Climate Change Science, Knowledge and Impacts on Water Resources in South Asia: A Review

Paper 1

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Contents

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Acronyms and Abbreviations

AR5	Fifth Assessment Report of the IPCC
CMIP5	Fifth phase of the Coupled Model Intercomparison Project
ENSO	El Nino Southern Oscillation
GBM	Ganges-Brahmaputra-Meghna River System
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLOF	Glacial Lake Outburst Floods
HKH	Hindu Kush Himalayas region
IPCC	Intergovernmental Panel on Climate Change
MG	Megawatt
RCP	Representative Concentration Pathways
SAWI	South Asia Water Initiative
SST	Sea Surface Temperature
WHO	World Health Organization

1. Introduction

1.1 Importance of Water to Key Sectors

The seven countries of South Asia (Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka) are home to about a quarter of the world population, but contain only about 4.5% of the world's annual renewable water resources, unevenly distributed between countries. Except for Bhutan and Nepal, the inhabitants in all seven countries share per capita water availability that is below the world average and that continues to decline in response to growing populations. The impacts in some places are dramatic, with rapidly declining groundwater levels and degradation in water quality. It is estimated that by 2025, per capita water availability could be less than 1,000 m^3 indicating extreme water stress on par with the worst-affected countries in the Middle East.

Some 95% of all water abstracted in South Asia (from which 60% and 40% originate from surface water and groundwater, respectively) is used by the agriculture sector. This value is much higher than the 70% world average, whilst the sector's contribution to GDP across the region continues to decline, despite a high proportion of the workforce and total population directly depending on agriculture. 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 river basins are managed and developed in the upper reaches of major river systems in South Asia. A combination of growing demand for the resource and declining quality is exerting severe pressures on ecosystems in the region, particularly in downstream parts of basins, causing serious impacts on the provision of ecosystem services (e.g. environmental flows) and species biodiversity which are vulnerable to changes in flow seasonality and climate patterns.

1.2 Climate Change and Water Resources Management

Climate change involves warming of the Earth's atmosphere. This addition of energy to the global system has profound impacts on the hydrological cycle through a number of mechanisms – increasing evaporation losses, sea water warming, changing the patterns and severity of weather events. Their effects on the water cycle have massive implications for human systems (social and economic) and the agro-ecosystems on which populations depends for food security and livelihoods.

Whilst these impacts are not necessarily negative – climate change can also have positive consequences such as a prolonged growing season – overall South Asia is expected to be negatively affected in different ways outlined in this report. Despite a significant level of uncertainty in the predicted effects of climate change, some statistically significant trends are already observed and further anticipated (e.g. sea level rise; global warming and its effect on glacier hydrology) allowing clear management response. Where other climate trends are more uncertain, it is important that particular management responses do not 'lock-in' approaches that may need flexibility to respond to future unanticipated consequences of (climate) change. Chosen interventions should be flexible enough to deliver maximum benefits under a range of conditions instead of being designed for what are thought to be the "most likely" future conditions. Whilst ecosystems provide a wide range of services, including climate and flood regulation, so increasing their resilience is vital, at the same time it is perhaps wise to reduce reliance on ecosystem services to the extent possible.

1.3 Summary of Knowledge about Climate Risks

Major identified climate-related risks in South Asia include increased frequency and intensity of floods and droughts (associated with increasing water scarcity), intensified erosion caused by changes in rainfall patterns and land cover, sedimentation and siltation reducing groundwater recharge and water storage capacities (as a result of the interaction of land use changes and hydrological cycles), intrusion of saltwater into inland water systems due to sea level rise and reduction in river system outflows, and damage to water quality through more intensive usage as a result of changes in water availability, access and use. Given the diversity and complexity of the issues and challenges in South Asia, an adaptive water resources management approach is important. A key 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.

1.4 Objective of the Approach

The South Asia Water Initiative (SAWI) is designed to support countries to improve and deepen transboundary dialogue, enhance the basin and water resources knowledge base, strengthen water institutions, and support investments that lead to sustainable, fair and inclusive development. This report was produced as part of SAWI phase I which aims to build knowledge, tools and capacity across the region to assist governments in adapting to emerging climate challenges in the water sector. Envisaged support includes development of effective policy frameworks as well as practical planning, development and management actions that highlight and address the need for adaptation.

This **Report 1** is one of 3 reports commissioned by the World Bank to assess opportunities for adaptation to climate change in South Asia and describes the scientific understanding of predicted impacts of climate change on water resources and associated risks in South Asia. Specifically, the report aims: i) to provide a state of the art knowledge synthesis on climate trends and their expected impacts on climate-related hazards and associated risks; ii) to identify knowledge gaps and priorities for knowledge improvement in order to anticipate more effectively climate-related disasters and to plan for greater adaptation/protection.

Report 2 assesses the enabling policy framework (existing policy, legislation, strategies and plans) focusing on the degree to which principles of Integrated Water Resources Management (IWRM) are identified and embedded in the water and climate policy landscape to address the key water-related climate risks faced by each country.

Report 3 assesses the adequacy of the government institutional and economic landscape for adapting to climate change. It establishes the importance of water resources to South Asia's economy and the need to place water management at the centre of the National Climate Change Response Strategies.

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 NGOs, together with analyses and critiques of water resource, climate change and related risk assessments published in the academic literature. This study relies on publications available online, exclusive of information published in local language.

1.5 Structure of the Report

This report contains 7 chapters. **Chapter II** provides a brief description of the climate, surface water and groundwater resources and water uses in South Asia in the context of transboundary river basins, while differentiating natural climate variability from anthropogenic climate change. It concludes by reviewing water and climate information that is key to water resource planning, operation and management. **Chapter III** reviews the main climate-related risks in South Asia. **Chapter IV** reviews existing knowledge about historical and projected trends in rainfall, temperature and sea-level, as well as available tools for climate projections, their limitations and possible solutions to cope with uncertainties. **Chapter V** explains how changes in rainfall and temperature are altering groundwater recharge on one hand, and annual and seasonal river flows in areas where river flows partly originate from melting glacier and snow, on the other. **Chapter VI** explores the aggravating effects of climate change on risk levels. **Chapter VII** concludes by identifying gaps in current knowledge and suggesting recommendations to improve knowledge, understanding and anticipation of climate-related disasters.

Inserted in the chapters, several boxes aim to emphasise important notions whose understanding is critical for an efficient management of water resources to adapt to rising climate-related risks. Box 1 provides definitions of key concepts including hazard, exposure, risk, vulnerability and resilience. Box 2 provides explanations to help differentiating climate variability and climate change, two phenomenon which are often mixed up. Box 3 details an example of decision tools to address uncertainties in climate projections in water resources projects.

Box 1. Definitions

In this report, we follow the most common definitions of the terms hazard, exposure, risk, vulnerability and resilience.

While **hazard** refers to the 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, infrastructures, environments) that could be adversely affected. Füssel and Klein (2006) define 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'. Thus risk measures the extent of the expected loss from climate change. Note that hydrologists measure the reliability of water supply in terms of the risk that they will not be able to meet demand in a given year. **Vulnerability** measures the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change (International Panel on Climate Change 2007b). **Resilience** describes the ability of a system, including management systems, to adapt to the impacts of climate change without excessive harm. It is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures.

2. Climate and Water Resources

This chapter provides an overview of climate, water resources, water uses and water management in each country of South Asia.

Box 2. Climate concepts

Natural climate variability and human induced climate change are sometimes confused. Here we distinguish between these concepts and explain the implications of both natural climate variability as well as human-induced climate change for South Asia's water resources.

Climate variability describes variability of, for instance, precipitation in spatial and temporal scales beyond that of individual weather events. The familiar sequence of a monsoonal rainy season starting in April-May followed by a dry winter season starting between October and December is an example of natural seasonal variability across most of South Asia. There is also spatial variability in this climate pattern, with the southwestern parts of South Asia typically being 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 inter-annual climate variability results from the tropical Pacific Ocean surface temperature (SST) anomalies related to the El Nino Southern Oscillation (ENSO) (Kumar et al. 2006). At a lower frequency, monsoon variations are tele-connected to the Atlantic multi-decadal oscillation of the related SST (Kucharski et al. 2009). While all multi-decadal cycles in climate time series are not well understood (cf. the Hurst phenomenon: cf. 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 infrastructures. 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 water resource planning and management implications. First, the more variable the climate, between seasons and between years, the larger irrigation and water supply storage needs to be to achieve a given level of security of supply. Similarly, flood control dams also need to be larger to cope with increasingly large floods. Secondly, there is likely to be a greater need for irrigated agriculture to maintain food security when rain-fed systems experience more frequent drought. Thirdly, a high degree of climate variability implies a need for good climate and water resources monitoring, so that approaching droughts can be anticipated and planned for.

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 GHG emissions, land-use change and emissions of aerosols. This warming will likely change the average climate and its inter-annual variability over the long-term (beyond multiple decades), experienced in a particular region or location. The change may occur over periods ranging from decades to millennia. Thus, engineers cannot assume that infrastructure designed for past climates will be suitable and reliable for the future; in other words the stationary assumption no longer holds. Global warming of either 2°C (best case scenario) or 4°C (increasingly likely scenario) in South Asia would induce unprecedented and more frequent heat extremes over larger areas, water availability would decline by between 20-50% depending on the rate of global warming, crop yields could decrease, and terrestrial ecosystems could be altered (World Bank, 2013). These impacts constitute significant risks to humans and the natural environment.

2.1 Climate

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

2.1.1 Rainfall

The region can be divided into six climatic zones (Figure 1): tropical wet, tropical dry, semi-arid, arid, humid, subtropical and highlands. The tropical wet zone receiving the largest amount of rainfall includes southern Sri Lanka, Bangladesh and Southwest India. Due to the Southwest Monsoon bringing moisture and warm air from the Indian Ocean, annual rainfall exceeds 2,500mm/year (Punyawardana, 2002; Karmalkar et al. 2012). Some 70%–90% of annual precipitation falls during the monsoon between June and September. The Himalayan range contributes to generating the highest rainfall per annum observed in the world, due to orographic effects. The driest countries of South Asia, located in the arid and semiarid climate zones, receive less than a fifth of the annual amount of rainfall recorded in the wettest parts of the region (Table 1). Low rainfall observed in Afghanistan and Pakistan is due to the presence of a high mountain range in the south, limiting the intrusion of the monsoon, influence of which weakens in a northwesterly direction. Most of the precipitation is in the form of snowfall during late winter and early spring months in high elevation areas (Wang 2006; Kottek et al 2006; Peel et al 2007; Goswami 2005).

Between these two extremes, other areas receive intermediate levels of rainfall. Spatial variations in mean annual rainfall can be very marked. For instance, mean annual rainfall in Sri Lanka varies from 800 mm to 5000 mm, leading to three distinct climatic zones: dry zone (<1750 mm per year), intermediate zone (1750 to 2500 mm per year) and wet zone (> 2500 mm per year) (Punyawardana, 2002).

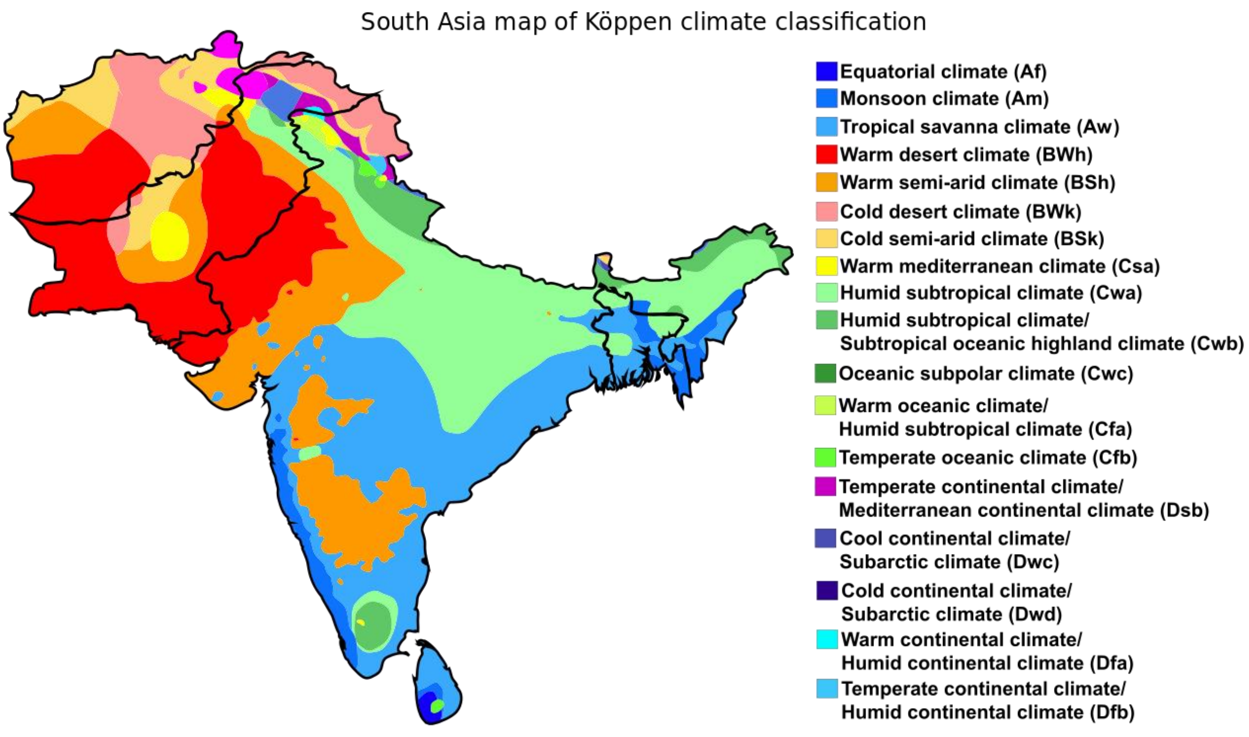

Figure 1. Climate regions in South Asia according to Köppen Climate classification

