

# **Climate Risks and Solutions: Adaptation Frameworks for Water Resources Planning, Development and Management in South Asia**

## **Background Paper 1**

### **Review of Climate Change Science, Knowledge and Impacts on Water Resources in South Asia**

**Guillaume Lacombe, Pennan Chinnasamy and Alan Nicol**



## About this Report

This is one of three papers commissioned by the World Bank and jointly implemented with the International Water Management Institute (IWMI) as part of the first phase of a two-phase Technical Assistance (TA) project to assess the opportunities for adaptation to climate change in the water sector in seven countries in South Asia (Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka). The TA – Climate Risks and Solutions: Adaptation Frameworks for Water Resources Planning, Development and Management in South Asia – is funded by the South Asia Water Initiative (SAWI), a partnership of the governments of Australia, Norway and the United Kingdom.

**Background Paper 1** (this paper) describes the scientific understanding of predicted impacts of climate change on water resources and associated risks.

Lacombe, G.; Chinnasamy, P.; Nicol, A. 2019. *Review of climate change science, knowledge and impacts on water resources in South Asia. Background Paper 1*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 73p. (Climate Risks and Solutions: Adaptation Frameworks for Water Resources Planning, Development and Management in South Asia). doi: 10.5337/2019.202

<http://www.iwmi.cgiar.org/Publications/Other/PDF/sawi-paper-1.pdf>

**Background Paper 2** assesses the suitability of the enabling policy frameworks (existing policy, legislation, strategies and plans) for adapting to the impacts of climate change.

Davis, R.; Hirji, R. 2019. *Review of water and climate change policies in South Asia. Background Paper 2*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 120p. (Climate Risks and Solutions: Adaptation Frameworks for Water Resources Planning, Development and Management in South Asia). doi: 10.5337/2019.203

<http://www.iwmi.cgiar.org/Publications/Other/PDF/sawi-paper-2.pdf>

**Background Paper 3** assesses the financial, economic, and institutional landscape for adapting to climate change.

Suhardiman, D.; de Silva, S.; Arulingam, I.; Rodrigo, S.; Nicol, A. 2019. *Review of water and climate adaptation financing and institutional frameworks in South Asia. Background Paper 3*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 110p. (Climate Risks and Solutions: Adaptation Frameworks for Water Resources Planning, Development and Management in South Asia). doi: 10.5337/2019.204

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Lacombe, G.; Chinnasamy, P.; Nicol, A. 2019. *Review of climate change science, knowledge and impacts on water resources in South Asia. Background Paper 1*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 73p. (Climate Risks and Solutions: Adaptation Frameworks for Water Resources Planning, Development and Management in South Asia). doi: 10.5337/2019.202

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*Front cover photograph:* A scientist measuring the water collected in a pond created under the Underground Taming of Floods for Irrigation (UTFI) approach in Jiwai Jadid village, Rampur District, Uttar Pradesh, India (*photo:* Prashanth Vishwanathan/IWMI).

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The first phase was implemented under the overall guidance of Dr. Rafik Hirji (formerly Senior Water Resources Specialist, Task Team Leader, World Bank) and Dr. Alan Nicol (Strategic Program Leader - Promoting Sustainable Growth, IWMI), who led the team from IWMI. The background papers were presented and reviewed at the Regional Conference on Risks and Solutions: Adaptation Frameworks for Water Resources Planning, Development and Management in South Asia, which was held in Colombo, Sri Lanka, on July 12-13, 2016. This regional conference was attended by 65 national, regional and international climate change and water resources experts, including over 20 representatives of governments in the region.

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## ACRONYMS AND ABBREVIATIONS

amsl	Above mean sea level
APHRODITE	Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation
AR4	Fourth Assessment Report of the IPCC
AR5	Fifth Assessment Report of the IPCC
cm	Centimeter
CMIP5	Coupled Model Intercomparison Project Phase 5
CO <sub>2</sub>	Carbon dioxide
ENSO	El Niño Southern Oscillation
GBM	Ganges-Brahmaputra-Meghna river system
GCM	General circulation model
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographic Information System
GLOF	Glacial lake outburst flood
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
HKH	Hindu Kush Himalayan region
IPCC	Intergovernmental Panel on Climate Change
ICESat-2	Ice, Cloud and land Elevation Satellite-2
InSAR	Interferometric Synthetic Aperture Radar
km <sup>2</sup>	Square kilometer
km <sup>3</sup>	Cubic kilometer
Mha	Million hectares
mm	Millimeter
Mm <sup>3</sup>	Million cubic meters
MW	Megawatt
NASA	National Aeronautics and Space Administration
NGO	Nongovernmental organization
RCP	Representative Concentration Pathway
SAR	Synthetic Aperture Radar
SAWI	South Asia Water Initiative
SMAP	Soil Moisture Active Passive
SPHY	Spatial Processes in Hydrology
SST	Sea surface temperature
SWOT	Surface Water and Ocean Topography
TRMM	Tropical Rainfall Measuring Mission

*Note:* All dollar amounts stated in the report are US dollars.

## EXECUTIVE SUMMARY

This report reviews the status of water resources and climate trends, and their expected impacts on water-related hazards and associated risks in South Asia, one of the world's regions most vulnerable to climate change. The monsoon-driven climate combines intense rainfall generating devastating floods that alternate with extensive dry periods. Both these affect densely populated areas prone to floods that become water scarce during droughts because irrigation infrastructure is weak.

Half the region is drained by two transboundary river basins: the Ganges-Brahmaputra-Meghna (GBM) and the Indus. The GBM Basin is supplied mainly by monsoonal rains. About 20-40% of the water resources in the Ganges River Basin are used for irrigation, while the Brahmaputra and Meghna rivers remain largely unexploited as they flow through India. The Indus includes some of the highest mountain ranges and the largest area of nonpolar perennial ice cover in the world.

The availability of water resources within South Asian countries depends on a combination of climate, topographical, land-use and socioeconomic factors. The contribution of surface water entering each country to the total renewable water resources ranges from very low (as in Bhutan) to more than 90% (as in Bangladesh, located in the GBM Delta). Per capita water resources are scarce in India and Pakistan and are much more abundant in Bangladesh, Bhutan and Nepal. These national averages hide disparities within the countries.

Groundwater is a critical resource for all sectors, but mainly for agriculture (dry-season irrigation). Alluvial deposits in the floodplain of the largest rivers (such as the densely populated floodplains of the GBM and Indus) exhibit high yield. Recharge rates are mainly due to either the rainfall infiltration (up to 300 mm/year in the GBM Delta in Bangladesh) or stream water percolation (Indus in India and Pakistan). In contrast, hard rock aquifers store groundwater in deep fissures that are generally less accessible and provide lower water yields because of lower recharge rates (such as mountainous areas in Bhutan and Nepal).

Water quality is a major problem exacerbated by climate change. In the Ganges, risks of pathogenic contaminations increase with higher temperature and increased hydrologic extremes. Water quality is usually higher in the upper parts of the large river basins, due to lower population densities generating less pollution than in the lower flat deltaic regions (such as the Plain of Dhaka). However, dangerous concentrations of natural contaminants such as arsenic and fluoride exist in many upstream areas. While water quality is high in the upstream Indus and its tributaries, effluents from agricultural drainage and wastewater from cities and industries seriously affect water quality downstream. Salinity is an additional problem in more than 60% of the area of the Indus irrigation system.

Total water withdrawals in South Asia represent about one-quarter of the available renewable freshwater resources. This fraction varies from about 5% (Bangladesh, Bhutan, Nepal) to 75% (Pakistan). While water is mainly used for agricultural purposes, domestic water demand is increasing, driven by socioeconomic and demographic changes. Groundwater is growing in importance as a resource, accounting for 40% of total water use across South Asia but around 80% in Bangladesh (where surface water, though abundant, is commonly polluted). Groundwater has become the mainstay of irrigated agriculture over much of Bangladesh, India, and in some provinces of Nepal and Pakistan, often inducing problems of over-abstraction, and natural and anthropogenic contamination.

South Asia is a hot spot of water-related risks, accounting for some 40% of natural disasters recorded globally. Major water-related risks include: floods (flash floods, riverine floods and coastal floods) and droughts; landslides and erosion, especially in mountainous and semiarid areas where soils are exposed to intense rain events; sedimentation and siltation, which reduce groundwater recharge and water storage capacity, thus limiting dry-season irrigation and hydropower production; intrusion of saltwater into inland water systems due to sea-level rise and/or reduction of river streamflow; and diseases caused by water pollution enhanced by modified surface water and groundwater fluxes. The magnitude, frequency and seasonality of these water-related risks are altered in different ways by the changing climate.

Anticipating the effect of climate change on these water-related risks requires, first, an understanding of future climate trends. Unlike rainfall projections, which are characterized by high uncertainties,

trends in temperature are expected to be more homogeneous spatiotemporally. The smallest increases in temperature are likely to occur along the coasts of Bangladesh, southern India and Sri Lanka. Greater increases will be observed at higher latitudes in Afghanistan, Bhutan, northern India, Nepal and Pakistan. Compared to the twentieth century, average annual temperatures could rise by more than 2 °C in South Asia by the middle of the twenty-first century and exceed 3 °C by the late twenty-first century under a high-emissions scenario.

Temperature increase in the Indo-Pacific Oceans is expected to strengthen the monsoon due to higher evaporation rates from the ocean and an increase in moisture supply to the continent. However, rainfall projections remain uncertain over South Asia because of difficulties in modelling the complex atmospheric dynamics of the monsoon. Some changes are worth highlighting, even though they have low statistical insignificance ( $p\text{-value} > 0.1$ ). According to the Fifth Phase of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Representative Concentration Pathway (RCP) 4.5 intermediate emissions scenario, Bangladesh, Bhutan, India and Sri Lanka will be exposed to a 10% increase in annual rainfall by the end of the twenty-first century, with greater statistical significance in Sri Lanka (for more information on CMIP5 and RCP, see Box 4.1 in Chapter 4). The greatest increases in annual rainfall, reaching 20%, are likely to happen in southwest India and southern Pakistan. In contrast, rainfall is likely to decrease by about 10% in Afghanistan and Nepal. An earlier onset of the Asian monsoon is expected, according to the most reliable projections.

Global mean sea level will continue to rise during the twenty-first century, with rates likely to exceed those observed during the past three decades. Compared to the period 1986-2005, and under a low emissions scenario, a global rise of 26-55 cm is expected by the end of the twenty-first century, and up to 1 m under the high emissions scenario. An increased intensity of tropical cyclones and associated storm surges is expected to worsen the damage caused by sea-level rise.

In the GBM, combined changes in glacier, seasonal snow extent and precipitation will have little effect on the system hydrology. In the Indus Basin, hydrological effects will vary depending on elevation and associated dominant regimes (glacial, nival or pluvial). At low elevations where the pluvial regime of the monsoon dominates, changes in rainfall patterns will produce more intense runoff and floods, which are expected to increase in frequency and intensity. An anticipated earlier onset of the monsoon is expected to shift the flood pulse toward an earlier date in the year. At middle altitudes, summer runoff is positively correlated with winter precipitation and negatively correlated with summer temperature (due to snow sublimation). Both are expected to increase, resulting in uncertain direction in future flow change. Above 5,000 m, summer runoff is positively correlated with summer temperature, but not correlated with precipitation of the preceding winter. Total runoff is likely to increase initially but, as glacier masses shrink, it will ultimately fall sharply. However, in some areas (such as the Karakoram), summer temperatures are currently falling. The combination of these trends suggests a response to climate change in glacial regimes of the Upper Indus Basin that differs from the rest of the world. Trends in glacier melt may also be affected by changes in their albedo (reflectance or optical brightness) induced by growing black carbon emissions from China and India.

Climate change is exacerbating all water-related risks. More intense and concentrated rainfall generates sharper and more destructive flash floods, especially in mountainous areas (Afghanistan, northern Bangladesh, Bhutan, northern India, Nepal, northern Pakistan, Sri Lanka), and more erosion and downstream siltation (especially in semiarid areas such as Afghanistan, northern India and Pakistan), with loss of water storage capacity and reduced groundwater recharge (due both to altered rainfall patterns and siltation of water bodies). Temperature rise is also inducing complex changes. Greater snowmelt and ice melt increase the risk of glacial lake outburst floods (GLOFs) (e.g. in the glacial regions of Bhutan, India, Nepal and Pakistan), while earlier flood peaks in the year (springtime) in snow-fed/ice-fed rivers (such as the Indus) do not match the peak demand for irrigation water in the summertime, compromising food security. Meanwhile, the water demand for certain crops is rising under a warmer environment. Greater evaporation losses from surface water reservoirs and reduced groundwater recharge due to increased siltation in alluvial plains both exacerbate the water deficit for such crops. Crop yield may decline in areas

that are already warm, due to excessive heat. Sea-level rise, combined with more intense and frequent cyclones, is inducing destructive coastal flooding (especially in low-lying and densely populated areas such as Bangladesh) and salt contamination of coastal aquifers (as in Sri Lanka). Prolonged droughts are affecting all the countries during the dry season, especially where food demand is rising in relation to population growth and economic development. Semiarid and arid zones (such as Afghanistan, northwest India and Pakistan) are the most vulnerable to meteorological and hydrological droughts, worsened by glacier melting in their upstream parts, reduced groundwater recharge and reservoir siltation. These factors affect not only agriculture but also industrial and domestic water uses.

Several anthropogenic factors are exacerbating water-related risks. Unsustainable rates of pumping exceeding recharge rates (mainly in Bangladesh, India and Pakistan) are threatening groundwater availability and quality. Land-use changes, especially in mountainous areas, are accelerating erosion, reducing water infiltration and groundwater recharge, and increasing the risk of floods and downstream siltation.

Despite significant efforts to monitor water resources, several knowledge gaps remain about how much water is available and how it is distributed (Box ES.1). These gaps stem mainly from limitations in the management of data collection networks, the limited number of sensors deployed around South Asia and, in some cases, the unwillingness of government agencies to share data. The maintenance of hydrometeorological stations tends to be neglected in many countries, especially in remote and high-altitude areas or regions prone to political conflict. Even though groundwater contamination is occurring in many parts of South Asia, current knowledge on the distribution of contaminants is still limited due to the lack of monitoring, especially of deep aquifers. Overall, satellite technology is now enabling the measurement of total surface water and groundwater volumes and its various components, as well as monitoring how these amounts change over time, but spatiotemporal resolution remains limited.

**Box ES.1. Knowledge gaps about the availability and distribution of water in South Asia under climate change.**

Addressing the water-related risks discussed here would involve a range of interventions.

Reduction of climate-related risks requires accurate information and understanding of how the quality and quantity of water vary spatiotemporally, and which drivers affect these variations. The understanding of several processes needs to be improved:

- Changes in glacier and snow mass balances, especially in the Indus Basin.
- Role of the atmospheric brown cloud in climate change.
- Distribution of groundwater contaminants, especially in deep aquifers.
- Groundwater-surface water linkages in the Indo-Gangetic Basin.
- Dynamics and causes of land subsidence in major river deltas in the context of sea-level rises.

At the local level, simple management approaches are not systematically adopted, though they could reduce risks associated with floods, droughts and contaminated water. These approaches include agricultural water-saving strategies, flood preparedness and precautions against contaminations by polluted water. Several factors hinder these improvements:

- Insufficient number and lack of maintenance of monitoring stations.
- Restricted access to data by many governments.
- Disconnect between government officials, local residents and scientists.
- In some cases, the limited capacity for data analysis and forecasting.

Coping with droughts requires more efficient water usage, a better understanding of hydrometeorological processes that control the variability of water resources over time and space, improved models to predict droughts, and effective water supply infrastructure to divert and store water. From a data and knowledge management perspective, coping with floods requires mapping flood-prone areas, improving forecasting to strengthen preparedness of exposed populations, and strengthening communication to reduce risks to populations. Early warning systems aim to provide time for exposed populations to take appropriate actions to minimize damage and casualties caused by droughts, floods and landslides. Community-centered approaches must be prioritized (see Box ES.2). Choices about policies and modes of implementation for various development options need to be based on an improved understanding of environment potentials and limits, and of perceived needs. Closing the knowledge gap will require structural and technical improvements in data collection and analysis. It will also require enhancements in the ability to evaluate and address the crucial questions about policies and implementation.

Box ES.2 presents some recommendations along these lines.

### **Box ES.2. Recommendations.**

Improved preparedness against the risks of floods, water shortages and water contamination requires a range of structural and non-structural responses.

#### **Improving resilience to droughts**

Solutions include more parsimonious water use, better understanding of hydrometeorological processes, more powerful models to predict droughts, and sound selection of sites and structures to store water. Steps to improve water-use efficiency and productivity include reducing water losses due to leakage from irrigation canals, evaporation from soils and reservoirs, and deep percolation from the root zone. To attain these objectives, it is necessary to better disseminate knowledge from research institutions through agricultural extension services to farmers, and implement more water-efficient agricultural policies. At the plot level, drip irrigation, soil mulching and soil amendments are options to reduce water losses through evaporation and percolation. Water-use efficiency should also be considered at the scale of transboundary river basins. Water should be shared between countries (between India and Pakistan in the Indus Basin; and between India and Bangladesh in the GBM). In the Hindu Kush Himalayas, most of the hydropower barrages are run-of-the-river types with limited storage capacity. With the reduction or total disappearance of glaciers and snow that provide storage to sustain dry-season flows during the summer, more artificial storage capacity will be required to buffer against greater seasonal variations in river flows. Improved management of upstream land use should help reduce siltation in downstream reservoirs.

#### **Improving flood preparedness**

While the mapping of flood-prone areas can yield insights on how to limit vulnerable settlements in exposed areas, forecasting floods improves the preparedness of exposed populations. Mapping flood-prone areas requires collecting data on climate, hydrology, topography, geology, land cover, soil and satellite imageries of vulnerable infrastructure. Hydrological models predict and forecast the extent, magnitude and frequency of future floods. Early warning systems aim to provide time for the exposed population to take appropriate actions to minimize flood-induced damages and possible casualties. Forecasting involves the conversion of data into forecasts (using meteorological and hydrological models) that are transmitted to decision makers, who then release warnings for

(Continued)

**Box ES.2. Recommendations. (continued)**

local authorities to take appropriate actions. Early warning systems generally operate at the scale of watersheds, while action units follow administrative boundaries. Improving the dissemination of forecasts is required to precisely identify the path of warning from forecasters to persons responsible for actions. One way to reach this goal is to encourage sharing of information, especially in border areas where international cooperation is required to establish evacuation plans. Approaches centered on village communities should be prioritized as they are low-cost, effective and relevant to local conditions in flood-prone areas.

**Combining short- and long-term approaches**

In the short term, efforts to integrate climate adaptation and to reduce disaster risk will help mitigate and withstand shocks to human security and economic development, and minimize the costly recovery process. Support for effective disaster relief and recovery needs to continue, along with proactive efforts to reduce risk, such as integrating comprehensive risk assessments and risk-reduction measures into the national economic and development policy. In the longer term, governments, businesses and communities need to prepare for different and more intense climate impacts and extreme events. Measures may include providing adequate infrastructure or services, and mainstreaming climate change considerations into the planning processes.





# Chapter 1. Introduction

## Importance of Water to Key Sectors

The seven countries in South Asia considered in this study (Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka) are home to 23.7% of the global population, but contain only about 4.6% of the global annual renewable water resources, which are unevenly distributed between countries and river basins.<sup>1</sup> Except for Bhutan and Nepal, per capita water availability is below the world average and continues to decline as populations increase. The impacts in many places are dramatic, with rapidly declining groundwater levels and degradation in water quality causing severe health issues.

More than 90% of all water abstracted in South Asia is used by the agriculture sector, in comparison to 70% globally. Sixty percent (60%) of agricultural water uses in South Asia rely on surface water and 40% on groundwater. Meanwhile, the contribution of the agriculture sector to the gross domestic product (GDP) continues to decline across the region, despite a high proportion of the workforce and total population directly depending on agriculture for their livelihoods (FAO 2016). A small but increasingly important portion of available water is used to meet domestic needs and the growing industrial sector. Increasing demand for hydropower is shaping the way the upper reaches of major river systems in South Asia are being developed and managed. A combination of growing demand for water resources and declining quality is exerting severe pressures on ecosystems in the region, particularly in downstream parts of basins. This is seriously impairing the provision of ecosystem services (such as environmental flows) and species biodiversity, which are vulnerable to changes in flow seasonality and climate patterns.

