Chapter 4: Water

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Date of Draft: 18 October 2019

Notes: TSU Compiled Version

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Executive Summary

This chapter builds on findings from previous IPCC Assessments and assesses new scientific evidence on impacts of climate change on various components of the hydrological cycle and the associated impacts on all relevant water use sectors and society. This chapter concludes that water insecurity will be the first component of the ongoing climatic change that will directly impact people's lives and livelihoods globally, and will hence, be the first visible and palpable manifestation of climate change experienced on an everyday basis by billions of people. Building on political, analytical and action frameworks for adaptation in the water sector, few principles enabling successful adaptation are outlined by this chapter. These are: strong political support, inclusion of indigenous people's knowledge, participative polycentric governance mechanisms; just, equitable and gender inclusive institutions and processes and adequate financing.

Centrality of water

Water security is defined as access to adequate quantities of acceptable quality water, in ways that safeguards livelihoods and ecosystems, and makes societies resilient to water related hazards, and underpins all sustainable development goals (*robust evidence, high agreement*). The number of people currently exposed to water insecurity is in the order of billions (*high confidence*). While current development trajectories; lifestyles; population growth and water use remain important drivers of existing water insecurity, future projections show that climate change will further exacerbate the risk of water scarcity and insecurity in several regions of the world *(medium evidence; high agreement)*. *{4.1}*

The hydrological cycle is affected by both climatic and non-climatic factors. There is increasing confidence in attribution of a number of hydrometeorological changes to climate change, including anthropogenic climate change, but attribution of societal impacts brings additional methodological challenges *(high confidence)* *{4.1.2}*

Observed and projected changes in hydrological cycle

Precipitation (P) and evapotranspiration (ET) and soil moisture have increased in the global mean, but with substantial regional variations (*high confidence*). Climate models project global average precipitation to increase by between 1% and 3% per [degree] C global warming. *{4.2.1}*

Accelerated melting and thawing of cryospheric components such as glaciers, snow and ice and permafrost are observed as well as projected for most cold regions of the world *(robust evidence; high agreement)*. Glacier melt rate accelerated by 1.5–2 times in the early 21st century compared 1950–2000 worldwide (*medium evidence, high agreement*). This impacts populations, including Indigenous people who depend on ice, snow and permafrost for water, food, energy and other services such as aesthetic, cultural and spiritual services (*high agreement, medium evidence*). *{4.2.2}*

For observed annual runoff series for most parts of the world, the presence of a statistically significant climate-driven trend remains uncertain. Future changes in annual runoff and/or streamflow will follow projected precipitation patterns (*medium confidence*). Different sectors of society will be affected by changes in runoff regardless of the direction of changes. *{4.2.3}*

Groundwater levels have declined in many important aquifers around the world, particularly in semi-arid environments, in response to intensification of groundwater irrigated agriculture (*high confidence*) as well as the impacts of climate change on recharge and evapotranspiration processes (*medium confidence*). Due to the lack of long-term observation data, future projections have *very low confidence*. Extreme annual groundwater recharge is commonly associated with intense rainfall and flooding events mostly in the tropics (*medium evidence, high agreement*) showing that groundwater may prove to be climate resilient source of freshwater in the tropics in the future (*medium confidence*). *{4.2.4}*

Climate change causes further water quality degradation in polluted areas through extreme events such as droughts and floods (*medium confidence*). Non-climatic drivers like land-use changes, agricultural intensification induced fertilizer and pesticide use, industrialization, urbanization etc. that increases pollutant

loads and causes higher water extraction will further reduce river dilution capacities and will dominate over climate impacts (*robust evidence, medium agreement*). *{4.2.5}*

In the areas with high anthropogenic influence, the impacts of land cover changes are much more significant in affecting soil erosion and sediment flux, compared with the influence of climate change (*robust evidence, high agreement*). There is high uncertainty in soil loss projections due to influence of non-climate drivers (*robust evidence, high agreement*). Societal impacts in developing countries are more pronounced than in developed ones; ranging from human deaths to reduced food production, water contamination, and infrastructure/settlement damages (*robust evidence; medium to high agreement). {4.2.6}*

Globally, there are more areas with significant increases in frequency, intensity and /or amount of heavy precipitation than with decreases *(high confidence)*. Projections for 21st century show a general increase in the intensity of heavy precipitation (*medium confidence*) except in some regions in the subtropics (*low confidence*). *{4.2.7.1}*

Drought and flood risks are projected to increase globally, as a consequence of the combined increases in hazards and exposed population (*medium evidence, strong agreement*). *{4.4.1}*
Frequency and/or magnitude of floods have changed over the past several decades. The most visible changes are registered in the snow dominated regions, where the warming induced changes in timing, magnitude and frequency of snowmelt floods (*high agreement and robust evidence)*. In many cases a clear link to climate variability or change is demonstrated, but non-climatic factors are often a dominant factor, especially for societal impacts *(high confidence)*. *{4.3.7.2}*

The long-term global trend in drought frequency and severity remains inconclusive. Similarly, there is *low to medium confidence* in global scale drought projections. The impact of increasing CO2 on plant water use efficiency is identified as a major source of discrepancy between different sets of projections *(high confidence)*. *{4.2.7.3}*

Societal impacts due to changes in hydrological cycle

Climate induced changes in hydrological cycle lead to water insecurity and has profound sectoral and cross sectoral impacts *(strong evidence, high agreement)***.** *{4.4, 4.5}*

Agriculture is the largest consumptive water use sector. Negative impacts on the agricultural sector – including livestock production, fisheries and aquaculture- because of climate induced water hazards and scarcity or changes in water availability have been observed across regions and crops, though climate change attribution remains challenging *(high confidence)*. Agricultural water use is projected to increase globally, due to global dietary changes, as well as increased water requirements through climate change *(strong evidence, high agreement)*. The Poor have been and will be disproportionally affected, as they often rely on rain-fed agriculture in marginal areas with high exposure and vulnerability to water-related stress and have low adaptive capacity *(medium evidence, high agreement)*. *{4.3.1}*

Hydropower is a largely a non-consumptive use of water. While non-climatic drivers (e.g. design, execution) play an important role in the efficient production of hydropower, costs are being affected by multiple climate induced water hazards, rising water temperature, and heatwaves (*medium evidence and medium agreement)*. *{4.3.2}*

Climate change, through its impact on water availability and quality, affects sanitation and human health by increasing the risk of diseases, directly or indirectly *(robust evidence, high confidence)*. This risk is projected to increase in the future (*medium evidence, high agreement*). Health impacts are differentiated along gender and age lines and climate change has and is expected to exacerbate these vulnerabilities and impacts *(medium evidence, high confidence) {4.3.3}*

Climate change has already affected and will continue to affect urban and municipal water uses (*medium evidence, high agreement*). While the urban water sector is vulnerable to climate change, observed changes in urban areas cannot be solely attributed to climate change (*high confidence, medium evidence*). Projected future hydrological changes – both in terms of increase and decrease of stream flows will threaten existing urban water infrastructure in most regions (*very high confidence*). *{4.3.4}*

Climate change is one of the key drivers of the loss and degradation of freshwater ecosystems and unprecedented decline and extinction of many freshwater dependent populations (*high agreement, robust evidence*). Changes in precipitation and temperatures are projected to affect all types freshwater ecosystems and their species. Freshwater biodiversity is expected to decrease proportionally to the degree of warming and precipitation change (*medium agreement, limited evidence*). *{4.3.5}*

It is unclear whether inland navigation and transportation systems have been affected by climate change (*limited evidence, high agreement*). Yet, rising temperatures, increasing precipitation patterns resulting in a higher the likelihood and intensity of water-related hazards, will result in negative impacts on inland navigation and transportation systems (*medium evidence, high agreement*). *{4.3.6}*

There is *low agreement* as to the causality between climatological change in the hydrological cycle and the risk of a conflict. However, there is *high agreement* that climatic changes, coupled with other socio-economic and political factors, multiply tensions at both the intra-state and the inter-state level. *{4.4.2}*

There is robust empirical evidence that climate induced hydrological changes have both increased and decreased the likelihood of migration, depending on the socio-economic, political, and environmental context *(strong evidence, high agreement)*. Evidence on future migration estimates, particularly in relation to migrant destinations is weak (*medium evidence; medium agreement*) *{4.4.3}*

Climate change is impacting cultural uses of water among communities in the Arctic and high mountain areas (*robust evidence, high agreement*), as well as First Nations and Indigenous peoples elsewhere (*limited evidence, high agreement),* these impacts are exacerbated by historical, socioeconomic and political marginalisation (*robust evidence, high agreement*). *{4.4.4}*

Synergies, trade-offs and enabling principles for water related adaptation interventions

Institutional constraints and barriers, including path dependency, are amongst the most important factors hindering effective adaptation, generally and in the water sector in particular *(high confidence)*. Many adaptation measures have considerable water footprint (*high confidence*) and need to be managed proactively to reduce negative feedback loops, while increasing positive synergies with other sustainable development initiatives (*high agreement, medium evidence*) For some regions, insufficient water availability has the potential to become a hard limit to adaptation *(limited evidence, medium agreement)*. Especially for the poor, loss and damage from melting of glaciers has been reported, even where some adaptation has occurred *(limited evidence, high agreement) {4.5.3}*.

Political, analytical and action frameworks *{4.5}* underlie adaptations interventions in the water sector. Most successful solutions to tackle water insecurity share a few enabling principles. These include: participative polycentric governance mechanisms; just, equitable and gender inclusive institutions and processes; strong legal and political systems; adequate financing; Indigenous and Local knowledge (*robust evidence, high agreement)*. *{4.6}*

Participation of traditionally excluded groups such as women and marginalized communities (e.g. Indigenous people and ethnic minorities) contributes to a more equitable and socially just adaptation actions (*robust evidence, high confidence*). Climate induced water changes are in fact not equally felt across gender, class, age and physical ability (*robust evidence, high agreement)*. *{4.6.1, 4.6.3}*

The effectiveness of adaptation measures and strategies will improve when local, indigenous and traditional ecological knowledges will be combined and integrated with technical understandings of climate change *(robust evidence, high agreement)*. *{4.6.4}*

Governance ensuring interconnectedness from global to local levels, with multiple actors, bottom up and top-down linkages, well-coordinated and enhanced efforts to adapt to climate induced water challenges and hazards, can lead to effective results *(medium evidence, high agreement) {4.6.2}*

The design and the implementation of climate adaptation planning approaches can be constrained by the lack of a strong political support (*robust evidence, high agreement*). *{4.6.5}*

Water sector adaptation garners a major share both of public and private adaptation funds (*robust evidence, high agreement),* yet several barriers remains for least developed countries to access these funds (*high agreement, medium evidence*). *{4.6.6}*

4.1 Centrality of Water in Climate and Development

Risks emanating from various aspects of water insecurity have emerged as a major global challenge. Water security is defined as "*the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*" (UN-Water, 2013). The Global Risks Report by the World Economic Forum lists water crisis as one of the top five risks in all its reports since 2015 (WEF, 2015; WEF, 2016; WEF, 2017; WEF, 2018; WEF, 2019). Water also features prominently in Sustainable Development Goals (SDGs), with SDG 6 focusing on ensuring access to water and sanitation for all, and SDG 11 addressing water-related disasters. Water underpins all SDGs (Ait-Kadi, 2016; Mugagga and Nabaasa, 2016). None of the SDGs can be met without access to adequate and safe water. Efficient water allocation and use is also vital for economic growth in the face of climate change and without such approaches, by 2050, the gross domestic product (GDP) of countries like India, China and Central Asia and that of African countries may be lowered by 6 to 12 percent (GCA, 2019).

Anthropogenic climate change impacts every aspect of water security through changes in water availability, increases in water induced disasters due to extreme climatic events, and changes in ecosystems supported by water. All these directly impacts human societies. These climatic drivers further interact with non-climatic drivers as consumption patterns, population growth and various development trajectories, including the need for poverty alleviation and meeting of SDGs in many parts of the developing world, and further exacerbates water insecurity faced by billions of people around the world. The worst affected are always the poor and vulnerable groups as women, children, ethnic minorities, the elderly and the disabled, mostly in developing countries, but increasingly also elsewhere in the world due to the increasing scale and magnitude of water induced disasters (Hoegh-Guldberg et al., 2018b). Overall, the impacts of too little water e.g. droughts, water pollution or too much water e.g. floods and extreme rainfall events is already been felt by the majority of the world population (Kummu et al., 2016). While climate change directly affects the availability of fresh water across space and time, it also affects water requirements for different uses, for example for irrigation, potentially adding to existing stress (Bijl et al., 2018). With the added stressor of climate change, globally a larger fraction of land and population will be affected by increasing water scarcity due to climate change: projections estimate an increase in water scarcity for 0.5 to 3.9 billion people depending on model and measure of water scarcity due to climate change (Gosling and Arnell, 2016) (see Box 4.1 for various definitions of water scarcity).