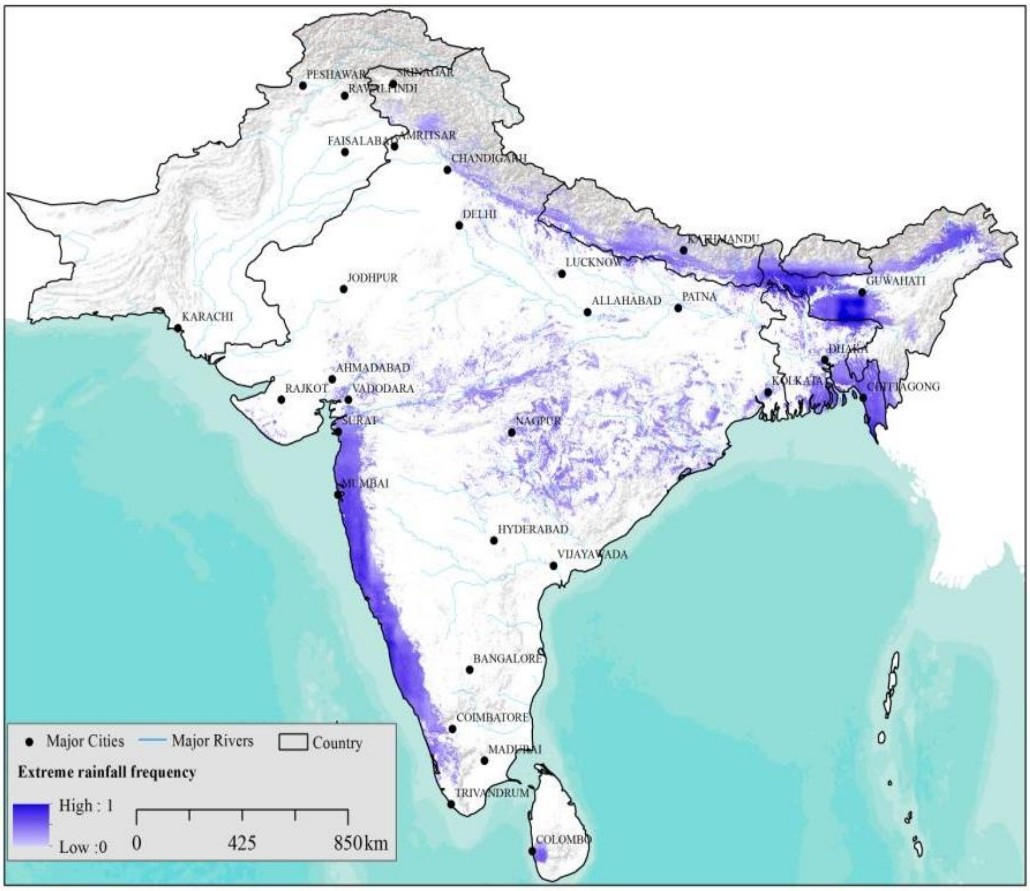

Figure 2. Spatial distribution of extreme precipitation frequency based on 62 years' long time series of Aphrodite and TRMM rainfall datasets (Giriraj et al., 2016)

2.1.2 Temperature and Evaporation

Temperature varies considerably across the sub-continent, influenced not only by the altitude and latitude (getting colder in the north and/or at higher elevation), but also by the proximity of the coast (buffering effect of the ocean), by the blocking effect of the Himalayas that reduce the intrusion of northern cold winds in the Indian Plain, and by the cooling effect of the monsoons and aerosols (e.g. natural cloud covering and brown cloud effect in the Ganges Valley). Seasonal variations of temperature are more pronounced in the North in accordance with greater inter-annual variations in day length and inclination of solar rays. However, the northern part of the Indian plain remains cool in winter as 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 summer. The mountainous north is colder and receives snowfall at high altitudes.

Combined to temperature, relative air humidity (RH) controls variations of standard evapotranspiration (ET) and evaporation rates. For instance, mean RH varies from about 80% in Sri Lanka, down to 20% in the semi-arid and arid parts of Afghanistan and Pakistan exhibiting the highest ET rates across the region. These drought-prone areas are vulnerable to high potential water losses in surface water reservoir by evaporation and crop water stresses. Conversely, high-elevation countries like Bhutan and Nepal are exposed to lower temperature and lower ET, implying lower crop water stresses but also lower maximum crop yield even with optimal water supply.

2.2 Water Resources

2.2.1 Surface Water

The bulk of water resources available in rivers, lakes, reservoirs, snow pack, glaciers and aquifers originates as rainfall and snow in respective countries (referred as '*internal renewable water resources*' in Table 1) and from upstream stream-flow in neighbouring countries (referred as '*surface water entering the country*' in Table 1). Internal renewable water resources vary according to rainfall patterns and the fraction of rainfall that is either converted to surface runoff, infiltrates to recharge aquifers or is lost by evaporation or non-productive evapo-transpiration. On average, runoff ratios vary between 14% in Pakistan where a significant part of rainfall water is lost through evaporation, and 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. The sum of these two water resources (*internal renewable water resources* and *surface water entering the country*) constitutes the bulk of the *total renewable water resources.* The contribution of surface water entering the country to the total renewable water resources varies between 0% (e.g. Bhutan located in the upstream part of the Brahmaputra River Basin; Sri Lanka forming an island) and more than 90% (e.g. Bangladesh located in the delta of the Ganges, Brahmaputra and Meghna River System, referred as GBM).

Table 1. Water resources in South Asian countries. Sources: FAO. 2016. AQUASTAT Main Database - Food and Agriculture Organization of the United Nations (FAO). Website accessed on 18/02/2016 and http://data.worldbank.org/ Note that some figures may vary and contrast with the statistics provided by the countries, due to differences in baseline periods combined to high inter-annual variability of water resources (rainfall and streamflow). This table aim to provide values for country comparisons.

		Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Sri Lanka	South Asia
Area (10^3 km^2)		652.8	148.5	38.4	3,287	147.2	796.1	65.6	5,135.9
Population (10^6 inhab)		32.5	161.0	0.8	1,311	28.5	188.9	20.7	1,743
Density (inhab.km^{-2})		50	1,084	20	399	194	237	316	339
Rainfall or snowfall	mm.$year^{-1}$	327	2,666	2,200	1,083	1,500	494	1,712	970
	km^3.$year^{-1}$	213	396	84	3,560	221	393	112	4,980
Internal renewable water resources	km^3.$year^{-1}$	47	105	78	1,446	198	55	53	1,982
	As % of rainfall	22%	27%	92%	41%	90%	14%	47%	40%
Surface water entering the country (km^3.$year^{-1}$)		10	1,122	0	635	12	265	0	2,044
Groundwater water resource as % of total renewable water resource		16%	2%	9%	19%	9%	19%	13%	13%
Water from snow melt as % of total renewable water resources		92%	0%	17%	10%	8%	57%	0%	11%
Total renewable water resources (km^3.$year^{-1}$)		65	1,227	78	1,911	210	247	53	3,791
Total renewable water resources per capita (m^3.$inhab^{-1}$.$year^{-1}$)		2,008	7,622	100,645	1,458	7,372	1,306	2,549	2,175

While regional variations in internal renewable water resource mainly reflect varying sizes of countries (from 53 km^3 in Sri Lanka to 1,446 km^3 in India) (Table 1), per capita total renewable water resource is indicative of the abundance or scarcity of the water resource for the population. An amount of 1,700 $m^3.inhab^{-1}.year^{-1}$ has, in the past, been considered a minimum level of water requirement (Falkenmark and Widstrand, 1992) based on a set of assumptions about type of economic development and future potential. According to this indicator, India and Pakistan are water scarce while Nepal, Bangladesh and Bhutan exhibit the highest values (Table 1). However, these figures offset contrasts within each country. For instance, a significant portion of the agricultural lands in Bhutan depends on seasonal rainfall. Only about 12.5% of arable land is irrigated thus far (SaciWaters, 2004). For Bhutanese living in the hills, water flowing in the large rivers in deep gorges of the country is mostly out of reach and 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 the highest in Afghanistan, Pakistan, Bhutan, India and Nepal (Table 1). This volume of ice and snow originates from the Hindu Kush Himalayas region (HKH), mainly above 2,000m. It is of key importance to the countries, acting as natural water storage to sustain dry season flows and enable irrigation.

Glaciers and seasonal snow-packs are natural hydrological buffers releasing water during the drier periods, such as spring and autumn, when the flows of some catchments in this region are at their lowest. Similarly they may act to buffer inter-annual variability as well releasing water during warmer drier years and accumulating during wetter colder years (Barnett et al., 2005).

2.2.2 Aquifers

Groundwater in South Asia is a critical resource that is under increasing pressure. Some regions are underlain by aquifers extending over large areas. Floodplain alluvial deposits usually accompany the largest rivers, for example the vast aquifer beneath the densely-populated floodplains of the GBM and Indus River Basin. Sedimentary rocks, especially Quaternary loose sediments are thick with good storage capacity (e.g. lower GBM, lower Indus River Basin). The best yielding aquifers are located in the alluvial deposits of the Gangetic plain in India (Rajmohan and Prathapar, 2013) (Figure 3). In contrast to sedimentary aquifers, hard rock aquifers store groundwater in deep fissures which are technically less accessible and less sustainable because of lower recharge rates (e.g. in mountainous regions like Bhutan and Nepal). Water quality issues (e.g. arsenic contamination) are making use of deep aquifer groundwater less relevant in West Bengal (Rajmohan and Prathapar, 2013). In mountainous areas, 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, including shallow karstic (e.g. Jaffna Peninsula in Sri Lanka - Imbulana et al., 2004; Panabokke and Perera, 2005), deep confined, coastal sand, shallow regolith and lateritic. Table 1 indicates volumes of groundwater resource availability in each country.

Recharge rates vary from less than 2 mm/year (central part of the Indus Basin) to more than 300 mm/year in the GBM delta (Figure 3) (Mukherjee et al., 2015). Most of the northern and north western regions have less water yielding aquifers, due to presence of mountainous karst aquifers (e.g. Himalayan) and semi-arid regions (e.g. Afghanistan and Pakistan).

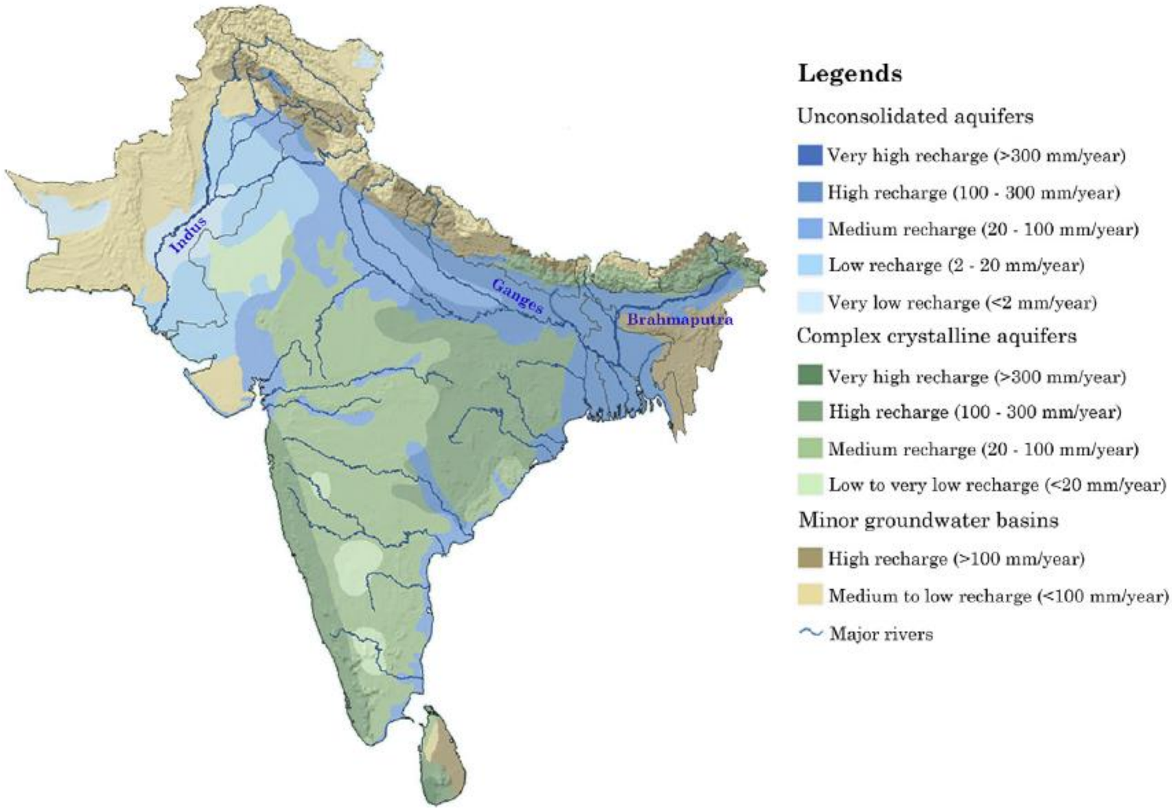

Figure 3. Aquifers and recharge rates in South Asia (Mukherjee et al., 2016).

2.2.3 Transboundary Rivers and Aquifers

More than half of the surface area of South Asia is drained by the GBM, the Indus and the Helmand River Basins (Table 2).

The Ganges-Brahmaputra-Meghna River System

The GBM is the second largest basin in the world (Table 2). The Brahmaputra and Meghna River Basins are supplied mainly by monsoon rains from June to September with some areas receiving between 5,000 and 10,000mm of rainfall annually. The Ganges River is supplied by monsoon rains and snow totalling about 500-1,000mm/year, with some areas receiving up to 2,000 mm. This situation results in flooding in the foothills of Nepal and the lower Gangetic plains of India and Bangladesh. Glaciers and seasonal snow contribute 3% and 7% of mean annual flow in the Brahmaputra and Ganges basins, respectively (Savoskul and Smakhtin, 2013b). Total renewable water resources in the Ganges Basin amount about 552 km^3, including about one third of groundwater resources. Between 20% and 40% of the water resources in the Ganges River Basin are used (Amarasinghe et al., 2016), mainly for irrigation, while the Brahmaputra and Meghna Rivers remain largely unexploited in their Indian portion, at least, due to the terrain being non-conducive to large-scale irrigation. According to the systematic classification of the Uttarakhand Environment Protection and Pollution Control Board’s, water quality in the Ganges River is extremely low, mainly due to contamination by faecal coliform. Although water quality improves along upper tributaries and in aquifers, other contaminants are of growing concerns (arsenic, fluoride etc.,). Due to lower population densities, the water quality in the Brahmaputra Basin is much higher, especially in the upper part of the Basin, upstream of the densely populated alluvial plain of Dhaka. However, groundwater quality in this basin is also characterized in some place by dangerous concentrations of arsenic and fluoride (Subramanian, 2004). Most of the aquifer in the downstream part of the GBM (i.e. in Bangladesh) is made of sedimentary alluvial and deltaic deposits of three major rivers forming an unconfined aquifer covering an area of about 215,000 km^2 (UN-IGRAC, 2014) with recharge rates (>300 mm/year) among the highest in South Asia (Mukherjee et al., 2015).

The Indus River Basin

Ice and snow meltwater represents about 35-40% of the mean annual flow of the Indus River (Savoskul and Smakhtin, 2013b) which contains the world's greatest area of non-polar perennial ice cover (22,000 km^2). Ice and snow serve as natural water storage providing perennial supplies to river's mainstream and some of its tributaries. About 300 km^3 of water are withdrawn annually in the Indus River Basin, mainly by Pakistan (63%) and India (36%), the remaining 1% being withdrawn by Afghanistan and China. While 7% of this volume is used for domestic and industrial purposes, 93% is for irrigation on some 26.3 million ha of lands mainly located in the river delta, 53% with surface water and 47% with groundwater (Table 2).

The Indus Basin is underlain by an extensive unconfined aquifer covering about 16 million ha of which 10 million are saline (Haider et al., 1999). The aquifer is recharged by precipitation, seepage from rivers and irrigation canals, and percolation from irrigated schemes. The deep water table (>30 m) was in a state of hydrological equilibrium before the development of canal irrigation systems (including the largest contiguous irrigation scheme in the world). 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 and almost all shallow freshwater is now polluted with pesticides and nitrogenous fertilizers from agriculture, and sewage.