## Climate Risks

South Asia faces many interrelated climate risks. The frequency and intensity of floods and droughts may rise (associated with increasing water scarcity). Erosion may intensify because of changes in rainfall patterns and land cover (possibly increasing or decreasing groundwater recharge). Sedimentation and siltation may reduce groundwater recharge and water storage capacities (as a result of the interaction of land-use changes and hydrological cycles). Saltwater may intrude into inland water systems due to sea-level rise and a reduction in river system outflows. Water quality may be degraded through more intensive usage as a result of changes in water availability, access and use, as well as by modified glacier hydrology controlled by changes in climate (rainfall, temperature, solar radiation, aerosol concentrations) and by micro/macro particle deposition influencing albedo (reflectance or optical brightness of the snowpack) and melting rates.

Given the diversity and complexity of the issues and challenges in South Asia, an adaptive water resources management approach is recommended. A foundation for such a response is a better understanding of climate-related risks, the identification of knowledge gaps, and the development of adaptation frameworks for the water sector.

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<sup>1</sup> These percentages are based on the South Asia and global population figures of 1.744 billion and 7.349 billion, respectively (UN 2015), and the following figures from the AQUASTAT database (FAO 2016): 1,982 km<sup>3</sup> of internal annual renewable water resources in South Asia; 42,810 km<sup>3</sup> of global annual renewable water resources.

## **The Need for Flexible Adaptation to Climate Change and Water Resources Management**

The ongoing global warming resulting from an increased concentration of greenhouse gases (GHGs) in the atmosphere has profound impacts on the hydrological cycle through a number of mechanisms — increasing evaporation losses, seawater warming, and changing patterns and severity of weather events. Their effects on the water cycle have massive implications for human systems (social and economic) and the agroecosystems on which populations depend for food security and livelihoods (IPCC 2014, Assessment Box SPM.2 Table 1).

These impacts are not necessarily negative; climate change can also have positive consequences such as a prolonged growing season and a higher yield (Singh et al. 2014). Overall, however, South Asia is expected to be negatively affected from climate change in numerous ways as discussed in this report. Despite a significant level of uncertainty in the predicted effects of climate change, some statistically significant trends are already being observed and anticipated to continue in the future (e.g., sea-level rise, global warming and melting of glaciers). Required management responses include water storage development, greater efficiency in crop water use, and more effective early warning systems against climatic and hydrologic extremes such as landslides. Where other climate trends are more uncertain, it is important that particular management responses do not “lock in” approaches that may not provide the flexibility required to respond to future unanticipated consequences of (climate) change across sectors. Chosen interventions should be sufficiently flexible to deliver maximum benefits under a range of conditions rather than being designed for what are thought to be the “most likely” future conditions.

### **Objective of the Report**

The South Asia Water Initiative (SAWI) is designed to support countries in improving and deepening transboundary dialogue, enhancing the knowledge base of basin and water resources, strengthening water institutions, and backing investments that lead to sustainable, fair and inclusive development. This report contributes to the SAWI objectives of building knowledge, tools and capacity across the region to assist governments in adapting to emerging climate challenges in the water sector. Envisaged support includes the development of effective policy frameworks as well as practical planning, development and management actions that highlight and address the need for adaptation.

This is one of three reports commissioned by the World Bank to assess opportunities for adaptation to climate change in South Asia. It summarizes the scientific understanding of predicted impacts of climate change on water resources and associated risks (see Box ES.2). Specifically, this report provides a synthesis of the state-of-the-art knowledge on climate trends and their expected impacts on climate-related hazards and associated risks. It also identifies knowledge gaps and priorities to improve knowledge in order to anticipate climate-related disasters more effectively and to plan for greater adaptation/protection.

The report is based on a desk study of water resources and climate change documents available on government websites and the websites of international agencies and nongovernmental organizations (NGOs), together with analyses and critiques of water resources, climate change and related risk assessments published in the academic literature. It relies on publications available online in English and, therefore, does not consider information published in local languages.

### **Structure of the Report**

This report has six chapters. *Chapter 2* briefly describes the climate, surface water and groundwater resources, and water uses in South Asia, focusing on transboundary river basins, and differentiating natural climate variability from anthropogenic climate change. It concludes by reviewing water and climate information that is key to the planning, operation and management of water resources. *Chapter 3* examines the main

climate-related risks in South Asia. *Chapter 4* summarizes existing knowledge on historical and projected trends in rainfall, temperature and sea level, and reviews available tools for climate projections, their limitations and possible solutions to cope with uncertainties. *Chapter 5* explores the exacerbating effects of climate change on risk levels. *Chapter 6* concludes by identifying gaps in current knowledge and suggesting recommendations to improve knowledge, understanding and anticipation of climate-related disasters.

This report adopts the most common definitions of the terms hazard, exposure, risk, vulnerability and resilience (Box 1.1).

#### **Box 1.1. Definitions.**

*Hazard* refers to a physical phenomenon that has the potential to cause damage and losses to human and natural systems (UNISDR 2009; IPCC 2014).

*Exposure* represents the presence of the elements at risk (e.g., buildings, infrastructure, environment) that could be adversely affected. In terms of exposure to climate change, Füssel and Klein (2006) defined exposure as “the nature and degree to which a system is exposed to significant climatic variations” and “the sensitivity of a system denotes the [...] dose-response relationship between its exposure to climatic stimuli and the resulting impacts.”

*Risk* is “the combination of the probability of an event and its consequences.” (IPCC 2007). Thus, risk measures the extent of the expected loss from climate change.

*Vulnerability* measures the degree to which geophysical, biological and socioeconomic systems are susceptible to, and unable to cope with, the adverse impacts of climate change (IPCC 2007).

*Resilience* describes the ability of a system, including the management systems, to adapt to the impacts of climate change without excessive harm. Resilience is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters to improve future protection and risk-reduction measures.



## Chapter 2. Climate and Water Resources

This chapter provides an overview of the climate, water resources, water uses and water management in each country of South Asia considered in this study. Box 2.1 opens the discussion by explaining the distinctions between natural climate variability and man-made climate change.

### **Box 2.1. Natural climate variability and climate change induced by humans.**

Natural climate variability and human-induced climate change are sometimes confused. This box explains these concepts and their implications for South Asia's water resources.

*Climate variability* describes natural variability of factors such as precipitation over time and space in scales beyond that of individual weather events. The familiar sequence of a monsoonal rainy season starting in April and continuing into May followed by a dry winter season starting between October and December is an example of natural seasonal variability across most of South Asia. This climate pattern is also characterized by spatial variability. The southwestern parts of South Asia are, typically, the first to receive the monsoonal rains coming from the Arabian Sea and the Bay of Bengal. The climate also varies considerably between years. Some of the natural year-to-year climate variability results from anomalies in the sea surface temperature (SST) of the tropical Pacific Ocean related to the El Niño Southern Oscillation (ENSO) (Kumar et al. 2006). Over the course of several decades, monsoonal variations are connected to the Atlantic oscillation of the related SST (Kucharski et al. 2009). While not all multidecadal cycles in climate time series are well understood (such as the Hurst phenomenon; see Koutsoyiannis 2003), the conventional practice has been to use a reference period of about 30 years to characterize the variability of the climate in order to design water infrastructure. This stationarity assumption allows engineers to plan for infrastructure by assuming that future hydrology repeats itself and will be the same as that experienced in the past (Davis 2011). Climate variability has a number of implications for water resources planning and management. First, the greater the variability of the climate between seasons and between years, the greater the necessity for irrigation and water storage to achieve a given level of security of supply. Similarly, flood control dams also need to be larger to cope with increasingly large floods. Second, as droughts become more frequent, there is likely to be a greater need for irrigated agriculture to maintain food security for rain-fed systems. Third, a high degree of climate variability implies a need for good monitoring of climate and water resources to anticipate and plan for approaching droughts.

*Climate change* describes the change in climate variables caused by the warming of the Earth's atmosphere as a result of human activities such as increasing greenhouse gas (GHG) emissions, land-use change and emissions of aerosols. This warming will likely change the average climate and its variability in a particular region or location across a wide range of temporal scales – sub-daily, daily, monthly, seasonally, interannually and decadal. Thus, engineers and planners cannot assume that infrastructure or plans based on past climates will be suitable and reliable for the future. In other words, the stationary assumption no longer holds.

### **Climate**

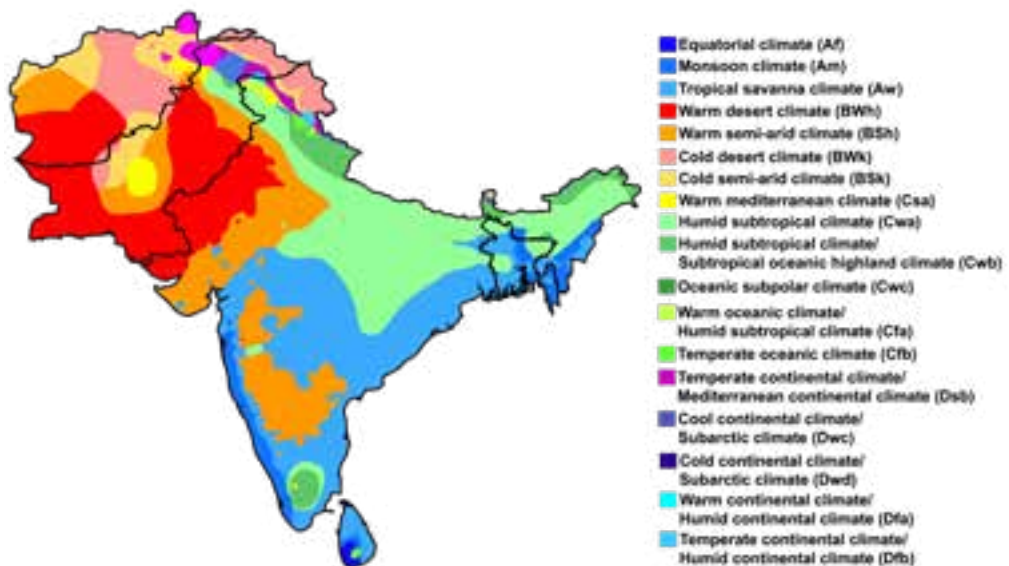
The origin and availability of water resources vary considerably across South Asia, mainly depending on elevation, rainfall, temperature and evapotranspiration patterns.

## Rainfall

The region can be divided into six major climatic zones (Figure 2.1): tropical wet, tropical dry, semiarid, arid, humid subtropical and highlands. The tropical wet zone receiving the largest amount of rainfall includes southern Bangladesh, southwest India and Sri Lanka. Annual rainfall across the region averages 970 mm/year, with high contrasts between countries (Table 2.1). About 70-90% of annual precipitation falls during the monsoon season between June and September. The Himalayan range generates among the highest annual rainfall observed in the world, due to orographic effects (Figure 2.2). The driest countries of South Asia, located in the arid and semiarid climate zones, receive less than one-fifth of the annual amount of rainfall recorded in the wettest parts of the region (Table 2.1). Low rainfall in Afghanistan and Pakistan stems from the presence of a high mountain range in the south, which limits the intrusion of the monsoon, whose influence weakens as it proceeds northwest. In high-elevation areas, most of the precipitation is in the form of snowfall during late winter and early spring months (Goswami 2005; Wang 2006; Kottke et al. 2006; Peel et al. 2007).

Between these two extremes are other areas that receive intermediate levels of rainfall. Spatial variations in mean annual rainfall can be highly marked. For instance, mean annual rainfall in Sri Lanka varies from 800 mm to 5,000 mm, leading to three distinct climatic zones: dry zone (< 1,750 mm/year); intermediate zone (1,750 to 2,500 mm/year); and wet zone (> 2,500 mm/year) (Punyawardana 2002).

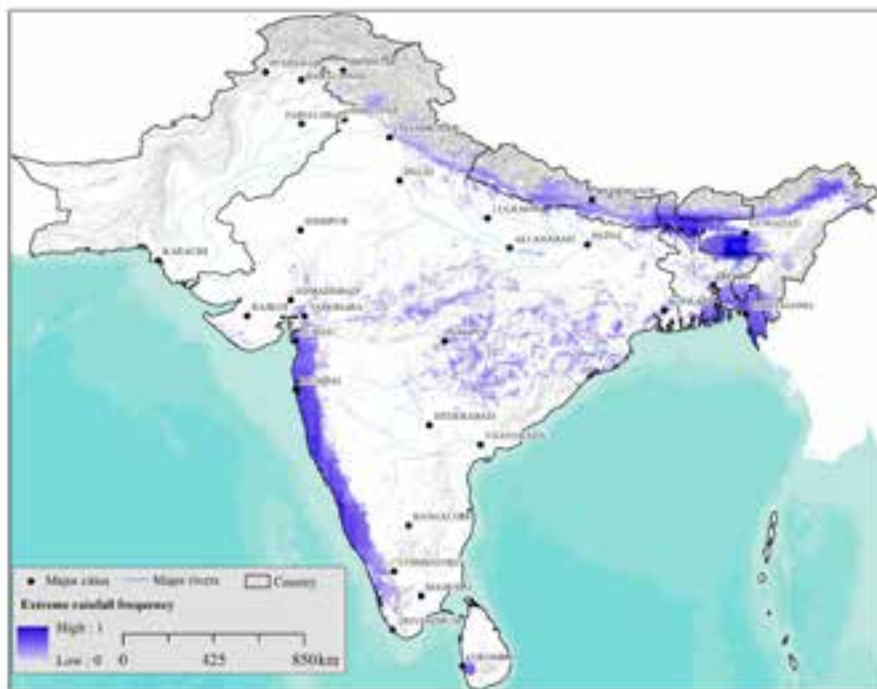
FIGURE 2.1. Climate regions in South Asia according to the Köppen Climate Classification.



*Source:* Derived from the world maps of Köppen Climate Classification (Peel et al. 2007). Enhanced, modified and vectorized by Ali Zifan.

*Note:* The three-letter labels within parenthesis divide climates into five main groups. The first letter refers to tropical (A), dry (B), temperate (C), continental (D) and polar (E) climates. The second letter indicates the seasonal precipitation type. The third letter indicates the level of heat. Refer to Peel et al. (2007) for definitions of all the three-letter labels.

FIGURE 2.2. Spatial distribution of extreme precipitation frequency based on 62-year time series of Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) and Tropical Rainfall Measuring Mission (TRMM) rainfall datasets.



Source: Amarnath et al. 2017.

Note: APHRODITE and TRMM are gridded rainfall products (Yatagai et al. 2012; Huffman et al. 2007).

### ***Temperature and Evaporation***

Temperature varies considerably across the subcontinent and this is influenced by several factors. Temperature decreases with increasing altitude and latitude. The proximity of the coast buffers the effect of the ocean; the Himalayas reduce the intrusion of northern cold winds in the Indian Plain; the monsoons and aerosols tend to cool down the summer temperatures; and the Asian brown cloud warms up the atmosphere in the Ganges Valley (Ramanathan et al. 2005). Seasonal variations of temperature are more pronounced in the north in accordance with greater variations in day length and inclination of solar rays throughout the year. However, the northern part of the Indian Plain remains cool in the winter because it is protected from the northern cold winds. The southern parts of South Asia exhibit the warmest annual temperature averages, while the northern belt of the Indo-Gangetic Plains can become even warmer in the summer. The mountainous north is colder and receives snowfall at high altitudes.

Combined with temperature, relative air humidity controls variations of standard evapotranspiration and evaporation rates. For instance, mean relative air humidity varies from about 80% in Sri Lanka to 20% in the semiarid and arid parts of Afghanistan and Pakistan that exhibit the highest standard evapotranspiration rates across the region.<sup>2</sup> These drought-prone areas are vulnerable to high potential water losses in surface water reservoirs (due to evaporation) and to crop water stress. Conversely, high-elevation countries such as Bhutan and Nepal are exposed to lower temperature and evapotranspiration, implying lower crop water stress and lower maximum crop yield, even with optimal water supply.

<sup>2</sup> Standard evapotranspiration can be much higher than actual evapotranspiration under water-deficient conditions.

TABLE 2.1. Water resources in South Asian countries.

	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Sri Lanka	South Asia
Area (thousand km <sup>2</sup> )	653	148	38	3,287	147	796	66	5,136
Population (million inhabitants)	32	161	0.8	1,311	28.5	189	21	1,743
Density (inhabitants/km <sup>2</sup> )	50	1,084	20	399	194	237	316	339
Rainfall or snowfall - mm/year	327	2,666	2,200	1,083	1,530	494	1,712	970
- km <sup>3</sup> /year	213	396	84	3,560	225	393	112	4,980
Internal renewable water resources								
- km <sup>3</sup> /year	47	105	78	1,446	198	55	53	1,982
- as a percentage of rainfall	22	27	92	41	90	14	47	40
Surface water entering the country (km <sup>3</sup> /year)	10	1,122	0	635	12	265	0	
Groundwater as a percentage of total renewable water resources	16	2	9	19	9	19	13	
Water from snowmelt as a percentage of total renewable water resources	92	0	17	10	8	57	0	
Total renewable water resources (km <sup>3</sup> /year)	65	1,227	78	1,911	210	247	53	
Total renewable water resources per capita (m <sup>3</sup> /inhabitant/year)	2,008	7,622	100,645	1,458	7,372	1,306	2,549	1,137

Sources: FAO 2016; <http://data.worldbank.org/>.Notes: km<sup>2</sup> = square kilometers; km<sup>3</sup> = cubic kilometers; m<sup>3</sup> = cubic meters; mm = millimeters.



## Water Resources

### Surface Water

Water resources available in rivers, lakes, reservoirs, snowpack, glaciers and aquifers originate as rainfall and snow (both referred to as total precipitation) in the respective countries (referred to as *internal renewable water resources* in Table 2.1) and from upstream streamflow produced in neighboring countries (referred to as *surface water entering the country* in Table 2.1).

Internal renewable water resources vary according to precipitation patterns and the fraction of precipitation that is either converted to surface runoff, infiltrated to recharge aquifers, or lost by evaporation or non-productive evapotranspiration. On average, runoff ratios per country (i.e., the ratio between total precipitation and total streamflow) vary from 14% in Pakistan (where a significant part of rainwater is lost through evaporation) to more than 90% in Bhutan and Nepal (where evaporation is much lower than precipitation, and where the mountainous and steep terrain transforms most rainfall into surface runoff, despite significant vegetation cover) (Singh and Karki 2004).

Surface water entering the country varies according to the location of the country within river basins. In each country, the sum of these two water resources (*internal renewable water resources* and *surface water entering the country*) constitutes the *total renewable water resources*. *Internal renewable water resources* is the only countrywide water resource figure that can be added up for regional assessment. Accumulating other figures such as *renewable water resources* for regional assessment would lead to overestimations because of double counting river flow of transboundary river basins. The contribution of surface water entering the country to the total renewable water resources varies between 0% (as in Bhutan, which is located in the upstream part of the Brahmaputra River Basin, and the island nation of Sri Lanka) and more than 90% (as in Bangladesh).

Some figures may vary and contrast with the statistics provided by the individual countries, because of differences in baseline periods combined with high year-to-year variability in water resources (rainfall and streamflow). This table aims to provide consistent values for country comparisons.

While regional variations in internal renewable water resources (from 53 km<sup>3</sup> in Sri Lanka to 1,446 km<sup>3</sup> in India) mainly reflect varying country areas (Table 2.1), per capita total renewable water resources are indicative of the abundance or scarcity of the water resource for the population. An amount of 1,700 m<sup>3</sup>/inhabitant/year is considered a minimum level of water requirement (Falkenmark and Widstrand 1992), based on a set of assumptions on the type of economic development and future potential. According to this indicator, India and Pakistan are water scarce while Bhutan, Bangladesh and Nepal are the most water-abundant countries (Table 2.1). However, these average values hide contrasts within each country. For instance, a significant portion of the agricultural land in Bhutan depends on seasonal rainfall. Only about 12.5% of arable land is irrigated (National Environment Commission 2007). For Bhutanese living in the hills, water flowing in the large rivers in deep gorges of the country is mostly out of reach because of the lack of proper water infrastructure. The lack of flat terrain also limits the utilization of water for irrigation. The proportion of total renewable water resources originating from snowmelt and ice melt is highest in Afghanistan, Pakistan, Bhutan, India and Nepal (Table 2.1). The volume of ice and snow producing river streamflow is located in the Hindu Kush Himalayan (HKH) region, mainly above 2,000 m. It is vital to the countries, as it acts as a natural water storage sustaining dry-season flows and enabling irrigation when the flows of other catchments, below the snow line, are at their lowest. It can even buffer year-to-year climate variability by accumulating more ice and snow during wetter and colder years, and releasing more water from ice melt and snowmelt during warmer and drier years (Barnett et al. 2005).