Impacts of climate induced changes to the hydrological cycle have been documented across a range of sectors (Figure 4.1), including agricultural production, human health and vector-borne diseases (Mora et al., 2018). In 2015, according to data from the United Nations (UN), approximately 844 million people lacked access to safe drinking water and roughly 2.3 billion people did not have access to safe sanitation (WHO and UNICEF, 2017). On average, between 1996 to 2005, at least 4.3 billion people (71% of the global population) were affected by water scarcity for at least 1 month/year and at least 1.8 billion faced water scarcity between 4 to 6 months/year (Mekonnen and Hoekstra, 2016). In 2018, over 35 million people were affected by floods (WMO, 2019). Globally, between 81 million and 109 million people are reported to be at risk of river flooding (Alfieri et al., 2017). Extreme droughts and floods, including more intense monsoons and El Niño events that cause both droughts and floods, are projected to become more common, and the areas exposed to serious droughts and floods will increase by 15% to 44% by 2050 (GCA, 2019). Droughts and floods have been singled out as determinants of internal (Joarder and Miller, 2013; Afifi et al., 2015; Mastrorillo et al., 2016; Thiede et al., 2016; FAO, 2017) and international (Obokata et al., 2014; Nawrotzki and Bakhtsiyarava, 2017) migratory decisions, often through adverse agricultural conditions causing economic losses (Mastrorillo et al., 2016; Miletto, 2017; Nawrotzki and DeWaard, 2018). According to the United Nations High Commissioners for Refugees (UNHCR) Protection and Return Monitoring Network, around 883,000 new internal displacements were recorded between January and December 2018, of which 32% were associated with flooding and 29% with drought (UNDRR, 2019). The hydrological year 2017–2018 was the thirty-fifth consecutive year with negative mass balance for global glaciers, with a mass balance of -0.7m water equivalent based on results from a subset of glaciers (WMO, 2019). Such water scarcity is manifested, among other things, in increased time spent by women fetching water in developing countries (Becerra et al., 2016; GGCA, 2016) leading to adverse health consequences, particularly for vulnerable groups such as women, children and the elderly (Hutton and Chase, 2016; Abid et al., 2018).

Water scarcity also increases exposure to and incidence of several waterborne diseases (Hodges et al., 2014; Asante, 2015; Ebi and Nealon, 2016; Baylis, 2017; Kohlitz et al., 2017).

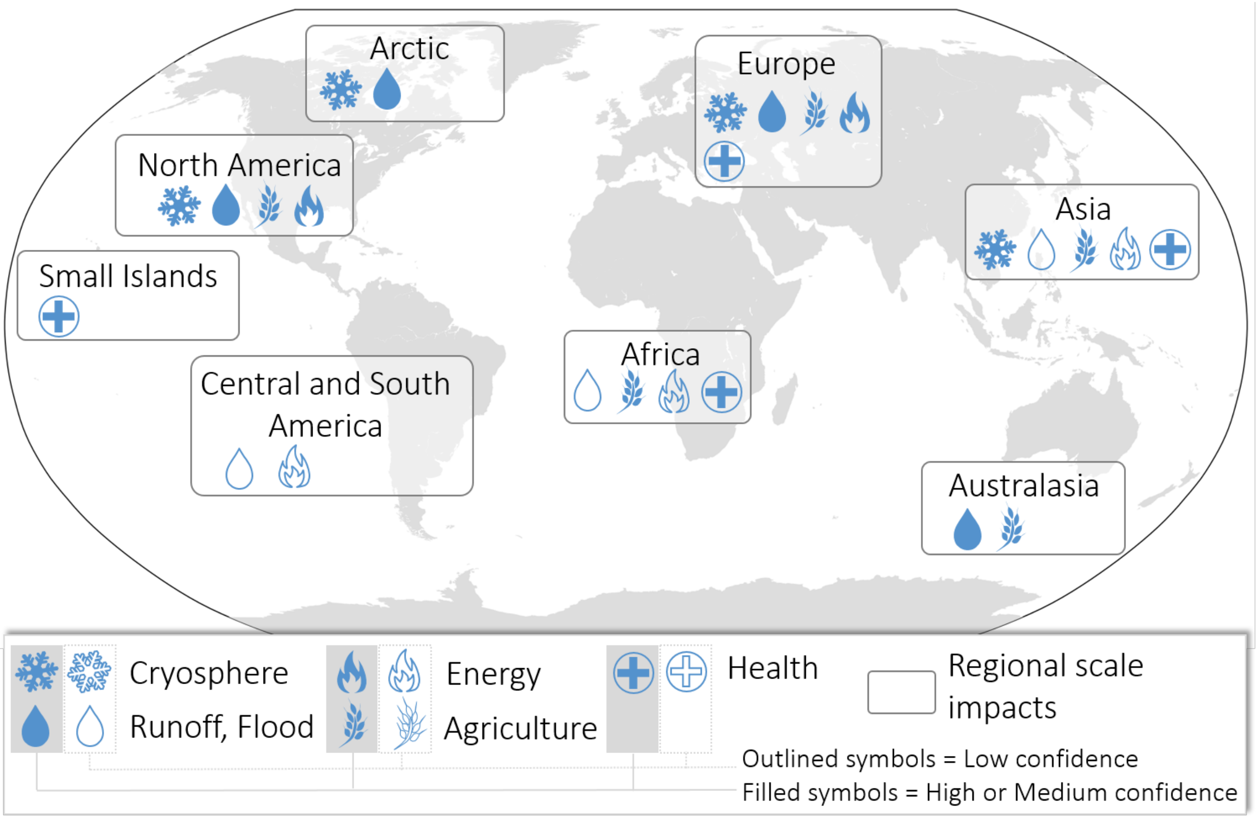


Figure 4.1: Global patterns of water-related physical changes and their impacts in recent decades attributed to climate change, based on studies since the AR5. Symbols indicate categories of attributed physical changes or impacts and confidence in attribution.

Agriculture and irrigation account for the largest proportion of consumptive water use. In 2012, 275 million hectares of land (~20% of global cropped area) was irrigated, accounting for over 50% of food production (FAO, 2016a). Both surface and groundwater is used for irrigation and in some pockets of the world, groundwater is over-exploited. Groundwater also meets domestic water requirement of roughly half the world's population and provides 38% of global consumptive water demand (Rodell et al., 2018). Among all economic activities, the agriculture sector has been one of the sectors most directly affected by drought. In 2016, approximately 16.4% of global electricity was generated by hydropower the largest source and still growing of renewable energy globally (IEA, 2018). Such growth can however be hampered by depleted reservoirs and stream flows due to reduced precipitations and increased temperature (WRI, 2015; Fan et al., 2018; Savelsberg et al., 2018; UNDRR, 2019). Between 16 % and 39% of cities experienced surface-water deficits globally between 1971–2000. If environmental flow requirements are accounted for, these numbers increase to 36 % and 63%, respectively. Even under a scenario where urban water gets the highest priority, more than 440.5 million people in cities globally will face a water deficit by 2050 (Flörke et al., 2018). The situation is particularly precarious in the global South where majority of population lack access to piped water – the cheapest source of water (WRI, 2019).

In summary, water insecurity will be the first component of the ongoing climatic change that will directly impact people's lives and livelihoods globally and will hence, be the first visible and palpable manifestation of climate change experienced on an everyday basis by billions of people.

As vulnerability and resultant water insecurity impact all aspects of human society, this chapter draws on previous IPCC reports (4.1.1) and new methodologies thereafter (4.1.2) and assesses the impacts of climate change on natural and human dimensions of the water cycle with a particular focus on current status of water-related vulnerability and adaptation interventions. Section 4.2 discusses observed and projected changes in various components of the hydrological cycle and their societal impacts and detects which parts of these changes are directly attributable to climate change. Section 4.3 assesses the observed impacts and projected risks of changes in hydrological cycle on various water use sectors, and section 4.4 assesses the same for cross sectoral impacts. Wherever possible projections and risks assessments presented for future impacts are framed both in terms of global warming levels and time horizons, as these are useful for informing mitigation policy under the Paris Agreement as well as for informing adaptation planning. Section 4.5 assesses the current status of adaptation and barriers to adaptation from both global and local perspectives. Lessons of what works and what does not from both a global and local context is finally distilled and synthesized in section 4.6 which then goes on to outline the enabling principles of workable adaptation solutions in water space (Figure 4.2).

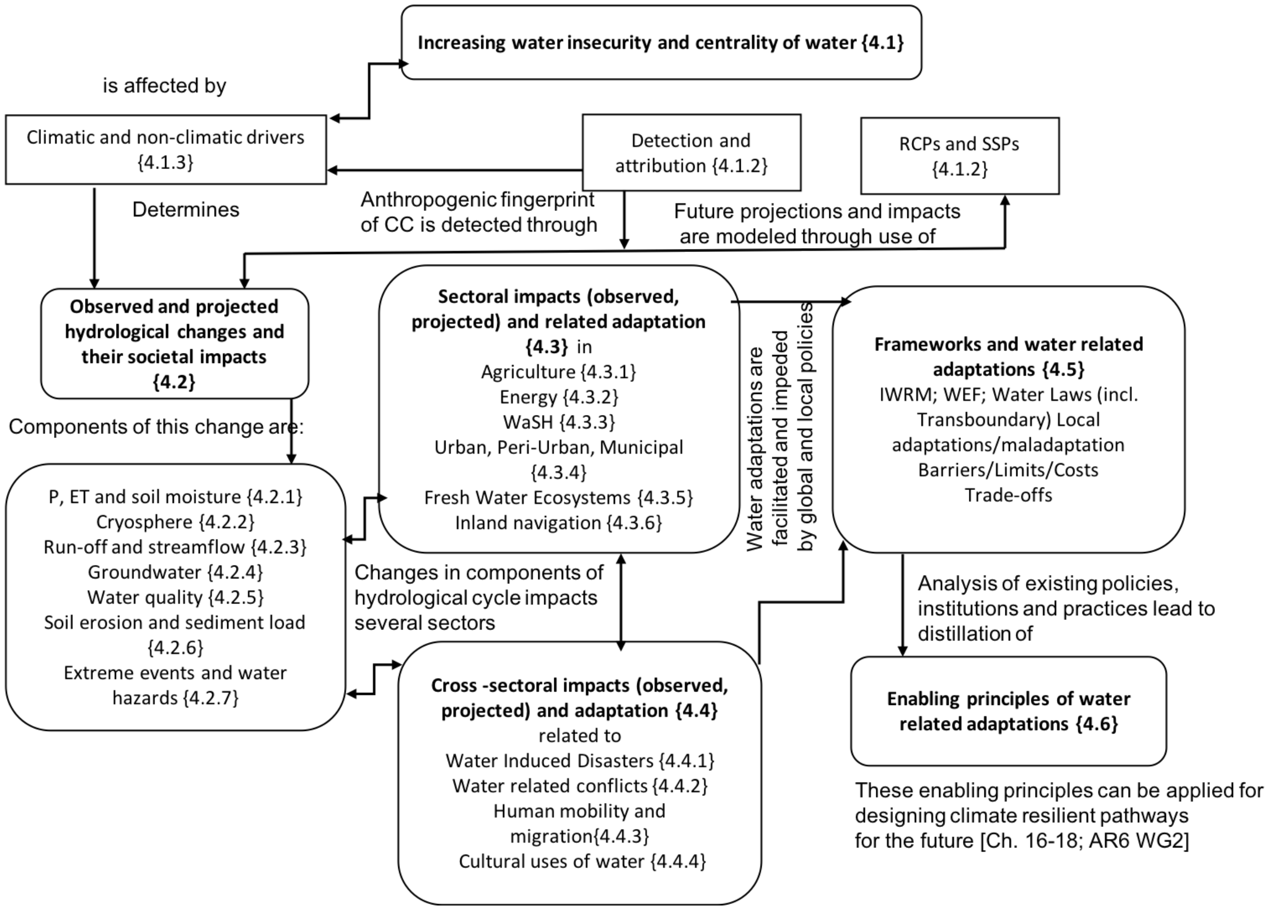


Figure 4.2: Storyline and structure of Chapter 4

[START BOX 4.1 HERE]

Box 4.1: Different Measures of Water Scarcity

Climate change will alter the availability of water over space and time (section 4.2). In addition to climate change, many human activities contribute to water scarcity along multiple dimensions (White, 2014; Mancosu et al., 2015; Bond et al., 2019; Damania et al., 2019). The very initial definition of water scarcity focused on physical water availability in per capita terms (Falkenmark et al., 1989), though very soon, it was realized that water scarcity is not just an outcome of lack of water availability, but that lack of access to water due to economic or institutional barriers can also lead to water scarcity (Seckler et al., 1998). Since then, a variety of indicators of water scarcity have been put forward, highlighting the various dimensions such as water quality and environmental flows that define water security. This box provides selected examples of elements of water scarcity. Many other integrated approached to describing water scarcity have been developed (e.g. (Sullivan, 2002; Lissner et al., 2014).

Physical water scarcity (Figure 1a) indicates a situation in which an insufficient quantity of water is available to meet requirements (Falkenmark et al., 1989; Alcamo et al., 2000; Vörösmarty et al., 2010; Bond et al., 2019). The most commonly used measure of physical water scarcity is the Falkenmark indicator, which measures the amount of renewable freshwater that is available per capita (Falkenmark et al., 1989; White, 2014).

Economic water scarcity (Figure 1b) describes a situation where "human, institutional, and financial capital limit access to water, even though water in nature is available locally to meet human demands" (Seckler et al., 1998; Rijsberman, 2006; WWDR, 2019). Economic water scarcity can also occur where infrastructure exists but the distribution of water is inequitable (Jaeger et al., 2017).

Water quality (Figure 1c) is another relevant aspect affecting water security (Zeng et al., 2013; Liu et al., 2016a); determinants to consider include issues such as water temperature, salinity, nutrient levels and other pollutants (van Vliet et al., 2017). Water pollution does not decline with economic growth: rather it appears that the range of pollutants increases with wealth (Damania et al., 2019). Decreasing water quality compared to quantity can have an equally or even more severe impact on health, agriculture and the environment and climate change will continue to affect water quality along multiple lines (section 4.2.5).

Environmental water scarcity (Figure 1d) is the main cause for biodiversity loss, as it directly degrades ecosystems (Pastor et al., 2014). The water essentially needed by the environment, termed environmental flow requirements (EFRs), is defined as "the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (Acreman and Dunbar, 2004; Declaration, 2007). Environmental flow requirements have only recently been incorporated into the assessments of water scarcity (Liu et al., 2016a; Liu et al., 2017).