Table 2. Major River Basins in South Asia: hydrology and country sharing (Aquastat, 2016), http://www.jrcb.gov.bd

		Ganges	Brahmaputra	Meghna	GBM	Indus	Helmand
Surface area (km^2)		1,087,000	552,000	82,000	1,721,000	1,165,000	306,500
Mean flow (km^3/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
% 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
% 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

The Helmand River Basin

This Helmand Basin (Table 2) is arid and semi-arid. 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 Mountains to the Eastern and Parwan Mountains, and finally to the unique Sistan depression between Iran and Afghanistan (Favre and Kamal, 2004). The Sistan depression is a large complex of wetlands, lakes and lagoons, being an internationally-recognized haven for wetland wildlife and 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. This river, managed by the Helmand and Arghandab Valley Authority is used extensively for irrigation, although a build-up of mineral salts has decreased its usefulness in watering crops. Its waters are essential for farmers in Afghanistan and Iran. A number of hydroelectric dams have created artificial reservoirs on some of the Afghanistan's rivers including the Kajakai on the Helmand River. 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 shared by Afghanistan, whereas less than 4% is occupied by Pakistan (Table 2).

2.3 Water Uses

Total water withdrawals in South Asia represents about 27% of the total available renewable surface water and groundwater resources. This fraction varies from about 5% (in Bangladesh, Bhutan and Nepal) to 74% in Pakistan (Table 3). The lower percentages are due to overwhelming flow discharge (e.g. Bangladesh) or to very limited water usage and access (e.g. Bhutan and Nepal).

On average, groundwater accounts for about 40% of total water use across South Asia with regional variations from 0% in Bhutan (where surface water is abundant and available all year round) to 80% in Bangladesh (where surface water, though abundant, is commonly polluted). Although these averages may hide regional discrepancies and seasonal variations, they provide a basic idea of levels of overall water resource exploitation in the country. While water is mainly used 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, agriculture water use continues to increase due to intensification with farming seeking to keep pace with food demand.

Table 3. Water uses in South Asian countries. Sources: FAO. 2016. AQUASTAT Main Database - Food and Agriculture Organization of the United Nations (FAO). Website accessed on 18/02/2016 and http://data.worldbank.org/

	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Sri Lanka	South Asia
Total water use as % of total renewable water resources	31%	3%	0%	40%	5%	74%	25%	27%
Total water use (km^3/year)	20.4	35.9	0.3	761.0	9.5	183.5	12.9	1023.5
Agricu. water use (km^3/year)	20.0	31.5	0.3	688.0	9.3	172.4	11.3	932.8
Industr. water use (km^3/year)	0.2	0.8	0.0	17.0	0.0	1.4	0.8	20.2
Munici water use (km^3/year)	0.2	3.6	0.0	56.0	0.1	9.7	0.8	70.4
Surface water use (km^3/year)	16.7	7.4	0.3	396.5	7.6	121.9	5.1	550.4
Groundwater use (km^3/year)	3.7	28.5	0.0	230*	1.9	61.6	7.8	325.7
Groundwater use as % of total water use	18%	79%	0%	36%	21%	34%	60%	39%
Groundwater use as % of total renewable groundwater resources	34%	2%	0%	53%	10%	24.8%	15%	63%
Agriculture water use as % of total water use	98%	88%	94%	90%	98%	94%	87%	91%
Agriculture land (10^3 km^2)	379.1	91.1	5.2	1,802.8	41.2	362.8	27.4	2,709.6
Irrigated land (10^3 km^2)	32.1	50.5	0.4	663.3	11.7	199.9	5.7	963.5
Irrigated land as % of agriculture land	8%	55%	6%	37%	28%	55%	21%	36%

Other sources: (National Statistics Bureau, 2009) for Bhutan. *: highest in the world (Shah, 2010).

2.3.1 Agriculture

In all South Asian countries, rainfall remains the main water source for agriculture (by area coverage). Irrigation represents only a third of all agricultural land, with wide national disparities (from 45% in Bangladesh and Pakistan to 92% in Afghanistan). On average, irrigation uses more than 90% of the volume of water used in South Asia with variations ranging from 87% in Sri Lanka to 98% in Afghanistan and Nepal. About one third of irrigation water is pumped from aquifers (Table 3), the remainder is pumped or diverted from rivers and reservoirs. In India, the agriculture sector consumes 60% of the total groundwater extraction (Hoekstra 2013). The dramatic growth in groundwater use in India, Pakistan and Bangladesh is making natural groundwater recharge rate becoming far unsustainable, as evidenced by quick drops in water table levels.

2.3.2 Hydropower

Hydropower production does not consume water (with the exception of net evaporation losses from any reservoirs constructed) but requires continuous outflow to sustain turbine operation at a required rate. Greater storage capacity in hydropower dams is required to absorb greater seasonal contrast between high- and low-flows so that turbine discharge remains stable throughout the year. If properly operated, by buffering seasonal variations in river flow regime, hydropower dams may enhance downstream dry season flow (providing potential additional water resources to downstream users but also threatening ecosystems) as well as reducing flood risks by storing excess flood waters during high-flow season. Areas with potential for hydropower development are characterized by high annual rainfall, river flow with limited sediment content (to minimize reservoir siltation), availability of land and steep terrain to generate sufficient head for power production. Upstream countries in South Asia (especially Bhutan, India and Nepal) are well-suited, including proximity to markets where there is high demand for energy.

Bhutan and Nepal are at a less advanced stage of development compared to India and Sri Lanka. Almost all of hydropower dams are run-of-the-river with generating capacity limited during the dry season. The selling of electricity to India is a driver of hydropower development in Bhutan and Nepal. The fragile mountain geology requires that careful planning be implemented for the selection of sites and development of hydropower. The gross hydropower potential of India is estimated to be 148,700 MW as installed capacity. Further, small, mini and micro hydropower schemes (with a capacity of less than 3 MW) have been assessed as having almost 6,782 MW of installed capacity.

2.3.3 Domestic and Drinking Water Uses

Access to sufficient and good quality drinking water is very unequal across South Asian countries. Trends include increasing groundwater depletion and pollution (Shamsudduha, 2013), irregular climate patterns causing droughts and destructive floods, lack of solid and reliable infrastructure and competition with agriculture 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, both of which are exposed to recurrent floods and high water demand.

A lack of water infrastructure makes sustainable access to safe drinking water in Afghanistan the lowest in Asia. More than half of the urban population has no access to improved water resources and 80% of the population in rural areas drink contaminated water (MDG, 2005).

Although Pakistan receives most of the Indus River water by volume, per capita water availability (at 1,306 m^3/year) is the lowest in South Asia (Table 3). Some 13% of the population (28 million inhabitants) do not have access to improved drinking water resources, only 53% of the total rural population has access to safe drinking water supply, and the remainder access untreated surface water resources (e.g. streams, canals, ponds or springs) (Mirza and Ahmad, 2005). In 1995, around 12.4 km^3/year of untreated water was discharged into water bodies (Ahmad, 2008), including 0.5 and 0.3 km^3/year of sewage from Karachi and Lahore, respectively; this was often reused without treatment for drinking causing numerous water-borne diseases. In Bhutan and Nepal, about 40% of the population still does not have access to safe drinking water (MoE, 2005).

2.3.4 Industries

Together with Bangladesh, India is the country where industries consume the greatest share of all water usages, representing 2% of the total water withdrawal. In this country, more than 70% of industrial water use is for energy generation (Aggarwal and Kumar 2011), the remaining being used for engineering industries (CSE, 2004). Water for energy is mainly for cooling thermal power stations. This is not only the dominant industrial demand but the fastest growing (in relative terms) demands at least in India and constraints on availability (e.g. during drought) has significant downstream economic consequences. In recent years, groundwater has also been used along with surface water for industrial purposes. The total industrial water demand is expected to increase to 80 km^3 and 143 km^3 by 2025 and 2050, respectively, which will be 8.5 and 10% of the total withdrawal (CSE, 2004; Aggarwal and Kumar 2011). In Bangladesh, if business as usual continues in the development of the textile sector, an additional water demand of over 3.4 km^3 by 2030 is expected, equivalent to the annual water needs of a population of approximately 75 million people. 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 high-polluting sector (ARUP, undated).

2.3.5 Importance of Groundwater

In the dry season or when the monsoon is delayed, aquifers provide critical natural groundwater supplies, often better protected from pollution contamination and evaporation losses compared to surface reservoirs. Groundwater-fed irrigation has become the mainstay of irrigated agriculture over much of India and Bangladesh, Punjab and Sindh provinces of Pakistan, and the Terai plains of Nepal. Traditionally, surface water from ponds and rivers was used to provide both drinking and irrigation water supplies in all South Asian countries. However, over the last few decades groundwater has largely replaced surface water-fed water sources (Shamsudduha, 2013). This is one of the main factors behind the decline and degradation of groundwater resources in the range, coupled with problems of mismanagement, inadequate waste disposal and natural and anthropogenic contamination.

2.4 Managing Water Resources

2.4.1 Water and Climate Information

Informed water resource management, planning and development requires reliable information on precipitation, streamflow, groundwater recharge and water quality, and how they vary over space and time. For example, flood prevention requires flood forecasting, early warning systems and mapping of flood-prone areas. In the HKH, the prevention of Glacial lake outburst floods (GLOF) requires good understanding of glacier processes, lake formation and sedimentations. Droughts should be predicted using climate models, remote sensing and satellite technology. Information about groundwater recharge requires monitoring and characterization of aquifers, identification and protection of key recharge zones. Landslide and erosion can be better controlled with information about soil and interaction with land-use and hydrology as well as water infrastructure. Protection of water quality requires improved knowledge about water treatment, surface/groundwater interactions, monitoring of the impact of a warming environment on various sources of contaminants. In order to prevent coastal floods, not only cyclone and storms should be accurately predicted, but also sea level rise should be monitored in order to anticipate spatio-temporal variations in sea level and impacts on coastal flooding and groundwater contamination.

2.4.2 Key Water Management Decision

Table 4 compiles information about climate risks with a focus on knowledge, governance, infrastructure, planning/management and communication/education/participation.

Table 4. Climate-Related Risks to Water Resources and Potential Adaptation Actions

Climate Risks	**Knowledge**	**Governance**[1]	**Infrastructure**	**Planning/management**	**Communications / Education / Participation**
1. Primary risks					
a) Changes in precipitation (especially monsoon)	Research; weather monitoring	Coordination between meteorological, water and agriculture agencies	Dams; inter-basin transfers; groundwater recharge (including artificial options)	Flexible irrigation management systems; inter-sector responses to assist adaptation	WUAs and FOs involvement; capacity development; communication to farmers and other stakeholders
b) Sea-level rise[2]	Monitoring; research	Coordination between water agencies, agriculture and other water using sectors, and coastal authorities	Embankments; sub-surface groundwater barriers, maintaining and restoring natural shorelines	Groundwater use plans; controls over groundwater use;	Involvement of coastal communities; capacity development
c) Temperature extremes	Research; monitoring	Coordination between water, energy and productive sectors	Soil and water conservation; improved water supply infrastructure	Mapping trends and designing for peak demands	Prevention of risk through public information and information sharing
2. Secondary risks					
a) Floods	Monitoring and early warning systems	Coordination (inter-agency, government-public)	Embankments; Dams; flood refuges	Flood management plans; restrict development on floodplains; flood mapping; flood insurance	Public awareness of flood risk areas; capacity strengthening
b) Droughts	Weather prediction and early warning communications; research; monitoring	Allocation priorities and planning mechanisms; coordination between agriculture / power / water resources / water supply; local institutional capacities	Dams; inter-basin transfers; groundwater development	Water allocation plans; conjunctive use; demand management including pricing; water efficiency technologies; irrigation and urban water management; recycling and reuse	Involvement and sharing local solutions; capacity development

[1] Note that some governance actions transcend specific threats – separation of regulation and operations leads to good governance
[2] Includes only water resources threats from sea-level rise (principally contamination of coastal aquifers)

		to manage scarce water resources and improvise			
c) Reduction in groundwater recharge	Monitoring and characterization of aquifers; research into groundwater; database on groundwater-related information,	Coordination between 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 over groundwater use including indirect regulation; artificial recharge; conjunctive use	Awareness of groundwater limitations; capacity development
c) Increased erosion, landslides and sedimentation	Research into soil management and protection	Coordination between land, water, energy and other agencies	Sedimentation dams	Land management; riparian management; soil conservation	Awareness of soil loss; participation and local solutions; capacity development
d) Reduced water quality (surface water and groundwater)	Monitoring; research into water quality treatment	Coordination between water resource 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 on pollution risks and prevention measures, polluter pays principle
e) Glacial Lake Outburst Floods (GLOF)	Research; monitoring and early-warning systems	Coordination between departments working on disaster management, geology, hydro-meteorology	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 local infrastructure development and their O&M; capacity strengthening

3. Climate Risks

South Asia concentrates over 40% of natural disasters recorded globally. This high exposure to risks is primarily due to two geographic features: the Indian Ocean that generates humid air masses directed northeast toward the South Asian sub-continent (the southwest Monsoon accumulating 70%–90% of annual precipitation between June and September), and the Himalayan mountain belt that condenses this humidity through an orographic effect and creates diluvium precipitation resulting into some of the world's largest rivers carrying huge volumes of water and sediments into the plains of Pakistan, India, and Bangladesh. Many countries in the region share common geological formations and river basins, and natural hazards frequently transcend national boundaries.

Climate-related risks are various in severity, types and scales of impacts. Some are gradually worsened by climate change e.g. water availability progressively reduced by increasing evaporation and decreasing groundwater recharge rates, erosion rates gradually increasing in response to climate change induced land-use change. Other are more abruptly worsened by more frequent extreme events including floods, droughts and storms. The severity of these disasters closely depends on the ways the 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 studied countries in South Asia.

Among all types of natural disasters droughts have caused by far, the largest number of casualties in the last century (6.1 million people of which 69% were in India and 31% in Bangladesh http://www.emdat.be/). Storms and cyclones are the second major source of fatalities (865,000), followed by riverine and flash floods (including GLOF) and landslides. In contrast, the number of people affected by landslides (4.6 millions) far exceeds that affected by other disaster types, including floods and droughts (1 million each), and storms and cyclones (390,000). Floods have led to the largest damage by cost (86 billion USD, equivalent to 70% of all economic losses caused by natural disasters in the region). Landslides are next and have caused an estimated 37 billion USD in damage, followed by storms and cyclones.

Compared to these 4 categories of disaster (riverine and flash floods, droughts, storms, landslides and cyclones), coastal floods have caused far fewer casualties, affected fewer people and 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 management.

Countries most affected by landslides include India, Bangladesh, Pakistan, Afghanistan and Nepal. Due to its tropical climate, relatively flat topography with dense vegetation, Sri Lanka is the least exposed to landslides. Data from Bhutan should be considered carefully because of the likely numerous gaps in the records.