### Groundwater

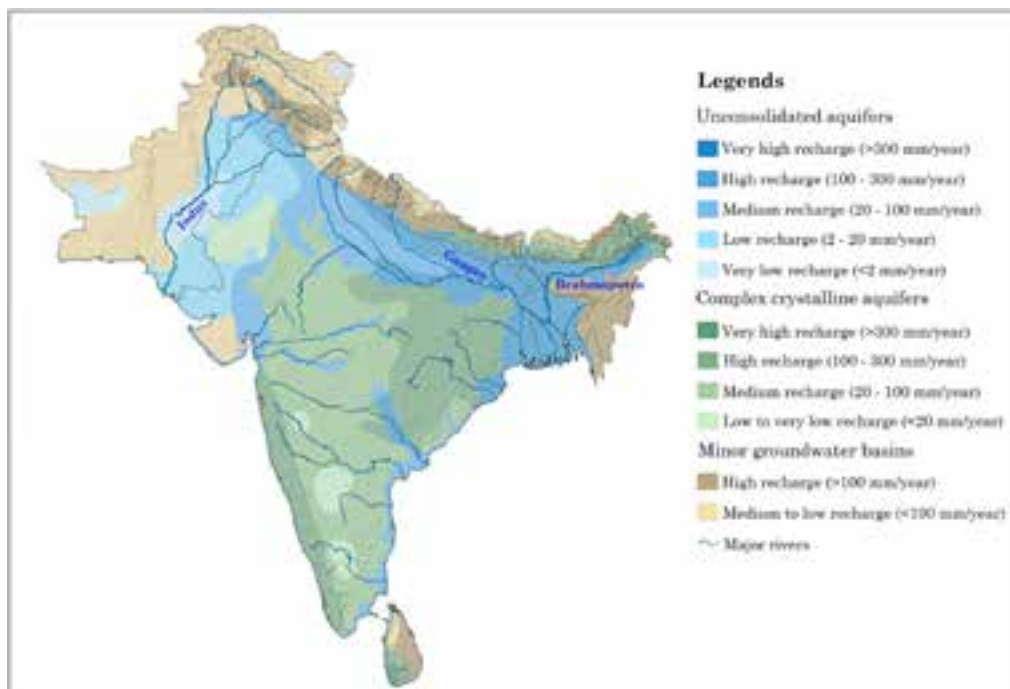
Groundwater is a critical resource that is under increasing pressure in South Asia. Some regions are underlain by aquifers extending over large areas. The largest rivers have floodplain alluvial deposits, such as the vast aquifer beneath the densely populated floodplains of the Ganges-Brahmaputra-Meghna (GBM)

river basin and the Indus River Basin. Sedimentary rocks, especially quaternary loose sediments, are thick with good storage capacity (e.g., Lower GBM Basin, Lower Indus River Basin). The best-yielding aquifers are located in the alluvial deposits of the Gangetic Plains in India (Rajmohan and Prathapar 2013) (Figure 2.3).

In contrast to the alluvial aquifers, hard rock aquifers store groundwater in deep fissures that are technically less accessible and less sustainable because of lower recharge rates (e.g., in mountainous regions such as Bhutan and Nepal). Water quality issues (e.g., arsenic contamination) (Box 2.2) are decreasing the importance of using deep aquifer groundwater in some regions as in West Bengal (Rajmohan and Prathapar 2013). In mountains, groundwater generally occurs in complexes of joint hard rocks and in both shallow and deep alluvial valleys (Pandey and Kazama 2011). In coastal areas, aquifers can be of various other types: shallow karstic (limestone) (e.g., Jaffna Peninsula in Sri Lanka) (Imbulana et al. 2006; Panabokke and Perera 2005), deep confined coastal sand, shallow regolith and lateritic aquifers. Table 2.1 indicates the availability of volumes of groundwater resources in each country.

Recharge rates vary from less than 2 mm/year (central part of the Indus Basin) to more than 300 mm/year (GBM Delta) (Figure 2.3) (Mukherjee et al. 2015). Most of the northern and northwestern regions have lower-yielding aquifers because of the presence of mountainous karst aquifers (e.g., in the Himalayans) and semiarid regions (e.g., Afghanistan and Pakistan).

FIGURE 2.3. Aquifers and recharge rates in South Asia.



Source: Mukherjee et al. 2015.

### **Box 2.2. Groundwater quality in South Asia.**

Groundwater quality is highly variable across South Asia. In addition to anthropogenic pollution from cities, industries and agriculture, the presence of several natural contaminants threatens the availability of safe water in many areas. Of these, the widespread presence of elevated concentrations of dissolved arsenic and fluoride, and high salinity causes much concern. The extent and effect of other emerging and unidentified groundwater contaminants (e.g., nitrate, pesticides, radiogenic isotopes, microorganisms such as bacteria and antibiotics) are yet to be fully accounted for (CGWB 2014).

Elevated and widespread concentrations of geogenic arsenic in groundwater have largely reduced the usable groundwater resources in South Asia. High arsenic concentrations prevail in the coastal south of Bangladesh (Ahmed et al. 2004); in large parts of India (CGWB 2015), particularly in the north, where shallow alluvial aquifers are depleted of dissolved oxygen (anoxic) (Mukherjee et al. 2008; Saha et al. 2010); in the recent alluvial and deltaic aquifers of the Indus Plain of Pakistan, specifically in the Punjab and Sindh regions (Smedley 2005); and in the densely populated southern region of Nepal (Thakur et al. 2011). Most of the aquifers associated with the rivers flowing through the Siwalik Hills in the Himalayan piedmonts are enriched with arsenic (Mukherjee et al. 2009), possibly from groundwater drainage in the rivers. This natural pollution is exacerbated by groundwater pumping in most of these regions, accelerating horizontal and vertical groundwater fluxes that further mobilize contaminants naturally present in the rocks (Mukherjee et al. 2011; Harvey et al. 2002).

All coastal aquifers are prone to saline intrusions of seawater, particularly during the monsoon and storm surges and specifically in the flat deltaic zones, where exchange surfaces between brackish water and aquifers are large (as in the Bay of Bengal and Arabian Sea). In some cases, inland brackish water (as in the Indus Basin) contaminates aquifers, enhancing the dissolution of minerals and/or agricultural pollution (CGWB 2015). Intensive groundwater use (as in coastal areas of Sri Lanka), sea-level rise and deltaic land subsidence (as in the GBM Delta) amplify these dynamics (Rajasooriyar et al. 2002; Brown and Nicholls 2015).

High concentrations of groundwater fluoride are present in the crystalline aquifers of 19 states in India (Arora and Maheshwari 2006; CGWB 2015), and are also observed in Punjab, Sindh and Baluchistan in Pakistan (Tariq 1981). Several aquifers in India have elevated levels of groundwater iron and nitrate (CGWB 2015). Chemical fertilizers and pesticides, mainly from agriculture, are present in the major GBM Basin (Saha and Alam 2014). Nitrate contamination affects some parts of Sri Lanka, which lacks an effective sanitation system (Villholth and Rajasooriyar 2010).

Microbiological contaminations of aquifers exist in many parts of South Asia (such as in Bangladesh; see BGS 2001), especially under anoxic conditions. In contrast to the aquifers in the GBM Basin, aquifers in the Indus Basin are relatively laden with oxygen (oxic). The high amount of nitrate in groundwater facilitates pathogenic pollutions around the cities of Karachi, Lahore, Rawalpindi and Islamabad (Chilton et al. 2001).

### ***Transboundary Rivers and Aquifers***

More than half the area of South Asia is drained by the GBM, Indus and the Helmand river basins (Table 2.2).

#### ***The Ganges-Brahmaputra-Meghna (GBM) River System***

The Brahmaputra and Meghna rivers (Table 2.2) are supplied mainly by monsoonal rains from June to September. Some areas receive between 5,000 and 10,000 mm of rainfall annually. The Ganges River is

supplied by monsoonal rains and snowmelt totalling about 500-1,000 mm/year, with some areas receiving up to 2,000 mm/year. This results in flooding in the Terai of Nepal and the Lower Gangetic Plains of India and Bangladesh (Chinnasamy 2017a, 2017b; Chinnasamy et al. 2015a). It is estimated (with some uncertainties) that glaciers and seasonal snow contribute 3% of mean annual flow in the Brahmaputra Basin and 7% in the Ganges Basin (Savoskul and Smakhtin 2013b). The total renewable water resources in the Ganges Basin amount to about 552 km<sup>3</sup>. Between 20% and 40% of the water resources in the Ganges River Basin is used (Amarasinghe et al. 2016a, 2016b; Chinnasamy et al. 2017) mainly for irrigation, while the Brahmaputra and Meghna rivers remain largely unexploited as they flow through India, because rainfall is sufficient and the terrain is not conducive to large-scale irrigation. According to the systematic classification of the Uttarakhand Environment Protection and Pollution Control Board, water quality in the Ganges River is extremely low, mainly due to contamination by fecal coliform. Although water quality is better in the upper tributaries and in aquifers, a number of other contaminants, including arsenic and fluoride, are of growing concern. Due to lower population densities, the water quality in the Brahmaputra Basin is much higher than in the other major rivers, especially in the upper part of the basin, upstream of the densely populated alluvial plain of Dhaka. However, groundwater quality in this basin is characterized in some locations by dangerous concentrations of arsenic and fluoride (Subramanian 2004). Most of the aquifers in the downstream part of the GBM (in Bangladesh) (Figure 2.4) consist of sedimentary alluvial and deltaic deposits of three major rivers, forming an unconfined aquifer of about 215,000 km<sup>2</sup> (IGRAC 2014) with recharge rates (> 300 mm/year) among the highest in South Asia (Mukherjee et al. 2015).

FIGURE 2.4. The Ganges-Brahmaputra-Meghna (GBM) river system.



Source: Wikimedia.org ([https://commons.wikimedia.org/wiki/File:Ganges-Brahmaputra-Meghna\\_basins.jpg](https://commons.wikimedia.org/wiki/File:Ganges-Brahmaputra-Meghna_basins.jpg)).

### *The Indus River Basin*

The Indus River rises on the Tibetan Plateau, draining the highest mountain ranges of the world. This basin contains the world's largest area of nonpolar perennial ice cover (22,000 km<sup>2</sup>). The area of winter snow cover is an order of magnitude greater (Archer et al. 2010). The climate of the Upper Indus is strongly influenced by the mountain ranges' restriction on the penetration of monsoonal rainfall, which generally stops on the southern margin. Precipitation in the trans-Himalayan Karakoram and Hindu Kush ranges occurs primarily

as snow in the winter and spring as a result of westerly winds. Below elevations of 2,500 m, total rainfall is less than 200 mm/year. Precipitation exceeds 1,500 mm/year at elevations above 5,000 m (Wake 1989). Ice and snow serve as natural water storage, providing perennial supplies to the river's main stem and some of its tributaries. Renewable water resources yield 287 km<sup>3</sup>, of which 74% originates from the Pakistani part of the Indus Basin. Replenishable groundwater resources (90 km<sup>3</sup>) are split between India (30%) and Pakistan (70%), with an overlap between available surface water resources (about 250 km<sup>3</sup>) and replenishable groundwater resources (about 100 km<sup>3</sup>). Irrigated agriculture currently accounts for more than 95% of blue (liquid) water withdrawals in the Indus Basin. Only about 11% of domestic water and 9% of industrial water in the basin is consumed. The remainder is returned to the system (Laghari et al. 2012).

The arid and semiarid environment of the plains includes storage reservoirs and the largest integrated irrigation system in the world, with a command area of approximately 18 million hectares (Mha). About 60% of the water in the Indus Basin is utilized for irrigation (Table 2.2).

The Indus Basin is underlain by an extensive unconfined aquifer covering about 16 Mha, of which 10 Mha are saline (Haider et al. 1999). The deep water table (> 30 m) was in a state of hydrological equilibrium before the development of canal irrigation systems. While water quality is high in the upstream Indus River and its tributaries, effluents from agricultural drainage and wastewater from cities and industries seriously affect water quality in downstream parts of the basin. Groundwater is brackish in 60% of the Indus Basin Irrigation System. Almost all shallow freshwater is now polluted with pesticides and nitrogenous fertilizers from agriculture, as well as sewage, or is naturally contaminated with arsenic.

TABLE 2.2. Major river basins in South Asia: Hydrology and country sharing.

		Ganges	Brahmaputra	Meghna	GBM	Indus	Helmand
Surface area (km <sup>2</sup> )		1,087,000	552,000	82,000	1,721,000	1,165,000	306,500
Mean flow (km <sup>3</sup> /year)		525.4	624.8	160.9	1,311.2	207.0	15
Mean runoff (mm/year)		483	1,132	1,963	762	178	45
Percentage of the basin in the country	Afghanistan	--	--	--	--	6	85
	Bangladesh	4	7	43	7	--	--
	Bhutan	--	7	--	3	--	--
	India	79	36	57	64	39	--
	Nepal	14	--	--	8	--	--
	Pakistan	--	--	--	--	47	4
Percentage of the country in the basin	Afghanistan	--	--	--	--	11	40
	Bangladesh	32	27	24	83	--	--
	Bhutan	--	100	--	100	--	--
	India	26	6	1	33	14	--
	Nepal	100	--	--	100	--	--
	Pakistan	--	--	--	--	65	1

Source: FAO 2016; <http://www.jrcb.gov.bd>.

Note: Three percent (3%), 50% and 8% of the Ganges, Brahmaputra and Indus basins, respectively, are located in China. Eleven percent (11%) of the Helmand Basin is located in Iran.

### *The Helmand River Basin*

The Helmand Basin (Table 2.2) is either arid or semiarid. Most of the water resources originate from snowmelt in the mountainous upper reaches. This endorheic basin is confined by the southern Hindu Kush ranges on the north, East Iranian ranges to the west, and by mountain ranges in the Baluchistan Province of Pakistan to the south and east (Whitney 2006). The Helmand River drains water from the Sia Koh and Parwan mountains on the east side of the basin to the Sistan depression between Iran and Afghanistan (Favre and Kamal 2004) on the west. The Sistan depression is a large complex of wetlands, lakes and lagoons, and is an internationally recognized haven for wetland wildlife, surrounded by the

world's windiest desert. The river remains relatively salt-free for much of its length, unlike most rivers with no outlet to the sea. However, in some parts, the build-up of mineral salts limits its use for irrigation. However, the Helmand River is essential for farmers in Afghanistan and Iran. Groundwater is present in thick, unconsolidated to semi-consolidated basin-fill sediments consisting of sand, undifferentiated and conglomerate sediments, and rocks. Water drawn from the unconfined water-table aquifer is contaminated not only with bacteria but also with a high concentration of dissolved salts (Palmer-Moloney 2014). More than 85% of the river basin area is within Afghanistan and 4% is within Pakistan (Table 2.2).

## **Water Uses**

Total water withdrawals in South Asia represent about 27% of the total available renewable surface water and groundwater resources. This varies from less than 5% (in Bangladesh, Bhutan, and Nepal) to 74% in Pakistan (Table 2.3). While water is used mainly for agricultural purposes, domestic water demand is increasingly driven by changing lifestyles and demographics caused by, and reflecting, changing socioeconomic development. At the same time, agricultural water demands continue to increase due to intensification, with farming seeking to keep pace with food demand.

Groundwater accounts for about 40% of total water use across South Asia, varying from 0% in Bhutan (where stream water is abundant year round) to 80% in Bangladesh (where surface water, though abundant on an annual basis, is commonly polluted or lacking during the dry season). In the dry season or when the monsoon is delayed, aquifers provide critical natural reserves, often better protected from pollution and evaporation losses compared with surface water reservoirs. Groundwater-based irrigation has become the mainstay of irrigated agriculture over much of India and Bangladesh, Punjab and Sindh provinces of Pakistan, and in the Terai Plains in Nepal, which have a high potential for cost-effective development of groundwater-based irrigated agriculture. Traditionally, surface water from ponds and rivers was used to provide water for both drinking and irrigation purposes in all the South Asian countries. However, over the last few decades, groundwater uses have greatly increased (Shamsudduha 2013). This is one of the main factors behind the decrease in, and degradation of, groundwater resources, coupled with problems of mismanagement, inadequate waste disposal and wastewater treatment, and natural and anthropogenic contamination.

## ***Agriculture***

One-third of all agricultural land in South Asia is irrigated (Table 2.3), with wide national disparities (from 6% in Bhutan to 55% in Bangladesh and Pakistan). On average, more than 90% of the volume of water used in South Asia is for irrigation, ranging from 87% in Sri Lanka to 98% in Afghanistan and Nepal. About one-third of irrigation water is pumped from aquifers (Table 2.3). The remainder is pumped or diverted from rivers and reservoirs. The dramatic increase in groundwater use in India, Pakistan and Bangladesh is exceeding natural groundwater recharge rates, making the current levels of usage unsustainable, as evidenced by the rapid fall of water tables in many instances (Chinnasamy and Agoramoorthy 2015).

## ***Hydropower***

The production of hydropower does not consume water (except for net evaporation losses from any reservoirs constructed), but requires sufficient water storage volumes to sustain the operation of turbines at a required rate. Hydropower dams can buffer seasonal variations in the river flow regime. In the dry season, they can increase downstream flow (providing potential additional water resources to downstream users, but also threatening ecosystems). In the high-flow season, they can reduce flood risk by storing excess floodwater. Areas with potential for hydropower development are characterized by high annual precipitation, river flow with limited sediment content (to minimize reservoir siltation and turbine damage), and availability of land and steep terrain to generate sufficient head for hydropower production. Upstream countries in South Asia (especially Bhutan, India, Nepal and Pakistan) are well suited for hydropower production, including proximity to markets where there is a high demand for energy.

TABLE 2.3. Water uses in South Asian countries.

	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Sri Lanka	South Asia
Total water use as a percentage of total renewable water resources	31.0	3.0	0	40.0	5.0	74.0	25.0	27.0
Total water use (km <sup>3</sup> /year)	20.4	35.9	0.3	761.0	9.5	183.5	12.9	1,023.5
Agricultural water use (km <sup>3</sup> /year)	20.0	31.5	0.3	688.0	9.3	172.4	11.3	932.8
Industrial water use (km <sup>3</sup> /year)	0.2	0.8	0.0	17.0	0.0	1.4	0.8	20.2
Municipal water use (km <sup>3</sup> /year)	0.2	3.6	0.0	56.0	0.1	9.7	0.8	70.4
Surface water use (km <sup>3</sup> /year)	16.7	7.4	0.3	531.0 <sup>a</sup>	7.6	121.9	5.1	550.4
Groundwater use (km <sup>3</sup> /year)	3.7	28.5	0.0	230.0 <sup>b</sup>	1.9	61.6	7.8	325.7
Groundwater use as a percentage of total water use	18.0	79.0	0	36.0	21.0	34.0	60.0	39.0
Groundwater use as a percentage of total renewable groundwater	34.0	2.0	0	53.0	19.0	24.8	15.0	63.0
Agricultural water use as a percentage of total water use	98.0	88.0	94.0	90.0	98.0	94.0	87.0	91.0
Agricultural land (103 km <sup>2</sup> )	379.1	91.1	5.2	1,802.8	30.0	362.8	27.4	2,709.6
Irrigated area (103 km <sup>2</sup> )	32.1	50.5	0.4	663.3	13.7	199.9	5.7	963.5
Irrigated area as a percentage of agricultural land	8.0	55.0	6.0	37.0	45.0	55.0	21.0	36.0

Sources: FAO 2016; <http://data.worldbank.org/>. For Bhutan: National Statistics Bureau 2009.

Notes: <sup>a</sup> This volume includes the direct use of agricultural drainage water that represents 14.9% of total water withdrawals (FAO 2016).

<sup>b</sup> Highest in the world (Shah 2010).