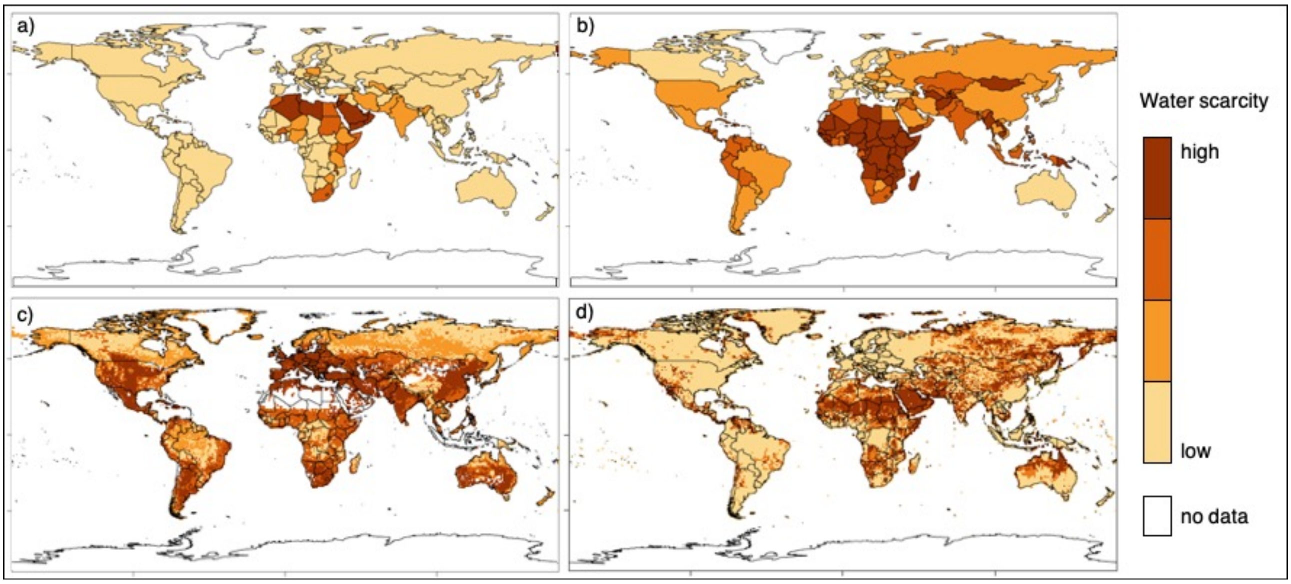


Figure Box 4.1.1: Different measures of water scarcity provide very distinct global distributions: a) Physical Water scarcity (AQUASTAT- (FAO, 2016b)based on (Falkenmark et al., 1989)); b) Economic water scarcity (total population with access to safe drinking-water from AQUASTAT (FAO, 2016b) c) Clean water scarcity (water quality risk based on: (Damania et al., 2019); d) Environmental water scarcity: Calculation based on (Pastor et al., 2014) using LPJmL data (Schaphoff et al., 2018)

[END BOX 4.1 HERE]

4.1.1 Points of Departure

Assessment Report 5 (AR5) concluded that 80% of the world's population is faced with threats to water security. Negative impacts on streamflow, its seasonality (specifically in cryospheric zones), decline in raw water quality, projected reduction in renewable surface water and groundwater in most dry tropical regions and projected increase in drought (meteorological, agricultural and hydrological) in dry regions were highlighted in AR5 (Jiménez Cisneros et al., 2014)

Special report on 1.5 degree (SR1.5), comparing the impacts 1.5° C and 2.0° C, assessed that limiting global warming to 1.5°is expected to substantially reduce the probability of extreme droughts, precipitation deficits and risks associated with water availability in some regions as compared to a 2.0°C warmer world. Higher risks to natural and human systems in a 2.0°C world would mean increased vulnerability for the poor, showing that socio-economic drivers are expected to have greater influence on water related risks and vulnerabilities than changes in climate alone. The number of people facing serious water shortage and high-water stress was estimated to be around 1.1 billion, or 17% of global population, of which the majority live in South and East Asia, Middle East and North Africa (Hoegh-Guldberg et al., 2018b).

Special Report on Climate Change and Land (SRCCL) stated that over-extraction is leading to groundwater depletion (*high confidence*) and that precipitation reduction, coupled with human drivers, will have a role in causing desertification as water driven soil erosion is projected to increase due to climate changed *(medium confidence*). Population vulnerable to impacts related to water is going to increase progressively at 1.5°C, 2°C and 3°C of global warming, with half of those impacted residing in South Asia, followed by Central Asia, West Africa and East Asia. SRCCL stated that improved irrigation techniques (e.g. drip irrigation) and moisture conservation (e.g. rainwater harvesting using indigenous and local practices), can increase resilient agriculture (Mirzabaev et al., 2019).

Special Report on Oceans and Cryosphere in a Changing Climate (SROCC) confirmed findings from AR5, with robust evidence on declines in snow cover and negative mass balance in most glaciers globally. Glacier melting seriously threatens water supply to mountain communities and the millions living downstream through water shortages jeopardizing hydropower generation, irrigation and urban water uses. Additionally, Artic hydrology, and vegetation will be affected by changes to permafrost decreasing water security and negatively impacting the health and cultural identity of Arctic communities (Hock et al., 2019).

Assessment Report 6 (AR6) Working Group I (WGI) (Douville et al., in preparation) concluded that it is *very likely* that anthropogenic activities have affected the global water cycle since pre-industrial times. Additionally, it stated with *medium confidence* that climate change has increased water withdrawals globally. These changes are expected *with high likelihood* to intensify, although geographical pattern and magnitude will remain uncertain, requiring flexible adaptation measures. While it is *highly likely* that pattern of forced hydrological response will remain relatively robust across the twenty-first century whatever the mitigation policy is, the magnitude of global water cycle changes will increase proportionally to global warming, and with it, the amount of the global population affected by water availability issues. *Confidence is high* that strong and rapid mitigation initiatives are needed to avert the manifestation of climate change in all components and features of the global water cycle.

Table 4.1: [PLACEHOLDER FOR SECOND ORDER DRAFT: If useful, a table with three columns to include what AR5 Chapter 3 stated and what we are adding to that, and if there is change in confidence levels of any of the findings between the two assessment periods.]

4.1.2 Methodological Developments

This chapter relies on literature from both the natural and the social sciences and is grounded on data gathered through different methodological approaches. These sciences produce data and results at different scales: from the global to the local. Aware of the complexity involved in translating global projections to the local scale to craft appropriate adaptation measures, this chapter differs from previous water chapters in AR5 due to its multidisciplinary entry point, use of information generated through new methodological advancement in hydrological science and modelling that have been developed since AR5 as well as inclusion of local, indigenous and traditional ecological knowledge for understanding these changes.

4.1.2.1 Advances in Detecting Hydrological Changes from Satellite Data

Given the continuing widespread decrease in the number of streamflow monitoring stations (Fekete et al., 2015; Laudon et al., 2017), alternative methods for reconstruction of runoff changes particularly for data sparse regions have been advanced. Discharge estimation from altimetry measurement and snow and ice cover estimates from satellite remote sensing since the 1970s have improved understanding of past changes in the hydrological cycle at large scales, particularly in ungauged and poorly-gauged river basins (*high confidence*). Advancements in automated processing of satellite data allow monitoring past changes in surface water condition that occurred in response to climatic and non-climatic drivers at global and regional scales (Donchyts et al., 2016; Pekel et al., 2016; Ji et al., 2018; Busker et al., 2019; Nardi et al., 2019). An automatic correction of systematic biases in satellite images (Yamazaki et al., 2017) makes it possible to obtain more realistic river routing at continental to global scales. After AR5, new global and continental scale gridded runoff datasets were derived from long-term reanalysis data. When combined with the available in-situ data, it leads to improved runoff data and runoff change assessments over multiple scales (Hobeichi et al., 2019) (*medium evidence, medium agreement*).

4.1.2.2 Advances in Reanalysis, Bias correction, and Downscaling

Climate forcing input data to drive global hydrological models have been developed based on station observations, climate reanalysis (climate models driven with all available up-to-date data) and/or remote sensing data often with 0.5° by 0.5° spatial resolutions and time resolutions shorter than daily, for periods as early as 1901 until recent years (e.g. (Iizumi et al., 2014; Müller Schmied et al., 2016)). Such global retrospective meteorological forcing data sets, a hybrid of reanalysis data and gridded observations, are used to reduce biases of climate variables obtained from General Circulation Models (GCMs) (Iizumi et al., 2017). To overcome the scale gap between the spatial resolutions of GCMs (e.g., order of hundred kilometres) and the desired scale to assess impact on water (e.g., several kilometres), climate variables obtained from GCMs are often downscaled using regional climate models or statistical methodology. There is *medium confidence* and *high agreement* that the selection of bias correction method or downscaling method impacts modelled hydrological variables (Müller Schmied et al., 2016; Maraun et al., 2017).

4.1.2.3 Advances in Hydrological Modelling for Impact Assessment

Until recently, three main approaches were used to simulate hydrological consequences of climate change on different spatial scales (Kundzewicz et al., 2018a): (1) from hydrological model forced by bias-corrected, downscaled output of global (or regional) climate models' ensemble (Krysanova et al., 2017; Zaherpour et al., 2018); (2) from hydrological model forced by input constructed from delta-changed historical climate observations (Vano and Lettenmaier, 2014; Gelfan et al., 2017); (3) directly from global or regional climate model (Koirala et al., 2014; Dai, 2016a; Ficklin et al., 2018). Following the climate model-hydrological model-impact assessment chain, a methodological shift has occured after AR5: from the use of one hydrological model with a large ensemble of climate projections (mostly CMIP5-based) to the use of hydrological model sets (Hattermann et al., 2017). Different hydrological models, being driven by the same climate projections, can provide deviating results, so the impact assessments based on averaging over the hydrological model ensemble are assumed to be more credible than a single model-based assessment (Kundzewicz et al., 2018a) (*medium evidence, medium agreement*). Both global and regional hydrological model sets have been increasingly used for impact studies, particularly within the framework of the Inter-Sectoral Impact Model Inter-comparison Project (Box 4.2 ISIMIP). At the basin scale, global hydrological models show weaker performance in the historical period and provide more uncertain runoff projections than the regional models (*robust evidence, high agreement*) (Gosling and Arnell, 2016; Hattermann et al., 2017), and the former demonstrate more pronounced increase in impact uncertainty with time (*medium evidence, medium agreement*) (Hattermann et al., 2018). Difference in assessment uncertainty is due partly to the global hydrological models being commonly used without any calibration and testing in contrast with the regional hydrological models (Krysanova et al., 2018; Kundzewicz et al., 2018a). It has been further demonstrated that climate projections are commonly the main source of uncertainty in hydrological impact assessments (Clark et al., 2016; Joseph et al., 2018; Kundzewicz et al., 2018a) (*high confidence*). However, hydrological model-based uncertainty can also be notable for some variables (e.g. low flow in permafrost regions (Hattermann et al., 2018) and basins (e.g. dry basins comparing with wet ones (Pechlivanidis et al., 2017)). Studies published after AR5 focused on quantifying the contribution of internal atmospheric variability in hydrological projection uncertainty (Seiller and Anctil, 2014; Gelfan et al., 2015). Computational cost reduction and advancement in computationally efficient schemes allow to conduct evaluation of hydrological models performance for different reference periods and more detailed assessment with higher spatial and temporal resolutions, including multiple climate and socioeconomic scenarios, attribution of impacts and accounting for complex water processes at regional and continental scales (*high confidence*).

Accumulation of statistics on hazard, exposure and vulnerability has been improving model based stimation of impacts, loss and damage, and cost and benefit of adaptations to water related disasters (*moderate confidence*). Reported exposures caused by water related disasters on databases such as EM-DAT and NatCat SERVICE have been used to calibrate modelled exposures or past trends in vulnerabilities (Jongman et al., 2012; Tanoue et al., 2016). Current local resilience to hazard (e.g., flood protection standard (Scussolini et al., 2016) provides initial condition and helps to quantify additional adaptations required to projected changes.

[START BOX 4.2 HERE]

Box 4.2: Inter-Sectoral Impact Model Intercomparison Project

The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) is a community-driven activity bringing together impact modelers to create a framework for multi-model climate-impact simulations across sectors and scales. Following the first ISI-MIP involving 28 global impact models from five sectors: global water, agriculture, biomes, health, coastal systems (Warszawski et al., 2014) and aimed at providing outcomes for AR5, the current longer-term phase incorporates regional impact models, additional eight sectors (regional water, fisheries and marine ecosystems, permafrost, terrestrial biodiversity, regional forests, agro-economies, lakes, and energy), and involves more than 100 modeling groups. The main output of ISI-MIP is an open-access archive (isimip.org/gettingstarted/data-access/#for-external-non-participant-users) of simulations.

The key research results obtained within the ISI-MIP Water sector can be broadly divided into the following three groups:

- Evaluation of regional hydrological models (rHMs) and rHMs-based impact assessment: Comprehensive studies were carried out for 12 large river basins worldwide using nine calibrated rHMs driven by five climate projections for four RCPs (see synthesis in (Krysanova et al., 2017)). The models' performance evaluated with 14 criteria was good for the monthly and seasonal dynamics and for high flows, but weaker for low flows. The analysis of hydrological indicators (percentiles Q10, Q50, Q90 and indices of 3 months high and low flow periods) under RCP8.5 demonstrates robust positive trends for the Arctic basins Lena and MacKenzie and robust negative trends for the Tagus basin, all with a high certainty. The overall fractions of uncertainty for the annual mean flow projections in the ensemble runs averaged over 12 basins were 57% for GCMs, 27% for RCPs and 16% for rHMs, and similar distribution was found for high flows.

- Evaluation of global hydrological models (gHMs): An ensemble of six gHMs for 40 large river basins worldwide was evaluated by (Zaherpour et al., 2018). For monthly runoff, the gHMs models generally perform better in the wetter equatorial and northern hydrobelts than in drier southern hydrobelts. Nevertheless, the authors found a general trend towards overestimation of mean annual runoff and indicators of upper and lower extremes for the majority of models. In several cases gHMs failed to capture the timing and magnitude of seasonal cycle. The study highlights the need for improvement of gHMs and models weighting based upon their performance.