3.1 Floods

Due to their size and sediment levels, the largest rivers of South Asia are difficult to manage and regularly cause flooding (Kundzewicz et al., 2009). Highly densely populated lowland areas are exposed to coastal floods worsened by sea level rise and high intensity cyclones from the Indian Ocean. Riverine floods lead to significant indirect losses including the degradation of agricultural land which subsequently diminishes agricultural productivity, impacting rural development and income opportunities, as well as the contamination of surface water and groundwater, either with salt intrusion or pollutant dissemination. Floods also damage water infrastructure including hydropower dams and irrigation schemes. This last decade saw the highest number of reported flood disasters with the greatest spatial coverage on record. These included the devastating floods in Pakistan in 2010 and the Uttarakhand flood in India in 2013. Riverine floods occur when rivers over-spill, in contrast with flash floods, which are much more localized and often confined in narrow valleys.

3.1.1 Flash Floods

Excess rainfall can cause flash flooding the destructive power of which is aggravated by steep slopes. Their hydrograph is characterized by a sharp rise and recession. Flash floods usually last no more than a few hours or more, rarely days. Reduced soil infiltration (e.g. in urban areas) magnifies the impact of flash floods. High flow velocity generally causes extensive damage to crops and properties (Mirza and Ahmad, 2005). Population settled along river banks and foothills, over steep slopes, and low-lying slums and squatter settlements are more vulnerable to flash floods (ICIMOD, 2010; Gautam et al., 2013; Shrestha, 2008).

Afghanistan

The mountainous north-east of the country is more exposed to flash floods because of high precipitation in the spring or during the summer monsoon in the south, and the snow accumulation at higher altitudes that melts up 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. Families saw their houses and water infrastructure (irrigation canals, wells and water supply networks) destroyed, accompanied by serious loss of spring crops and livestock. The lack of infrastructure, inadequate disaster preparedness, and poor socio-economic conditions render Afghanistan particularly vulnerable, explaining why this country includes the highest number of flood-related deaths in the world (CPHD, 2011).

Bangladesh

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).

Bhutan, India, Nepal and Pakistan

GLOFs are a catastrophic discharge of water from glacier lakes due to failure or breach of unstable end moraine or ice dams formed at the end of these lakes. The first and second types of glacier lakes are called moraine-dammed and ice-dammed glacier lakes, respectively. Almost all glacier lakes in Nepal are moraine-dammed due to very rich debris making relatively large lateral and end moraine compared to others glaciers in the world. Ice dammed lakes are very rare, and are considered less dangerous. Glacier lakes evolve over time, depending on temperature variations and sedimentation rates. About 8,880 glacial lakes have been recorded in Bhutan, India, Pakistan, Nepal and the Ganges basin in China in the late 1990s and early 2000. Of these, 204 were listed as potentially dangerous (Shrestha et al., 2015).

Some 56 GLOFs have been reported in the HKH since the 1970s, more than 60% having occurred since 2010. These GLOFs resulted in significant damage to people, crops, infrastructure, and hydropower plants. In 1984, a GLOF of Lake Dig Tsho caused severe disaster to lives (4-5 people died) and property downstream. The lake was drained suddenly and sent a 10 to 15 m high surge of water and debris down the Koshi River for some 90km. About 1 million cubic meters (Bm^3) of water was released, creating an initial peak discharge of 2,000 m^3/s. This spectacular natural event eliminated all the bridges for 42 km downstream with loss of life and 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 relatively low, compared to other climate-related risks in neighbouring countries.

3.1.2 Riverine Floods

With the onset of the monsoon in June, all rivers start swelling and bring flood water to alluvial plains (i.e., in the GBM from June to September) (Mirza and Ahmad, 2005; Winsemius et al 2015). About 50% of the world's population exposed to the hazard of river flooding are located in South Asia, specifically in India, Bangladesh, Pakistan and Afghanistan (Luo et al., 2015). Of the South Asian countries, Sri Lanka is the least impacted.

Afghanistan

The Amu River is the largest river flowing along Afghanistan's borders. Every year, it swells and changes 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 had been affected by such event in the Feyzabad District.

Bangladesh

Bangladesh is the world most densely-populated country (Table 1) and consists largely of a low, flat topography (60% of the country lies between 0 and 6 metres above mean sea level). About 80% of the country is included in the floodplains of the GBM. Due to its downstream location in the GBM, Bangladesh is draining an area twelve times its size (Table 2). On average, 22% of the country is flooded each year. The continued development of upstream parts of the basin, deforestation in the Himalayas, diking along channels, land degradation and erosion have aggravated the flood situation. From 1987 to 2007, Bangladesh experienced 5 large floods (Mirza, 2011). In 1988 and 1998, the peak flows of the Brahmaputra and the Ganges 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 cyclonic surges.

India

Out of 164 flood-prone countries in the world, India is ranked the highest in terms of exposed population, with 21 million people affected annually. Infrastructure with an equivalent value of 14 billion USD - almost 1% of national GDP - is exposed annually and this figure is estimated to increase tenfold by 2030 (Luo et al., 2015). Overall, some 40 million ha 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 a fifth of the country, posing high risks to riverine populations. Luo et al (2015) indicate that 710,000 people in Pakistan are exposed to river flood risks annually, while in some years, the number of affected reaches up to 21 million people (Syvitski et al., 2013). Over the last 6 years, Pakistan witnessed 3 major floods. The 2009 floods were caused by a major embankment breach that changed the course of the flood water entirely (Winsemius et al., 2013). The lack of planned accommodation to river sediment load is one major reason that has led to many riverine floods in Pakistan (Syvitski et al., 2013; Winsemius et al., 2013). The catastrophic 2010 flood along the Indus River was caused by exceptional rainfall in conjunction with a reduction in conveyance capacity of water and sediment, dam and barrage-related backwater effects (Syvitski et al., 2013). On average, annual floods in Pakistan results in a loss of 1% of total GDP, which is equivalent to 1.7 billion USD. The 2010 floods cost the country 10 billion USD in damage.

3.1.3 Coastal Floods

Today, coastal floods are mainly due to cyclones creating local seal-level surges as described below. In future, the rise from sea level is expected to worsen coastal flooding as detailed in section V-1-3. Cyclones and storms originating from the Indian Ocean are the major cause of coastal floods that hit low-lying and coastal parts of Bangladesh. Elevation in the sea level by just a metre, in response to strong winds for example, frequently causes disasters. Over the last 40 years, 520,000 deaths have been recorded, 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 along Bengal, Orissa and Andhra Pradesh is prone to tropical cyclones causing devastating coastal floods. For instance, the super cyclone that hit the Orissa Coast in October 1999 had wind speed of 260 km.h^{-1} with heavy rains, and a storm-surge of 9 m above mean sea level at Paradip, which penetrated 35 km inland (Mirza and Ahmad, 2005). According to the State Relief Commissioner’s Office in Bhubaneshwar, nearly 10,000 people died; over 2,000 people were injured; more than 370,000 cattle perished; and 1.6 million ha of paddy and 33,000 ha of other crops were damaged. Several villages were completely wiped out and over a million people made homeless.

3.2 Droughts

Due to their large geographic extent, droughts affect the greatest number of people, compared to other disasters in South Asia and results from water shortage either from rainfall, surface water or aquifers. All countries in South Asia are drought-prone. Lack of precipitation can significantly impact agricultural output since approximately 60% of cultivated areas in South Asia are rain-fed (Table 3). Droughts affect people through water shortage, food deprivation and sometimes associated heat waves.

Two main types of droughts exist. First, a *meteorological* drought corresponding to prolonged periods with rainfall amount far below inter-annual averages that mainly affect agriculture. Their magnitude is enhanced by the duration of the rainless period and temperature and wind factors that can exacerbate water stress. And second, a *hydrological* drought which occurs when water levels in rivers, lakes, reservoirs and aquifers fall below an established statistical average, usually following a meteorological drought. Hydrological droughts may also occur during times of average precipitation if the water demand is high and increased use has lowered water reserves. In some case, drops in groundwater level are accompanied by salt intrusion because of inversed lateral gradients and water flux from saline rocks. It is also possible that in the absence of sufficient rainfall, vertical infiltration of surface water declines substantially, allowing vertical ascension of saline groundwater by capillary effect and evaporation, contaminating topsoil layers with salt.

Apart from the inherent 30-year cycle of the monsoons, droughts have been found to be more frequent during the years following ENSO events and the warming of the Eastern Equatorial Pacific Ocean. At least half the severe failures of monsoon since 1871 have occurred during El Niño years (Webster et al., 1998). Countries mostly affected by droughts are located in semi-arid and arid areas (Figure 1) like Afghanistan, Pakistan and some parts of India or where river flows become very low during the dry season (Bangladesh), partly due to upstream flow diversion. In Bhutan, Nepal and Sri Lanka, droughts have minor effects compared to other climate-related disasters.

Afghanistan

Afghanistan is one of the most drought-sensitive countries in the world because of its significant dependence on agriculture, its generally arid climate, political fragility and associated years of conflicts and vulnerable irrigation infrastructures. Only a low share of the population enjoys access to improved water sources (27%) (CPHD. 2011) and 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 just before it enters Bangladesh. Reduction of dry season flows causes severe water shortage across the country and in the South West region in particular, and is aggravating salinity intrusion and environmental degradation (Rahaman, 2009). Groundwater development has for long been seen as a solution to cope with surface water shortage. However, high concentration of arsenic and fluoride are threatening populations relying on such ground resources while coastal areas tend to be exposed more frequently to salinity issues. Beside hydrological droughts, Bangladesh experienced 20 meteorological droughts in the last 50 years (Ramamasy and Baas, 2007). The 1978-79 drought affected half of the cultivated land and population, destroying over 2 million tons of rice. Similar large-scale droughts followed in the 1980s and 1990s.

Bhutan

Although not primarily exposed to droughts, Bhutan may experience dry spells. Most of Bhutan’s farmers are subsistence farmers, and hence with failure of the monsoon or untimely rainfall, crop losses and associated damage to livelihoods are the main issue.

India

Most drought problems in India are related to the availability of food, safe drinking water and shelter. The extent of the drought disaster that occurred in 1979-1980 was evident in large areas of Northern and Eastern India that affected more than 38 million ha of cropped areas and endangered the lives of 130 million cattle and more than 200 million people. Droughts not only affect surface water availability but also the recharge of aquifers which are currently depleted by unsustainable pumping rates.

Nepal

Even though Nepal has not been associated with severe droughts in the past, this country has witnessed drought-related stress in recent years. Streams in mountainous regions tend to deplete in response to greater abstraction, while groundwater in the Terrai region is being used at unsustainable rates (Thakur and Upadhyaya, 2014). In this situation, hydrological droughts result predominantly from increased water demand rather than a reduction of rainfall input to the water system. Droughts affect farming, livelihood management and domestic use. Crop failure due to lack of irrigation water has forced many farmers to leave the land fallow. As a result, there has been migration from drought-hit areas and an increase in import of food and water from other regions NPC (2013). Poverty-stricken western regions are more vulnerable to droughts as they cannot migrate easily to other regions, and cannot afford imported food and water. Groundwater potential is limited in this mountainous country and still largely untapped and therefore has limited drought alleviation capacity. Arsenic contamination is also a major problem, especially in the southern half of the country.

Pakistan

Alongside Afghanistan, Pakistan is the most water-scarce country in South Asia due to its semi-arid climate. With growing population and food demand, large irrigation areas can become rapidly water-stressed. Some years receive less than half of the long-term rainfall average of 500mm/year (e.g. 2000, 2001 and 2002 when millions of cattle died due to shortage of fodder crops and several thousand people were forced into migration) (World Bank, 2012). Because of repeated droughts and rising water demand, aquifers of Baluchistan province are dropping by 3.5 m annually, and are estimated to run out in a couple of decades (Mirza and Ahmad, 2005) with massive internal displacements expected.

Sri Lanka

Since Sri Lanka is close to the equator, warm conditions prevail for most of the year. This hot weather combined with weak or delayed monsoon rains, results in droughts affecting agricultural productivity in parts of the country. On average, 8 droughts occur annually over the country, without exhibiting any particular trends over time (DIMS, 2015). Most droughts are recorded from January to March and August to September, which are the inter-monsoon months for the region. In terms of spatial distribution, southern regions have more droughts.

3.3 Groundwater Contamination

The contamination of groundwater by various pollutants results from anthropogenic dynamics or processes related to the current climate dynamic, or a combination of both. Anthropogenic processes are discussed in section VI-5. Climate impacts include i) reduced aquifer recharge caused by decreasing rainfall, greater evaporation rates and/or siltation of recharge sites such as in alluvial delta, all leading to water table drawdown followed by horizontal or vertical transfer of pollutants; and ii) saline water intrusion in coastal aquifers in response to sea level rise (Mirza and Ahmad 2005) and/or in response to reduction of dry season flow in river deltas (e.g. in the Lower Ganges; Shamsudduha, 2013). Countries mostly impacted by climate-related risks include Afghanistan, Bangladesh, India, Pakistan and Sri Lanka.

Afghanistan

Groundwater quality in the Kabul Basin is highly spatially variable, with some areas showing high concentrations of dissolved solids (Broshears et al., 2005; Akbari et al., 2006). A significant aggravating factor of groundwater pollution in this semi-arid country includes limited renewal of groundwater due to limited recharge and storage capacities (Mack et al 2014), thus maintaining high concentration levels of contaminants (no dilution).

Bangladesh

The major climate-related causes of groundwater contamination currently observed in Bangladesh include saline contamination of coastal aquifers during storm surges. While this source of groundwater contamination is expected to increase in the future with rising sea levels, it remains anecdotal today compared to the effect of other anthropogenic processes including the increase in groundwater use (Rajmohan and Prathapar, 2013) and associated lateral flux mobilizing endogenic contaminants (e.g. arsenic) (Chakraborti et al., 2013; Smith et al., 2000), and increasing infiltration of toxic residual from agricultural, urban and industrial activities (Zahid and Ahmed, 2005).

India

The 7,500 km-long Indian coastline is prone to groundwater contamination by saltwater intrusion, especially during meteorological droughts and where groundwater levels are depleted to the sea level (e.g. in Tamil Nadu, Pondicherry and Gujarat) (Garduño et al., 2011). 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 (Uzma and Latif, 2013). The coastal aquifers of Sindh are unfit for human consumption due to natural arsenic contamination (Zubair et al., 2014), salt water intrusion and anthropogenic pollutants (mixing of human sewage, fertilizers, etc.) (Aamir et al., 2016).

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^2 and are intensively used. The water from these aquifers meets the demand of the tourist industry, human settlements and intensive agriculture along the coasts. The freshwater is recharged during the monsoon and is used throughout the year. Over extraction can lead to coning of the fresh water lens and ingress of underlying brackish water, thus polluting the aquifers.

3.4 Cyclones

After droughts, storm and cyclones are the second cause of loss of life and property in South Asia. Although cyclones can generate inland floods (these effects have been described previously), they are more known for the damages they cause along coastal areas where they can induce destruction caused by strong winds and sea water surges. Because most of the cyclones originate from the warm Indian Ocean, their effect is strongest near the coast and particularly over flat lands. Most affected countries include Bangladesh, India, Pakistan and Sri Lanka. Bangladesh is subjected to strong cyclones originating in the Bay of Bengal during April-May and September-November (Karmalkar et al., 2012). Damage can reach several billions US dollars (Mirza, 2003) and casualties in the hundreds of thousands. 42 major cyclones hit coastal areas over the last 125 years, including 14 in the past 25 years (Das Gupta et al., 2005).