Bhutan and Nepal are at a less advanced stage of development compared to India and Sri Lanka. Almost all hydropower dams are run-of-the-river type, with generating capacity limited during the dry season. The selling of electricity to India is a potential driver of hydropower development in Bhutan and Nepal. The fragile mountain geology requires careful planning for the selection of sites and development of hydropower.

### ***Domestic and Drinking Water Uses***

Access to sufficient, good-quality water for domestic use is very unequal across South Asia. Countries are affected, to varying degrees, by increasing groundwater depletion and pollution (Shamsudduha 2013), irregular climate patterns causing droughts and destructive floods, lack of sound and reliable infrastructure, and competition with agricultural water users. Countries most affected by limited access to domestic water include Afghanistan (due to low availability and problems of access caused by poverty and years of damage to infrastructure), and Bangladesh and Pakistan (because of exposure to recurrent floods and high water demand).

Afghanistan has Asia's lowest sustainable access to safe domestic water because of a lack of water infrastructure. More than half the urban population has no access to improved water resources and 80% of the population in rural areas drink contaminated water (Islamic Republic of Afghanistan 2005).

Although Pakistan receives most of the water from the Indus River, per capita water availability (1,306 m<sup>3</sup>/year) is the lowest in South Asia. Some 13% of the population (28 million people) does not have access to improved water resources for domestic use. Only 53% of the total rural population has access to safe drinking water. The remainder accesses untreated surface water from sources such as streams, canals, ponds or springs (Mirza and Ahmad 2005). In 1995, around 12.4 km<sup>3</sup>/year of untreated wastewater was discharged into water bodies (Ahmad 2008), including 0.5 km<sup>3</sup>/year and 0.3 km<sup>3</sup>/year of sewage from Karachi and Lahore, respectively. This tainted water was often reused without treatment for drinking purposes, causing high incidence of waterborne diseases. In Nepal, about 40% of the population still does not have access to safe drinking water (MoE 2005). In contrast, in Bhutan, about 97% of the population has access to improved drinking water sources, according to the annual health bulletin of Bhutan (Tenzin Wangmo, Chief Environment Officer, Water Resource Coordination Division, National Environment Commission of Bhutan, pers. comm.).

### ***Industries***

Bangladesh and India have the highest proportion of industrial water use, representing more than 2% of the total water withdrawals. In India, more than 70% of industrial water withdrawals are for energy generation (Aggarwal and Kumar 2011). The remainder is used for industries (CSE 2004). Water for energy is mainly used to cool thermal power stations. Typically, about 5-10% of these withdrawals is consumed through evaporation. This is not only the dominant industrial demand, but the fastest growing demand (in relative terms) — at least in India — and constraints on availability (such as during droughts) have significant downstream economic consequences. Improved efficiency of the water cooling process could significantly reduce this industrial water demand and the pressure on downstream ecosystems (Markandya et al. 2017). In recent years, groundwater has also been used along with surface water for industrial purposes. Total industrial water demand is expected to increase to 80 km<sup>3</sup> in 2025 and 143 km<sup>3</sup> in 2050, which will be 8.5% and 10% of total use (CSE 2004; Aggarwal and Kumar 2011). In Bangladesh, if business as usual continues in the development of the textile sector, it is anticipated that there will be an additional water demand of more than 3.4 km<sup>3</sup> by 2030, which is equivalent to the annual water needs of a population of approximately 75 million. Current groundwater abstraction rates are close to their limit, and growth of the textile sector will require the development of new sustainable water supplies and effluent treatment facilities for such a high-polluting sector.

## **Managing Water Resources**

### ***Water and Climate Information***

Informed water resources planning, development and management require reliable information on precipitation, streamflow, groundwater recharge and water quality, and how they vary over space and time. For example, flood or drought preparedness requires flood or drought forecasting, early warning systems, and mapping of flood- and drought-prone areas. In the HKH Region, the reduction of risks related to glacial lake outburst floods (GLOFs) requires a good understanding of glacier processes, lake formation and sedimentation. Landslides and erosion can be better controlled with information on soil and interaction with land uses, hydrology and water infrastructure. Protection of water quality requires enforcement of laws and regulations, improved knowledge about water treatment, improved understanding of surface water-groundwater interactions, and monitoring of the impact of a warming environment on various sources of contaminants. In order to anticipate coastal floods and their possible effect on coastal groundwater quality, cyclones, storms, sea-level rise and land subsidence should be monitored.

### ***Key Water Management Decisions***

Table 2.4 compiles information on climate risks with a focus on knowledge, governance, infrastructure, planning/management, and communication/education/participation.



TABLE 2.4. Climate-related risks to water resources and potential adaptation actions.

Climate risks	Knowledge	Governance <sup>a</sup>	Infrastructure	Planning/management	Communication/education/ participation
1. Primary risks					
Changes in precipitation (especially monsoon)	Research; weather monitoring	Coordination among meteorological, water and agricultural agencies	Dams; inter-basin transfers; groundwater recharge (including artificial options)	Flexible irrigation management systems; responses across sectors to assist adaptation	Involvement of water user groups and farmer organizations; capacity development; communication to farmers and other stakeholders
Sea-level rise <sup>b</sup>	Research; monitoring	Coordination among water agencies, agriculture and other water-using sectors, and coastal authorities	Embankments; subsurface groundwater barriers; maintaining and restoring natural shorelines	Groundwater use plans; controls on groundwater use	Involvement of coastal communities; capacity development
Temperature extremes	Research; monitoring	Coordination among water, energy and productive sectors	Soil and water conservation; improved water supply infrastructure; afforestation	Mapping trends and designing for peak demands	Prevention of risk through public information and information sharing
2. Secondary risks					
Floods	Monitoring and early warning systems	Coordination (interagency, government-public)	Embankments; dams; flood shelters	Flood management plans; restrict development on floodplains; flood mapping; flood insurance	Public awareness of flood-risk areas; capacity strengthening

(Continued)

TABLE 2.4. Climate-related risks to water resources and potential adaptation actions (continued)

Climate risks	Knowledge	Governance <sup>a</sup>	Infrastructure	Planning/management	Communication/education/ participation
Droughts	Weather prediction and early warning communications; research; monitoring	Allocation priorities and planning mechanisms; coordination among agriculture, power, water resources, water supply; local institutional capacities to manage scarce water resources and improvisation	Storages; inter-basin transfers; groundwater development	Water allocation plans; conjunctive use; demand management, including pricing; water-efficient technologies; irrigation and urban water management; recycling and reuse	Involvement and sharing of local solutions; capacity development
Reduction in groundwater recharge	Monitoring and characterization of aquifers; research into groundwater; database on groundwater-related information	Coordination among agriculture, domestic water supply, industrial water use, water resources; public ownership of groundwater	Check dams; recharge ponds; managed aquifer recharge development	Groundwater use plans; controls on groundwater use, including indirect regulation; artificial recharge; conjunctive use	Awareness of groundwater limitations; capacity development
Increased erosion, landslides and sedimentation	Research on soil management and protection; monitoring and early warning systems	Coordination among land, water, energy and other agencies	Sedimentation dams	Land management; riparian management; soil conservation	Awareness of soil loss; participation and local solutions; capacity development

(Continued)

TABLE 2.4. Climate-related risks to water resources and potential adaptation actions (continued)

Climate risks	Knowledge	Governance <sup>a</sup>	Infrastructure	Planning/management	Communication/education/ participation
Reduced water quality (surface water and groundwater)	Monitoring; research on water quality and treatment	Coordination among water resources and industry/water supply and sanitation agencies	Wastewater treatment and pollution treatment plants	Water quality standards and enforcement; wastewater and pollution treatment, including through incentives and disincentives; recycling and reuse	Awareness of pollution risks and prevention measures; polluter pays principle
GLoFs	Research; monitoring; and early warning systems	Coordination among departments working on disaster management, geology and hydrometeorology	Artificial lowering of lake levels	Hazard and risk management protocols; planning for natural disaster management	Public awareness of flood- risk areas; opportunities to effectively participate in the development, operation and maintenance of local infrastructure; capacity strengthening

*Notes:*

<sup>a</sup> Some governance actions transcend specific threats. For instance, separation of regulation and operation leads to good governance.

<sup>b</sup> Includes only threats to water resources from sea-level rise (principally, contamination of coastal aquifers).



## Chapter 3. Climate Risks

About 40% of natural disasters recorded globally occur in South Asia. Several geographic features account for the high exposure to climate risks. The Indian Ocean generates humid air masses directed northeast toward the South Asian subcontinent. The resulting southwest monsoon deposits 70-90% of annual precipitation between June and September. The Himalayan Mountain belt forces this moist air to rise, condensing this humidity through an orographic effect and creating flooding precipitation. The results are some of the world's largest rivers, which carry huge volumes of water and sediments into the plains of Pakistan, India and Bangladesh. Low-lying and flat coastal areas are usually densely populated, and have inadequate flood protection infrastructure, making them highly vulnerable to riverine and coastal flooding. In the driest countries of the region, water resources are dominated by ice melt and snowmelt, the availability of which is threatened by global warming.

Climate-related risks vary in severity, type and scale of impacts. Some risks are gradually worsened by climate change. For instance, water availability may progressively reduce as evaporation increases and groundwater recharge rates decrease. Erosion rates may gradually increase in response to changes in land use induced by climate change and other drivers. Other risks are more abruptly worsened by more frequent extreme weather events, including floods, droughts and storms. The severity of these disasters closely depends on how countries use different water resources, which are differentially affected by climate change (modified rainfall patterns, sea-level rise and temperature rise). This chapter reviews existing climate-related risks in each of the seven countries of South Asia considered in this study.

Among all the types of natural disasters in South Asia, by far, droughts have caused the largest number of casualties in the last century. Some 6.1 million people died from droughts, of whom 69% was in India and most of the other 31% in Bangladesh ([www.emdat.be](http://www.emdat.be)). Storms and cyclones are the second major source of casualties (865,000), followed by riverine and flash floods, including GLOFs and landslides. In contrast, the number of people affected by landslides (4.6 million) far exceeds that affected by other types of disasters.<sup>3</sup> Floods have caused the largest damage in terms of cost (USD 86 billion, equivalent to 70% of all economic losses caused by natural disasters in the region). Landslides are next and have caused damages estimated at USD 37 billion, followed by storms and cyclones, and droughts ([www.emdat.be](http://www.emdat.be)).

Compared to these four categories of disasters (droughts, storms and cyclones, riverine and flash floods, and landslides), coastal floods have caused far fewer casualties, affected fewer people, and have led to less damage, mainly in India and Bangladesh (<http://www.emdat.be/>). Climate-related risks of erosion are more difficult to quantify because they indirectly affect populations and damage infrastructure, mainly through the loss of soils in upland areas and siltation of reservoirs downstream. Their linkage to climate conditions is also compounded by a number of other drivers, including land-use changes.

### Floods

Because of their size and sediment levels, the largest rivers of South Asia are difficult to manage and regularly cause flooding (Kundzewicz et al. 2007). Lowland areas that are densely populated are exposed to coastal floods, which are worsened by sea-level rise and high-intensity cyclones from the Indian Ocean. Riverine floods, which occur when rivers spill over, lead to significant indirect losses, including the degradation of agricultural land — which subsequently diminishes agricultural productivity, impeding rural development and income opportunities. Indirect losses also include the contamination of surface water and groundwater, either with saltwater intrusion or pollutant dissemination. Floods damage water infrastructure, including hydropower dams and irrigation schemes. The decade 2005-2015 saw the highest number of reported flood disasters in South Asia, with the greatest spatial coverage on record. These included the

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<sup>3</sup> The people affected include those who were injured or suffered from damage to property and other losses.

devastating floods in Pakistan in 2010 and the Uttarakhand flash flood in India in 2013. In contrast to riverine floods, flash floods are much more localized and often confined to narrow valleys (Mirza 2011).

### ***Flash Floods***

Excess rainfall can cause flash flooding and its destructive power is aggravated by steep slopes. Usually, hydrographs of flash floods are characterized by a sharp rise and recession. Flash floods usually last no more than a few hours. Reduced soil infiltration (as in urban areas) magnifies the impact of flash floods. High-flow velocity causes extensive damage to crops, control embankments and properties (Mirza and Ahmad 2005). Populations settled along riverbanks and foothills, on steep slopes, and in low-lying slums and squatter settlements are particularly vulnerable to flash floods (Shrestha 2008, 2010; Gautam et al. 2013; Chinnasamy 2017b). The mountainous northeast of Afghanistan is the region most exposed to flash floods in the spring and early summer because of high precipitation and the accumulation of snow at high altitudes, which melts until July. In 2009, at least 202,000 people were affected by spring floods in 13 monitored flood-prone provinces, representing about 2% of the total population in these areas. Houses and water infrastructure (irrigation canals, wells and water supply networks) were destroyed, and families suffered serious loss of spring crops and livestock. The lack of infrastructure, inadequate disaster preparedness and poor socioeconomic conditions explains why this country includes the highest number of flood-related deaths in the world (CPHD 2011). Eastern and northern areas of Bangladesh, adjacent to the border with India, are vulnerable to flash floods resulting from heavy rainfall occurring over hilly and mountainous regions. The normal period of flash flooding is late April to early May and from September to November (Mirza and Ahmad 2005).

### ***Glacial Lake Outburst Floods (GLOFs)***

GLOFs are catastrophic discharges of water from glacial lakes that occur when unstable end moraine or ice dams formed at the end of these lakes are breached or fail. The first and second types of glacial lakes are called moraine-dammed and ice-dammed glacial lakes, respectively. Almost all glacial lakes in Nepal are moraine-dammed. Very rich debris accumulates as relatively large lateral and end moraine, compared to other glaciers in the world. Ice-dammed lakes are rare and are considered less dangerous. Glacial lakes evolve over time, depending on temperature variations and sedimentation rates. About 8,790 glacial lakes were recorded in Bhutan, India, Nepal, Pakistan and the Ganges Basin in China in the late 1990s and early 2000s. Of these, 204 were listed as potentially dangerous (Shrestha et al. 2015).

Some 56 GLOFs have been reported in the HKH Region since the 1970s, more than 60% having occurred since 2010. These GLOFs have resulted in significant damage to people, crops, settlements and hydropower plants. In 1984, a GLOF of the Lake Dig Tsho in Nepal caused severe damage to property and loss of lives downstream. The lake was drained suddenly and sent a 10-15-m high surge of water and debris down the Koshi River for some 90 km. About 1 million cubic meters ( $\text{Mm}^3$ ) of water was released, creating an initial peak discharge of 2,000  $\text{m}^3/\text{second}$ . This spectacular natural event eliminated all the bridges for 42 km downstream, with loss of life and damage to property (Fushimi et al. 1985; Galey 1985; Ives 1986).

Compared to the general attention given to GLOFs, the actual scale of the disasters in terms of casualties is fairly low relative to other climate-related risks in neighboring countries, mainly because population densities are much lower in the high mountains than in the plains.

### ***Riverine Floods***

With the onset of the monsoon in June, river flow increases and brings floodwater to alluvial plains in the GBM river system from June to September (Mirza and Ahmad 2005; Winsemius et al. 2015). About 50% of the world's population exposed to the hazards of river flooding are located in South Asia, specifically in Afghanistan, Bangladesh, India, Pakistan and Sri Lanka (Luo et al. 2015).

### *Afghanistan*

The Amu and Helmand are the largest rivers flowing along Afghanistan's borders. Every year, they swell and change course during the spring and summer months, washing away settlements, traditional irrigation systems and irrigated agricultural land. In 2010, between 1,800 and 2,500 families in 14 villages were affected by such an event in the Fayzabad District.

### *Bangladesh*

Bangladesh is the world's most densely populated country (Table 2.1) and consists largely of a low, flat topography (60% of the country lies between 0 and 6 m above mean sea level [amsl]). About 80% of the country is included in the floodplains of the GBM. Due to its downstream location, Bangladesh receives inflow from river basins with an area 12 times its size (Table 2.2). On average, 22% of the country is flooded each year. The continued development of upstream parts of the basin, deforestation in the Himalayas, upstream embankments along channels, land degradation and erosion have aggravated the flood situation. From 1987 to 2007, five large floods occurred in Bangladesh (Mirza 2011). In 1988 and 1998, the peak flows of the Brahmaputra and the Ganges rivers coincided, resulting in inundation of about 60% of the country (Khan 1999). The spatial extent of flooding is usually aggravated by heavy monsoonal rainfall and cyclone-driven surges.

### *India*

Out of 164 flood-prone countries in the world, India is ranked the highest in absolute numbers in terms of population exposed to floods, with 21 million people affected annually. Infrastructure worth USD 14 billion — almost 1% of the national GDP — is exposed annually. This figure is estimated to increase tenfold by 2030 (Luo et al. 2015). Overall, some 40 Mha of agricultural land are vulnerable to annual floods (Mirza 2011).

### *Pakistan*

About two-thirds of Pakistan lies in the Indus Basin. Floods can cover up to one-fifth of the country, posing high risks to riverine populations. Some 710,000 people in Pakistan are exposed to risks of annual river floods (Luo et al. 2015), although the number of people affected reaches as high as 21 million in some years (Syvitski and Brakenridge 2013). Between 2008 and 2013, three major floods occurred in Pakistan. The 2009 floods were caused by a major embankment breach that changed the course of the floodwater entirely (Winsemius et al. 2013). The lack of adequate plans and means to manage river sediment loads have led to many riverine floods in Pakistan (Syvitski and Brakenridge 2013; Winsemius et al. 2013). The catastrophic flood in 2010 along the Indus River was caused by exceptional rainfall in conjunction with a reduction in conveyance capacity of water and sediment, and dam and barrage-related backwater effects (Syvitski and Brakenridge 2013). On average, annual floods in Pakistan result in a loss of 1% of total GDP, which is equivalent to USD 1.7 billion. The floods in 2010 cost the country USD 10 billion in damages.

### *Sri Lanka*

The floods in Sri Lanka in 2017 resulted from a heavy southwest monsoon, worsened by the arrival of Cyclone Mora. The flood affected 15 districts and killed at least 208 people. Some 700,000 people were also affected.

### ***Coastal Floods***

Currently, coastal floods are mainly caused by cyclones creating local sea-level surges. In the future, sea-level rise is expected to worsen coastal flooding. Cyclones and storms originating from the Indian Ocean are the major cause of coastal floods that hit low-lying and coastal parts of Bangladesh. Changes in the sea level by just 1 m — in response to strong winds, for example — frequently causes disasters. Over the last 40 years, 520,000 deaths from coastal floods have been recorded in South Asia, of which

approximately 300,000 and 140,000 were caused by two cyclone events that occurred in 1970 and in 1991, respectively (World Bank 2012).

The eastern coastline of India in Bengal, Odisha and Andhra Pradesh is prone to tropical cyclones that cause devastating coastal floods. For instance, the super cyclone that hit the Odisha coast in October 1999 had a wind speed of 260 km/h with heavy rains, and a storm surge of 9 m amsl at Paradip, which penetrated 35 km inland (Mirza and Ahmad 2005). According to the State Relief Commissioner's Office in Bhubaneswar, nearly 10,000 people died; over 2,000 were injured; over 1 million were made homeless; more than 370,000 heads of cattle perished; 1.6 Mha of paddy and 33,000 ha of other crops were damaged; and several villages were completely wiped out.

## Droughts

All countries in South Asia are prone to drought. Because they extend over large geographic areas, droughts have induced the largest number of casualties in this region. Floods occur as a result of water shortages from rainfall, surface water or aquifers. Lack of precipitation significantly impairs agricultural output, since approximately 60% of cultivated areas in South Asia are under rain-fed farming (Table 2,3). Droughts affect people through water shortages, food deprivation and sometimes associated heat waves (Gupta et al. 2011).

Two main types of drought exist. A *meteorological* drought occurs during prolonged periods when rainfall is far below inter-annual averages. This type of drought mainly affects agriculture. The magnitude increases with the duration of the rainless period, and temperature and wind factors that can worsen water stress. A *hydrological* drought occurs when water levels in rivers, lakes, reservoirs and aquifers fall significantly below the statistical average, usually following a meteorological drought. Hydrological droughts may also occur during times of average precipitation, if water demand is high and increased use has lowered water reserves. In some cases, a decline in groundwater level is accompanied by saltwater intrusion, because of reversed lateral gradients and water flux from saline rocks. In the absence of sufficient rainfall, water infiltration from the surface can decline substantially, allowing vertical ascension of saline groundwater by capillary effect and evaporation, contaminating topsoil layers with salt.