- Cross-scale comparison of performance and impacts: A cross-scale intercomparison of performances in the reference period and simulated climate impacts was performed using nine rHMs (calibrated) and nine gHMs (not calibrated except of one) hydrological models for 11 large river basins (see synthesis in (Hattermann et al., 2017). In the reference conditions gHMs often show considerable biases in mean monthly and annual discharges and incorrect seasonality, whereas rHMs show a much better reproduction of discharge. The hypothesis of similarity of signals of change from two model sets is confirmed statistically only in five cases of eleven.

[END BOX 4.2 HERE]

4.1.2.4 Detection and Attribution: How Much of the Changes are Attributable to Climate Change?

Since AR5, tracing the effects of human influence on extreme weather events has become a major emerging area of understanding (Scott and Sugg, 2015b; Easterling et al., 2016). Following an impactful extreme event such as a heat wave, wildfire, drought, or flood, the demand for information about the role of climate change is intensified mainly from the media, regional disaster risk managers, insurance industry, litigators, and policy makers. Furthermore, planning for disaster risk management requires reassessments of the magnitude of impact-related variables expected to be experienced at different likelihood levels. Attribution of hydrometeorological impacts to anthropogenic climate change consists of two steps: attribution of impacts to climate change, regardless of the cause; and attribution to anthropogenic causes. Cramer et al. (2014) presented evidence that a number of water-related impacts could be attributed to climate change, but with little attribution to drivers of climate change whether anthropogenic or natural. However, Bindoff et al. (2013) presented new, stronger evidence that hydrometeorological changes could be attributed to anthropogenic influence through increasing radiative forcing by greenhouse gas (GHG) and aerosol emissions, and also presented emerging evidence that some aspects of land hydrological change could be attributed to anthropogenic influence of atmospheric CO_2 concentrations acting on land ecosystems. The majority of attribution studies assessed in WGI focussed on long-term trends, with a few on extreme events.

The techniques for detection and attribution of extreme weather events have developed substantially since the AR5 (Bindoff and Min, 2013). An event attribution (EA) statement is based on a specific metric that characterizes the extreme nature of the event in question, rendering relevance for the occurrence of similar types of events in the future. The change in likelihood of an extreme event due to the effects of human influences on the climate is usually expressed in terms of the fraction of attributable risk (FAR) (Allen, 2003) or the probability ratio.

Different event attribution approaches have been developed. Coupled Model Approaches extracts large samples of the impact-related climatic variable from global coupled model (GCM) ensembles of the factual and counterfactual (world that might have been without human influences) worlds to estimate the probabilities of the event of interest under both scenarios, from which estimates of the FAR or Relative Risk (RR) are obtained. For such attribution assessments, it is important that the models are rigorously evaluated against observations (Perkins et al., 2015).

Sea Surface Temperature Forced Atmosphere Only Model Approaches are similar to the GCM approach, but uses atmosphere only climate model (AGCM) with simulations representing the factual world conditioned on the observed evolution of sea surface temperature (SST) and ice cover, and simulations of the counterfactual world conditioned on SSTs and ice cover of a 'world that might have been,' had there been no human influence on climate (Ciavarella et al., 2018). Prescribed SSTs in an AGCM are used rather than using coupled models, as this can reduce model biases and enable more ensemble members to be simulated. This is because atmosphere-only simulations are less computationally expensive. This approach potentially results in a better representation of extreme events, and improved signal-to-noise ratio. However, the lack of atmosphere–ocean coupling could lead to a less accurate representation of extreme events strongly affected by atmosphere-ocean interactions (Stott et al., 2016). While removing the anthropogenic greenhouse gas forcing from the modelled atmosphere is straightforward, estimating the pattern of warming to be removed from the observed SSTs and sea ice is the largest source of uncertainty in this approach that cannot be evaluated against observations. Other commonly used attribution approaches are analogue-based approaches; empirical approaches and broad-scale approaches.

Confidence in attribution of water-related extremes (extreme precipitation events, droughts, and storms) can sometimes be lower than for extreme temperature events (Stott et al., 2016). The observational basis is regarded as less secure, and climate models may not always perform well in capturing relevant features of the events. Confidence depends on the processes involved. Seneviratne et al. (in preparation) draw an important distinction between dynamic (atmospheric circulation) and thermodynamic (energy balance, including evaporation) effects. Seneviratne et al. (in preparation) assign *high confidence* to thermodynamic contributions to increasing drought severity from greenhouse forcing, but *low confidence* to dynamic contributions. They also assign *high confidence* to anthropogenic contributions to increased intensification of precipitation which is dominated by thermodynamic effects with some dynamic contributions. Confidence in attribution results increases if independent methods lead to similar conclusions. For example, consensus among different process-based models can increase confidence, as can explanation with well-founded conceptual models.

Europe, North America, Australasia, and Asia currently have a disproportional amount of published EA studies. Among other publications, annual reports of the Bulletin of the American Meteorological Society (BAMS) on explaining extreme events of the previous year from a climate perspective have been published since 2012 (Peterson et al., 2012) and contributed to the increase in geographical coverage of event attribution studies. Given the regional differences in modes of climate variability, such as El Niño / Southern Oscillation, and responses to external climate forcings, it is important to close gaps in global coverage (Central and South America, Africa, West Asia and Eastern Europe) of detection and attribution studies.

In general, studies have shown clear evidence for human influence having increased the likelihood of many extremely warm seasonal temperatures and reduced the likelihood of extremely cold seasonal temperatures in many parts of the world. The influence on the probability of extreme precipitation events, droughts, and storms is less evident, but some evidence is emerging for some cases (Section 4.2.7). Most of the published studies have focused on the meteorological nature of events, rather than their impacts which would in many cases require the consideration of additional geophysical and socioeconomic (e.g., exposure and vulnerability to natural hazards) processes. For instance, streamflows computed using hydrological models come closer to the drivers of flood or drought impacts on people. As the attribution techniques are extended to account for further impact-relevant variables, it is expected that the results will become more suitable for regional to local decision making on management of water resources and disasters risk.

4.1.2.5 Scenarios for Projecting Change – RCPs and SSPs

The Representative Concentration Pathways (RCPs) and the Shared Socioeconomic Pathways (SSPs) provide scenarios of future changes in climate forcings and socio-economic change, and are used, among other things, to quantify the water-related impacts of climate change. Differences in climate model responses to RCP forcing lead to large uncertainties in projected regional water impacts. Projected risk for people and society also depend very strongly on the choice of socioeconomic scenario. For example, risk of water insecurity depends not only on limited availability of fresh water but also on the number of people exposed to this and their sensitivity to reduced water availability. These in turn depend on socioeconomic factors such as population size and demographics, local infrastructure, the character and state of the economy, and factors which affect access to water.

RCPs are primarily defined in terms of the concentrations of CO_2, other GHGs and short-lived forcing agents such as ozone and aerosols, and in CMIP5-based research assessed in AR5 the RCPs were also accompanied by standardized scenarios of land use / land cover change (van Vuuren et al., 2011). One development since AR5 include the inclusion of different mixes of CO_2 and other forcing agents for a given radiative forcing, which could potentially affect hydrological cycle processes sensitive to the concentration of CO_2 and/or the geographical pattern of radiative forcing or land use (see 4.1.3). Another development is that the RCPs used in the 6th Coupled Model Intercomparison Project (CMIP6) climate models are paired with specific SSPs, including land use scenarios associated with that SSP.

SSPs provide quantitative scenarios of key characteristic of human society over the 21st Century (O'Neill et al., 2017). These consist of quantified scenarios and accompanying narratives representing possible future trends in large-scale (global and world regional) societal character and natural systems over the 21st century. The five SSPs are designed to cover diverging sets of societal conditions representing combinations of high and low challenges to climate change mitigation and adaptation. They are quantified in terms of demographics (Jones and O'Neill, 2016), economic development, welfare, environmental and ecological factors, resources, metrics for governance, technological development, policies (excluding climate policy) and broader societal factors, and feature narratives describing the scenario of evolution of these pathways.

These pathways affect the exposure and vulnerability of people to hydrological hazards and hence affects the risks and impacts of climate change relating to water.

4.1.2.6 Inclusion of Indigenous Knowledge in this Chapter

While most previous IPCC assessments have failed to incorporate Indigenous Knowledge and Local Knowledge (IK and LK) (Ford et al., 2016), this chapter strives to include these perspectives to assess impacts, vulnerability and adaptation to climate change-induced water-related hazards. IK and LK knowledge is embedded in social institutions (Naess, 2013), particular places, relationships and practices (Muir, 2010) and often use holistic frameworks that bring together natural and spiritual worldviews (Boillat and Berkes, 2013; Cochran et al., 2013). Non-Western knowledge has been integrated in this chapter by engaging directly with indigenous contributing authors and by using a multiple evidence base approach, as done by the IPBES (Tengö et al., 2014; Tengö et al., 2017). Incorporating non-Western knowledge systems warrants the recognition of different worldviews; the extractive nature of colonialism as both an historical and contemporary process in the production of climate change; challenges to traditional knowledge and alienation from traditional territories (Bohensky et al., 2013; Pyhala et al., 2016; Nursey-Bray and Palmer, 2018; Huntington et al., 2019). Explicit attention needs to be paid in relation to differential vulnerability to water-related hazards and to political and cultural sovereignty of indigenous groups from other marginalized groups in relation to water rights and usage (Cameron, 2012; Ford et al., 2016).

4.1.3 Climatic and Non-Climatic Drivers of Changes

The water cycle is affected by both climatic and non-climatic factors. Climatic factors include greenhouse-forced warming, regional forcing by aerosols, and the impacts of land cover changes and urbanisation on the surface energy and moisture budgets (*high confidence*). Rising CO_2 concentrations also affect the water cycle via plant physiological responses affecting transpiration (*medium confidence*). Direct human interventions in river systems and groundwater are a first-order driver (*high confidence*).

Increased global-scale radiative forcing by increasing greenhouse gas concentrations, partly offset by aerosols and land surface albedo change, drives increased evaporation from the land and ocean surface, increasing moisture content of the atmosphere (Trenberth, 1998). A warmer atmosphere also has more capacity to hold moisture (Trenberth, 1998). This increases specific humidity and global mean precipitation. Regional precipitation responses vary according to changes in atmospheric circulation. The warmer surface also drives stronger convection and more extreme precipitation (Giorgi et al., 2019). Since aerosols are short-lived, their concentration in the atmosphere has substantial geographical variation and this drives changes in atmospheric circulation, which affects precipitation patterns, for example by affecting the Asian monsoon (Ganguly et al., 2012; Singh et al., 2019). Rising atmospheric CO_2 concentrations generally cause decreased plant transpiration which affects soil moisture, runoff, streamflows and the return of moisture to the atmosphere for rainfall as well as surface temperature (Skinner et al., 2017), although in some regions these can be offset by increased leaf area (“global greening”) driven by elevated CO_2, land use change, nitrogen deposition and effects of climate change itself. Increased concentrations of ozone can also impact plant functioning with knock-on effects on transpiration.

Direct human interventions in the water cycle include extraction of surface water and groundwater for drinking water, irrigation and other fresh water uses, and impoundment of streamflows behind dams to form reservoirs (Donchyts et al., 2016). The consequences of these are substantial. Anthropogenic land cover change alters the nature of vegetation cover which in turn affects evapotranspiration (Li et al., 2015b) and the interception of precipitation by vegetation canopies (de Jong and Jetten, 2007). Urbanisation can affect precipitation in a number of ways: increased sensible heat flux can destabilise the local atmosphere and cause increased precipitation (Kusaka et al., 2014) or a shift from heavy to extreme precipitation (Niyogi et al., 2017). Urbanisation can also decrease the permeability of the land surface, which can increase fast runoff unless specific measures are taken with drainage and reduce local rainfall by decreasing the return of moisture to the atmosphere (Wang et al., 2018). Agriculture can affect soil permeability, and irrigation can reduce river flows and groundwater levels via extraction and alter precipitation by increasing it locally (Alter et al., 2015). Irrigation can change the timing of monsoons by affecting the land-sea contrast (Guimberteau et al., 2012; Singh and Singh, 2015), and alter precipitation remotely through changes in advection of moisture (de Vrese et al., 2016). Paddy rice can affect climate via emissions of methane (Begum et al., 2019).

4.2 Observed and Projected Hydrological Changes and their Societal Impacts

4.2.1 Precipitation, Evapotranspiration, and Soil Moisture

Precipitation, evapotranspiration and soil moisture are all observed to have increased in the global mean, but with substantial regional variations in changes including decreases as well as increases (*high confidence)*. Although climate change is a major driver, and some changes can be directly attributed to anthropogenic climate change, other drivers of change are also important, such as land use change, irrigation and urbanisation, and plant physiological responses to elevated CO_2 (*high confidence*). Climate models project increased precipitation in the global average, but again with substantial regional variations including decreased precipitation in some areas, but with large uncertainty due to disagreement between models (*high confidence*). These regional variations and uncertainties are reflected in regional variations and uncertainties in evapotranspiration and runoff. Plant physiological responses to CO_2 may partly or completely offset some of the warming-driven increase in evapotranspiration (and hence soil moisture loss), especially in the tropics where the simulated CO_2 responses is strongest (*medium confidence*).

4.2.1.1 Observed Changes in Precipitation

Global mean precipitation increased since the start of the twentieth century (*high confidence*) including northern hemisphere land in mid to high latitudes and some parts of the tropics. However, precipitation decreased on average across the tropics overall.