3.5 Siltation and Landslide

Siltation is the deposition of sand and clay particles that originate from erosion of soil material. This process is frequent over steep terrain, accelerated by heavy rainfall, stream erosion, snowmelt, earthquakes, changing groundwater levels, volcanic eruptions and anthropogenic factors (e.g. land-use changes) (Ahmed and Suphachalasai, 2014; Arora et al 2014; Meraj et al 2015; Mitra and Sharma, 2012). Landslides occur due to unstable slopes and occurrence has increased over recent years due to more intense anthropogenic activities, especially deforestation, particularly in the HKH (e.g. in Nepal) (Shrestha, 2008; Immerzeel et al., 2012; Bajracharya et al., 2011; Shrestha et al., 2015).

In the Indus River Basin, perennial runoff, partly sustained by ice- and snowmelt is responsible for high erosion rates on hillslopes where vegetation is sparse and the soil is fragile due to semi-arid climate and agriculture intensification. The Indus River and its tributaries carry about 0.44 km^3 of sediment annually of which nearly 60% remains in the system where it is deposited in natural depressions, reservoirs, canals and irrigation schemes. In the Tarbela catchments, 167 m^3 of silt are eroded per square kilometre per year. The Mangla and Tarbela Dams/Reservoirs play an important role in the economy of the country by providing cheap hydroelectric power and water for irrigation. Due to sedimentation, these reservoirs are losing about 0.031 and 0.14 km^3/year in live 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 794×10^6 tons of sediments are transported by the Ganges Rivers each year. 80 ± 10% comes from the High Himalaya, 20 ± 10% from the Lesser Himalaya. About 8% of the river sediment are deposited on floodplains and delta plains in Bangladesh. The remaining ~ 45%, is deposited in the subaqueous delta and the Bengal Fan (Wasson, 2003). High sediment deposition rates in the delta of the GBM partly compensates land subsidence (Brown and Nicholls, 2015) and therefore contributes to slow down the negative effects of sea level rise.

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

This chapter reviews available updated information about climate change, how it will affect rainfall, temperature and sea level, the available models for prediction, their limits and how to cope with uncertainties in water management.

4.1 Climate variables

4.1.1 Precipitation

Observed trends

Rainfall trends over the past century in South Asia are characterised by strong variability, with both increasing and decreasing trends observed in different countries (CDKN and ODI, 2014). Lacombe and McCartney (2014) reviewed recent Indian-wise trend analyses of rainfall over the last century. The authors concluded that due to high spatiotemporal variability of rainfall arising from complex atmospheric dynamics, past studies have often produced inconsistent results. Using rainfall data from the Indian Meteorological department, the authors analysed recent trends in monthly and seasonal cumulative rainfall depth, number of rainy days and maximum daily rainfall, and in the monsoon occurrence (onset, peak and retreat) over the period 1951-2007. They evidenced a 95%-field-significant earlier monsoon onset in Northern India, a 99%-field-significant increase/decrease in pre-monsoon rainfall depth in northeast/southwest India and confirmed that there have been more extreme rainfall events and fewer weak rainfall events in the central Indian region. General trend patterns were found to align well with the geography of anthropogenic atmospheric disturbances and their effect on rainfall, confirming the paramount role of global warming in recent rainfall changes.

Projections

Even though state-of-the-art general circulation models (GCM) exist, there are considerable challenges in predicting monsoon rainfall changes due to the difficulty in modelling regional precipitation distribution, especially in South Asia where the atmospheric dynamics controlling the monsoon are difficult to model (Turner and Annamalai, 2012). Increased greenhouse gas (GHG) concentration 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 continent. However, rainfall projections remain uncertain over South Asia. Figure 4 illustrates predicted rainfall changes over South Asia, using the most recent ensemble models (5^{th} phase) of the Coupled Model Intercomparison Project (CMIP5) (IPCC, 2014). Based on the intermediate RCP4.5 emission scenario and focusing on the median projection of the CMIP5 (i.e. 50% percentile) over the period 2046-2035 (central panel in Figure 4), Bangladesh, Bhutan, India and Sri Lanka will be exposed to a 10% increase in annual rainfall with greater statistical significance in Sri Lanka. Greatest increases in annual rainfall, reaching 20%, will be observed in southwest India and south Pakistan. In contrast, Afghanistan and Nepal will exhibit rainfall declines down to -10%. An earlier monsoon onset is expect according to the most reliable past projections (Annamalai et al., 2007).

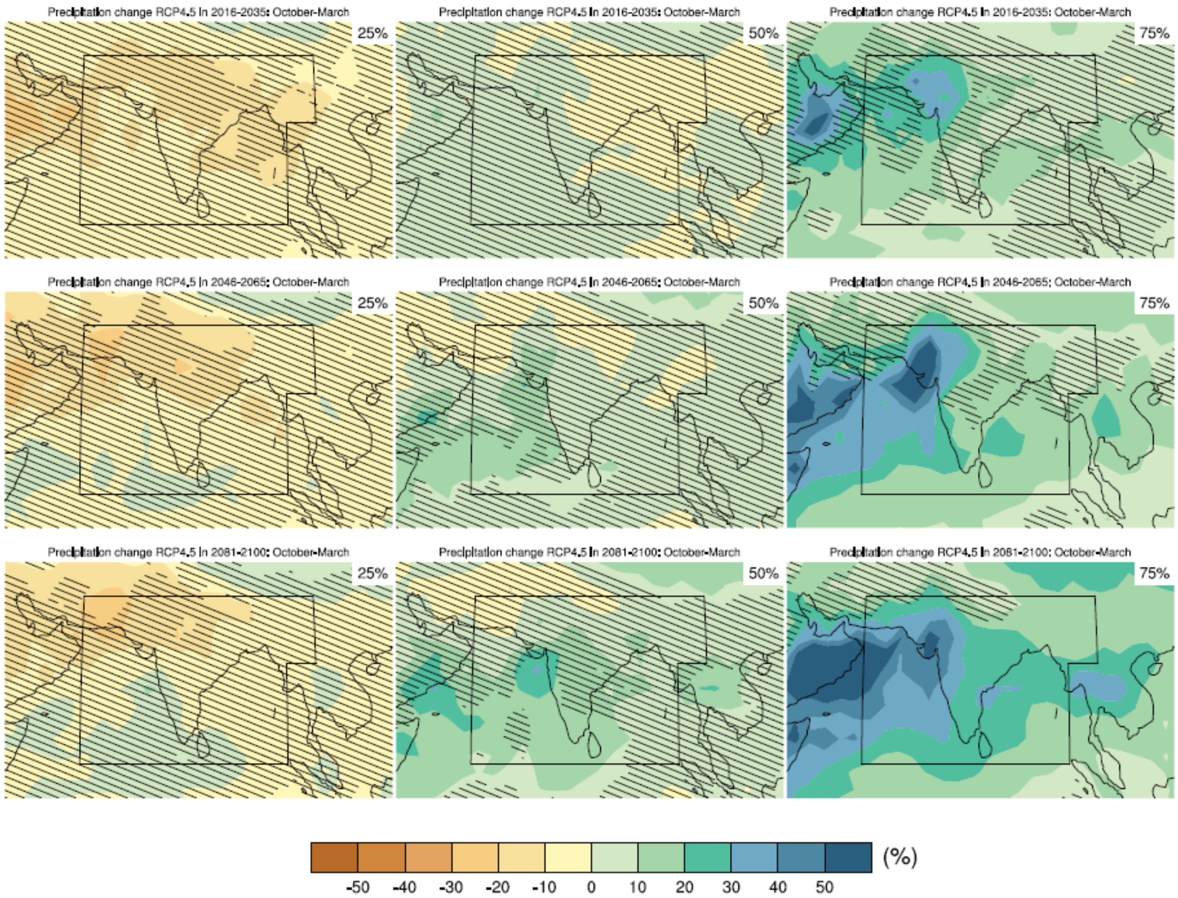

Figure 4. Precipitation changes in 2016–2035, 2046–2065 and 2081–2100 with respect to 1986–2005 in RCP4.5. For each point, the 25th, 50th and 75th percentiles of the CMIP5 distribution is shown; this includes both natural variability and inter-model spread. Hatching denotes areas where the 20-year mean differences of the percentiles are less than the standard deviation of model-estimated present-day natural variability of 20-year mean differences (IPCC, 2013)

The fact that i) the natural inter-decadal variability of rainfall is of the same magnitude as the projected long-term trend in annual rainfall (cf. hatching in Figure 4) and ii) the direction of the projected trends (either positive or negative) change according to the percentiles of the distribution of the CMIP5 ensemble considered, reveal great uncertainty in terms of projected rainfall in South Asia.

4.1.2 Temperature

Observed trends

The Intergovernmental Panel on Climate Change (IPCC) has reported that warming occurred across most of the South Asian region over the 20th century and into the 2000s, and that there were 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. The Thar Desert also shows enhanced warming, but increases are less pronounced than in the Eastern Himalayas. Warming hotspots include Nepal, Bangladesh and most parts of India (particularly, the tropical region), compared with Pakistan and the Greater Himalayan region (Sheikh et al., 2014).

Projections

Unlike rainfall projections exhibiting regional contrasts in trends and magnitude and high uncertainty, future trends in temperature are expected to be more homogeneous over space and time. However, rising temperature rates will not be uniform across the continent (Figure 5). The lowest increases in temperature will be observed along the coasts of Southern India, Sri Lanka and Bangladesh. The stronger temperature increases will be observed at higher latitudes in Afghanistan, Bhutan, Nepal and Pakistan. Compared to the average in the 20th century, average annual temperatures could rise by more than 2°C in South Asia by the mid-21st century and exceed 3°C by the late-21st century under a high-emissions scenario. Oceans in subtropical and tropical regions of Asia will warm under all emissions scenarios and will warm most at the surface.

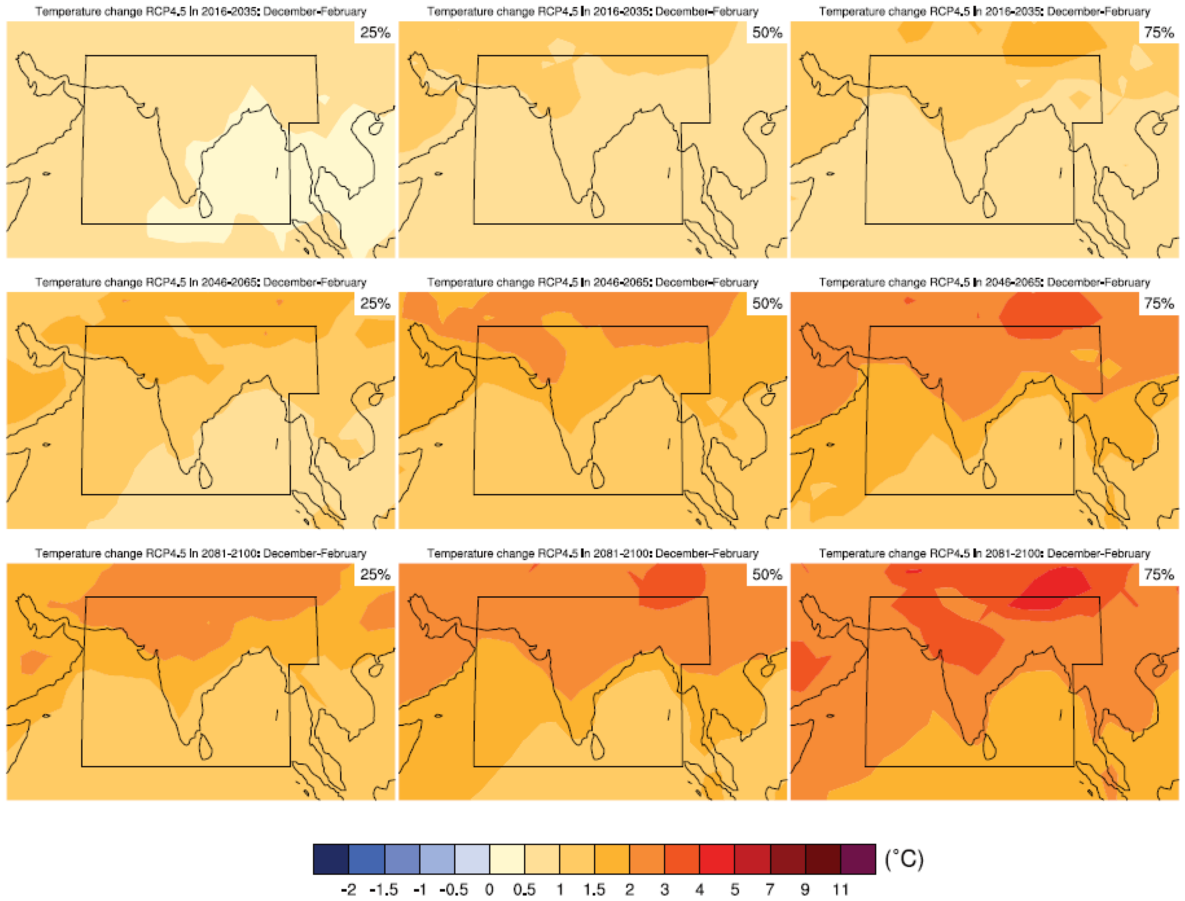

Figure 5. Mean annual temperature changes in 2016–2035, 2046–2065 and 2081–2100 with respect to 1986–2005 in the RCP4.5 scenario. For each point, the 25th, 50th and 75th percentiles of the distribution of the CMIP5 ensemble are shown; this includes both natural variability and inter-model spread (IPCC, 2013)

4.2 Sea Level Rise

Observed trends

Globally, the rate of sea level rise since the 1850s has been larger than the average rate during the previous 2,000 years. Shifting surface winds, the dilatation of warming ocean water, and the addition of melting ice can alter ocean currents which, in turn, lead to changes in sea level that vary from place to place (IPCC, 2014). Past and present 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 2 decades varied between 2 and 5mm/year along the South Asian coasts with local minimum of 0 and 1mm/year in the Indus Delta and along the western side of the southern Indian Peninsula, respectively (Nicholls and Cazenave, 2010).

Projections

Global mean sea level will continue to rise during the 21st century. Under all emissions scenarios – low and high – the rate of sea level rise will very likely exceed that observed during the past 3 decades. Mean sea level rise by the last 2 decades of the 21st century (as compared to sea levels in 1986–2005) will likely be in the ranges of 26–55 cm under a low-emissions scenario, and up to 98 cm by 2100 under the high emission scenario. Projections indicate that the average height of waves in Indian Ocean monsoons will not change greatly (IPCC, 2014; CDKN and ODI, 2014)

4.3 River Flow and Groundwater Recharge

By modifying rainfall and temperature patterns, climate change alters river flows, groundwater and their interaction, and generates associated risks (drought, floods, siltation, erosion, evaporation losses and groundwater contamination). While modified precipitation can alter river flow all over South Asia, temperature rise alters flow regimes mainly in river basins which are partly fed by snow and ice melting occurring in the HKH (cf. related countries in Table 1). It should be noted that, while climate change is expected to modify river flow patterns, rising water demands across sectors, and land-use changes, are expected to also have significant effects on the water cycle and associated river flow regimes as discussed in section V-5.