In addition to the inherent 30-year cycle of the monsoons, droughts have been found to be more frequent during the years following El Niño Southern Oscillation (ENSO) events (Dai 2012) and the warming of the Eastern Equatorial Pacific Ocean. At least half the severe failures of monsoons since 1871 have occurred during El Niño years (Webster et al. 1998). Countries most affected by droughts are located in semiarid and arid zones (Figure 2.1), including Afghanistan, Pakistan and some parts of India or nations where river flows are very low during the dry season (Bangladesh), partly due to upstream flow diversion. In Bhutan, Nepal and Sri Lanka, droughts are relatively minor compared to the effects of other climate-related disasters.

### *Afghanistan*

Afghanistan is one of the most drought-sensitive countries in the world because of its generally arid climate, vulnerable irrigation infrastructure and significant dependence on agriculture. These conditions are exacerbated by political fragility and associated years of conflicts. Only a small proportion of the population has access to improved water sources (27%) (CPHD 2011). Alarming groundwater depletion rates worsen the effects of surface water shortages.

### *Bangladesh*

During the dry season from October to May, Bangladesh receives only the residual flow after diversion and upstream use. The Farakka Barrage in India diverts water from the Ganges River just before it enters Bangladesh. Reduction in dry-season flows causes severe water shortage across the country, particularly in the southwest region, and is aggravating salinity intrusion and environmental degradation (Rahaman 2009). Groundwater development has long been considered a solution to cope with surface water



shortages. However, high concentrations of arsenic and fluoride are threatening populations that rely on such groundwater resources, while coastal areas tend to be exposed more frequently to salinity issues. Besides hydrological droughts, Bangladesh experienced 20 meteorological droughts in the last 50 years (Ramamasy and Baas 2007). The 1978-1979 drought affected half the cultivated land and population, equivalent to a loss of 2 million tons of rice. Similar large-scale droughts followed in the 1980s and 1990s.

#### *Bhutan*

Although not generally exposed to droughts, Bhutan does experience dry spells. Most of Bhutan's farmers are subsistence farmers. Hence, with failure of the monsoon or untimely rainfall, crop losses and associated damage to livelihoods are the main issues.

#### *India*

Drought-related problems in India include food deficiencies and the lack of safe drinking water, inducing higher food prices, which particularly affects the urban poor. The drought disaster that covered large areas of northern and eastern India in 1979-1980 affected more than 38 Mha of cropped areas, and endangered the lives of 130 million cattle and more than 200 million people. Droughts not only affect the availability of surface water in India but also the recharge of aquifers, which are being depleted by unsustainable pumping rates.

#### *Nepal*

Even though severe meteorological droughts have not occurred in Nepal, drought-related stress has risen in recent years. Streams in mountainous regions tend to be depleted in response to greater abstraction (Thakur and Upadhyaya 2014). Such hydrological droughts result predominantly from increased water demand rather than a reduction in rainfall. However, recent changes in the pattern of rainfall have led to spells of drought of up to 3 weeks, typically during the wet season, severely reducing crop yields, and followed by flash floods, negatively affecting populations.

Droughts affect farming, livelihood management and domestic water use. Lack of irrigation water has led to crop failure, which has forced many farmers to leave the land fallow or to harvest poor yields. As a result, migration from drought-hit areas has increased, along with greater imports of food and water from other regions (NPC 2013). Inhabitants of the poverty-stricken western regions are more vulnerable to droughts because they cannot migrate easily to other regions and cannot afford imported food and water. Groundwater potential is limited in this mountainous country. The potential, if any, is still largely untapped and, therefore, has limited capacity to alleviate drought. Arsenic contamination is also a problem, especially in the southern half of Nepal.

#### *Pakistan*

Alongside Afghanistan, Pakistan is the most water-scarce country in South Asia because of its semiarid climate. With both population and food demand increasing, large areas of irrigated land are rapidly becoming water stressed. In some years, rainfall is less than half of the long-term average of 500 mm/year. In 2000, 2001 and 2002, for instance, millions of cattle died due to a shortage of fodder crops, and several thousand people were forced into migration (World Bank 2012). Because of repeated droughts and increasing water demand, water tables in Baluchistan Province are decreasing by 3.5 m annually and are estimated to run dry in a couple of decades. Massive internal displacements are expected.

#### *Sri Lanka*

Since Sri Lanka is close to the equator, warm conditions prevail for most of the year. This warm weather, when combined with weak or delayed monsoonal rains, results in droughts that affect agricultural productivity in parts of the country. On average, eight droughts occur annually across the country (DIMS 2015). Most droughts occur during the months between monsoons, from January to March and August to September. Southern regions experience more droughts.

## **Groundwater Contamination**

The pollution of groundwater from human activities and natural processes is worsened by climate change. There are two main climate impacts. First, aquifer recharge is reduced in areas subject to decreasing rainfall, greater evaporation rates, and/or siltation of recharge sites, such as in the alluvial delta. This leads to drawdown of water tables, followed by horizontal or vertical transfer of pollutants. Second, saline water intrudes into coastal aquifers as the dry-season flow decreases in river deltas such as the Lower Ganges (Shamsudduha 2013). Countries mostly affected by climate-related risks of groundwater contamination include Afghanistan, Bangladesh, India, Pakistan and Sri Lanka.

### *Afghanistan*

Groundwater quality in the Kabul Basin varies greatly from one locale to another, with high concentrations of dissolved solids in some areas (Broshears et al. 2005). A significant factor aggravating groundwater pollution in this semiarid country is the limited renewal of groundwater due to inadequate recharge and storage capacities (Mack et al. 2014). High concentrations of contaminants are maintained with no dilution.

### *Bangladesh*

The major climate-related cause of groundwater pollution currently observed in Bangladesh is the saline contamination of coastal aquifers during storm surges. This source of groundwater contamination is expected to increase in the future as the sea level rises. Other anthropogenic processes are currently more important causes of contamination. Ongoing pumping in aquifers, which depletes the local groundwater level (Rajmohan and Prathapar 2013), will accelerate pollution through lateral movements of contaminants such as arsenic (Smith et al. 2000; Chakraborti et al. 2013). Increasing infiltration of toxic residual from agricultural, urban and industrial activities is also spreading contaminants (Zahid and Ahmed 2006).

### *India*

The 7,500 km-long Indian coastline is prone to groundwater contamination by saltwater intrusion, especially during meteorological droughts and in areas where groundwater levels are depleted to the sea level (such as in Tamil Nadu, Pondicherry and Gujarat) (Garduño et al. 2011; Chinnasamy and Sunde 2016; Chinnasamy and Agoramoorthy 2015). The presence of tidal rivers and estuaries above an aquifer can also lead to salinization of the aquifer as water infiltrates downward.

### *Pakistan*

Salinity is increasing in most of the coastal areas, especially in the lower deltaic plain region of Pakistan and the Bela Plain (Mujtaba and Latif 2013). Water from the aquifers of Sindh and Punjab is unfit for human consumption due to natural arsenic contamination (Zubair et al. 2014), saltwater intrusion, and anthropogenic pollutants such as human sewage and fertilizers.

### *Sri Lanka*

Elevated levels of pathogens, nitrate, chlorine, heavy metals and sulphates are present in aquifers. Along the coast of Sri Lanka, shallow sand aquifers cover 1,250 km<sup>2</sup> and are intensively used. The water from these aquifers meets the demand of the tourist industry, human settlements and intensive agriculture along the coast. Freshwater is recharged during the monsoon season and is used throughout the year. Over-extraction can lead to coning of the freshwater lens and ingress of underlying brackish water, thus polluting the aquifers.

## Cyclones

Although cyclones can generate inland floods, they are better known for the damage they cause along coastal areas, where strong winds and surges of seawater destroy infrastructure. Because most cyclones originate from the warm Indian Ocean, their effect is strongest near the coast and particularly over flat lands. The most affected countries include Bangladesh, India, Pakistan and Sri Lanka. Bangladesh is subjected to strong cyclones originating in the Bay of Bengal from April to May and September to November (Karmalkar et al. 2012). Damage can reach several billion dollars (Mirza et al. 2003) and casualties in the hundreds of thousands. Over the last 125 years, 42 major cyclones have hit coastal areas in South Asia, including 14 in the past 25 years (Das Gupta et al. 2005).

## Siltation and Landslides

Siltation is the deposition of soil particles that originate from erosion of soil material. Erosion is frequent in steep terrain and is worsened by heavy rainfall, stream erosion, snowmelt, earthquakes, changing groundwater levels, volcanic eruptions and anthropogenic factors such as land-use changes (Mitra and Sharma 2012; Ahmed and Suphachalasai 2014; Arora et al. 2014; Meraj et al. 2015). Landslides occur because of unstable slopes, heavy rainfall and destabilization from earthquakes. These occurrences have increased over recent years due to more intense anthropogenic activities, especially deforestation, particularly in countries in the HKH Region, such as Nepal (Shrestha 2008; Bajracharya and Shrestha 2011; Immerzeel et al. 2012; Shrestha et al. 2017).

In the Indus River Basin, perennial runoff, partly sustained by ice melt and snowmelt, is responsible for high erosion rates on hillslopes, where vegetation is sparse and the soil is fragile due to the semiarid climate and intensification of agriculture. The Indus River and its tributaries carry about 0.44 km<sup>3</sup> of sediment annually. Nearly 60% remains in the system, where it is deposited in natural depressions, reservoirs, canals and irrigation schemes. In the Tarbela catchments, 167 m<sup>3</sup>/km<sup>2</sup>/year of silt are eroded. The Mangla and Tarbela dams/reservoirs play an important role in the economy of Pakistan by providing low-cost hydroelectric power and water for irrigation. Sedimentation is reducing the storage capacity of these reservoirs by 0.031 km<sup>3</sup>/year and 0.14 km<sup>3</sup>/year, which is equivalent to 0.3% and 1% of their total storage capacity, respectively. After 3 years of operation, the Warsak Dam was virtually fully silted, becoming a run-of-the-river dam with insignificant storage and flood-mitigation capacity (Mirza and Ahmad 2005), and reduced ability to sustain dry-season flow for downstream irrigation and navigation.

About  $794 \times 10^6$  tons of sediment are transported by the Ganges River each year; 80% ( $\pm 10\%$ ) comes from the High Himalaya and 20% ( $\pm 10\%$ ) comes from the Lower Himalaya. About 8% of the river sediment is deposited on floodplains and delta plains in Bangladesh. The remainder ( $\sim 45\%$ ) is deposited in the flooded area of the delta and the Bengal Fan (Wasson 2003). High sediment deposition rates in the delta of the GBM partly compensate for land subsidence (Brown and Nicholls 2015) and, therefore, mitigate the negative effects of sea-level rise.



## Chapter 4. Climate Change in South Asia: Knowledge, Tools and Limitations

This chapter reviews available information on climate change, with a focus on rainfall and temperature, and its effects on sea level rise. It reviews the predictive performance of the climate models of the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5). The chapter also presents suggestions to cope with uncertainties in water management (see Box 4.1).

### Box 4.1. Uncertainties in climatic and hydrologic projections.

Uncertainties in climate and hydrological projections are due to a range of factors, including the reliability and availability of data used to calibrate climate and hydrological models; limited understanding of climatic and hydrologic processes and thus the inevitable inaccuracy of models; the uncertainty in scenarios of future greenhouse gas (GHG) emissions; and the omission of other influential dynamics, such as modal and quantitative changes in water and land use.

*Climate models:* General circulation models (GCMs) compute climate variables and sea levels using scenarios of GHG emissions. Many different GCMs exist. Their differences include various representations and mathematical formulations of natural processes with varying spatial and temporal resolutions. Different GCMs usually produce different climate outputs, revealing the complexity of climate dynamics and the difficulty of predicting them, especially in monsoonal South Asia (IPCC 2014). To characterize this uncertainty, the CMIP was created in 1995 to coordinate experiments by different groups of modellers. The Fifth Phase of the CMIP (CMIP5) provides a multimodel context to assess the mechanisms responsible for differences in model output. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) uses the GCMs included in the CMIP5. Compared to the Fourth Assessment Report (AR4), AR5 climate simulations are improved at the continental scale, but precipitation simulations are still poorer than temperature simulations. While confidence in the representation of processes involving clouds and aerosols remains low, the ability to simulate ocean thermal expansion, glaciers and ice sheets, and thus sea level, has improved since AR4. The magnitude of uncertainties has not changed significantly, although these uncertainties are better characterized (IPCC 2014). Despite relatively coarse resolutions, CMIP5 models depict the hydrological cycle over South Asia reasonably well (Prasanna 2015). The sources of the largest uncertainties in South Asia include the poor representation of precipitation processes at high altitudes and across strong elevation gradients, and the paucity of high-altitude data for calibration.

*Representative concentration pathways:* In response to the uncertainty regarding future GHG and aerosol emissions, and land-use changes, representative concentration pathways (RCPs) describe four pathways of GHG emissions and atmospheric concentrations, air pollutant emissions, and land use in the twenty-first century. They include one stringent mitigation scenario that aims to likely keep global warming at less than 2 °C above pre-industrial temperatures (RCP 2.6), two intermediate scenarios (RCPs 4.5 and 6.0), and one scenario with very high GHG emissions (RCP 8.5). Scenarios without additional efforts to constrain emissions (“baseline scenarios”) lead to pathways ranging between RCP 6.0 and RCP 8.5. The land-use scenarios in the RCPs illustrate a wide range of possible futures, ranging from net reforestation to further deforestation. These four scenarios produce ranges of change in monthly precipitation and temperature.

*Hydrological models:* Different hydrological models that produce acceptable results for an observed baseline period may respond differently when faced with the same climate change scenario. There are several types of hydrological models. Fully distributed, physically based models can detail a

(Continued)

**Box 4.1. Uncertainties in climatic and hydrologic projections.** (continued)

range of processes, potentially at a very fine spatial scale, but require an extensive range of data. Semi-distributed or lumped models adopt a more conceptual approach for process description. Global hydrological models employ large model grid sizes and simplified process descriptions (Thompson et al. 2013). The main hydrological modelling challenges in South Asia stem from the limited understanding of the processes regulating glacial melt in a complex orographic environment, and the hydrological processes involved in extreme weather events, as well as inadequate hydrologic data, poor understanding of surface water-groundwater interactions, and little data on consumptive water use. The limited observation networks and data availability for both precipitation and river flows present further difficulties for validating models and estimates of water balances (Mathison et al. 2015).

**Climate Variables**

Changes in atmospheric and ocean temperature, and their spatial variability, are the primary drivers of changes in precipitation in South Asia.

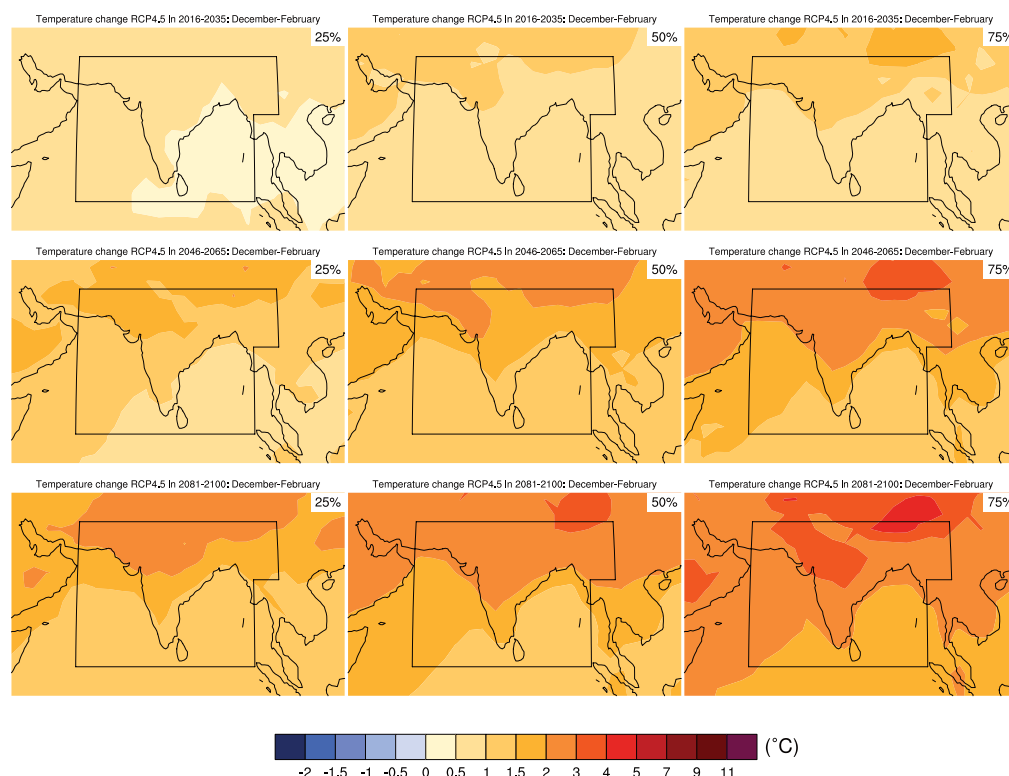
***Temperature******Observed trends***

IPCC has reported that warming occurred across most of the South Asian region over the twenty-first century, with more temperature extremes. Records indicate that there were more warm days and fewer cold days (CDKN and ODI 2014). The warming influence is greater in the Eastern Himalayas compared with that in the Greater Himalayas. Warming is also enhanced in the Thar Desert, but increases are less pronounced than in the Eastern Himalayas. Warming hot spots include Nepal, Bangladesh and most parts of India (particularly the tropical region), compared with Pakistan and the Greater Himalayan Region (Sheikh et al. 2015).

***Projections***

Unlike rainfall projections, which are characterized by contrasts in trends and magnitude across the region and high uncertainty, future trends in temperature are expected to be more monotonic spatiotemporally. However, rising temperature will not be uniform across South Asia (Figure 4.1). The smallest increases in temperature will be observed along the coasts of southern India, Sri Lanka and Bangladesh. The largest temperature increases will be observed at higher latitudes in Afghanistan, Bhutan, northern India, Nepal and Pakistan. The Himalayan-Gangetic Region is warming at rates greater than the surrounding Indian Ocean, especially during the pre-monsoonal period (April to May) (Gautam et al. 2009). This phenomenon is enhanced by reduced snow cover over the Himalayas (Goes et al. 2005), which reduces albedo. Compared to the average in the twentieth century, average annual temperature could increase by more than 2 °C in South Asia by the mid-twenty-first century and these increases could exceed 3 °C by the late twenty-first century under a high-emissions scenario. Oceans in subtropical and tropical regions of Asia will warm under all emissions scenarios and will warm mostly at the surface.

FIGURE 4.1. Mean annual temperature changes in 2016-2035, 2046-2065 and 2081-2100 in relation to the period 1986-2005 under the RCP 4.5 scenario.



Source: IPCC (2013, Figure AI.60, page 1374).

Notes: For each point, the 25<sup>th</sup>, 50<sup>th</sup> and 75<sup>th</sup> percentiles of the distribution of the CMIP5 ensemble are shown; this includes both natural variability and inter-model spread (IPCC 2013). Compared to Figure 4.2, the absence of hatching reflects statistical significance of temperature changes greater than rainfall changes.

## Precipitation

### Observed trends

Rainfall trends over the past century in South Asia have been characterized by strong variability, with both increasing and decreasing trends observed in different countries (CDKN and ODI 2014). A review of recent India-wide trend analyses of rainfall over the twentieth century concluded that, due to high spatiotemporal variability of rainfall arising from complex atmospheric dynamics, past studies have often produced inconsistent results (Lacombe and McCartney 2014). Inconsistencies and discrepancies between the results of different studies were due to several possible factors: the differences in the periods studied, especially when time-series exhibit cycles that span over several decades; the spatial variability; different definitions of the variables studied tested for trend detection; the use of different statistical tests; and the selection of different decision thresholds for the statistical significance.