AR5 concluded that global mean precipitation increased between 1901–2008, but with low confidence in the magnitude of change due to substantial differences between datasets (Hartmann, 2013). Although increased precipitation was seen in most areas, particularly in northern hemisphere high latitudes, decreases were seen in the Mediterranean, West Africa and East Africa, south-east Africa and parts of China, but with differences between datasets for the latter. The increases in global mean and northern hemisphere high-latitude precipitation were attributable to anthropogenic influences (Bindoff et al., 2013).

A global land network of 67,200 monitoring stations (Becker et al., 2013; Schneider et al., 2014) indicates that global mean land precipitation increased from 1901–2010 (Gu and Adler, 2015), although satellite data for 1979–2014 do not show a significant trend over that period (Adler et al., 2017).

Precipitation increased over northern hemisphere land in mid- to high-latitudes both over 1901–2010 in station data (Gu and Adler, 2015) and 1979–2014 in satellite data (Adler et al., 2017). Increases in North America are also seen from 1930 to 2004 in the globally-gridded CRU precipitation dataset based on surface stations and statistical interpolation (Kumar et al., 2013), but trends in other regions are less statistically significant.

In the tropics and sub-tropics, observed precipitation changes are more varied and also show less agreement between datasets. Both land stations and satellite data generally suggest increased precipitation over equatorial South America, southern Africa, South-East Asia, and northern Australia, and decreased precipitation in equatorial Africa and central and southern South America (Gu and Adler, 2015; Adler et al., 2017). The gridded CRU data shows increases in south-eastern South America and northern Australia (Kumar et al., 2013). Decreased precipitation is seen in equatorial Africa and central and southern South America in station and satellite data (Gu and Adler, 2015; Adler et al., 2017) and in the Sahel and the northern Indian subcontinent in gridded data (Kumar et al., 2013). The strength of the Indian summer monsoon declined from 1950 to 2005 (Ramesh and Goswami, 2014; Saha et al., 2014). Overall, land stations show a general decrease in the tropics and sub-tropics from 1901–2010 (Gu and Adler, 2015).

Increasing global precipitation arises from a generally moister atmosphere due to increased evaporation and the increased water-holding capacity of the warmer atmosphere. Where the signal of change can be detected from the noise of internal climate variability, which is more the case at very large scales, these changes can be attributed to anthropogenic climate change (Douville et al., in preparation). Attribution of regional-scale observed large-scale precipitation changes to radiatively-forced climate change remains a challenge (Sarojini et al., 2016). Some regional changes can be attributed to changes in aerosol radiative forcing which shows a high degree of spatial variability. Irrigation can increase precipitation locally (e. g., the Sahel: Alter et al. (2015)) and remotely (e. g., irrigation in Asia affects precipitation in Africa: de Vrese et al. (2016)) and delay the Indian monsoon onset by decreasing the land-sea contrast (Guimberteau et al., 2011). Land cover change also has an influence. Large-scale systematic detection and attribution studies with GCMs have not yet shown a detectable signal in precipitation due to these effects, but may not yet be able to represent these effects fully (Douville et al., in preparation).

The decline in the Indian summer monsoon rainfall may be linked to increasing temperatures in the Indian Ocean and western tropical Pacific which modify the atmospheric circulation (Saha et al., 2014), although land use changes may also play a role.

4.2.1.2 Projected Changes in Precipitation

Climate models project global mean precipitation to continue to increase (*high confidence*), and there is agreement on projected increases in high latitudes. All models project decreased precipitation in some regions, including mid-latitudes and especially parts of the tropics (*high confidence*) although the specific details of increased and decreased precipitation vary between models. Multi-model mean projections do not necessarily represent the most likely outcome, and does not highlight the large changes that are possible but which can largely cancel each other in the multi-model mean (*high confidence*).

AR5 and SR1.5 agreed with earlier assessments that global annual mean precipitation is projected to increase with global warming (Collins et al., 2013a). At regional scales, precipitation was projected to increase at northern high latitudes and much of the moist tropics, but with varying levels of confidence in the latter, and decrease in the Mediterranean and southern Africa. In other regions, signs of change were inconsistent between models. SR15 assigned *medium confidence* to a projected increase of mean precipitation in high-latitudes at 2°C versus 1.5°C of global warming (Hoegh-Guldberg et al., 2018b).

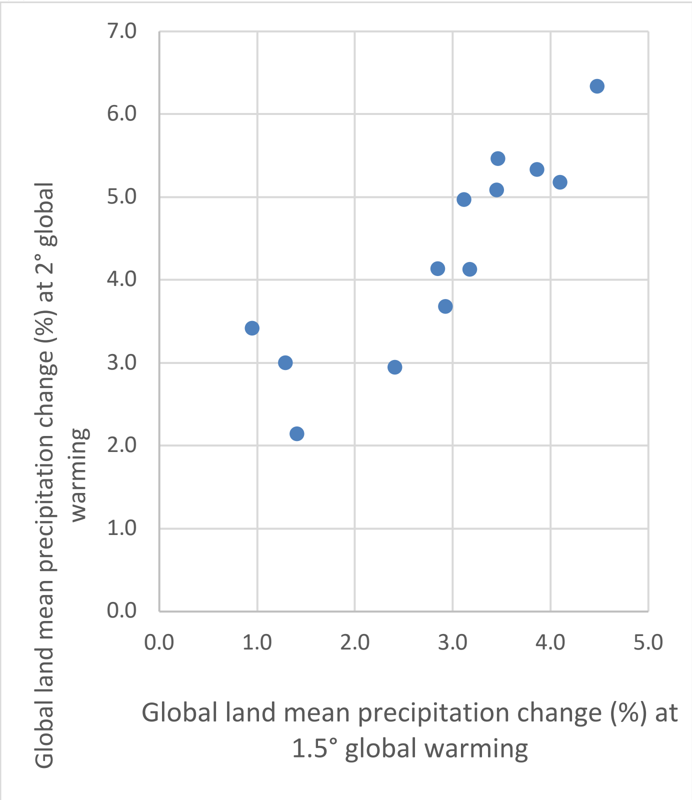
The CMIP5 models project global mean precipitation to increase by approximately 1 to 3% per °C global mean warming (Allan et al., 2014; Giorgi et al., 2019), consistent with observational constraints (Allan et al., 2014). Although at any particular global warming level there is range of projected precipitation changes, individual models consistently show a larger increase at, for example, 2°C global warming compared to 1.5°C (Betts et al., 2018a). At 4°C, global mean precipitation increase is projected to increase by around 8% (Allan et al., 2014).

Regional patterns of precipitation change vary substantially, with decreases projected in many areas despite the overall increase in the global mean (Giorgi et al., 2019). The level of agreement on the magnitude and sign of the change also varies between regions (Figure 4.3b). Increased precipitation is consistently projected in high-latitude regions, equatorial Africa and South East Asia. Decreased precipitation is consistently projected in the Mediterranean region and southern Africa. In many other regions, such as northern South America, central North America and central Europe, there is disagreement among models, with some projecting increases and some projecting decreases. Although at the global scale, wet regions are projected to become wetter and dry regions drier, this patterns are not necessarily followed at regional to local scales (Kent et al., 2015). Broadly, increased global warming magnifies regional precipitation changes but the global pattern remains similar, although between 1.5°C and 2°C the local differences may also be due to internal variability or differing levels of spatially-heterogeneous radiative forcing from aerosols, depending on the emissions scenario (Betts et al., 2018a).

A focus on the multi-model mean may not be helpful to decision makers as it may not necessarily represent the most likely outcome and does not highlight the large changes that are possible, but which largely cancel each other in the multi-model mean.

[PLACEHOLDER FOR SECOND ORDER DRAFT: section to be updated with information from the new CMIP6 models which are not yet fully available.]

(a)


7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
Global land mean precipitation change (%) at 2° global warming
Global land mean precipitation change (%) at 1.5° global warming

(b)

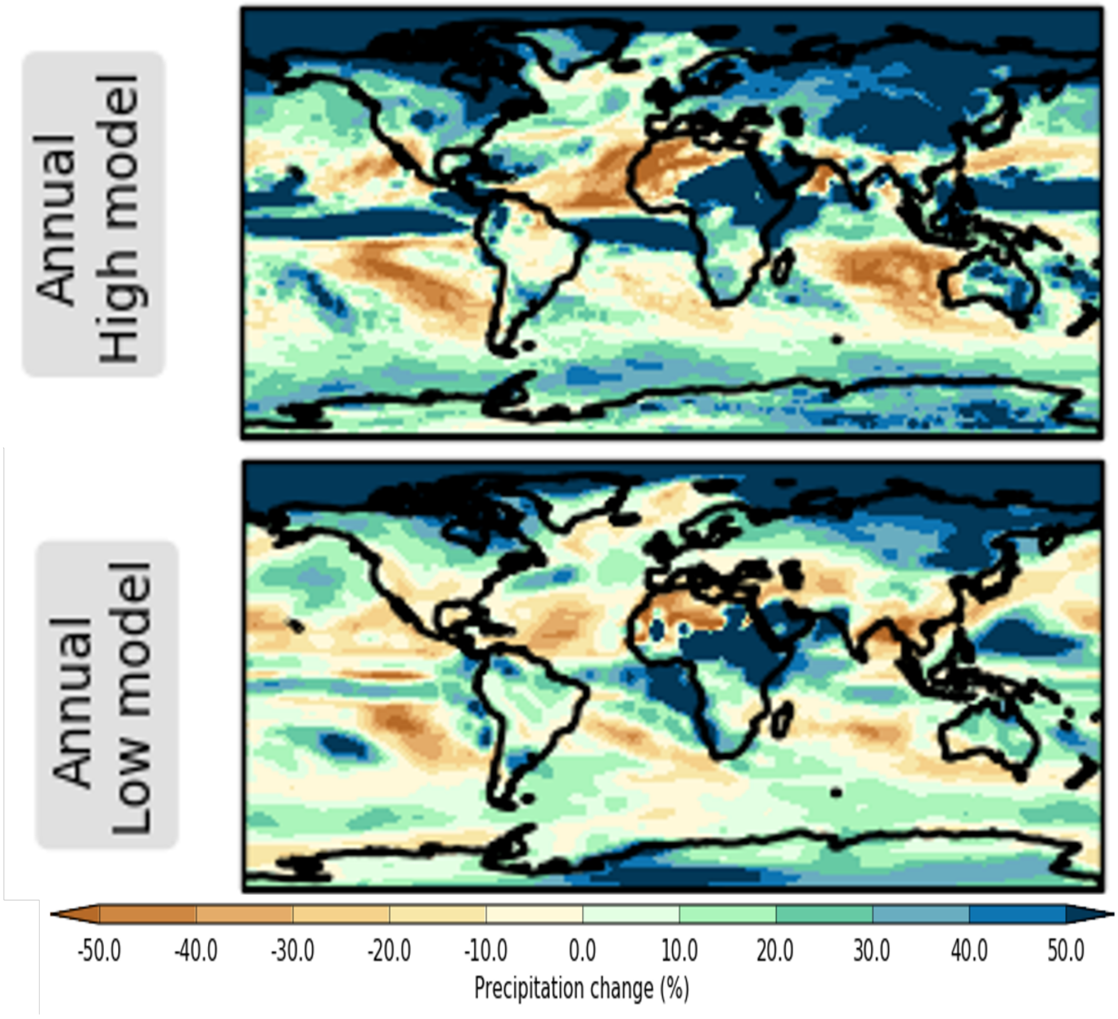

Annual High model
Annual Low model
-50.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0
50.0
Precipitation change (%)

Figure 4.3: (a). Projected changes in global land mean precipitation relative to 1981–2010 at 2°C vs. 1.5°C. Projections are from a 13-member ensemble with the EC-Earth and HadGEM3 global atmosphere models driven by prescribed changes in sea surface temperatures, sea ice and atmospheric composition from selected members of the CMIP5 multi-model ensemble with RCP8.5 (Betts et al., 2018a; Koutroulis et al., 2019). (b) Projected changes in annual mean precipitation at 4°C global warming for 2 CMIP5 GCMs with "low" and "high" precipitation responses. [PLACEHOLDER FOR SECOND ORDER DRAFT: to be updated using CMIP6 projections and further developed to illustrate the range of outcomes at local scales by using "high" (largest increase/smallest decrease) and "low" (smallest increase/largest decrease) precipitation changes in individual grid boxes].

4.2.1.3 Observed Changes in Evapotranspiration

There is *high confidence* that evapotranspiration (ET) is increasing in most regions, however, in highly vegetated areas of the tropics, the stomatal effect leads to decreasing ET.

AR5 found increasing ET from 1982 until the late 1990s then little change. In arid and semi-arid regions, ET trends followed precipitation trends. Increased surface solar radiation from reduced aerosol pollution increased ET in the humid part of Europe. In the southern hemisphere, increases in ET were constrained by moisture availability (Hartmann, 2013).

Many studies have reported increases in global ET for the recent period: e.g. +0.54 mmyr^{-2} (1981 to 2012) (Zhang et al., 2016b), +1.18 mmyr^{-2} (based on observations) or +0.93±0.31 mmyr^{-2} (based on LSMs) for 1982 to 2010 (Mao et al., 2015), +0.88mmyr^{-2} from remote sensing data (1982–2013) (Zhang et al., 2015). Decreases in ET are reported for western Amazon and central Africa (Miralles et al., 2013), though this is not the case across all datasets (Zeng et al., 2018a).