4.3.1 Effect of Temperature Rise on Snow Melt and River Flow

Global warming has two distinct effects on glaciers, taking place over different time scales. On a seasonal scale, it induces earlier spring melt of snow accumulated during the winter. Over years, it leads to a gradual decline in ice and snow pack. Since 1850, records suggest that the volume of perennial ice and snow cover that had accumulated over centuries in the HKH has continuously reduced[3] (Bolch et al., 2012). Glacier area and volume reduced by 14-28% and 11-40%, respectively, from 1960 to 2000. Maximum seasonal snow cover area reduced by 5-15% between the 1961-1990 and 2001-2010, equivalent to a 9-27% reduction in maximum seasonal water storage capacity (Savoskul and Smakhtin, 2013a). The contribution of ice and snow meltwater to river flow varies both in space and time. 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) (Table 1 and Table 2). Between 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 Basins (Savoskul and Smakhtin, 2013b). The most pronounced change occurred in the composition

[3] 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).

of glacier runoff: the share of the non-renewable component in the total glacier runoff increased from 16-30% to 26-46% in all study basins. Warmer temperatures not only accelerate ice and snow melting but also increase the ratio of rainfall versus snowfall, resulting in melting ice not being replenished (Shrestha et al., 2015). According to the SPHY model, by 2050, the reductions in glacial area in the Indus, Ganges and Brahmaputra Basins are likely to be -24%, –35% and –45%. Although the Indus Basin shows the smallest relative decrease, 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 degrees Celsius, with total basin ice reserves reduced to 20-50% of the baseline 1961-1990 (Lutz and Immerzeel, 2013).

4.3.2 Combined Effect of Temperature and Rainfall Changes on River Flows

Changes in annual discharge

While temperatures will increase with considerable certainty throughout South Asia (Figure 5), there is more uncertainty about precipitation patterns (Figure 4). Under all climate scenarios until 2050, the amount of ice and snow meltwater will decrease in relation with the reduction of the volume of glacier, 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 and snow melt to river flow are projected to increase and decrease, respectively. Overall, no significant change in total annual flow is projected until at least 2050 in all basins because the retreat of glaciers will be compensated for by an increase in precipitation and an increase in ice melt (Lutz et al., 2014).

Change in flow seasonality

Depending on the stream flow composition (glacial melt, snow melt, rainfall, base flow), the regime 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 will have little effect on hydrological regimes (Savoskul and Smakhtin, 2013b). Currently, the streamflow peak is mainly controlled by the monsoon rainfall peak. In contrast, the reduction of glaciers and seasonal snow cover will significantly affect the seasonality of river flow in the Indus Basin. A shift of streamflow peak from summer to early spring months is anticipated as seasonal snow will start melting earlier in the year. Within the Upper Indus, a decrease in flow is expected from April through to August for the Kabul River, mainly because of reduced rainfall (Shrestha et al., 2015). In addition, the earlier monsoon onset anticipated for the coming decades is expected to emphasize this shift toward an earlier start of the flood pulse (Annamalai et al., 2007).

4.3.3 Effects of Temperature and Rainfall Changes on Groundwater Recharge

A sustainable groundwater recharge rate is higher or close to the discharge rate. Concentrated and/or shortened monsoon and more extreme rainfall events reduce the time duration required for rain water to infiltrate the soil, also resulting in more frequent and intense flash floods (USGS, 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 top soil zones and recharged in the water table (USGS, 1993). Such impacts are already being felt in Afghanistan, Pakistan and India, where there are more extreme events and droughts. Groundwater levels remain below sustainable levels (Shah, 2010; Taylor et al., 2013). Though with high levels of uncertainty, South Asia may face a reduction in groundwater recharge by 10% in 2050s in response to climate change (Clifton et al., 2010). However, there are also possible reverse effects given that rainfall change is not the only driver of modified recharge rates. In high latitude regions, recharge may in fact be enhanced by increased spring snowmelt due to increasing winter temperatures, while in alluvial areas, more frequent floods may increase recharge. Prior to development of widespread irrigation across the Indus and GBM basins, recharge through 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 monsoon season, where extensive flooding infiltrates to the shallow aquifer. For much of the year, however, the Ganges river system receives water from groundwater as base-flow, rather than provides recharge (MacDonald et al., 2010). This comparative analysis indicates that the effect of climate change on groundwater recharge will mostly occur 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 and thus reduce recharge (Shah and Lele, 2011). In short, the picture is complex and generalised assertions need to be avoided. The practical solution to addressing the wider challenge of groundwater availability will most likely lie in localised monitoring and in managing demand across a range of user groups.

4.4 Knowledge Limitations and Uncertainties

Uncertainties in climate and hydrological projections are due to a range of factors: the reliability and availability of input data used to calibrate the climate and hydrological models, the robustness and efficiency of these models, the possible bias in model parameterization, and the uncertainty in future GHG emissions, aerosol and land-use changes.

4.4.1 Climate Models

Climate projections use GCMs to compute future trends in climate variables and sea level. Many different GCMs exist. Their differences include various representations and mathematical formulations of natural processes and different spatial and temporal resolution of simulated variables. Different GCMs usually produce different climate outputs, revealing the complexity of climate dynamics and the difficulty of prediction, especially in monsoonal South Asia (IPCC, 2014). To characterize this uncertainty, the Coupled Model Intercomparison Project (CMIP) was created in 1995 in order to coordinate climate model experiments by different groups of modellers using different GCMs. The fifth phase of the CMIP (CMIP5) provides a multi-model context to assess the mechanisms responsible for model output differences. The 5th assessment report (AR5) of the IPCC use the GCMs belonging to CMIP5. Compared to AR4, improvements in AR5 climate projections are evident in simulations at the continental scale. However models continue to perform less well for precipitation than for surface temperature. Confidence in the representation of processes involving clouds and aerosols remains low. Together with advances in scientific understanding and capability, the ability to simulate ocean thermal expansion, glaciers and ice sheets, and thus sea level, has improved since the AR4. Compared to AR4, the magnitude of the uncertainty has not changed significantly, but new experiments and studies have led to a more complete and rigorous characterization of the uncertainty in long-term projections (IPCC, 2014). A specific review of the CMIP5 simulations for South Asia (Prasanna, 2015) confirms the results reported in the global IPCC document (2013) and indicates that the CMIP5 GCMs, despite their relatively coarse resolution, have shown a reasonable skill in depicting the hydrological cycle over the South Asian region. The most important issues in South Asia includes the poor representation of precipitation processes at high altitude and across strong elevation gradients and the paucity of high altitude data for calibration.

4.4.2 Scenarios: The Representative Concentration Pathways

Because of the uncertainty related to future emission in GHG, aerosols and land-use changes, representative concentration pathways (RCP) describe 4 different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. They include 1 stringent mitigation scenario that aims to keep global warming likely below 2°C above pre-industrial temperatures (RCP2.6), 2 intermediate scenarios (RCP4.5 and RCP6.0) (cf. Figure 4 and Figure 5), and 1 scenario with very high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions (‘baseline scenarios’) lead to pathways ranging between RCP6.0 and RCP8.5. The land use scenarios of RCPs show a wide range of possible futures, ranging from a net reforestation to further deforestation. These 4 scenarios produce ranges of change in monthly precipitation and temperature.

4.4.3 Hydrological Models

The final source of uncertainty in climate change hydrological impact assessments is associated with the hydrological models used to translate climatological changes into hydrological impacts. Alternative hydrological models that produce acceptable results for an observed baseline period may respond differently when faced with the same climate change scenario. Hydrological models include fully distributed, physically based models which can detail a range of processes, potentially at a very fine spatial scale, but which require an extensive range of data. Semi-distributed or lumped models adopt a more conceptual approach for process description, whilst 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 events. The limited observing 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).

4.5 Integrating Climate Change in Water Resource Management

4.5.1 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 context than for informing investments and policy choices. Two fundamental and unavoidable issues limit the utility of climate projections: i) 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. Ii) It is not always clear whether the effects of changes in climate on a certain water resources project are significant relative to the impacts of changes in other non-climate factors (e.g. demography, land use, and economic changes). Project planners are therefore ill-equipped to incorporate uncertain climate information into a broader (all-uncertainty) 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 to how best manage those risks to improve system robustness and flexibility.

4.5.2 Available Approaches

Placing risk management at the heart of decision making will help South Asia cope with climate change. No methodology has yet been generally accepted for assessing the significance of climate risks relative to all other risks in water resources projects. The need for such a process has recently been elevated. There is a need for a pragmatic process for risk assessment of water resources projects to serve as a decision support tool to assist project planning under uncertainty.

A project manager must account for many kinds of uncertainties when seeking approval for funding from a donor or board; most important, the project must be shown to be cost-effective, flexible, and robust. Several approach exist, including the decision tree framework (Ray and Brown, 2015) (illustrated in Box 3) which provides a method to evaluate the robustness of a project to climate change. It helps allocating effort to any water resources project components depending on sensitivity to climate risk. 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 3. The decision tree approach

This approach (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 (i.e. ice- and snowmelt fed river inflow modified by changes in temperature and rainfall) and other variables (e.g supplied hydropower price, sediments) might affect the project's optimal design capacity. 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. 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 that translates water availability into hydropower production. Results indicate that the original design of 335 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 project resiliency 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 resource management. The stakeholder-trusted model 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). Stakeholder-preferred investment bundles were then stress-tested in detail to identify any vulnerabilities, including institutional and financial variables. Ultimately, this approach 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 system-level trade-off analysis can help bring clarity and consensus (Geressu and Harou, 2015; Karki et al., 2016).

5. Effect of Climate Change on Climate-related Risks

By modifying rainfall patterns, increasing temperature, sea level and the frequency and magnitude of storms and cyclones, climate change is modifying the temporal and spatial distribution of climate-related risks and their level. Increased frequency of extremes events leads to increased riverine, coastal and flash flooding. Combined to temperature rise, upstream hillslope erosion and downstream reservoir siltation will all lead to increased water- and food-shortages, reduction of renewable surface water and groundwater resources, especially in dry subtropical regions, and intensified competition for water among sectors. Climate-related risks are amplified for those lacking the essential infrastructure and services or living in exposed areas (Shrestha et al., 2015). Higher exposure to climate-related risks can also enhance social inequalities and economic shocks, poverty, spread of infectious diseases, and food insecurity causing considerable and fundamental threats to human life, livelihoods, property, political stability, the economy, and the environment. Over the longer-term, risks include decadal changes in land-use patterns that can further intensify landslides and flash-floods, as well as loss of longer-term recharge capacity for important aquifers. Over time, too, these larger, more structural changes in a region's climate affect population distribution and livelihoods, and also shift patterns of demand for energy and other resources. There is an important distinction to make, therefore, between 'short-wave', 'medium wave', and 'long-wave' risks associated with climate change.

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

5.1 Floods

With on-going climate change, the number of flood disasters has already started increasing over the past few decades (EM-DAT, 2014). This rising trend is expected to continue in the near future (IPCC, 2014; CDKN and ODI, 2014).

5.1.1 Flash-floods Induced by Changes in Rainfall Patterns and Temperature Rise

The intensity of extreme rainfall events is likely to increase in future as a consequence of increasing convective activity during the summer monsoon, suggesting the possibility of more frequent flash floods across South Asia and particularly over mountainous regions (Mirza and Ahmad, 2005). The accelerated melting of glaciers caused by rising temperature explains the rising number and size of glacial lakes in the Himalaya (Mirza and Ahmad, 2005). The gradual rise in glacier lakes may lead to more frequent GLOF by over-powering dams due to increasing water pressure (Mool et al., 2001). In Nepal, about 1.6 million people live downstream of moraine-dammed lakes. Several hydropower projects either in operation, under construction or planned are associated with rivers that have moraine-dammed lakes at their head, potentially generating GLOF (Shresthaet al., 2015).

5.1.2 Riverine Floods

Of all of these flood types, the *riverine floods* are the most pervasive and have long-term impacts on land-use, the economy and most development strategies. Overall, the warming of the India Ocean is expected to bring larger amount of rain over the South Asian continent during the monsoon period. The resulting changes in rainwater input will vary according to locations and remain partly unknown due to high uncertainty in rainfall projections. The more confidently anticipated effects of climate change in relation with more extreme rainfall events is the increase of the magnitude of extreme floods in the alluvial plains of major rivers

(Mirza, 2011), resulting in greater spatial extent and longer flood duration in the GBM and Indus River Basins, as well as other alluvial rivers. Although these floods are essential for rice production as they provide nutrients through silting and required amount of water, excessive spatial extent and duration may delay cropping cycles, damage properties and contribute to the spread of infectious diseases.

5.1.3 Coastal Floods Aggravated by Sea Level Rise and Increased Storm Frequency

Impacts of sea level rise are various. The lowest lying lands will be totally submerged, especially Bangladesh and Pakistan (Figure 6). Coastal lands that will remain above the mean sea level will be exposed to more frequent inundations, erosion (CWC, 2008) and salinity intrusion causing agricultural yield losses, e.g. along the Saurashtra coast (Gujarat, India) (Bhattacharya et al., 2012) and salt contamination of surface water and groundwater (e.g. the Minjur aquifer in Tamil Nadu, India, and in Pakistan), (Tabrez et al., 2008). 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-meter sea level rise (Mirza and Ahmad, 2005).

