidemiology of tornado destruction in rural northern Bangladesh: risk factors for death and injury. *Disasters*, **35**, 329–345, doi:10.1111/j.1467-7717.2010.01214.x.

Sunny, B. S., 2017: 1 dead, 28 injured from rice mill boiler explosion in Dinajpur. *Dhaka Tribune*, http://www.dhakatribune.com/bangladesh/nation/2017/04/20/rice-mill-explosion-dinajpur/ [2017/06/07].

Swain, A., 1996: Displacing the Conflict: Environmental Destruction in Bangladesh and Ethnic Conflict in India. *Journal of Peace Research*, **33**, 189–204, doi:10.1177/0022343396033002005.

Syvitski, J. P. M., A. J. Kettner, I. Overeem, E. W. H. Hutton, M. T. Hannon, G. R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, L. Giosan, and R. J. Nicholls, 2009: Sinking deltas due to human activities. *Nature Geoscience*, **2**, 681–686, doi:10.1038/ngeo629.

Tao, F. and Z. Zhang, 2013: Climate Change, High-Temperature Stress, Rice Productivity, and Water Use in Eastern China: A New Superensemble-Based Probabilistic Projection. *Journal of Applied Meteorology and Climatology*, **52**, 531–551.

Taylor, K. E., R. J. Stouffer, G. A. Meehl, K. E. Taylor, R. J. Stouffer, and G. A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, **93**, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Than, K., 2013: Bangladesh Building Collapse Due to Shoddy Construction. *National Geographic*, http://news.nationalgeographic.com/news/2013/13/130425-bangladesh-dhaka-building-collapse-world/ [2017/03/27].

The Guardian, 2013: Bangladesh factory collapse blamed on swampy ground and heavy machinery. *The Guardian*, https://www.theguardian.com/world/2013/may/23/bangladesh-factory-collapse-rana-plaza [2017/03/27].

Thiele-Eich, I., K. Burkart, and C. Simmer, 2015: Trends in Water Level and Flooding in Dhaka, Bangladesh and Their Impact on Mortality. *International Journal of Environmental Research and Public Health*, **12**, 1196–1215, doi:10.3390/ijerph120201196.

Troy, T. J., M. Konar, V. Srinivasan, and S. Thompson, 2015: Moving sociohydrology forward: a synthesis across studies. *Hydrology and Earth System Sciences*, **19**, 3667–3679, doi:10.5194/hess-19-3667-2015.

Uddin, R. and N. H. Huda, 2011: Arsenic poisoning in Bangladesh. *Oman Medical Journal*, **26**, 207, doi:10. 5001/omj.2011.51.

UN Department of Humanitarian Affairs, 1986: Bangladesh - Hail Storm/Tornado Apr 1986 UNDRO Information Reports 1-2. Technical report, UN Department of Humanitarian Affairs, Relief Web.

UN-Habitat, 2016: World Cities Report 2016. Technical report.

United Nations, 2007: World Urbanization Prospects: The 2005 Revision. CD-ROM Edition- Data in Digital Form, United Nations Population Division, Department of Economic and Social Affairs, New York, NY, USA.

United Nations Population Division, 2017: World population prospects. Technical report, United Nations, Department of Economic and Social Affairs, New York.

van Geen, A., Y. Zheng, Z. Cheng, Y. He, R. Dhar, J. Garnier, J. Rose, A. Seddique, M. Hoque, and K. Ahmed, 2006: Impact of irrigating rice paddies with groundwater containing arsenic in Bangladesh. *Science of The Total Environment*, **367**, 769–777, doi:10.1016/j.scitotenv.2006.01.030.

Vineis, P., Q. Chan, and A. Khan, 2011: Climate change impacts on water salinity and health. *Journal of Epidemiology and Global Health*, **1**, 5–10, doi:10.1016/j.jegh.2011.09.001.

Wada, Y., L. P. H. Van Beek, F. C. Sperna Weiland, B. F. Chao, Y. H. Wu, and M. F. P. Bierkens, 2012: Past and future contribution of global groundwater depletion to sea-level rise. *Geophysical Research Letters*, **39**, 1–6, doi:10.1029/2012GL051230.

Wagener, T., M. Sivapalan, P. a. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson, 2010: The future of hydrology: An evolving science for a changing world. *Water Resources Research*, **46**, n/a–n/a, doi:10.1029/2009WR008906.

Wassmann, R., S. Jagadish, S. Heuer, A. Ismail, E. Redona, R. Serraj, R. Singh, G. Howell, H. Pathak, and K. Sumfleth, 2009a: Chapter 2: Climate Change Affecting Rice Production. *Advances in Agronomy*, 59–122.