Transpiration accounts for much of the land-atmosphere water flux, so ET change depends on the plant physiological response to atmospheric composition change, in terms of CO_2 but also ozone, in addition to the effects of temperature, humidity, wind speed and precipitation change. With higher CO_2, a warming climate increases evaporative demand (e.g. Huang et al. (2015a); Berg et al. (2017)) but this is opposed by reduced stomatal conductance ('physiological effect') which reduces transpiration and increases leaf level water use efficiency (WUE). It also increases photosynthesis rates, though this may not be maintained in the long term (Warren et al., 2015). This increases leaf area index (LAI) ('structural effect') and transpiration; 55±25% of observed increases in ET (1980–2011) have been attributed to LAI change (Zeng et al., 2018b). However, overall transpiration change depends on the balance between these effects (e.g. (Tor-ngern et al., 2015; Ukkola et al., 2015)

There is evidence for recent increases in leaf-scale WUE from tree rings (14 ±10 %, broadleaf to 22 ±6 %, evergreen over 20th century (Frank et al., 2015)), carbon isotopes (30 to 35 % increase in 150 years (van der Sleen et al., 2014)) and satellite measurements (1982–2008) combined with data-driven models (Huang et al., 2015b). WUE is also affected by aerodynamic conductance (Knauer et al., 2017), nutrient limitation (Medlyn et al., 2015; Donohue et al., 2017), soil moisture availability (Bernacchi and VanLoocke, 2015; Medlyn et al., 2015), ozone pollution (King et al., 2013; Frank et al., 2015). It is not straightforward to scale the leaf-level response of WUE to increased CO_2 into a larger-scale transpiration response (Bernacchi and VanLoocke, 2015; Medlyn et al., 2015; Tor-ngern et al., 2015; Walker et al., 2015; Kala et al., 2016). There are other factors that modulate the effect on transpiration both temporally and spatially, for example: additional vegetation structural changes (Kim et al., 2015a; Domec et al., 2017), seasonal rainfall totals (Hovenden et al., 2014), vegetation disturbance and age (Donohue et al., 2017) and species (Bernacchi and VanLoocke, 2015). Increases in ET driven by increased LAI (from satellite observations 1982–2012) are estimated at 0.32 ± 0.07 mm/month per decade generating a climate forcing of -0.31 Wm^{-2} per decade (Zeng et al., 2017b).

There is *high confidence* that globally, the stomatal effect dominates the structural effect (Berg et al., 2017) but regionally this is not necessarily the case (Huang et al., 2015b; Ukkola et al., 2015). In dry regions, ET tends to increase due to increases in LAI (Huang et al., 2015b), but in densely vegetated regions, the stomatal effect dominates (Mao et al., 2015). Reductions in transpiration due to rising CO_2 concentrations may also be offset by a longer growing season (Frank et al., 2015).

4.2.1.4 Projected Changes in Evapotranspiration

The sign of projected ET change is dependent on region, but there is *high confidence* that ET will increase in mid/high latitudes and decrease in northern South America and southern Africa. This is similar to AR5, and consistent with precipitation changes.

An ensemble of projections with the HadGEM3-GC3 climate model (Murphy et al., 2018) also projects evapotranspiration increases in mid/high latitudes but decreases across the tropics (Figure 4.4). This resembles changes in CMIP5 except over central Africa and SE Asia (Berg and Sheffield, 2019).

Combined radiative and physiological effects suggest decreasing ET (<0.5mm/day) in northeastern South America, central America, the Mediterranean, and western Africa but increases (<0.5mm/day) in northern latitudes, eastern Africa and Australia (Swann et al., 2016; Berg and Sheffield, 2019). Projected ET decreases from the physiological effect are widespread but greatest in tropical forests (-0.5mm/day) (Swann et al., 2016; Kooperman et al., 2018). For a quadrupling of CO_2, the mean ET decrease from the physiological effect is 0.1 mm/day (Swann et al., 2016). A new stomatal scheme constrained by observations projected ET decreases of up to 2mm/day over central Europe (Kala et al., 2016), though LAI was fixed in this experiment so it could not offset the stomatal effect.

The physiological effect is important in hydrological cycle projections (Pu and Dickinson, 2014; Kamae et al., 2015; Richardson et al., 2018; Chadwick et al., 2019). Projections of hydrological change excluding the physiological effect may be flawed (Betts et al., 2015; Milly and Dunne, 2016; Swann et al., 2016; Chadwick et al., 2017). It accounts for 58% of global ET change (Lemordant et al., 2018). Reduced stomatal conductance feeds back on climate (Skinner et al., 2017) through surface fluxes (Halladay and Good, 2017; Lemordant et al., 2018; Lemordant and Gentine, 2019). Skinner et al. (2017) estimated ET change from the stomatal effect (-0.11mm/day) and from LAI (+0.03mm/day), but LAI may not increase in areas where it is already high (Lemordant et al., 2018). Increased LAI increases transpiration which depletes soil moisture but increases shading thus reducing evaporation from soil (Skinner et al., 2017). Global LAI projections from models are wide-ranging (0.1 to 1.4 m^2m^{-2}, (Mahowald et al., 2016)) as is the modelled sensitivity of ET to LAI (Zeng et al., 2016), which adds to projection uncertainty.

There is *high confidence* that ET will increase in mid/high latitudes but decrease in northern South America and southern Africa, but the sign of change is uncertain for central Africa and SE Asia.

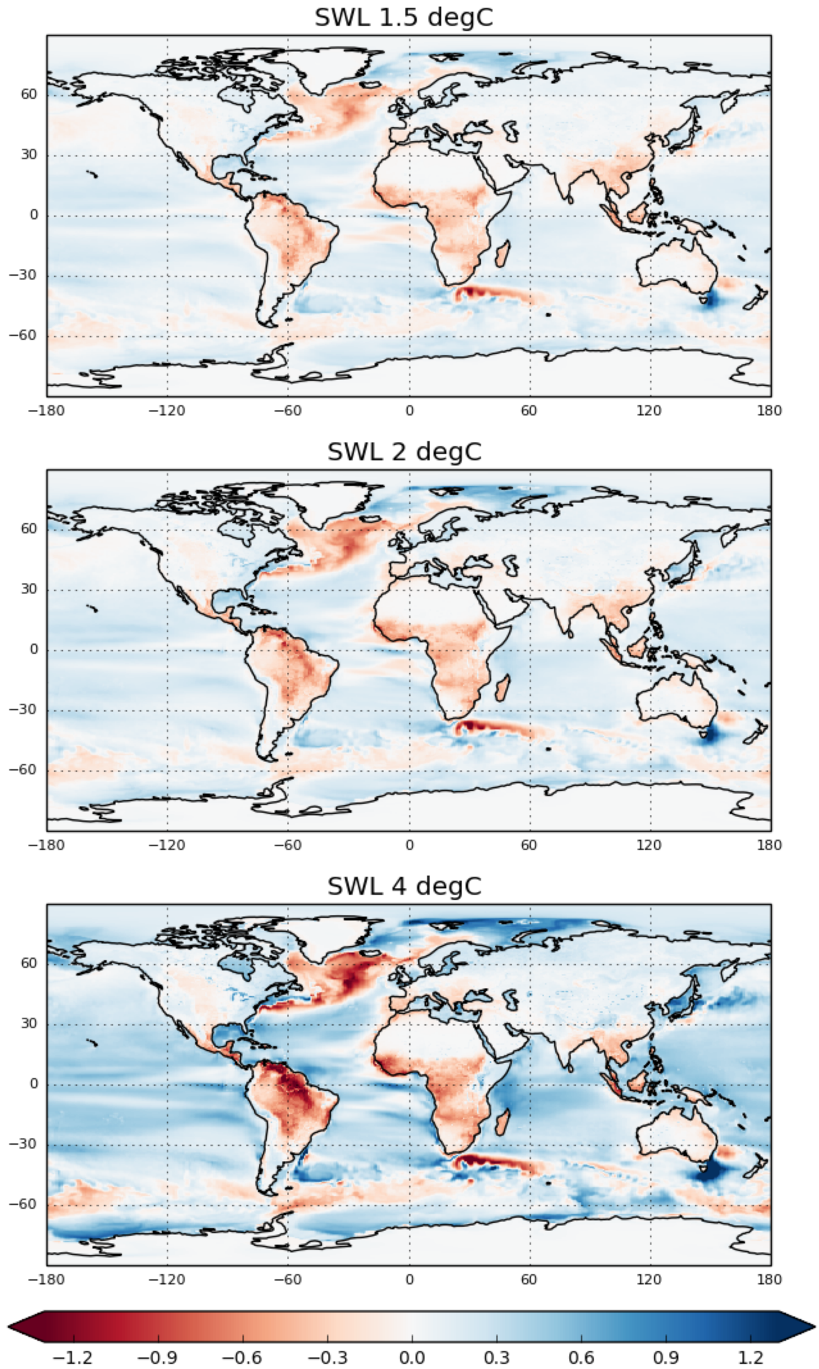


Figure 4.4: Ensemble mean change in evapotranspiration (mm/day) at 1.5°C, 2°C and 4°C global warming from a 20-member perturbed parameter ensemble with the HadGEM3-GC3 (CMIP6-generation GCM), relative to a baseline of 1900–1919.

4.2.1.5 Observed Changes in Soil Moisture

Soil moisture has decreased slightly in the global mean but with increases in some regions (*medium confidence*). Changes on interannual timescales relate to modes of internal climate variability such as ENSO (*medium confidence*).

AR5 (Hartmann, 2013) mentioned decreasing soil moisture as a limit on increasing evapotranspiration in the southern hemisphere, but also highlighted the limited availability of observed soil moisture data.

Since AR5, major advances have been made in observing soil moisture by satellite remote sensing using active and passive microwave measurements. New instruments have now been available for some years, e.g. the Advanced Microwave Sounding Radiometer for Earth Observation System (AMSR-E; (Njoku, 2004);

data coverage 2002–2011), AMSR-2 (Jackson et al., 2018), the Soil Moisture Ocean Salinity (SMOS; (Mecklenburg et al., 2016), and these are other data are being harmonised in the European Space Agency (ESA) Climate Change Initiative (CCI) soil moisture product to provide long-term records from the late 1970s onwards (Rahmani et al., 2016).

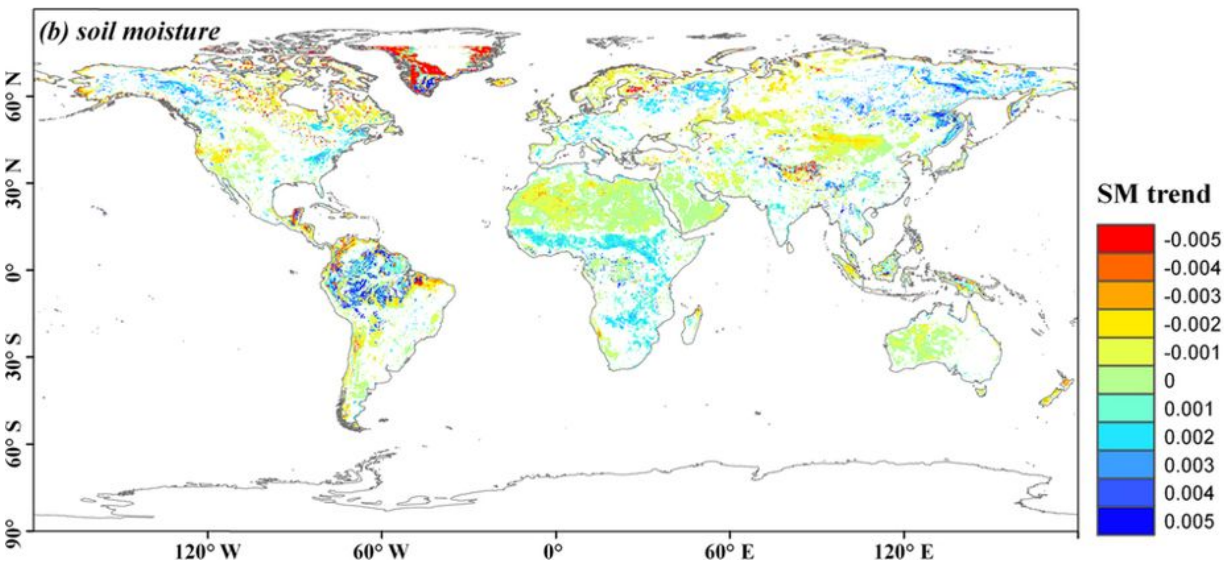
Global mean soil moisture has decreased slightly from 1982 to 2013 with a change rate of -0.002 per decade, but regional trends show both increases and decreases (Seneviratne et al., 2010; Feng and Zhang, 2015; Feng, 2016) (Figure 4.5). Soil moisture increased on approximately 7% of the global land including Amazonia, the Sahel, north-east Asia, smaller parts of Asia and parts of North America, while it decreased on approximately 22% of land including much of northern Europe and northern Canada, much of central Asia, the Sahara, western regions of Australia and near-coastal regions of northern South America (Feng and Zhang, 2015). Using the Special Sensor Microwave/Imager (SSM/I) to retrieve the soil moisture (Lu et al., 2011), the surface soil moisture in central Africa and South Africa region is increasing, while parts of northern Africa are decreasing from 1988 to 2007.

Soil moisture has increased in the Amazon basin, southern Africa and north-eastern Asia and decreased in northern Africa and central Asia (Feng, 2016). Trends of soil moisture include both drying and wetting zones ranging between −0.002 and 0.002 cm^3/cm^3 per decade. The geographical variations in trends are more complex than the common view of “Dry Get Drier, Wet Get Wetter”, with 15% of land following that paradigm while 8% follows the opposite, i. e, “Dry Get Wetter, Wet Get Drier”. This is broadly supported by analysis of changes in precipitation-evaporation based on surface observations (Greve et al., 2014). Discrepancies between soil moisture and precipitation exhibited in the most intensively cropped Huang-Huai-Hai Plain is attributed to substantial anthropogenic interference on the local water resources, including groundwater-fed irrigation (Qiu et al., 2016) (Section 4.2.4).

From 2002 to 2017, GRACE (Gravity Recovery And Climate Experiment) observations (Fasullo et al., 2016) show that global mean soil moisture exhibits interannual variability which largely correlates with ENSO (Humphrey et al., 2018) but associations of GRACE soil moisture changes with anthropogenic forcing are hard to discern at present (Fasullo et al., 2016).