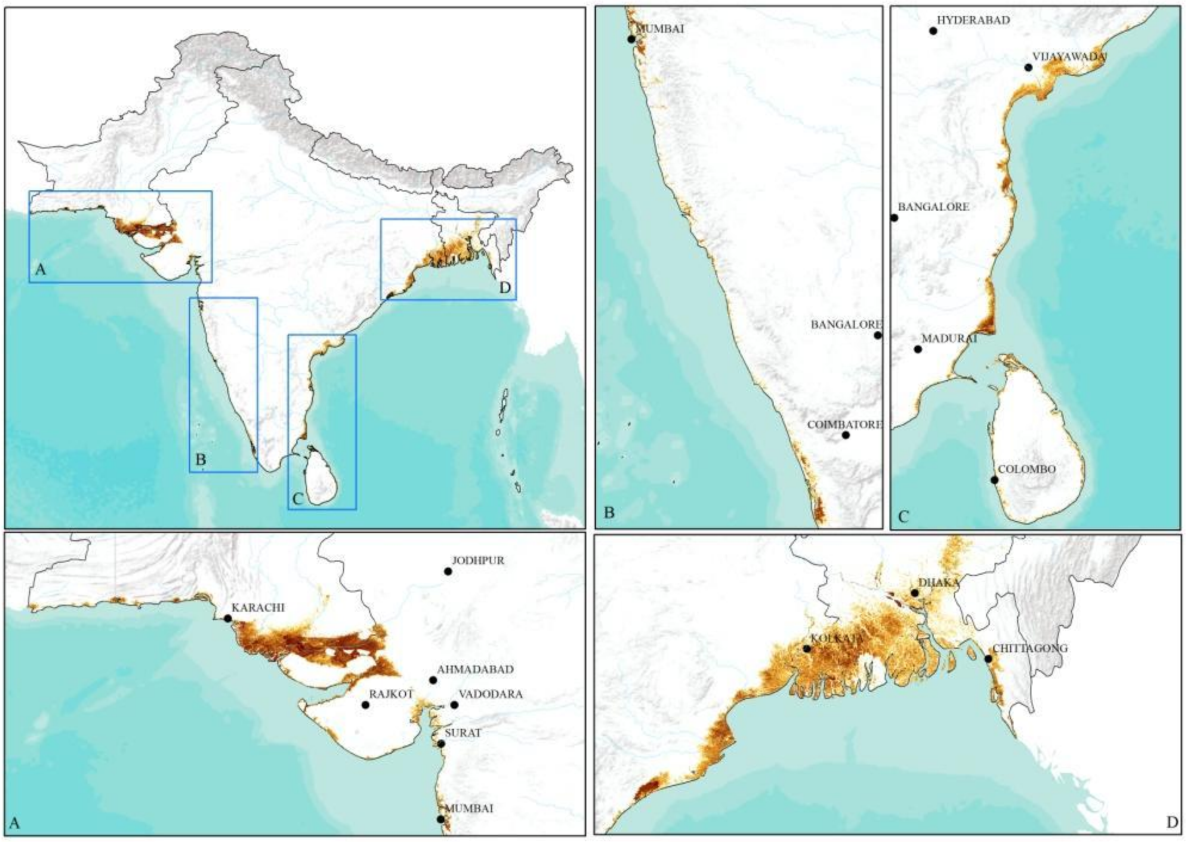

Figure 6. Composite index for sea level rise hazard. The value of exposure was calculated using a hazard index accounting for the rate of sea-level rise, the costal slope and elevation, tidal range, tsunami arrival height and geomorphology (Giriraj et al., 2016)

Net subsidence in the delta of the GMB system is about 5.6mm/yr. increasing the deleterious effect of sea level rise. The causes of this subsidence are multiple and difficult to disentangle.

There are attributed to a combination of tectonic effects, compaction, sedimentation and anthropogenic causes such as river embankments limiting sediment deposition in the flood plains. Continued groundwater abstraction and/or drainage may cause rates to locally increase (Brown S. and Nicholls, 2015).

5.2 Droughts

With climate change and increasing water demand, water-scarce areas will become even more vulnerable to droughts (Shretha et al, 2015), especially in areas where groundwater recharge is reduced in response to altered rainfall and flow patterns. Shifts in the seasonality of river flows (mainly in response to earlier snow melt in the year caused by temperature rise) will have major implications for regional food security, and power demand, especially when the timing of peak flows and growing seasons or peak energy demand do not coincide anymore. Peak discharge in snow-fed rivers observed during spring today will be smoothed and temporally extended during the earlier part of the year. Because river levels will also reduce 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 (King and Sturtewagen, 2010). As temperatures increase, evaporation will increase as well, accelerating water losses from reservoirs. This problem will be exacerbated where rainfall is expected to decrease (e.g. Afghanistan and Nepal, cf. Figure 4) and siltation to increase, reducing storage capacities, as already observed in the Lower Indus Basin in Pakistan (Mirza and Ahmad, 2005).

5.3 Groundwater Contamination

The Ghyben-Herzberg relation (Drabbe and Ghyben, 1889; Herzberg, 1901) states that a 1cm rise in sea level induces a 40 cm rise in the fresh water-saltwater interface in costal aquifers. In Bangladesh, over the next half century, millions of people will be affected by salt water intrusion in wells that supply drinking water from coastal aquifers, as a result of sea level rise. In India, salinity ingress is already noted in many coastal aquifers (Saurashtra Coast in Gujarat and the Minjur aquifer in Tamil Nadu), as a result of land subsidence whose effect will be worsened by sea level rise. Overland saline intrusion, already affecting the Sundarbans and coastal aquifers of West Bengal, will amplify with the climate change-induced sea level rise. In costal islands, the depth of the freshwater lens will decrease by 15m for a sea level rise of 0.1 m. As already mentioned, ongoing pumping in aquifers will accelerate pollution through lateral movements of contaminants driven by local groundwater level depletion. In Pakistan, because of the projected sea level rise, saltwater will penetrate further upstream and inland into the rivers, wetlands, and aquifers, which will be harmful to aquatic flora and fauna, and will threaten human water supplies, which is already the case in the lower Indus Plain. This effect will be particularly evident during droughts (Mirza and Ahmad, 2005) and aggravated by excessive pumping with tube wells. Same combination of increased water demand depleting aquifers, sea level rise and prolonged droughts in Sri Lanka will contribute to accelerating aquifer pollution (Gunaalan et al. 2014; Laattoe et al., 2013). This phenomenon is already occurring in many parts of the country.

5.4 Land-slide, 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) while about 26% of India and Sri Lanka’s 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 in hydropower reservoirs, leading to higher costs in hydropower maintenance thus making hydropower ventures not viable in some countries (Nepal et al., 2014). Nepal's Kali Gandaki project already faces tremendous losses due to increased sediment loading (Chinnasamy and Sood, 2016). Because climate change is already occurring, the aforementioned climate change induced impacts are already felt in Pakistan (Ashraf et al., 2015), Bangladesh (Molden et al., 2014), North western India (e.g. large impact in Uttarakahand) and Bhutan, mostly countries along the Himalayan range (Rana et al., 2013; Walling, 2011; Shrestha, 2013).

5.5 Non-climate Factors Aggravating Climate-related Risks

The impacts of hazard events are escalating not only due to 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: i) population growth in hazard-prone areas; ii) economic expansion; and iii) concentration of economic assets in expanding megacities and rapidly growing secondary cities.

5.5.1 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 exacerbate the problem. Practices such as the cultivation of crops on steep slopes, deforestation (in response to a greater timber demand and related trade goods from neighbouring countries) combined with livestock overgrazing, 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 accelerate surface runoff, thus intensifying the devastating effects of flash floods and siltation problems downstream. Reduced water infiltration into the soil also reduces groundwater recharge.

5.5.2 Increase in Groundwater Withdrawal and Contamination

With increased demand for food production and unpredictable rainfall patterns over the last decade, newly available high-yield motor-driven deep wells and boreholes, many farmers are now using groundwater for irrigation. Due to unregulated use and overexploitation, groundwater levels have depleted considerably over the past decade, especially in South Asian farming regions (Burness and Brill, 2001; Qureshi et al., 2010). Groundwater contamination is caused by a wide range of anthropogenic processes including i) groundwater pumping resulting in water table drawdown and lateral flux of dissolved geo-genic contaminants including arsenic (Williams et al., 2006; Heikens, 2006), fluoride, iron, salt, etc., ii/ infiltration of agricultural input (fertilizer and pesticides), domestic wastewater carrying bacterium load (E. Coli) and industrial effluents including various toxic products. Because the symptoms of arsenic poisoning take longer to appear, the full extent of the problem is unknown.

5.5.3 Population Increase in Flood-prone and Drought-prone Areas

The disaster potential of floods has increased in recent times also due to growth of settlements along the river valleys, construction of motor roads, bridges, and canals in downstream locations.

6. Conclusion

6.1 Summary

South Asia is one of the most vulnerable region to climate change in the world, due to a combination of factors: monsoon-driven climate with intense rainfall events, a diverse and dramatic topography with the Himalayan range dominating a large flood plain, high population densities especially in flood-prone areas (alluvial plains and coasts), weak infrastructure associated with high poverty levels, underperforming irrigation schemes in drought-prone areas, especially in semi-arid zones, and a high dependence on water resources the availability of which controls the performance of many important 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 (Bhutan, Nepal, Northern India, Northern Bangladesh, Northern Pakistan, Afghanistan), and more erosion and downstream siltation (especially in Pakistan) with loss of water storage capacity for dry season irrigation and hydropower production, and reduced groundwater recharge (due both to altered rainfall patterns and siltation of water bodies). **Temperature rise** is inducing i/ snow and ice melt beyond sustainable rates causing GLOF (Bhutan, Nepal, India, Pakistan), earlier flood peaks in the year (springtime) in snow/ice fed rivers (e.g. Indus Basin), not matching peak demand in summer time and compromising food security and hydropower production, ii/ greater crop water demand and evaporation losses from surface reservoirs, and iii/ reduced crop yield in already warm areas. **Sea level rise combined with more intense and frequent cyclones** is inducing destructive coastal flooding (especially in low-lying and densely populated areas, e.g. Bangladesh and the delta Sundarbans undergoing land subsidence) and salt contamination of costal aquifers (e.g. in Sri Lanka where most productive aquifers are along the coasts). **Prolonged droughts** are affecting all countries during the dry season, especially with the rising food demand related to overall population growth and economic development. Semi-arid and arid zones (e.g. Afghanistan, Pakistan, north-west India) are the most vulnerable to meteorological and hydrological droughts, worsened by glacier melting, reduced groundwater recharge and reservoir siltation, affecting not only agriculture but also domestic water uses.

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

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 water resources project components depending on sensitivity to climate risks and available adaptation tools.

For each country, Table 5 provides a list of climate-related risks ranked according to 3 levels (High, Medium and Low). This table is based on literature review with a focus on the assessment proposed by Giriraj et al. (2016), and data available in [**Error! Reference source ot found.**. This ranking corresponds to the current situation. In the future (as climate continues changing), costal floods and storm/cyclone will rise in associated risk levels, especially in Bangladesh. Although other risks will increase, they will not necessarily change category (high, medium, low) as they all increase concurrently. This ranking is based on an overall (and inevitably subjective) integration of damage costs, casualties and numbers of affected people.

A more rigorous approach should include objective and quantitative criteria like those compiled in [**Error! Reference source not found.**. However, data compiled in [**Error! ference source not found.** include many gaps and inaccuracies that prevent such rigorous assessment.

Table 5. Ranking of climate-related risks[4]

	Afghanistan	**Bangladesh**	**Bhutan**	**India**	**Nepal**	**Pakistan**	**Sri Lanka**
High risk level	Landslide Drought Groundwater depletion	Riverine flood Groundwater salinization Storm/cyclone	GLOF Flash flood Landslide	Drought Groundwater depletion Riverine flood Landslide	GLOF Flash flood Landslide	Drought Groundwater depletion Landslide	Drought Storm/cyclone Groundwater salinization
Medium risk level	Riverine flood Erosion/siltation Flash flood	Coastal flood Drought Groundwater depletion	Drought Erosion/siltation Storm/cyclone	Storm/cyclone Groundwater salinization Flash flood	Drought Erosion/siltation	Flash flood Groundwater salinization Erosion/siltation Coastal flood	Riverine flood Groundwater depletion Flash flood
Low risk level	GLOF Storm/cyclone	Erosion/siltation Flash flood Landslide	Riverine flood Groundwater depletion	GLOF Coastal flood Erosion/siltation	Riverine flood Storm/cyclone Groundwater depletion	Storm/cyclone GLOF Riverine flood	Erosion/siltation Landslide Coastal flood
Risks are non-existent	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

[4] This table aims to rank risks for each country considered individually but does not allow comparisons between countries (e.g. flash floods ranked as medium in India may cause more damage and casualties than flash floods ranked as high in Nepal, mainly because of differences in population and surface areas).

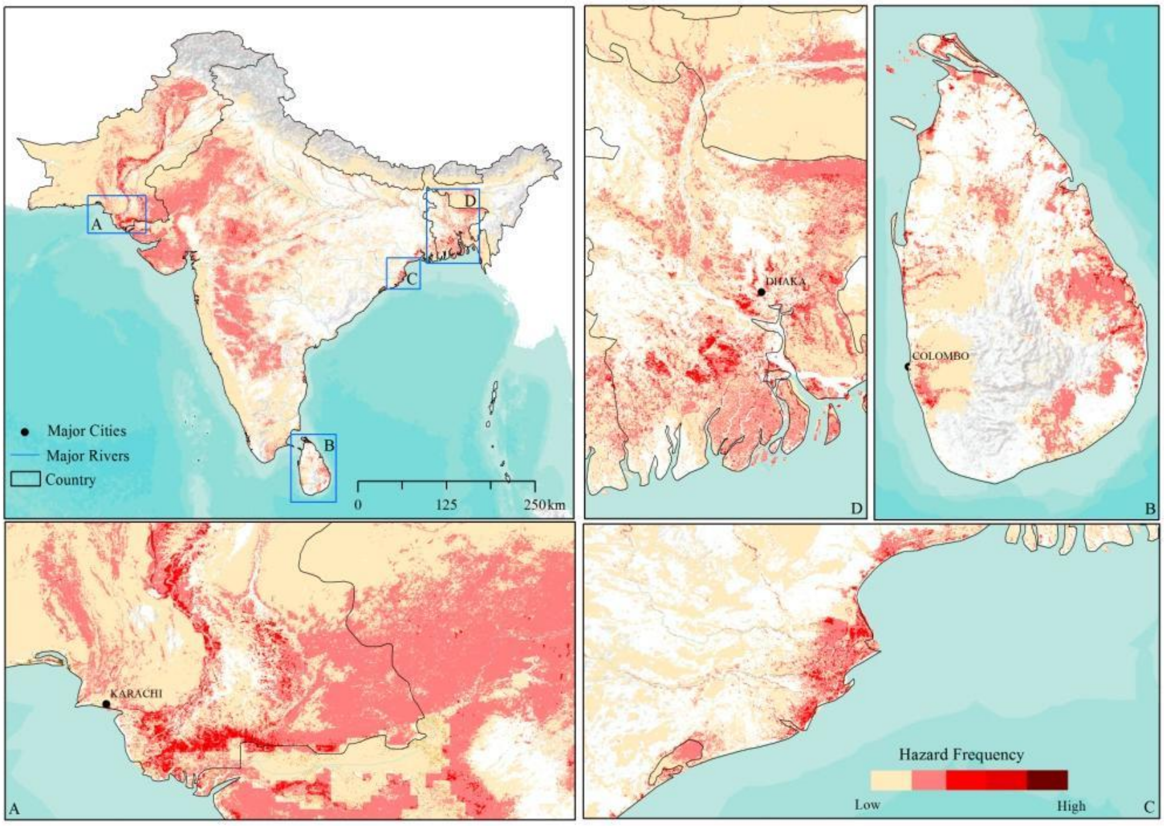

Figure 7. Overall climate-hazard map showing the combination of climate-related hazards (floods, droughts, extreme rainfall, heat waves and sea-level rise) and the hot spots in South Asia. The latter includes the part of Bangladesh, Sri Lanka, drought and floods impacts in Pakistan, north western India and coastal areas in eastern India (Giriraj et al., 2016)

Giriraj et al. (2016) quantitatively and systematically assessed multiple baseline climatic risks in South Asia (excluding Afghanistan), including droughts, floods, extreme temperature and 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 GIS which enabled a summary of associated human exposure and agriculture losses. A combined index based on hazard, exposure and adaptive capacity was introduced to identify areas of extreme risks mapped in Figure 7. Of the affected population, 72% are in India, followed by 12% each from Bangladesh and Pakistan. An analysis of individual hazards indicates that floods and droughts are the dominant hazards impacting agricultural areas followed by extreme rainfall, extreme temperature and sea-level rise. Based on this vulnerability assessment, all the regions of Bangladesh and the Indian States in Andhra Pradesh, Bihar, Maharashtra, Karnataka and Orissa; Ampara, Puttalam, Trincomalee, Mannar and Batticaloa in Sri Lanka; Sind and Baluchistan in Pakistan; Central and East Nepal; and the transboundary river basins of Indus and GBM are among the most vulnerable regions in South Asia.