For all these reasons, the numerous rainfall trend studies available for the seven countries of South Asia are not reported here. Instead, this discussion refers to a recent review (Lacombe and McCartney 2014) that focused on the largest country, India, and that aims to uncover consistencies among previous publications. Using rainfall data from the India Meteorological Department, the authors analyzed trends

in monthly and seasonal cumulative rainfall depth, number of rainy days and maximum daily rainfall, and in the monsoonal occurrence (onset, peak and retreat) from 1951 to 2007. They found evidence of earlier monsoonal onset in northern India (at a 95% level of field significance), and an increase in pre-monsoonal rainfall depth in northeast India and a decrease in southwest India (at a 99% level of field significance). They confirmed that there have been more extreme rainfall events and fewer weak rainfall events in central India.

General trend patterns were found to align well with the geography of anthropogenic atmospheric disturbances. Enhanced warming of the Himalayan-Gangetic Region and the relatively smaller surface warming of the Indian Ocean are strengthening the inflow of moist air from the ocean toward the continent, particularly during the pre-monsoon season in April and May (Gautam et al. 2009). The Himalaya chain acts as a barrier and most likely explains the rainfall increase observed in northern India before the monsoon (Lacombe and McCartney 2014). Because warm moist air transiting through the country is drawn into the rising air over northern India, central India receives less precipitation (Lau and Kim 2006).

The positive effect of the enhanced thermal land-sea contrast on rainfall extends to all of India in June (Lacombe and McCartney 2014), in response to stronger solar radiation and the reduction of snow cover over the Himalayan-Tibetan Plateau. Increased rainfall in June leads to regional atmosphere-land feedback that cools the land surface (Bollasina et al. 2008), possibly explaining the subsequent reduction in rainfall observed during the peak monsoonal months (July-August). The strongest rainfall decreases are observed in July along the southwest coast of India (Lacombe and McCartney 2014). In contrast, the increase in maximum daily rainfall (extreme weather events) during the monsoon may be attributable to the gradual increase in surface temperature of the sea (Goswami et al. 2006). Therefore, the rise in the magnitude of extreme rainfall events is predominantly controlled by the increased atmospheric moisture content, while the reduction of cumulative rainfall depth results from the weakening of the air flow in response to the reduced sea-land thermal contrast observed in July and August.

These consistencies of trends add validity to the attribution of rainfall changes to increasing GHG concentrations. The spatial variability of these extreme rainfall events has increased over time, with a tendency of wet areas to receive less rainfall and dry areas to receive more rainfall, suggesting the need to re-evaluate the planning of water transfers among basins (Ghosh et al. 2016).

The increase in atmospheric aerosol concentrations is another important anthropogenic driver of incoming solar radiation and long-term rainfall change. Since the 1930s, both sulfur dioxide (SO<sub>2</sub>) and fossil-fuel black carbon have increased sixfold in response to the nearly fourfold population increase and the accompanying industrialization in the Indo-Gangetic Plain (Ramanathan et al. 2005; Bollasina et al. 2011). Atmospheric aerosol loading generally starts in March/April and peaks in May. According to the “elevated heat pump” theory (Lau and Kim 2006), aerosols rising close to the southern slope of the Himalayas warm the middle and upper troposphere, enhancing the large-scale meridional temperature gradient and thereby amplifying the meridional circulation, drawing in more moisture from the Indian Ocean. This phenomenon amplifies the rainfall increase before the monsoon as observed in northern India (Lacombe and McCartney 2014). In addition, hygroscopic particles, such as sulfate aerosols, act as nuclei for cloud condensation, promote cloud formation and may enhance precipitation. However, the complex character of climate dynamics controlled by subtle combinations of local, regional and global natural and anthropogenic forcing (e.g., GHG and aerosol emissions), whose effects on atmospheric circulation are not yet totally understood, impedes the attribution of rainfall trends to aerosols (Turner and Annamalai 2012).

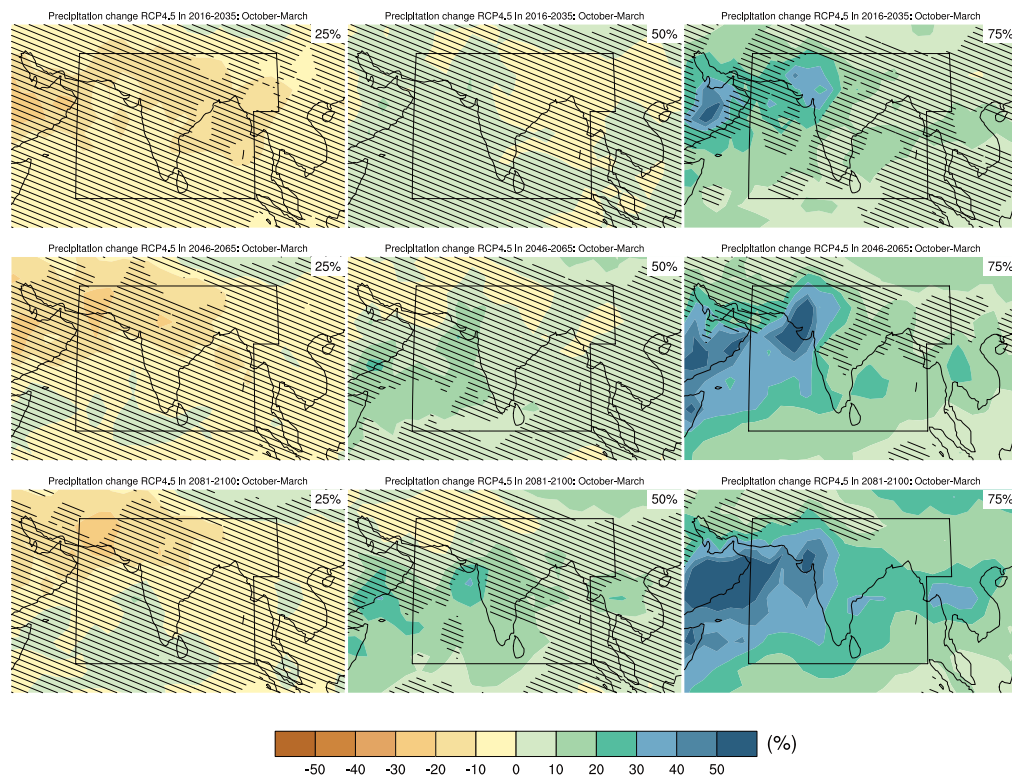
### *Projections*

Even though the accuracy of state-of-the-art GCMs continues to improve, there are considerable challenges in predicting changes in monsoonal rainfall due to the difficulty in modelling the regional distribution of precipitation, especially in South Asia, where the atmospheric dynamics controlling the monsoon are difficult to model (Turner and Annamalai 2012). Increased concentration of GHGs is expected to strengthen the monsoon through a temperature increase of the Indo-Pacific Oceans, leading to enhanced evaporation rates from the ocean and an increase in moisture supply to the subcontinent. However, rainfall projections



remain uncertain over South Asia. Figure 4.2 illustrates predicted rainfall changes over the region, using the most recent ensemble models (Fifth Phase) of the CMIP5 (IPCC 2014). Based on the intermediate RCP 4.5 emission scenario and focusing on the median projection of the CMIP5 (the 50<sup>th</sup> percentile) over the period 2016-2035 (center panel in Figure 4.2), Bangladesh, Bhutan, India and Sri Lanka will be exposed to a 10% increase in annual rainfall, with the highest statistical significance in Sri Lanka. The greatest increases in annual rainfall, reaching 20%, will occur in southwest India and southern Pakistan. In contrast, rainfall will decrease by about 10% in Afghanistan and Nepal. An earlier monsoonal onset is expected (Annamalai et al. 2007), while the year-to-year variability in rainfall is expected to increase (Turner and Annamalai 2012).

FIGURE 4.2. Precipitation changes in 2016-2035, 2046-2065 and 2081-2100 in relation to the period 1986-2005 under RCP 4.5 scenario.



Source: IPCC (2013, Figure AI.62, page 1376).

Notes: For each point, the 25<sup>th</sup>, 50<sup>th</sup> and 75<sup>th</sup> percentiles of the CMIP5 distribution are shown; this includes both natural variability and inter-model spread. Hatching denotes areas where the 20-year mean differences of the percentiles are less than the standard deviation of model-estimated, present-day natural variability of 20-year mean differences (IPCC 2013).

Projection of rainfall across South Asia remains highly uncertain, as revealed by the fact that, in many areas, the standard deviation of the model-estimated variability of present-day 20-year mean rainfall is higher than the projected precipitation changes (see hatching in Figure 4.2), and the direction of the projected trends (either positive or negative) changes according to the percentiles of the distribution of the CMIP5 ensemble considered.

Finally, it should be noted that the climate projections illustrated in Figures 4.1 and 4.2 were all derived from the RCP 4.5 GHG concentration scenario. Using a more adverse scenario that anticipates greater GHG concentrations (RCP 6 and RCP 8.5) would have likely resulted in more significant temperature and rainfall changes. This draws attention to the critical need to implement mitigation measures as soon as possible.

### ***Sea-level Rise***

#### *Observed trends*

Globally, the rate of sea-level rise since the 1850s has been higher than the average rate during the previous 2,000 years. Shifting surface winds, the dilatation of warming seawater and the addition of melting ice can alter ocean currents that, in turn, lead to changes in sea level that vary from place to place (IPCC 2014). Past and current variations in the distribution of land ice affect the shape and gravitational field of the Earth, which also cause regional fluctuations in sea level. Additional variations are caused by sediment and tectonics. Changes in sea level in the Indian Ocean have emerged since the 1960s, driven by changing wind patterns (CDKN and ODI 2014). Sea-level rise recorded over the last two decades varied between 2 mm/year and 5 mm/year along the South Asian coasts, with a local minimum of 0 mm/year in the Indus Delta and 1 mm/year along the western side of the southern Indian Peninsula (Nicholls and Cazenave 2010).

#### *Projections*

Global mean sea level will continue to rise during the twenty-first century. Under all emissions scenarios (low and high), the rate of sea-level rise will likely exceed that observed during the past three decades. Mean sea-level rise will likely be in the range of 26-55 cm under a low-emissions scenario by the last two decades of the twenty-first century (as compared to sea levels in 1986-2005), and up to 98 cm by 2100 under the high-emissions scenario. Projections indicate that the average height of waves in the Indian Ocean monsoons will not change greatly (IPCC 2014; CDKN and ODI 2014). The intensity of tropical cyclones and associated storm surges is expected to increase (Knutson et al. 2010), likely worsening the damage caused by sea-level rise. However, it is not clear whether there will be a shift in the timing of such events. Increased coincidence with river-flood peaks would have devastating consequences for Bangladesh.

### **River Flow and Groundwater Recharge**

By modifying rainfall, temperature and other climate variables (such as solar radiation), climate change alters river flows, groundwater and their interactions, and generates associated risks (e.g., drought, floods, siltation, erosion, evaporation losses and groundwater contamination). While modified precipitation can alter river flow throughout South Asia, temperature rise operates over distinctive zones to alter flow regimes through two main processes. The rise in standard evapotranspiration induced by warming and the related alteration of vegetation cover are likely altering surface streamflow production over the entire land area. In contrast, the hydrological impact of temperature rise through ice and snow melting is modifying flow regime in basins that include a significant portion in the HKH Region (see related countries in Table 2.1). While climate change is expected to modify river flow patterns, rising water demands across sectors, along with land-use changes, are expected to significantly affect the water cycle and associated river flow regimes, as discussed in Chapter 5.

#### ***Effect of Temperature Rise on Snowmelt, Ice Melt, and River Flow***

Global warming alters the cryosphere (the frozen part of the Earth system) in several ways. Quantifying these impacts is difficult due to uncertainties stemming from variations in climate change projections and partial understanding of the processes that control the cryosphere dynamic. The major impediments preventing accurate assessments include uncertainties about the influence of debris cover on glacier

melt, the role of ice and snow avalanches in the glacier mass budget, the possible discrepancies with past glacier changes as revealed from comparison of maps (Bolch et al. 2012), and the scarcity of large-scale, high-resolution modelling approaches that explicitly model snow and ice dynamics (Lutz et al. 2014). Records since 1850 suggest that the volume of perennial ice and snow cover that had accumulated over centuries in the HKH Region has continuously decreased (Bolch et al. 2012).<sup>4</sup> Glacier area and volume were reduced by 14-28% and 11-40%, respectively, from 1960 to 2000. Maximum seasonal snow cover area was reduced by 5-15% between the 1961-1990 and 2001-2010 periods, which is equivalent to a 9-27% reduction in maximum seasonal water storage capacity (Savoskul and Smakhtin 2013a). The contribution of ice melt and snowmelt water to river flow varies spatiotemporally.

Meltwater is a major source of water in regions with little summer precipitation (41% of river flow in the Indus Basin), and is less important in monsoon-dominated regions (25%, 20% and 18% of the river flow in the Brahmaputra, Ganges and Tamakoshi basins, respectively) (Tables 2.1 and 2.2). Between the periods 1961-1990 and 2001-2010, the contribution of meltwater to annual flow decreased by 6-25% in the Ganges and Brahmaputra river basins and by 5% in the Indus Basin (Savoskul and Smakhtin 2013b). The most pronounced change occurred in the composition of glacier runoff. The share of the non-renewable component in the total glacier runoff increased from 16-30% to 26-46% in all basins. Warmer temperatures not only accelerate ice and snow melting but also increase the ratio of rainfall to snowfall, resulting in melting ice not being replenished (Shrestha et al. 2017). According to the Spatial Processes in Hydrology (SPHY) model, by 2050, the glacial area will be reduced by 24% in the Indus, 35% in the Ganges and 45% in the Brahmaputra basins. Although the relative decrease is smallest in the Indus Basin, the absolute loss is likely to be the greatest because it has the largest glaciated area. However, in the Indus, Ganges, Brahmaputra and Amu Darya river basins, glaciers belonging to the large and medium-sized classes are expected to survive warming of 4-5 °C, with total basin ice reserves reduced to 20-50% of the 1961-1990 baseline (Lutz and Immerzeel 2013).

### ***Combined Effect of Temperature and Rainfall Changes on River Flows in the HKH Region***

#### *Changes in annual discharge*

While there is considerable certainty that temperatures will increase throughout South Asia (Figure 4.1), there is more uncertainty about precipitation patterns (Figure 4.2). Under all climate scenarios until 2050, the amount of ice melt and snowmelt water will decrease in relation to the reduction in the volume of the glacier in the region, while the amount of rainfall-runoff will increase in the upper basins of the Brahmaputra and Ganges rivers. In the Upper Indus Basin, the contribution of ice melt to river flow is projected to increase, while the contribution of snowmelt is expected to decrease. Overall, Lutz et al. (2014) anticipated an increase in runoff at least until 2050, caused primarily by an increase in precipitation in the upper Ganges and Brahmaputra basins and from accelerated melt in the Upper Indus Basin.

#### *Change in flow seasonality*

Depending on the streamflow composition (glacial melt, snowmelt, rainfall, baseflow), the regimes of different rivers will respond differently to climate change. In the Ganges and Brahmaputra basins, combined changes in glacier, seasonal snow extent and precipitation patterns may well have little effect on hydrological regimes (Savoskul and Smakhtin 2013b). The streamflow peak will continue to be controlled mainly by the monsoonal rainfall peak (Immerzeel et al. 2010). In contrast, in the Indus Basin, the reduction of glaciers and seasonal snow cover will significantly affect the seasonality of river flow. Combined changes in temperature and rainfall will have distinct hydrological effects, depending on the elevation that controls the three river regimes: nival, glacial and pluvial. The nival regime at middle altitudes is characterized by the melting of seasonal snow accumulated during the preceding winter and

<sup>4</sup> However, some glaciers in the highest parts of the central Karakoram have displayed evidence of growth (known as the Karakoram anomaly) (Shrestha et al. 2015).

spring. At very high altitudes, the glacial regime closely depends on the summer temperature. The pluvial regime depends on runoff from concurrent rainfall, mainly during the monsoonal season. Of these three regimes, the greatest flow contribution comes from the nival regime, because the seasonal snow area is an order of magnitude greater than the area of perennial snow and ice, although this area shrinks through the melt season. In this zone (e.g., Upper Jhelum Basin), summer runoff is positively correlated to winter precipitation and negatively correlated to summer temperature (due to snow sublimation). Since both winter precipitation and summer temperature are expected to increase (Archer et al. 2010), the direction of change in future flow is uncertain. River flow from very high catchments (e.g., Shyok, Hunza and Shigar rivers) represents less than 30% of the Indus to the margins of the mountains. In these catchments, summer runoff is positively correlated to summer temperature, but not correlated to the precipitation of the preceding winter. This leads to the conclusion that runoff will increase initially, but will ultimately decrease sharply as glacier mass shrinks. However, in some areas (e.g., Karakoram), summer temperatures, particularly minimum temperatures, are currently decreasing. The combination of these trends suggests a response to climate change in glacial regimes of the Upper Indus that differs from other tropical glaciers (Archer et al. 2010). In addition, all over the HKH region, the reduction in glacier albedo (reflectance or optical brightness) caused by deposition of black carbon emitted by India (Menon et al. 2010) and China (Xu et al. 2009; Li et al. 2016) is enhancing glacier melt. The monsoonal rainfall regime dominates on the southern foothills of the Himalayas. Although the seasonal volume of runoff resulting from rainfall is lower than from glacial and nival sources, rainfall produces more intense runoff and floods. These are expected to increase in frequency and intensity according to the climate projections (IPCC 2013). In addition, the earlier monsoonal onset anticipated for the coming decades is expected to shift the flood pulse earlier in the year (Annamalai et al. 2007).

### ***Effects of Temperature and Rainfall Changes on Groundwater Recharge***

In general, a sustainable groundwater recharge rate is higher or close to the discharge rate. Concentrated and/or shortened monsoonal and more extreme rainfall events reduce the time available for rainwater to infiltrate the soil, and can also result in more frequent and intense flash floods (Moreland 1993). Concurrently, increased soil erosion caused by intense rainfall and deforestation induces soil crusting that contributes to reduced soil-water infiltration. These factors directly and indirectly affect the amount of water stored in the topsoil zones and recharged to the water table (Moreland 1993). Such impacts are already being felt in Afghanistan, India and Pakistan, where there are more extreme weather events and droughts. Groundwater levels remain below sustainable levels (Shah 2010; Taylor et al. 2013; Chinnasamy and Agoramoorthy 2015). Though projections are very uncertain, South Asia may face a reduction in groundwater recharge by 10% in the 2050s as a result of climate change (Clifton et al. 2010).

Change in rainfall is not the only driver of modified recharge rates. In high-latitude regions, recharge may be enhanced by increased spring snowmelt due to increasing winter temperatures. In alluvial areas, more frequent floods can increase groundwater recharge, while arid and semiarid regions will face a reduction in groundwater recharge. Before development of widespread irrigation across the Indus and GBM basins, losses from the river system were a major source of recharge, particularly in the Indus River system, where rainfall decreases downstream. Groundwater recharge also occurs close to the Ganges River system during the monsoonal season, where extensive flooding infiltrates the shallow aquifer (MacDonald et al. 2015).

This comparative analysis indicates that the effect of climate change on groundwater recharge will occur mostly in response to modified rainfall patterns in the GBM Basin and modified hydrology in the Indus Basin. Since a good deal of natural recharge occurs in areas with vegetative cover, such as forests, changing evapotranspiration rates resulting from rising temperatures may reduce infiltration rates from natural precipitation, thus reducing recharge (Shah and Lele 2011).

## **Integrating Climate Change in Water Resources Management**

### ***Managing Uncertainty***

Though considerable investment has been made in climate modelling with the aim of benefiting decision makers, climate models have been more useful for setting the context than for informing investments and policy choices. One fundamental and unavoidable issue limits the utility of climate projections: the uncertainty associated with future climate is largely irreducible in the temporal and spatial scales that are relevant to water resources projects. GCMs are not able to predict variables that are most important for water resources projects, such as local hydrologic extremes (floods and drought). As a result, project planners gain little insight into the potential impact of climate change on their project. It is not always clear whether the effects of changes in climate on a particular water resources project are significant relative to the impacts of changes in other non-climate factors such as demographics, land use and economic changes. Project planners are, therefore, ill-equipped to incorporate uncertain climate information into a broader assessment of a project's probability of success, and thus to make intelligent modifications to the project design to reduce its vulnerabilities to failure. If the project planner succeeds in characterizing the relative importance of various risks and system vulnerabilities, the choice remains as how best to manage those risks to improve the robustness and flexibility of the system.