Changes in soil moisture are due to changes in the relative balance of precipitation and evapotranspiration, with climate changes being the main driver of soil moisture changes and vegetation change playing a secondary role through direct effects on evapotranspiration (Feng, 2016). There is inconsistent evidence on the magnitude of global land mean P-E and observed trends during the period of observationally constrained reanalyses (since 1980) (Douville et al., in preparation). Estimates of the annual global land mean P-E in the 1980s range from approximately 0.5 to 1.1 mm/day and estimates of change range from approximately -0.2 to 0.2 mm/day by the 2010s.

(a)



(b)

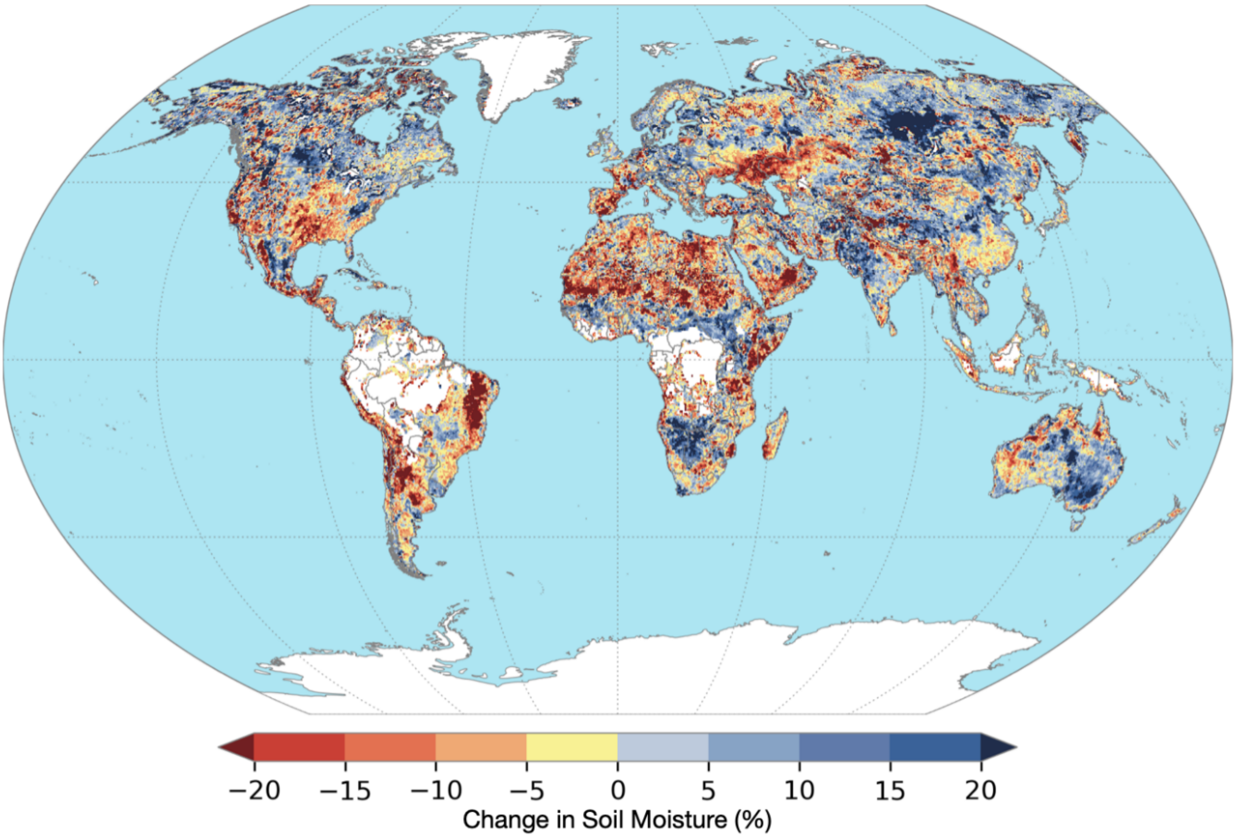


Figure 4.5: (a) Observed trends in global soil moisture from 1982 to 2013 from the ESA CCI soil moisture product. (b) Observed changes of the global surface soil moisture (0–5cm) from the year of 1978–2015, using the "COMBINED Product" of European Space Agency Climate Change Initiative Soil Moisture (ESA CCI SM v03.2) Data (https://www.esa-soilmoisture-cci.org/taxonomy/term/5). The ESA CCI SM v03.2 product consists of three surface soil moisture (0–5 cm) data sets: The "ACTIVE Product" and the "PASSIVE Product" were created by fusing scatterometer and radiometer soil moisture products, respectively; The "COMBINED Product" is a blended product based on the former two data sets. The time coverage is from 1978–11 to 2015–12 with a daily time step.

4.2.1.6 Projected Changes in Soil Moisture

Models project increased soil moisture in some regions and decreases in others, with the changes being larger at higher levels of global warming (*high confidence*) although there remains substantial disagreement on specific regional changes, especially due to differences in approach of using land models coupled to climate models or separately.

AR5 focused mostly on surface (upper 10 cm) soil moisture, summarized multi-model projections of 21st century annual mean soil moisture changes as broadly decreasing in the subtropics and Mediterranean region, and increasing in east Africa and central Asia across the RCPs, with the changes tending to become stronger as the strength of the forcing change increases (Collins et al., 2013b).

Current models project geographically varying changes in soil moisture with global warming, broadly with increasing soil moisture in high latitudes and decreases in lower mid-latitudes and sub-tropical semi-arid regions. However, uncertainties are very large. A key issue concerns the differences between soil moisture projections by the land surface components of Earth System Models (ESMs) themselves and projections with separate land models driven by meteorological quantities projected by ESMs. These differences arise from different treatments of the impact of plant physiological responses to elevated CO_2 which relatively reduce transpiration and relatively increase soil moisture. Many land models used for hydrological impacts assessments do not account for this effect and hence project greater decreases on soil moisture than ESMs, which mostly do account for this effect (Milly and Dunne, 2016; Swann et al., 2016).

A projection using the Palmer Drought Severity Index (PDSI) suggest that the observed decreasing trend in soil moisture will persist in the future, with decreasing soil moisture is projected for 70% of the ice-free land surface and no regions with significant increases (Zhao and Dai, 2015). This does not account for plant physiological responses to CO_2

In southern Europe, long-term mean soil moisture is projected to decline substantially in all seasons (Ruosteenoja et al., 2018). In summer and autumn, pronounced soil drying also afflicts western and central Europe. In northern Europe, drying mainly occurs in spring, in correspondence with an earlier melt of snow and soil frost. Uncertainties are high in dry regions and low in wet regions (Milly and Dunne, 2016; Cheng et al., 2017).

Results are conflicting for the projection of soil moisture changes at greater depth beyond the upper 10cm, with changes either being more negative changes near the surface (Berg et al., 2017), or, in contrast, an intensification of the drought in deep soils (> 20 cm) more dramatically than the surface soil, causing severe soil moisture stress in deep soils (Schlaepfer et al., 2017). Some regions of the northern middle to high latitudes exhibit negative annual surface changes but positive total changes.

4.2.1.7 Societal Impacts and Risks of Changes in Precipitation, Evapotranspiration and Soil Moisture

Reduced soil moisture is associated with an amplification of impacts, contributing to losses in rain-fed agricultural production (*limited evidence, high agreement*); increasing fire activity (*medium evidence, medium agreement*); as well as longer and more persistent heat waves (*limited evidence, medium agreement*).

In conjunction with evapotranspiration, soil moisture has been identified as one of the most important determinants of rain-fed agricultural production. Climate impacts on rain-fed agricultural production can be traced to soil moisture deficit rather than to high temperatures alone (4.3.1) (Alemaw and Simalenga, 2015; Bradford et al., 2017; Rossato et al., 2017). Such impacts are especially relevant to vulnerable subsistence farming communities, whose livelihoods depend on rain-fed production (4.3.1) (Savo et al., 2016; Castells-Quintana et al., 2018).

Increasing aridity due to climate change has also been linked to increased fire activity: in the United States, an additional 4.2 million hectares of forests burned over the period 1979–2015, which can be attributed to climate change. This is almost double the area that would have been expected in the absence of climate change (Abatzoglou and Williams, 2016). A contribution of climate change to increases in fire risks are also reported for the Mediterranean region (Turco et al., 2017).

Drier soil moisture conditions have also been associated with longer and more persistent heatwaves (Perkins et al., 2015), with strongest effects in central Europe, where feedback effects have contributed to the major heatwaves of 2003 and 2010 (Miralles et al., 2014). Long-term ability of soils to store carbon may be compromised with decreasing soil moisture levels, thus reducing terrestrial carbon sinks and potentially accelerating climate change (Green et al., 2019).

4.2.2 Cryosphere (Snow, Glaciers, and Permafrost)

4.2.2.1 Observed Changes in Cryosphere

Overall decrease of snow-dominated duration and extent has been observed during the end of 20th beginning of 21st century (*robust evidence, medium agreement*). Glacier melt rate accelerated by 1.5–2 times in the early 21st century compared 1950–2000 worldwide (*medium evidence, high agreement*). Globally, permafrost temperature increased in the early 21st century with the highest observed value in northwestern and northeastern Siberia (*medium evidence, medium agreement*).

AR5 reported shorter snowfall seasons over most of the Northern Hemisphere, with snowmelt seasons starting earlier, decreases in the extent of permafrost and increases in its average temperature as well as glacier mass loss in the most parts of the world (Jiménez Cisneros et al., 2014). SROCC (Hock et al., 2019) stated there is *a very high or high confidence* about (1) reduction in seasonal snow cover; (2) retreating and losing mass of the most of glaciers in all high mountain regions, increase in number of and area of glacier lakes; (3) warming and thawing of permafrost; (4) more and wetter snow avalanches.

Statistically significant negative trends in snow cover extend persist from late March (-5% during 1971–2014) to mid-June (-50% during 1971–2014) for the Northern Hemisphere, November and December exhibit statistically significant positive trends (5–10% during 1971–2014) (Hernández-Henríquez et al., 2015). Negative trends in snow-dominated duration of -2–6.5 weeks decade^{-1} dominate during 1971–2014 over the area with snow season of 28–44 weeks in Northern Hemisphere (about 23.3% of the total area with stable snow cover), the magnitudes of trends strengthen with increasing elevation and at lower latitudes (Allchin and Déry, 2018). Snow-dominated area of Northern Hemisphere has been decreasing during 1971–2014 with a rate of -0.2– -0.35 $\cdot 10^6$ km^2 decade^{-1} in March–April and August–September, -0.5 $\cdot 10^6$ km^2 decade^{-1} in July and -0.85– -1.0 $\cdot 10^6$ km^2 decade^{-1} in May–June. Summed positive trends outweigh losses from October to February with a peak gain of 0.415 $\cdot 10^6$ km^2 decade^{-1} in December, but their total magnitudes and spatial extent are considerably smaller than the summer losses (Allchin and Déry, 2018).

World glaciers has lost in average -0.48±0.2 m (mean value with 95% confidence interval) of mass in water equivalent (w.e) per year during 2006–2016 compared to 0.20 – -0.47 m w.e. y^{-1} mean decadal values in 1950–2000 (Zemp et al., 2015; Zemp et al., 2019). Despite the increase in glacier melt rate the decreased gaciered area already can't support rise in glacier runoff in in several regions around the globe (northern Peru, British Columbia, the Central Andes of Chile, Swiss Alps) (Stahl and Moore, 2006; Casassa et al., 2009; Baraer et al., 2012; Bard et al., 2015; Huss and Fischer, 2016).

Permafrost temperature near the depth of zero annual amplitude increased globally by 0.29 ± 0.12 °C during 2007–2016: by 0.39 ± 0.15 °C in the continuous (90–100% of area is permafrost) and by 0.20 ± 0.10° in the discontinuous (50–90% of area is permafrost) permafrost (Biskaborn et al., 2019). Warming of permafrost, covering 15 million km^2 or one quarter of the Northern Hemisphere (Gruber, 2012), accelerates the microbial breakdown of organic carbon and the release of the GHG, CO_2 and methane (Schuur et al., 2015).

Knowledge on occurring changes in cryosphere is limited by the scarcity of observations, especially in all high-elevation and high-latitude areas. Unlike glaciers and snow, the lack of in-situ observations on permafrost and river runoff still cannot be compensated by the remote sensing (Van Dijk et al., 2016; Walvoord and Kurylyk, 2016; Huang et al., 2018).

4.2.2.2 Projected Changes in Cryosphere

In most basins fed by glaciers, runoff is projected to increase during the 21st century with an approximately 15 years earlier 'peak water' for RCP8.5 compared with RCP2.6 (*medium evidence, medium agreement)*. Future projections suggest further decrease in snow amount and duration of snow accumulation period in mid-to-high latitudes and high mountains (*robust evidence, high agreement*) though the inter-model spread is considerable. Permafrost will continue to thaw throughout the 21st century (*robust evidence, high agreement*).

AR5 (Jiménez Cisneros et al., 2014) noted that that global glacier mass loss is *very likely* to further increase, estimated at the level from 20–30% under RCP2.6 to 40–70% under RCP8.5 by 2100. According to SROCC (Hock et al., 2019), it is *very likely* that glaciers in all mountain regions will continue to lose mass throughout the 21st century: from 29 ± 7% for RCP2.6 to 47 ± 10% for RCP8.5. With *high confidence* permafrost is expected to undergo increasing thaw and degradation in the 21st century but quantitative projections are scarce. According to SROCC Snow avalanche is projected to decrease at lower elevation and both increase and decrease at higher elevation as a result of balance between less snow and wetter snow (*medium evidence*).

Global glacier volume loss between 2010 and 2100 was estimated at the level of 25±6% under RCP2.6 scenarios, 33±8% under RCP4.5 (Huss and Hock, 2018), and from 48±9% to 64±5 % under RCP8.5 (Huss and Hock, 2015; Shannon et al., 2019). Some of the regional estimates are given in Table 4.2.