6.2 Knowledge Gaps

Sound water management and prevention of climate-related risks require accurate information and understanding of how water quality and quantity varies over time and space, which drivers affect these variations, at multiple scales, and how climate change will modify these relationships. This knowledge should help anticipating and minimizing risks of floods, droughts, contamination of surface water and groundwater, as well as erosion and downstream siltation.

6.2.1 Data

Climate variables

Hydro-meteorological stations, either manual or automatic, are used to monitor rainfall, temperature and other climate variables to derive potential evapotranspiration, and river discharge. These stations are used to accurately quantify water resources in order to adapt and mitigate water resources risks 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. This knowledge gap is due to limitations in the relevant science and technology, the vastly insufficient number of sensors deployed around South Asia, and data denial by many governments due to security concerns. The maintenance of hydro-meteorological stations tends to be neglected in many countries especially in remote areas or regions prone to political conflicts (Afghanistan). Mountainous areas, particularly in the HKH lack recording devices especially in high-altitude (>2500 m) and remote areas of the monsoon dominated Eastern Himalayas. Trend analysis and inputs for models that simulate climate, hydrology, glaciology, require more data, of greater resolution, and over a longer-term than the data available at present. Global models interpolate vast areas in the HKH region because of a lack 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, above that altitude, automatic weather stations will almost invariably be required. The absence of continuous routine manual measurements places further limitations on the reliability and completeness of data. Priority countries for extending measurement networks and rehabilitating meteorological stations on the ground include semi-arid and arid areas where rainfall is a critical constraint to economic development (e.g. Afghanistan, Pakistan), as well as mountainous areas (e.g. Bhutan, Nepal, Northern India) where rainfall pattern are still poorly understood and causing recurrent flash-flooding and droughts.

Another issue is the lack of information about the extent to which glacial mass and seasonal snow cover have diminished in the glaciated areas of the HKH over the past decades, mainly because of the lack of observational data of ice stores, snow and glacial melt discharges, snow depth and their water depth equivalence (Singh et al., 2011). One difficulty is the silting of stations on glaciers of variable mobility that creates further difficulties in measurement (Alford et al., 2012).

Box 4. Satellites for remote surface and groundwater monitoring

Satellites are dramatically changing the picture of ground data limitations, by enabling the measurement of total mass of water on Earth (including surface water and groundwater) and its various components, as well as to monitor how these amounts change over time. NASA satellite missions employ different sensors and techniques to measure each of these water reserves. The program GRACE (Gravity Recovery and Climate Experiment), launched in 2002, maps spatial and temporal variations in the earth's gravity field to detect changes in total mass of water in large regions. SWOT (Surface Water and Ocean Topography), scheduled for launch in 2020, will map surface water by measuring its height using radar. Other water-related NASA missions are TRMM (Tropical Rainfall Measuring Mission), launched in 1997, to be followed by GPM (Global Precipitation Measurement), scheduled for launch in 2014. The quantification of ice volume is now possible with ICESat-2 (Ice, Cloud, and Elevation Satellite-2). Other satellites include SMAP (Soil Moisture Active Passive) which use a radiometer and a synthetic aperture radar (SAR) to provide global measurements of soil moisture and its freeze/thaw state

Another important required effort will consist in aiming to compile climate date per basin and sub-basins and not only administrative boundaries as currently done in the majority of the countries. This should ease linking meteorological data with corresponding hydrological data for easier analyses of water cycles and hydrological disturbances induced by climate change.

Data on atmospheric pollutants collected to date have allowed generating awareness of the 'atmospheric brown cloud' but more systematic observational data are needed for the extensive modelling required to predict accurately the extent to which this mass of pollutant gases and micro-particles are contributing to a changing climate in the HKH region and globally. Similarly, reliable information on GHG emissions and sinks/sequestration are at present very limited and mostly not available for the HKH region.

Surface water and groundwater: qualities and quantities

Even though groundwater contamination is noted in many regions of South Asia, current knowledge on the distribution of contaminants is still limited because of the few observations and monitoring data available, especially in deep aquifers (>100m deep) (Chinnasamy et al. 2013; Rodell et al 2009; McDonald et al 2015). Given that the region has come to depend heavily on groundwater irrigation, greater analysis and sound policy on groundwater are critical for South Asia's sectoral water uses. In order to better understand South Asian groundwater system's vulnerability to climate change and to build resilient groundwater dependent systems, Clifton et al (2010) identified 4 criteria for assessment indicators: sensitivity (current level of exploitation), exposure to climate change, exposure of regional water resources to sea level rise and adaptive capacity.

Sea level rise and land subsidence

Monitoring of subsidence needs to be continued and improved to better understand it, especially in coastal countries with large delta where this phenomenon is occurring (e.g. Bangladesh, India, and Pakistan). Whilst longer-term surveying over a wider geographical area, such as by InSAR satellite data and GPS measurements are emerging, it is challenging to determine long-term trends as these measurements are undertaken on relatively short time-scales. Long-term, sustained investment in monitoring is required, to capture both short and long-term changes and disentangling the compounding effect of sea level rise.

6.2.2 Processes

Rainfall-runoff relationship

It is necessary to improve knowledge about the key determinants of the relationship between rainfall patterns and river flows, with the ultimate aim to better predict the hydrological consequence of climate changes in terms of available water resources and flood risks. This non-linear relationship is not straightforward and 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 runoff production, but also is an important source of CO_2 emissions. At present, land cover and land use information is usually collected without standard categorisation.

Flow production from ice and glacier melting

Variations in glacial melting patterns and volumes combined with changes in high-altitude hydrology, will affect agricultural production across the region (Malone, 2010). Efforts to quantify the volume of water contributed by glaciers to the larger hydrological system are still ongoing. As the summer monsoons weaken, precipitation decreases from the east to west. Under any reasonable future warming scenario glacier ice melt is slow, and therefore, cannot cause floods (Malone, 2010). Widespread biomass burning in Asia has produced black carbon which is a unique threat to glaciers and people. Black carbon accelerates melt rates of glaciers and causes or exacerbates respiratory illnesses. While many of the glaciers in the Himalayas are retreating, there is no conclusive evidence to suggest that this retreat is faster than any other location in the world (Malone, 2010). However, the need for mitigation and adaptation remains because glaciers and their melt rates comprise the wider hydrological system which include rainfall and snow. Glaciers do provide a small amount of runoff to the 1.5 billion people living downstream (Malone, 2010). The contribution is particularly large when it comes to the Indus Basin where the contribution to rivers from melting glacier ice is thought to be one-third or more. There are major gaps which remain in the understanding of the behaviour of the region's glaciers due to limited monitoring stations (Immerzeel et al 2012; Barnett et al 2005; Bolch et al., 2012).The Karakoram Anomaly which is present in some of the regions of the Himalayas complicates the approximations of glacial melt rates (Hewitt, 2005). While uncertainties remain about the actual contribution of glacial melt and their contribution to the overall volume of flow and the hydrological system due to anomalies such as the Karakoram Anomaly, and black carbon it is safe to conclude that climate adaptation and mitigation strategies should account for glacial melt as a factor.

6.2.3 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 due to the absence of precise and systematic monitoring network. Alford et al. (2012) indicate that considerable disconnect exists between government officials, local residents and scientists and as a result there is a large gap between methodologies to reduce hazard impacts and vital lifesaving information, especially in the mountainous regions of the Himalayas where landslides, siltation, forest fires, etc., are common.

6.3 Recommendations

Adaptation to climate change and mitigation of climate-related risks does not necessarily require to diversify strategies but to adjust existing adaptation options. Here we group recommendations to address the two main categories of climate-related risks: droughts and floods.

6.3.2 Recommendations to Cope with Droughts

Improving resilience to more intense droughts as a result of climate change involves a range of interventions including more parsimonious water use, a better understanding of hydro-meteorological processes that control the spatio-temporal variability of water resources, more powerful models used to predict droughts and a sound selection of sites and structures to store water.

Improved knowledge transfer about water use efficiency and water productivity

To cope with more severe droughts induced by climate change, improving water use efficiency and water productivity are often simple and cost-effective and also well-known. However, these techniques are not always applied for a number of reasons. One typical problem involve application of irrigation water volumes to crops larger than that which is actually required, leading to overuse and quicker drying up of water resources. In addition to saving applied irrigation water, other improvements include the reduction in water losses by leakage (in municipal distribution networks and irrigation canals), by evaporation (mainly from soils and reservoirs) and by deep percolation from fields. To reach these objectives, it is necessary to better disseminate knowledge from research institutions and agriculture extension services to farmers, and build capacities.

Where surface water and groundwater are becoming scarce, government incentives and awareness campaign should help controlling water consumption. Reducing consumptive water use through agriculture policies (i.e. restricting alfalfa irrigation in arid areas, reducing rice areas in the Punjab and sugarcane cultivation in semi-arid 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 belongs to countries where irrigation efficiency is among 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 implementation failure in irrigation systems, making water user associations more effective, 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, minimizing water loss through canal leakage is another solution for improved water use efficiency. Water use efficiency should also be considered at the scale of transboundary river basins where water should be equitably shared between countries (i.e. between India and Pakistan in the Indus Basin; 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).

Need to carefully design and plan reservoir to improve water storage capacity

More frequent, longer, and intense droughts expected in the future as climate continues warming, entails greater need for multi-year reservoir storage capacity, of which South Asia currently has very little, especially in arid and semi-arid areas and also where groundwater is depleting and worsening in quality (Lower Indus Basin). More storage not only signifies the building of new storage but also the reduction in sediment load of a river through improved management of land-use in the uplands, in order to reduce siltation in downstream reservoirs. To achieve its goal, it is necessary to change the business of building dams. Policy makers need to realise that delays in indecision are costly; that benefits have to be equitably shared; that environmental concerns need to be addressed rather than bypassed; and that mismanagement, corruption and poor governance have to be tackled forthwith (Shah and Lele, 2011). In the HKH, most of hydropower reservoirs are run-off-the-river with very little storage capacity. With the reduction or total disappearance of glaciers and snow that used to sustain dry season flows during the summer, it will be necessary to invest in more storage capacity in order to buffer greater seasonal variations in river flows.

To reach these objectives, it is necessary to accurately monitor river flows in order to characterize their variability, and simulate their expect variations under the changing climate, and design storage capacities accordingly.

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

The hydro-geological setting of an aquifer system both frames the resource problem as well as constrains the management solution. In the vast and fertile Indo-Gangetic plain with 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. In Pakistan's Punjab, surface water supplies can potentially be an answer not only to declining groundwater levels but also to salinization (Shah and Lele, 2011). It is therefore necessary to increase the number of monitoring wells to accurately survey the temporal and spatial variations in groundwater levels and better understand their connections with surface water bodies. Hydrological and groundwater modelling should help forecasting variations in groundwater and surface water availability under different climatic scenarios.

Improve drought forecasts by raising the capacity of analysis of large data sets

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

6.3.3 Early Warning Systems for Flood Prevention

From a data and knowledge management perspective, coping with floods includes 2 approaches: i/ mapping flood-prone areas in order to limit settlements in these exposed areas, ii/ forecast floods for a better preparedness of exposed population, leaving time to escape disaster. Each of these 2 measures necessitate 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.

Mapping 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, and soil maps, satellite imageries of vulnerable infrastructures. Ground measurements of river flow are hardly replaced by remote sensing technology, hence the need to deploy efforts to rehabilitate, maintain and expend these networks on the ground. To predict and forecast future flood extent, their magnitude and frequency, hydrological models integrate all this information, using time series of projected climate variables as input (e.g. rainfall, evapotranspiration). Most importantly, such models should account for the hydrodynamic properties of soils which play a central role in controlling the rainfall-runoff relationship. These models systematically need to be calibrated and validated using actual records of flow and rainfall in order to accurately predict future trends and extremes.

Forecasting floods with early warning systems

Early warning systems aim to provide time for exposed population to take appropriate actions to minimize flood-induced damages and possible casualties. They are expected to play a role of greater importance as extreme events will worsen in magnitude and frequency in a changing climate. Forecasting involves the conversion of data into forecasts (using hydrological models) that are transmitted to a decision maker who releases a warning and also draws hazard maps for local authorities who take appropriate preventive actions. Early warning systems for flood forecasts generally operate at watershed scales while action units follow the administrative boundaries. Improvement of forecast dissemination requires to precisely identify the path of 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 have to be defined. The implementation of quality controls of the early warning systems should help improving the emergency management of local authorities and communities. People-centered approaches have to be prioritized as they are low-cost, effective, and relevant to local conditions in flood-prone areas (Lacombe et al., 2012).

6.3.4 Capacity Building

Closing the knowledge gap not only requires structural and technical improvements (e.g. data measurement networks) but also necessitates to enhance the ability to evaluate and address the crucial questions related to policy choices and modes of implementation among development options, based on an understanding of environment potentials and limits and of needs perceived by the people in the countries. Capacity building is a long-term and continuing process, in which ministries, local authorities, non-governmental organizations and water user groups, professional associations, private sector, academics and others participate. Capacity building in the context of preparedness to climate risks in South Asia is important because the scale of climate change-induced impact is enormous, but appreciation of the problem is low. The link between research needs and supply is weak. Limited funding is allocated for research. Catalysing change needs continuous support. Educational and capacity building institutions are fragmented and interaction among them is inadequate. Curriculum is conventional and teaching materials insufficient. The education system is inertial to accommodate emerging constraints due to climate change impacts. Local government play an increasingly important role in enabling both planned and autonomous adaptation at local levels (ISET, 2008).

6.3.5 Combining Short- and Long-term Approaches

Both short- and long-term approaches to managing the impacts of climate risks are needed. In the short-term, integrating climate adaptation and disaster risk reduction will help withstand shocks to human security and economic development from which recovery can be costly. 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 national economic and development policy. In the longer term, governments, businesses and communities need not only to prepare for the kinds of climate impacts experienced up to now but also for different and more intense climate impacts and extreme events in the future. Measures may include providing adequate housing, infrastructure or services, or mainstreaming climate change into planning processes. There are good reasons to start now in the process of adapting to these longer-term risks. The IPCC cautions against overemphasising short-term outcomes or insufficiently anticipating consequences. Given that climate change cuts across sectoral boundaries, poorly conceived development programmes or sector-specific adaptation strategies could lower resilience in other sectors or ecosystems. Some development pathways, like rapid urbanisation 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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