### ***Available Approaches***

Integrating comprehensive risk assessments and risk reduction measures into the core of decision making will help South Asia cope with climate change. Several tools to support decision making allow water resource risks to be assessed to assist project planning under uncertainty. They can help allocate resources more effectively to water resources project components depending on the sensitivity to climate risks and available adaptation tools. The decision tree framework (Ray and Brown 2015) (Box 4.2) evaluates the robustness of a water resources project to climate change and indicates which project components are more sensitive to climate risks. Other tools for decision making under uncertainty include robust decision making, stochastic and robust optimization (including real options analysis), dynamic adaptive policy pathways, or information-gap decision theory.

#### **Box 4.2. The decision tree framework to estimating hydropower scenarios in Nepal.**

The decision tree framework (Ray and Brown 2015) was applied to the Upper Arun Hydropower Project in eastern Nepal and to the overall hydropower portfolio in the Koshi Basin (Karki et al. 2016). The analysis aimed to assess how climate change (river inflow fed by ice melt and snowmelt, modified by changes in temperature and rainfall) and other variables (such as the price of hydropower supplied, sediment load) might affect the optimal design capacity of the projects. Different combinations of planned hydropower capacity were also tested at the basin level. Performance metrics include the economic value of the project, and the total and dry-season hydropower production. Ultimately, this framework aims to help decision makers identify which investments can achieve robust outcomes and appropriately balance the system's benefits. When basins have complex interdependencies and when the various possible interventions are contested, such a system-level trade-off analysis can help bring clarity and consensus (Geressu and Harou 2015; Karki et al. 2016).

The robustness of the project was tested by simulating various climate scenarios using a hydrological model, including a glacier component, and a water system model, which translates water availability into hydropower production. Results indicate that the original design of 335 megawatts (MW) was not able to exploit the predicted increase in flows during the wet season. A design capacity of 1,000 MW emerged as an attractive alternative, although it was more sensitive to increases in capital costs and electricity prices. Input variables were selected in consultation with the Nepal Electricity Authority and relevant literature to ensure that their ranges of values are realistic. Historical records of temperature and precipitation were adjusted with the intention of going far beyond the ranges covered by the IPCC projections to demonstrate the resilience of the project to climate change.

The analysis went on to the later phases of the decision tree, even after climate risks were shown in phase 2 to be low, only because the investors and stakeholders wanted to know if a larger design size might capitalize on the opportunities for hydropower generation presented by more favorable conditions. Because the performance of hydropower assets depends on factors such as river flows, water management rules, and upstream and downstream water use, the basin-scale analysis aims for integrated water resources management. The model endorsed by the stakeholders was used to simulate the basin system over a 30-year period, given various options for infrastructure development and operating rules. The model was optimized to identify a small set of the highest-performing portfolios (the most efficient and robust combinations of options). Investment bundles preferred by the stakeholders were then stress-tested in detail to identify any vulnerabilities, including institutional and financial variables.

## Chapter 5. Effect of Climate Change on Climate-related Risks

Climate change is exposing populations to various risks related to modified climates (e.g., storms, cyclones, heat waves and droughts), to the alteration of water availability (e.g., modified river flow regimes and groundwater recharge, siltation of reservoirs), and to sea-level rise (e.g., coastal floods, saltwater intrusion in coastal aquifers). These factors are sometimes interrelated (e.g., exacerbation of sea-level rise by storm surges, combination of earlier snow melting and earlier monsoonal onset). Therefore, the predictability and impacts on populations are not uniform.

This chapter reviews the main effects that climate change will have on climate-related risks and how they vary between subregions.

### Floods

With ongoing climate change, the number of flood disasters has been increasing since the 1970s. This rising trend is expected to continue in the next few decades (IPCC 2014; CDKN and ODI 2014).

#### *Flash Floods Induced by Changes in Rainfall Patterns and Temperature Rise*

The intensity of extreme rainfall events is likely to increase as a consequence of increasing convective activity during the summer monsoon. More frequent flash floods are possible across South Asia, and particularly over mountainous regions (IPCC 2014; Mirza and Ahmad 2005). The accelerated melting of glaciers increases the number and size of glacial lakes in the Himalayas (Mirza and Ahmad 2005; Bolch et al. 2012). This can lead to more frequent GLOFs (Mool et al. 2001), threatening populations and infrastructure. In Nepal, about 1.6 million people live downstream of moraine-dammed lakes. Several hydropower projects in operation, under construction or planned are located downstream of moraine-dammed lakes that have potential for generating GLOFs (Shrestha et al. 2017).

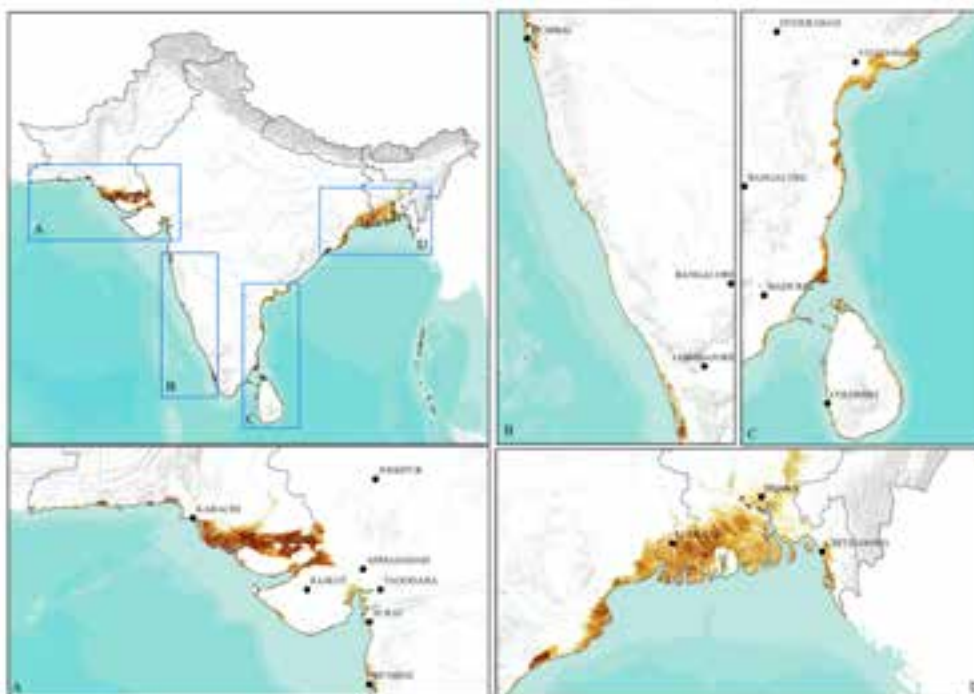
#### *Riverine Floods*

Of all flood types, *riverine floods* are the most pervasive and have long-term impacts on land use, the economy and most development strategies. The expected increased intensity of extreme rainfall events during the monsoonal period will likely result in greater spatial extent and longer flood duration in the GBM and Indus river basins (Apurv et al. 2015), as well as in other rivers. Although these floods are essential for rice production, as they provide nutrients through silting and the required amount of water, excessive spatial extent and duration may delay cropping cycles, damage properties and contribute to the spread of infectious diseases.

#### *Coastal Floods Aggravated by Sea-level Rise and Increased Frequency of Storms*

The low-lying lands will be totally submerged in the absence of protection, especially in Bangladesh (Dasgupta et al. 2010) and Pakistan (Figure 5.1). Coastal lands that will remain above the mean sea level, such as along the Saurashtra Coast in Gujarat, India, will be exposed to more frequent inundations (CWC 2008) causing agricultural yield losses (Bhattacharya et al. 2012). The increased frequency and magnitude of severe cyclones originating from the Indian Ocean, and associated storm surges, are expected to worsen damages caused by sea-level rise. It is predicted that some 25% of the Indus Delta, already retreating because of a sharply reduced silt load, will be submerged under a 2-m sea-level rise (Mirza and Ahmad 2005).

FIGURE 5.1. South Asia hot spots at high risk for hazards from sea-level rise (composite index).



Source: Amarnath et al. 2017.

Notes: The value of exposure was calculated using a composite hazard index accounting for the rate of sea-level rise, the coastal slope, elevation, tidal range, tsunami arrival height and geomorphology (Amarnath et al. 2017).

The delta of the GBM river system is subsiding by about 5.6 mm/year, increasing the deleterious effects of sea-level rise (Brown and Nicholls 2015). The causes of this subsidence are multiple and difficult to disentangle. They may include a combination of tectonic effects, compaction, sedimentation and anthropogenic causes such as river embankments limiting sediment deposition in the floodplains. Continued groundwater abstraction and/or drainage may cause rates to increase locally (Brown and Nicholls 2015).

## Droughts

With climate change and increasing water demand, water-scarce areas will become even more vulnerable to droughts (Dai 2012; Shrestha et al. 2017), especially in areas where groundwater recharge is reduced by altered rainfall and flow patterns. Peak discharge in snow-fed rivers, such as in the Indus Basin, that currently occurs in spring will be smoothed and extended during the earlier part of the year. Because river levels will also drop earlier in the year (at the end of the snow melting season), less water will be available during the peak water demand for hydropower and irrigation in the summer (King and Sturtewagen 2010). As temperatures increase, evaporation will also rise and increase evaporation losses from reservoirs. Crop water demand will increase due to increased evapotranspiration, with greater risk of drought stress (Rosenzweig et al. 2014). This problem will be exacerbated where rainfall is expected to decrease, as in Afghanistan and Nepal (Figure 4.2), and siltation to increase, reducing storage capacities, as already observed in the Lower Indus Basin in Pakistan (Mirza and Ahmad 2005).



## **Groundwater Contamination**

In Bangladesh, over the next half century, as sea levels rise, millions of people will be affected by saltwater intrusion in wells that supply drinking water from coastal aquifers. In India, saltwater intrusion is already occurring in many coastal aquifers such as the Saurashtra Coast in Gujarat and the Minjur aquifer in Tamil Nadu (Tabrez et al. 2008) as land subsides. The effect of subsidence on salinization will be worsened by sea-level rise. Overland saline intrusion, already affecting the Sundarbans and coastal aquifers of West Bengal, will be amplified by sea-level rise. As mentioned, ongoing pumping in aquifers will accelerate pollution through lateral movements of contaminants driven by depletion of local groundwater levels. In Pakistan, because of the projected sea-level rise, saltwater will penetrate further upstream and inland into rivers, wetlands and aquifers, which will harm aquatic flora and fauna. It will also threaten human water supplies, particularly during droughts. These effects will be aggravated by excessive pumping from tube wells and upstream water withdrawals from rivers. These negative effects on fauna, flora and humans are already happening in the Lower Indus Plain (Mirza and Ahmad 2005). In Sri Lanka, the same combination of increased water demand depleting aquifers, sea-level rise and prolonged droughts will contribute to accelerating aquifer pollution (Laattoe et al. 2013; Gunaalan et al. 2015). This phenomenon is already occurring in many parts of the country.

## **Landslide, Erosion and Siltation**

Landslides, erosion and siltation can be triggered by climate (e.g., extreme events), natural events (e.g., earthquakes) and anthropogenic factors (e.g., soil degradation), especially in mountainous regions with steep terrain (Bhutan, India and Nepal). About 26% of the Indian and Sri Lankan coastline will be affected by erosion (Ahmed and Suphachalasai 2014); these hazards will increase due to increased extreme rainfall events caused by climate change, intensified cyclones and sea-level rise. Increased erosion in uplands will increase siltation in water bodies, thus reducing groundwater recharge and storage in reservoirs, leading to higher costs in hydropower maintenance — thus making hydropower ventures less viable in some countries (Nepal et al. 2014). Nepal's Kali Gandaki project already faces tremendous storage losses due to increased sediment loading (Chinnasamy and Sood 2016). Because climate change is already occurring, the impacts induced by climate change previously discussed are already being felt in several countries along the Himalayan range (Walling 2011; Rana et al. 2013; Shrestha 2013): Pakistan (Zakaullah et al. 2014), Bangladesh (Molden et al. 2014), northwestern India (where there is a large impact in Uttarakhand), and Bhutan.

## **Non-climate Factors Aggravating Climate-related Risks**

The impacts of hazard events are escalating not only because of the increased incidence and intensity of climate events, but also because of changes in non-climatic underlying factors that influence exposure and vulnerability. Exposure is driven by a number of socioeconomic dynamics, including population growth in hazard-prone areas, economic expansion, and concentration of economic assets in expanding megacities and rapidly growing secondary cities. The main consequences of these dynamics include changes in land use, groundwater quality and quantity — all of which increase the vulnerabilities of the population to climate extremes.

### ***Land-use Change***

Environmental degradation and poorly planned land use are among the overarching factors behind an increase in disastrous flooding in the mountainous countries of South Asia. Most of the uplands usually combine the poorest, most physically degraded and agriculturally unproductive areas in countries of the region. If the geological, topographical (e.g., steep slopes) and climatic features naturally increase

the susceptibility of uplands to soil erosion, human activities worsen the problem. Practices such as the cultivation of crops on steep slopes and deforestation (in response to a greater timber demand and expanded trade with neighboring countries), combined with overgrazing by livestock and the unsustainable exploitation of scrubland and rangeland, all play a part in the soil degradation process. Soil erosion decreases the capacity of the soil to absorb rainfall and accelerates surface runoff, thus intensifying the devastating effects of flash floods and siltation problems downstream. Reduced water infiltration into the soil also reduces groundwater recharge.

### ***Increase in Groundwater Withdrawals and Contamination***

While the demand for food production is increasing in a context of unpredictable rainfall patterns, many farmers can now access and use groundwater for irrigation thanks to newly available high-yield, motor-driven deep wells and boreholes. Unregulated groundwater use has led to over-exploitation. Groundwater levels have fallen considerably over the past decade, in both farming regions and large cities (Burness and Brill 2001; Qureshi et al. 2010). Groundwater contamination is caused by a wide range of anthropogenic processes. Groundwater pumping draws down the water table and drives lateral flux of dissolved geogenic contaminants, including arsenic (Williams et al. 2006; Heikens 2006), fluoride, uranium, iron and salt. Infiltration of agricultural fertilizer and pesticides, domestic wastewater carrying bacteria (*E. coli*) and industrial effluents, including various toxic products, are also contaminating groundwater. Because the symptoms of arsenic poisoning take longer to appear, the full extent of the problem is probably underestimated.

### ***Vulnerable Populations***

Growth of settlements along the river valleys has also increased the disaster potential of floods. Climate-related risks are especially amplified for those lacking the essential infrastructure and services to avoid or minimize flood damage (Shrestha et al. 2017). Higher exposure to climate-related risks can also enhance social inequalities and economic shocks, poverty, the spread of infectious diseases and food insecurity, causing considerable and fundamental threats to human life, livelihoods, property, political stability, the economy and the environment.

## Chapter 6. Conclusion

### Summary

A combination of factors make South Asia one of the most vulnerable regions to climate change in the world. The intense rainfall events of the monsoon-driven climate, combined with the diverse and dramatic topography of the Himalayas, generate a huge and highly variable amount of water flowing to large and densely populated floodplains. Flood protection infrastructure is weak and is both a cause and consequence of poverty. Irrigation schemes underperform, despite high dependence on water resources. All these gaps exacerbate the vulnerability of South Asian populations to the rising water-related risks in the context of climate change, and contribute to the underperformance of various economic sectors, including agriculture, energy, industry, and rural and urban development.

Climate change is aggravating all climate-related risks. More intense and concentrated rainfall is inducing sharper and more destructive flash floods, especially in mountainous areas (Afghanistan, northern Bangladesh, Bhutan, northern India, Nepal and northern Pakistan). Enhanced erosion and downstream siltation (especially in Pakistan and Nepal) reduces water storage capacities for dry-season irrigation, hydropower production and groundwater recharge (due to both altered rainfall patterns and siltation of water bodies). Temperature rise increases the number of GLOFs (in Bhutan, Nepal, India and Pakistan). It also induces earlier flood peaks in the year (springtime) in snow- and ice-fed rivers (such as the Indus Basin). These peaks do not match peak irrigation demand in the summertime, thus compromising food security and hydropower production. Higher temperatures are inducing greater demand for crop water, reduced yields in already warm areas, greater evaporation losses from surface reservoirs and reduced groundwater recharge. Sea-level rise, combined with more intense and frequent cyclones, is inducing destructive coastal flooding (especially in low-lying and densely populated areas such as Bangladesh) and salt contamination of coastal aquifers (as in Sri Lanka, where most productive aquifers are along the coast). Droughts are affecting all countries during the dry season, especially with the rising food demand related to overall population growth and economic development. Semiarid and arid zones (e.g., Afghanistan, northwest India, Pakistan) are the most vulnerable to meteorological and hydrological droughts. Their detrimental effects are exacerbated by the reduction of snowmelt and ice melt river flow, reduction of groundwater recharge and reservoir siltation, which affect not only agriculture but also industrial and domestic water uses.

Several anthropogenic factors are exacerbating climate-related risks. Unsustainable rates of pumping (mainly in Bangladesh, India and Pakistan) are threatening water availability and quality. Land-use changes, especially in mountainous areas, are accelerating erosion (Afghanistan, Bhutan, India, Nepal, Pakistan), reducing water infiltration and groundwater recharge, and increasing the risks of floods and siltation downstream.

While temperature projections and their expected effects are well known and anticipated, rainfall projections are much more uncertain and require a decision framework that can help allocate resources more effectively to the components of water resources projects depending on the sensitivity to climate risks and available adaptation tools.

Table 6.1 provides a list of climate-related risks for each country, ranked according to three levels (high, medium and low). The table is based on a literature review, with a focus on the assessment proposed by Amarnath et al. (2017) and disaster data available at <http://www.emdat.be/>. This ranking corresponds to the current situation. In the future (as the climate continues to change), coastal floods and storms/cyclones will rise in associated risk levels, especially in Bangladesh. Although other risks will increase, they will not necessarily change category (high, medium, low), because they will all increase concurrently. This ranking is based on an overall (and inevitably subjective) integration of damage costs, casualties and the number of people affected. A more rigorous approach should include objective and quantitative criteria.

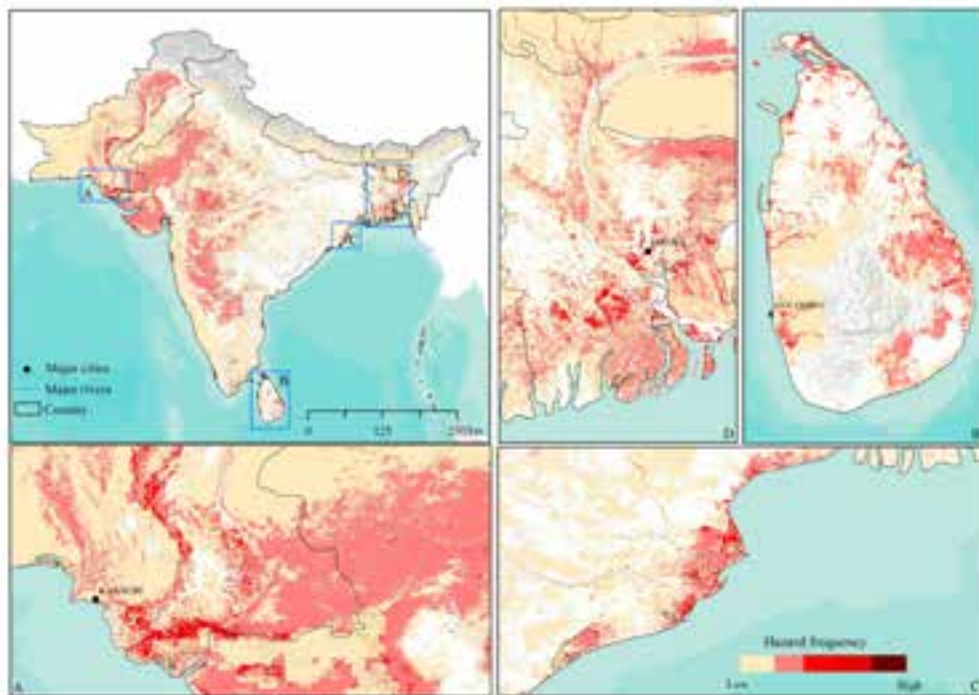
TABLE 6.1. Ranking of climate-related risks.