Wassmann, R., S. Jagadish, K. Sumfleth, H. Pathak, G. Howell, A. Ismail, R. Serraj, E. Redona, R. Singh, and S. Heuer, 2009b: Chapter 3: Regional Vulnerability of Climate Change Impacts on Asian Rice Production and Scope for Adaptation. *Advances in Agronomy*, 91–133.

Webster, P. J., V. O. Magaña, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. *Journal of Geophysical Research: Oceans*, **103**, 14451–14510, doi:10.1029/97JC02719.

Wesselink, A., M. Kooy, and J. Warner, 2017: Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. *Wiley Interdisciplinary Reviews: Water*, **4**, e1196, doi:10.1002/wat2.1196.

Whitehead, P. G., E. Barbour, M. N. Futter, S. Sarkar, H. Rodda, J. Caesar, D. Butterfield, L. Jin, R. Sinha, R. Nicholls, and M. Salehin, 2015: Impacts of climate change and socio-economic scenarios on flow and water quality of the Ganges, Brahmaputra and Meghna (GBM) river systems: low flow and flood statistics. doi:10.1039/c4em00619d.

WHO, 1946: The Constitution. World Health Organization, Adopted by International Health Conference.

World Bank, 2017: World Bank DataBase. `http://databank.worldbank.org`, online; Accessed: 20 February 2017.

World Meteorological Organization, 2017: Global Weather & Climate Extremes Archive. `https://wmo.asu.edu`, online; Accessed: 20 February 2017.

World Nuclear Association, 2017: Nuclear Power in Bangladesh. Http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/bangladesh.aspx [2017/06/06].

World Wide Fund For Nature, 2001: Dams accused of role in flooding: Research Paper: "Dams and Floods". *Relief Web*, http://reliefweb.int/report/bangladesh/dams-accused-role-flooding-research-paper-dams-and-floods [2017/06/07].

Xu, J., R. E. Grumbine, A. Shrestha, M. Eriksson, X. Yang, Y. Wang, and A. Wilkes, 2009: The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods. *Conservation Biology*, **23**, 520–530, doi:10.1111/j.1523-1739.2009.01237.x.

Yamane, Y., T. Hayashi, M. Kiguchi, F. Akter, and A. M. Dewan, 2013: Synoptic situations of severe local convective storms during the pre-monsoon season in Bangladesh. *International Journal of Climatology*, **33**, 725–734, doi:10.1002/joc.3460.

Yardley, J., 2013: Bangladesh Pollution, Told in Colors and Smells. *The New York Times*, http://www.nytimes.com/2013/07/15/world/asia/bangladesh-pollution-told-in-colors-and-smells.html [2017/06/06].

Yeh, S.-W., J.-S. Kug, B. Dewitte, M.-H. Kwon, B. Kirtmann, and F.-F. Jin, 2009: El Niño in a changing climate. *Nature*, **461**, 511–514, doi:10.1038/nature08316.

Yin, P. and X. Fan, 2001: Estimating R2 Shrinkage in Multiple Regression: A Comparison of Different Analytical Methods. *The Journal of Experimental Education*, **69**, 203–224, doi:10.1080/00220970109600656.

Yu, W., M. Alam, A. Hassan, A. S. Khan, A. Ruane, C. Rosenzweig, D. Major, and J. Thurlow, 2010: *Climate change risks and food security in Bangladesh*. earthscan.

Zeileis, A. and G. Grothendieck, 2005: zoo: S3 infrastructure for regular and irregular time series. *Journal of Statistical Software*, **14**, 1–27, doi:10.18637/jss.v014.i06.

Zhang, Y., P. Bi, J. E. Hiller, Y. Sun, and P. Ryan, 2007: Climate variations and bacillary dysentery in northern and southern cities of China. *Journal of Infection*, **55**, 194–200.

Zhao, L., R. Ding, and J. C. Moore, 2014: Glacier volume and area change by 2050 in high mountain Asia. *Global and Planetary Change*, **122**, 197–207, doi:10.1016/j.gloplacha.2014.08.006.

— 2016: The High Mountain Asia glacier contribution to sea-level rise from 2000 to 2050. *Annals of Glaciology*, **57**, 223–231, doi:10.3189/2016AoG71A049.

Zuo, J., S. Pullen, J. Palmer, H. Bennetts, N. Chileshe, and T. Ma, 2015: Impacts of heat waves and corresponding measures: a review. *Journal of Cleaner Production*, **92**, 1–12, doi:10.1016/j.jclepro.2014.12.078.

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