	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Sri Lanka
High risk level	Landslide Drought	Riverine flood Groundwater salinization	GLOF Flash flood	Drought	GLOF Flash flood	Drought Groundwater depletion	Drought Storms/Cyclones
	Groundwater depletion	Storms/Cyclones	Landslide	Riverine flood Landslide Flash flood	Landslide	Landslide	Groundwater salinization
Medium risk level	Riverine flood Erosion/Siltation	Coastal flood Drought	Drought Erosion/Siltation	Storms/Cyclones Groundwater salinization	Drought Erosion/Siltation	Flash flood Groundwater salinization Erosion/Siltation	Riverine flood Groundwater depletion Flash flood
	Flash flood	Groundwater depletion	Storms/Cyclones			Coastal flood	
Low risk level	GLOF Storms/ Cyclones	Erosion/Siltation Flash flood	Riverine flood Groundwater depletion	GLOF Coastal flood	Riverine flood Storms/Cyclones	Storms/Cyclones GLOF	Erosion/Siltation Landslide
		Landslide		Erosion/Siltation	Groundwater depletion	Riverine flood	Coastal flood
No risks	Coastal flood Groundwater salinization (caused by sea-level rise)	GLOF	Coastal flood Groundwater salinization (caused by sea-level rise)		Coastal flood Groundwater salinization (caused by sea-level rise)		GLOF

*Note:* GLOF = Glacial lake outburst flood.

Amarnath et al. (2017) quantitatively and systematically assessed multiple baseline climatic risks in South Asia (excluding Afghanistan), including droughts, floods, extreme temperature (heat waves), rainfall and sea-level rise. Erosion and siltation-related risks were not included in this analysis. These climatic hazards, along with population densities, were modelled using geographic information systems (GIS), which enabled associated human exposure and agricultural losses to be summarized. A combined index based on hazard, exposure and adaptive capacity was introduced to identify areas of extreme risk and these were mapped (Figure 6.1). Of the population affected, 72% is in India, followed by 12% each in Bangladesh and Pakistan. An analysis of individual hazards indicates that floods and droughts are the dominant hazards affecting agricultural areas, followed by extreme rainfall, extreme temperature and sea-level rise. Based on this vulnerability assessment, the following are among the most vulnerable regions in South Asia: all the regions of Bangladesh and the Indian states of Andhra Pradesh, Bihar, Maharashtra, Karnataka and Odisha; Ampara, Puttalam, Trincomalee, Mannar and Batticaloa in Sri Lanka; Sindh and Balochistan in Pakistan; central and east Nepal; and the transboundary river basins of the Indus and the GBM.

FIGURE 6.1. Overall climate hazard map showing the combination of climate-related hazards and the hot spots in South Asia.



Source: Amarnath et al. 2017.

Notes: Climate-related hazards = floods, droughts, extreme rainfall, heat waves and sea-level rise. Hot spots include a part of Bangladesh (panel D), Sri Lanka (panel B), areas of Pakistan and northwestern India, affected by drought and floods (panel A), and coastal areas in eastern India (panel C).

## Knowledge Gaps

Sound water management and prevention of climate-related risks require accurate information, and an understanding of how the quality and quantity of water vary spatiotemporally, the drivers that affect these variations at multiple scales, and how climate change will modify these relationships. Improved knowledge should help in anticipating and minimizing risk of floods, droughts, contamination of surface water and groundwater, erosion and downstream siltation.

## Data

### *Climate variables*

Meteorological stations, either manual or automatic, monitor rainfall, temperature and other climate variables, in combination with river monitoring stations, to understand and predict the different components of the water cycle and its spatiotemporal variability. The stations are used to accurately quantify water resources in order to adapt and mitigate water resources risks, including those caused by climate change.

Despite significant past efforts deployed to monitor water resources, several knowledge gaps remain about how much water is available and how it is distributed in South Asia. This knowledge gap is due to limitations in the relevant science and technology, the insufficient number of monitoring stations deployed in South Asia, and restrictions on access to data by many governments due to security concerns. The maintenance of hydrometeorological stations tends to be neglected in many countries, especially in remote areas or regions prone to civil and political conflicts (Afghanistan). Mountainous areas, particularly in the HKH Region, lack recording devices, especially at high altitudes (> 2,500 m) and in remote areas of the monsoon-dominated Eastern Himalayas.

Trend analysis and inputs for models that simulate climate, hydrology and glaciology require more data at higher resolution and over periods longer than what is available at present. Global models rely on interpolation across the vast areas in the HKH Region due to the absence of basic information. Manually maintained climate stations may be possible in some locations up to the altitudes of the highest villages (about 3,000 m), but automatic weather stations are almost invariably required above that altitude. The absence of continuous routine measurements places considerable limitations on the reliability and completeness of the data. Priority countries for extending measurement networks and rehabilitating meteorological stations on the ground include semiarid and arid areas where rainfall is a critical constraint to economic development (e.g., Afghanistan, Pakistan), as well as mountainous areas (e.g., Bhutan, northern India, Nepal) where rainfall patterns are still poorly understood, restricting the capacity to predict flash flooding and droughts. Remote sensing is creating new opportunities to extend monitoring in remote areas (Box 6.1).

Another gap is the lack of information on the extent to which glacial mass and seasonal snow cover have diminished in the glaciated areas of the HKH Region over the past several decades. This gap is mainly due to the lack of observational data on ice stores, snowmelt and glacial melt discharges and snow depth, and their equivalent water depths (Singh et al. 2011). Stations on glaciers are particularly difficult to maintain due to their remote location, the rugged terrain and a complex political situation (Bolch et al. 2012).

Climate data need to be compiled by basin and sub-basin and not by administrative boundaries alone, as currently done in the majority of the countries. More comprehensive data collection should ease steps to link meteorological data with corresponding hydrological data, and would improve analysis of water cycles and assessment of the hydrological disturbances induced by climate change.

Data on atmospheric pollutants collected to date have increased general awareness of the mass of pollutant gases and micro-particles that make up the atmospheric brown cloud. However, more systematic data observations are needed to enable the extensive modelling required to accurately predict the extent to which this mass is contributing to a changing climate in the HKH Region and globally (Turner and Annamalai 2012). Similarly, reliable information on GHG emissions and sinks/sequestration is limited at present and mostly not available for the HKH region.

**Box 6.1. Using satellite missions of the National Aeronautics and Space Administration (NASA) to remotely monitor surface water and groundwater.**

Satellites are dramatically reducing limitations on ground data by enabling the total mass of water on Earth (including surface water and groundwater) and its various components to be measured, and to monitor the ways in which these amounts change over time. NASA satellite missions employ different sensors and techniques to measure each of these water reserves. The Gravity Recovery and Climate Experiment (GRACE) program, launched in 2002, maps spatiotemporal variations in the Earth's gravity field to detect changes in total mass of water in large regions. Surface Water and Ocean Topography (SWOT), scheduled for launch in 2020, will map surface water by measuring its height using radar. Other water-related NASA missions include Tropical Rainfall Measuring Mission (TRMM), launched in 1997, followed by Global Precipitation Measurement (GPM). The quantification of ice volume is now possible with the Ice, Cloud and land Elevation Satellite-2 (ICESat-2). Other satellites include the Soil Moisture Active Passive (SMAP), which uses a radiometer and a synthetic aperture radar (SAR) to provide global measurements of soil moisture and its freeze/thaw state (Luccio 2013).

*Groundwater*

Even though groundwater contamination is occurring in many regions of South Asia, current knowledge on the distribution of contaminants is still limited because of the few observations and limited availability of monitoring data, especially in deep aquifers (> 100 m deep) (Rodell et al. 2009; Chinnasamy et al. 2013, 2015b, 2015c; MacDonald et al. 2015). Given that the region has come to depend heavily on groundwater for irrigation, and domestic and industrial supplies, greater analysis of, and sound policy on, this resource is critical for South Asia's sectoral water uses. To better understand the vulnerability of the region's groundwater system to climate change and to build resilient groundwater-dependent systems, Clifton et al. (2010) identified four criteria to improve assessment indicators: sensitivity (current level of exploitation); exposure to climate change; exposure of regional water resources to sea-level rise; and adaptive capacity.

*Land subsidence in the context of sea-level rise*

Monitoring of subsidence needs to be continued and improved to better understand the extent and rate in affected areas, especially in coastal countries with large deltas where this phenomenon is occurring (e.g., Bangladesh, India, Pakistan). While longer-term surveying over a wider geographical area, such as by Interferometric Synthetic Aperture Radar (InSAR) satellite data and Global Positioning System (GPS) measurements, is emerging, these measurements are undertaken on a relatively short time scale. Thus, it is challenging to determine long-term trends. Long-term, sustained investment in monitoring is required to capture both short- and long-term changes, and to disentangle the compounding effect of sea-level rise.

***Processes***

*Rainfall-runoff relationship*

It is necessary to improve knowledge on the key determinants of the relationship between rainfall patterns and river flows, with the ultimate aim of better predicting the hydrological consequence of climate changes in terms of available water resources and flood risks. This nonlinear relationship is not straightforward and is controlled by a range of factors, including vegetation and soil properties. Further research is needed to disentangle their hydrological controls. Rapidly changing land cover not only controls the production of runoff, but it is also an important source of carbon dioxide (CO<sub>2</sub>) emissions. At present, information on land use and land cover is usually collected without standard categorization.

### *Groundwater recharge processes*

The factors controlling groundwater recharge are multiple. They include meteorological drivers (mainly rainfall intensity and evapotranspiration), soil texture and depth, transmissivity and storage capacity of the aquifers, hydrological extremes, and topographic/geomorphological contexts. This picture is complicated by climate change and other anthropogenic forcing such as land-use changes, resulting in changing erosion and siltation rates directly impacting groundwater recharge rates. Hydrogeological data describing South Asian aquifers are still sparse and limit the understanding of the regional hydrogeology. Further data collection, compilation and modelling of groundwater-surface water interactions are required.

### *Flow production from ice and glacier melting*

Major gaps remain in the understanding of the behavior of glaciers in the region due to limited monitoring stations (Barnett et al. 2005; Immerzeel et al. 2012; Bolch et al. 2012).

### ***Forecasts, Projections and Early Warning Systems for Floods and Droughts***

Poor flood preparedness in South Asia is partly due to the lack of reliable data resulting from the absence of adequate and systematic monitoring networks. Alford et al. (2012) indicated that a considerable disconnect exists between government officials, local residents and scientists. As a result, there is a large gap between methodologies to reduce the impacts of hazards and vital life-saving information, especially in the mountainous regions of the Himalayas, where landslides, siltation, forest fires and the like are common.

### **Recommendations**

Adaptation to climate change and mitigation of climate-related risks do not necessarily require strategies to be diversified; rather, they can be adjusted to existing adaptation options. The discussion that follows groups recommendations to address the two main categories of climate-related risks: droughts and floods.

#### ***Recommendations to Cope with Droughts***

Improving resilience to more intense droughts resulting from climate change involves a range of interventions, including more parsimonious water use, sound selection of sites and structures to store water, a better understanding of hydrometeorological processes that control the spatiotemporal variability of water resources, and more powerful models used to predict droughts.

#### ***Improve knowledge transfers about water-use efficiency and water productivity***

To cope with more severe droughts induced by climate change, improving water-use efficiency and water productivity is often simple and cost-effective. However, these techniques are not always applied. Water-saving technologies are especially important, given the large share of water used for irrigated agriculture. More irrigation water is typically applied to crops than is actually required, leading to overuse and quicker depletion of water resources. Other improvements include the reduction in water losses due to leakage (in municipal distribution networks and irrigation canals), evaporation (mainly from soils and reservoirs) and deep percolation from fields. To attain these objectives, it is necessary to better disseminate knowledge from research institutions and agricultural extension services to farmers and other users, and build capacities.

Where surface water and groundwater are becoming scarce, awareness campaigns can help control water consumption. Reducing consumptive water use through agricultural policies (e.g., restricting irrigation of alfalfa in arid areas, and reducing rice areas in the Punjab and sugarcane cultivation in semiarid areas) should be helpful to save water. In hard-rock peninsular India and northern and eastern Sri Lanka, aquifer storage is small, the flow is local and sluggish, and natural recharge is limited. In this context, the self-regulation of groundwater users would be profitable to switch from destructive competition for



dwindling groundwater to constructive dialogue on productive and equitable use of available average recharge (Shah and Lele 2011).

Afghanistan is among the countries where field-scale irrigation efficiency is the lowest (25-30%) in South Asia. Improving this efficiency to a reasonable standard (40%) could lead to a 10-15% increase in water savings, possibly offsetting the long-term impact of rising temperatures on crop water requirements. Similarly, in India, the current water shortage could be partly resolved by minimizing water losses in irrigation systems, making water user associations more effective, and raising the technical and managerial capacity of irrigation departments (Shah and Lele 2011). At the plot level, micro-irrigation (drip irrigation), soil mulching and soil amendments are options to reduce water losses through evaporation and percolation. At the scale of the irrigation scheme, water loss through canal leakage should be minimized. Water-use efficiency should also be considered at the scale of transboundary river basins, where water should be equitably shared between countries (between India and Pakistan in the Indus Basin; and between India and Bangladesh in the GBM). Increasing crop water productivity is not the only solution. Reducing global loss and food waste is another (Kummu et al. 2012).

#### *Carefully design and plan reservoirs to improve their water storage capacity*

More frequent, longer and more intense droughts may be expected in the future as climate warming continues, entailing a greater need for multi-year reservoir storage capacity. South Asia currently has very little of such storage capacity, especially in arid and semiarid areas, and where groundwater is depleting and worsening in quality (Lower Indus Basin). Not only does new storage need to be built, but the sediment load of a river needs to be reduced through improved management of land use in the uplands to lessen siltation in downstream reservoirs. To achieve these goals, it is necessary to change the business of building dams. Benefits must be equitably shared. Environmental concerns need to be addressed rather than bypassed. Mismanagement, corruption and poor governance must be tackled (Shah and Lele 2011).

In the HKH Region, most of the hydropower barrages are run-of-the-river types with very little storage capacity. With the increased melting rate of glaciers in response to global warming, river flow will temporarily increase, offering an opportunity for storing greater volumes of water. This transition period will be followed by a reduction of streamflow as glaciers shrink. Concomitantly, the reduction of seasonal snow cover that used to provide storage to sustain dry-season flows during the summer will result in greater seasonal variations in river flows, suggesting the need for more reservoirs. These counteracting trends result in intricate hydrological changes. They should be carefully considered when planning new storages in the HKH Region. To reach these objectives, it is necessary to accurately monitor river flows to characterize their variability, simulate their expected variations under a changing climate, and design storage capacities accordingly. Decision support tools can help appropriately allocate resources and efforts, depending on climate sensitivities.

#### *Improve knowledge about the surface water/groundwater continuum and the management of conjunctive uses of surface water and groundwater*

The hydrogeological setting of an aquifer system both frames the resource problem and constrains the management solution. In the vast and fertile Indo-Gangetic Plains, which has huge aquifer storage, the groundwater-surface water linkages are critical. In the Indo-Gangetic Basin, planned conjunctive use of surface water and groundwater is required, especially by increasing groundwater use and enhancing aquifer recharge in upstream areas and improving surface water availability downstream, through improved rainwater harvesting systems. It is, therefore, necessary to increase the number of monitoring wells to accurately survey the spatiotemporal variations in groundwater levels and better understand their connections with surface water bodies. Hydrological and groundwater modelling should help forecast variations in the availability of both groundwater and surface water under different climatic scenarios.

### *Improve drought monitoring and early warning systems by raising the capacity of analysis of large datasets*

Droughts can be monitored in near real-time using remotely sensed drought indexes calculated with temperature and a range of vegetation indexes, which can be scaled regionally or globally. Due to the advancement of remote sensing technology, many satellite-based drought indexes have been advanced and employed over the last 30 years for both monitoring droughts and assessing their impacts. However, analytical capacities are often lacking in the poorest countries of the South Asia region and need to be improved.

### ***Early Warning Systems for Floods and Landslides***

There are several approaches from a data and knowledge management perspective to cope with floods and landslides: mapping areas prone to floods and landslides in order to limit vulnerable settlements in these exposed areas, design flood refuges and flood protection structures, and forecasting floods and landslides to improve preparedness of the exposed population and giving them more time to escape disaster with the use of early-warning systems. Each of these approaches necessitates different preparations that should account for the non-stationarity of the current climate patterns, the expected effect of climate change on rainfall patterns, and associated flow regimes and risks of landslides.

#### *Map flood-prone areas*

This exercise requires the collection of various data: observed flow time series, rainfall projections from climate models, topography from digital elevation models, geology, land use/land cover, soil maps and satellite imageries of vulnerable infrastructure. Remote sensing technology can replace physical measurements of river flow only partially; hence the need to deploy efforts to rehabilitate, maintain and expand hydrological monitoring networks on the ground. To predict and forecast the extent, magnitude and frequency of future floods, hydrological and hydraulic models are required that can integrate all this information, using time series of projected climate variables (e.g., rainfall, evapotranspiration) as inputs. Most importantly, such models should account for the properties of local soils and vegetation, which play a central role in controlling the rainfall-runoff relationship. These models need to be systematically calibrated and validated using actual records of flow and rainfall to accurately predict future trends and extremes.

#### *Improve early warning systems to forecast floods and landslides*

Early warning systems aim to provide time for the exposed population to take appropriate actions to minimize damages and possible casualties caused by floods and landslides. They are expected to play a greater role as extreme weather events, including GLOFs, will worsen in magnitude and frequency in a changing climate. Forecasting involves the conversion of hydrometeorological data (some originating from numerical weather models) into forecasts (using hydrological models) and hazard maps. These are then transmitted to decision makers and local authorities that release warnings and take appropriate preventive actions. Early warning systems for flood forecasts generally operate at watershed scale, while action units follow the administrative boundaries. Improving the dissemination of forecasts requires precisely identifying the path of the warning from forecast to persons responsible for actions. A way to reach this goal is to encourage sharing of data and information, especially in border areas where international cooperation is required to establish evacuation plans. Clear roles and responsibilities must be defined. The implementation of quality control systems in the early warning systems should help improve the emergency management of local authorities and communities. People-centered approaches involving village communities in the dissemination of the forecasts and in the preventive actions should be prioritized as they are low-cost, effective and relevant to local conditions in disaster-prone areas (Lacombe et al. 2012).

## **Building Capacity**

Closing the knowledge gap requires not only structural and technical improvements in areas such as data measurement networks but also sound policy choices and better modes of implementation of solutions. Capacity building is a long-term and continuing process in which ministries, local authorities, NGOs, water user groups, professional associations, the private sector, academics and others participate. Capacity building to improve preparedness for climate risks in South Asia is important because the scale of the impacts of climate change is enormous, but appreciation of the problem is low. Limited funding is allocated for research. Continuous support is needed to catalyze change. Educational and capacity building institutions are fragmented and interaction among them is inadequate. Curricula are conventional and teaching materials insufficient. Education systems should help educate and train people for the continuing and evolving demands of climate change. Local governments play an increasingly important role in enabling both planned and autonomous adaptation at local levels (ISET 2008).

## **Combining Short- and Long-term Approaches**

A combination of short- and long-term approaches to managing the impacts of climate risks is needed. In the short term, integrating climate adaptation and reducing disaster risk will help mitigate and withstand shocks to human security and economic development, and a costly recovery process. South Asian governments, businesses and communities can do much to anticipate and reduce risk, rather than reacting after impacts have occurred. Support for effective disaster relief and recovery needs to continue, along with proactive efforts to reduce risk, such as integrating comprehensive risk assessments and risk reduction measures into the national economic and development policy.

In the longer term, governments, businesses and communities need to prepare for the kinds of climate impacts experienced up to now, and also for different and more intense climate impacts and extreme weather events in the future. Measures may include providing adequate housing, infrastructure or services, and mainstreaming climate change considerations into the planning processes.

There are good reasons to start the process of adapting to these longer-term climate risks now. IPCC cautions against overemphasizing short-term outcomes or insufficiently anticipating consequences. Given that climate change cuts across sectoral boundaries, poorly conceived development programs or sector-specific adaptation strategies could lower resilience in other sectors or ecosystems. Some development pathways such as rapid urbanization of coastal zones can increase the vulnerability of certain groups to future climate change. This is a particular challenge for South Asia, where economies are growing rapidly and societies are undergoing significant demographic shifts (CDKN and ODI 2014).

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