Table 4.2: Percentage glacier volume loss (multi-model mean ± standard deviation) by the end of the 21st century.

AR6 Region	Glacier Region	Representative concentration pathways (RCP) scenarios			Reference
		RCP2.6	RCP4.5	RCP8.5	
North America	Alaska	32±11%	42±12%	58±14%	Huss and Hock (2015)
		-	-	89±2%	(Shannon et al., 2019)
	Western Canada	76±8%	86±8%	95±5%	(Huss and Hock, 2015)
		-	-	100±0%	(Shannon et al., 2019)
	Arctic Canada North	14±5%	18±7%	30±12%	(Huss and Hock, 2015)
		-	-	47±3%	(Shannon et al., 2019)
Asia	Russian Arctic	38±16%	51±20%	70±19%	(Huss and Hock, 2015)
		-	-	79±10%	(Shannon et al., 2019)
	Caucasus and Middle East	70±11%	84±8%	96±3%	(Huss and Hock, 2015)
		-	-	100±0%	(Shannon et al., 2019)
	High Mountains of Asia	36±8%	49±7%	64±5%	(Kraaijenbrink et al., 2017)
	Central Asia	54±13%	72±11%	88±7%	(Huss and Hock, 2015)
		-	-	99±0%	(Shannon et al., 2019)
Central and South America	Southern Andes	10±8%	21±11%	44±14%	(Huss and Hock, 2015)
		-	-	98±1%	(Shannon et al., 2019)
	Low latitudes*	79±9%	92±3%	98±0%	(Huss and Hock, 2015)
Africa		-	-	100±0%	(Shannon et al., 2019)
Europe	Central Europe	77±12%	89±8%	98±2%	(Huss and Hock, 2015)
		-	-	99±0%	(Shannon et al., 2019)
		63±11%	79±9%	94±4%	Zekollari et al (2018)
Australia	New Zealand	36±14%	58±10%	82±8%	(Huss and Hock, 2015)
		-	-	88±5%	(Shannon et al., 2019)

Notes:
*The Glacial region "Low latitudes" according to Randolph Glacier Inventory unites low latitudes of Africa and Americas (RGI-Consortium, 2017).

The expected hydrological consequence of deglaciation is a rise in glacier runoff until the maximum ('peak water') is reached, beyond which runoff decreases, because the reduced glacier area cannot support rising meltwater volumes anymore. In the majority of high-altitude areas "peak water" has already reached or is expected to be reached within the 1–2 next decades (Huss and Hock, 2018). The worldwide increase in glacier runoff until peak water relative to 1980–2000 can be substantial, and exceed 50% in some basins, with an average estimation of 20–30% (Lutz et al., 2014; Duethmann et al., 2016; Huss and Hock, 2018). Average modelled runoff increase is 26% for RCP2.6, 28% for RCP4.5 and 36% for RCP8.5 in the study by (Huss and Hock, 2018). The influence of the expected subsequent decrease in glacier runoff by the end of the 21st century will be more pronounced during droughts and dry season of the year (Farinotti et al., 2016; Huss and Fischer, 2016). Even the river basins with less than 2% ice coverage might experience runoff decreases greater than 10% due to glacier mass loss in at least one month of the melt season even under RCP2.6 scenarios, while under RCP4.5 and RCP 8.5 the projected decrease is mostly bigger by 1–6% and 1–10% (Huss and Hock, 2018).

Projections suggest further decrease in snow water equivalent (SWE) and snow cover extend (SCE) though the inter-model spread is considerable (Lute et al., 2015; Thackeray et al., 2016; Henderson et al., 2018) (Kong and Wang, 2017) (*medium evidence, medium* agreement). The average SWE in winter and spring over the Northern Hemisphere is projected be reduced by14.9% and 13.8%, respectively, relative to 1986-2005 when the global average surface temperature rises by 1.5 °C (in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively) (Kong and Wang, 2017). Spring SCE is projected to decrease by −3.7% ± 1.1% per decade over the 21st century under RCP 8.5 scenario compared to 1981−2010 (Thackeray et al., 2016).

Only 0–20.6% of contemporary permafrost area is expected to be left by 2100 under the RCP8.5 scenarios (Chadburn et al., 2017). At the level of 1.5 °C temperature rise permafrost area is projected to be reduced by 21.12%, 24.1% and 25.55% relative to 1986–2005 under RCP2.6, RCP4.5 and RCP8.5 scenarios according to (Kong and Wang, 2017), and by 27% relative to 1960–1990 under RCP8.5 scenarios according to (Chadburn et al., 2017). The southern boundary of the permafrost is projected the move to the North: 1–3.5° northward (relative to 1986–2005), particularly in the southern Central Siberian Plateau at the level of 1.5 °C temperature rise in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively (Kong and Wang, 2017), and by 2100 under the RCP8.5 to the north of 65°N in Canada and to the western part of the east Siberian Mountains (Guo and Wang, 2016). At the level of 2 °C temperature rise permafrost area is projected to be reduced by 60% relative to 1960–1990 under RCP8.5 scenarios (Chadburn et al., 2017).

4.2.2.3 Societal Impacts and Risks of Cryosphere Change

Accelerated melting and thawing of cryospheric components due to climate change impacts populations, including Indigenous people who depend on ice, snow and permafrost, either directly, or indirectly, for water, food, energy and other services such as aesthetic, cultural and spiritual services (*high agreement, medium evidence*).

SROCC highlighted the dependence of human populations living in the immediate vicinity of mountain and polar cryosphere on goods and services provided by the cryosphere, and the way they are being impacted by climate induced cryosphere changes (Hock et al., 2019; Meredith et al., 2019).

The cryosphere provides a number of goods and services – such as provisioning services e.g. irrigation, hydropower, urban and rural water supply, support for pastoral livelihoods; societal and cultural services like tourism; aesthetic values; and habitat services e.g. biodiversity, as well as disservices such as cryospheric disasters (Mukherji et al., 2019a). There is *high confidence* that the reduction of glaciers in the Upper Indus basin have negatively impacted glacier supported irrigation systems (Nüsser and Schmidt, 2016). Accelerated cryosphere melting induced changes in irrigation practices have been also reported in the Central Andes (Baraer et al., 2017), the Hindu Kush Himalayas (Hill Clarvis et al., 2014; Nüsser and Schmidt, 2016; Mukherji et al., 2019a), and Central Asia (Xenarios et al., 2018). Apart from impacts on irrigation systems in the immediate vicinity of glaciers, glacial melt water is also an important contributor to irrigation in the downstream regions of Indus and Ganges basins (Biemans et al., 2019). Numerous major cities in South America which are dependent on glacier melt for urban water (Chevallier et al., 2011; Soruco et al., 2017) have experienced high variability in domestic water supply. Cryosphere-supported tourism such as ski resorts in the Alps; and glacier tourism in Tibet have experienced shocks due to lower snow accumulation (Fischer et al., 2015; Mukherji et al., 2019b). Cryosphere related disasters like glacial lake outburst floods (GLOFs) have strong and negative societal impacts and studies have emphasized the need for use of local knowledge for devising appropriate risk reduction strategies (Ikeda et al., 2016).

Similarly, communities in the Polar regions, including the Indigenous people as well as the ecosystems on which they depend for their livelihoods and spiritual sustenance are at risk due to rapid cryospheric changes in the Polar regions (CAFF, 2013; Meredith et al., 2019). The northern regions are home to Indigenous and local people with traditional livelihoods including ice fishing and nomadic herding. For these people, the loss of permafrost and sudden, extreme cryosphere events have had livelihoods, health and spiritual-psychological impacts (Davydov and Mikhailova, 2011; Mustonen, 2015; Pecl et al., 2017). Loss of sea and lake ice has made ice fishing riskier (Mustonen, 2014) and there is a disruption in traditional harvest patterns due to near extinction of several cold-dependant species. Permafrost melt in Yamal in Central Siberia for instance led to the release of anthrax from historical campsites of the Nenets people killing a small boy and thousands of reindeer.

4.2.3 Runoff and Streamflow

4.2.3.1 Observed Changes in Runoff and Streamflow

Climate change and anthropogenic activities play an important role in observed alterations in runoff and streamflow around the world (*high confidence*). Yet, the magnitude of these drivers is region specific *(robust evidence, high agreement)*.

According to AR5 (Jiménez Cisneros et al., 2014), historical trends in annual streamflow have generally followed observed changes in regional precipitation and temperature in recent decades. More recent studies assessed by SR1.5 (Hoegh-Guldberg et al., 2018b) also concluded that the presence of a statistically significant climate-driven trend in the observed annual runoff series remains uncertain for most parts of the world.

There are no clear trends of change in mean runoff and streamflow on a global scale based on both observational and reconstructed datasets during recent decades (*medium confidence from medium evidence and high agreement)* (Alkama et al., 2013; Asadieh et al., 2016; Dai, 2016b). No significant trends were determined in the streamflow of 161 rivers over the period 1958–1992; and an extension to 2004 throughout the same catchments using reconstructed streamflow did not offer different results (Alkama et al., 2013). In a global analysis of observation-based streamflow (1979–2001), significant decreases were found in about one-half of the land areas, while increases in the other half (Asadieh et al., 2016). Longer term (1948–2012) observed streamflow time series showed statistically significant trends in only 55 (26 negative and 29 positive) of 200 large rivers across the globe (Dai, 2016b).

The spatial differences in annual mean runoff/streamflow trends around the world are influenced by climatic factors (particularly land precipitation and potential evaporation, prior to human interventions) (Zang and Liu, 2013; Greve et al., 2014; Hannaford, 2015; Ficklin et al., 2018). In general, runoff is always more sensitive to changes in precipitation than changes in potential evaporation. About 83% of the global land grid cells runoff showed high sensitivity to precipitation trends, while the remaining 17% (Berghuijs et al., 2017b) is controlled by other factors such as CO_2-vegetation interactions and human interventions (Zhou et al., 2015; Gudmundsson et al., 2016; Gudmundsson et al., 2017a). In arid and semi-arid environments, runoff sensitivity to precipitation changes is high, but sensitivity to other factors (e.g. changing climate variability and land use/land cover modifications) is even higher (Berghuijs et al., 2017b). Dryland environments cover approximately 33% of the global land surface; e.g., Sahara and surrounding areas, Southern Africa, Western and Central Australia, Middle East, some parts of the western US, Great Indian Desert, and Turkestan Desert. Yet, even within a river basin, the trends of change may differ, e.g. (Zang and Liu, 2013) showed that, largely due to climate change, runoff and streamflow increased significantly in upstream and mid-stream catchment areas, while they did not change considerably in downstream areas during 1960–2010 for the Heihe river basin, the second largest inland river in China. In cold climate regions, however, global warming has already affected snowpack accumulation and melt processes, which generally control quantity and timing of annual peak streamflow. In such environments, most studies reported increased wintertime streamflow due mainly due to more rainfall instead of snowfall during the season; decreasing snowmelt runoff because of less snow accumulation on the ground; earlier peak snowmelt runoff in response to spring temperature warming; and lower water level during early summer in rivers influenced by snowfall and snowmelt (e.g. (Irannezhad et al., 2015; Irannezhad et al., 2016; Brahney et al., 2017; Rets et al., 2018) (Section 4.2.7.2.1).

For river basins affected by anthropogenic activity (water withdrawal, land use/cover change, operation of dams and reservoirs, etc.), the role of climatic factors in observed runoff changes should be interpreted with caution (*high agreement, robust evidence*). The annual runoff changes in the western Songhuajiang River basin, the upper mainstream of the Yangtze River, and the western Pearl River basin are stimulated by recent climate changes, whereas on the rivers of northern China (Songhuajiang River, Liaohe River, Haihe River) and in middle-eastern China (Huaihe River and lower mainstream of the Yangtze River) they are mostly the result of anthropogenic factors (Liu and Du, 2017). The contribution of land-use factors to the runoff of north-western China had grown from 44% in 1980–1990s to 71% in the 2000s (Yin et al., 2017). Human activities were responsible for more than 90% of the change in runoff in each separate sub-basin of the Yellow River between 1960 and 2012 (Kong et al., 2016). For most rivers in Indiana, New York, Arizona and Georgia in the USA, the anthropogenic factors of runoff change have proved to be more significant than the climatic ones (Ahn and Merwade, 2014). Otherwise, there is a *high confidence* that in changes in the average and maximum runoff of predominantly snow-fed rivers, the climatic drivers prevail (Yang et al., 2015a; Bring et al., 2016; Tananaev et al., 2016; Frolova et al., 2017; Ficklin et al., 2018; Magritsky et al., 2018; Rets et al., 2018) (Section 4.2.7). Conclusions on the relative contribution of climatic and anthropogenic factors largely depend on the applied separation methodology that is important for taking decisions in water resources management (Dey and Mishra, 2017).

Trends in historical annual runoff and streamflow on different scales, from local to global, may differ substantially due to differences in observational data, study period, methodology applied, and most importantly human interventions (Dey and Mishra, 2017; Liu and Du, 2017; Zaherpour et al., 2018). Although there are different observational and simulated runoff and streamflow datasets (e.g. Global Runoff Data Center, GRDC), it is still very difficult to obtain and update long-term river discharge records in several regions, particularly Africa as well as South and East Asia (Dai, 2016b). When observed data are scarce, hydrological models are used to detect trends in runoff and streamflow. The models that simulate runoff and streamflow differ in a few ways: the input data; the number of models used; the number of rivers included; the size of catchments; the spatial resolution; the evaluation indices; the model performance and the study period (e.g. (Zhou et al., 2012; van Dijk et al., 2013; Hattermann et al., 2017)). However, the impacts of human activities (e.g. urbanization) on runoff and streamflow have not been taken into account by most of these models. Accordingly, Zaherpour et al. (2018) evaluated the performance of six global-scale hydrological models in simulating mean runoff in 40 catchments across eight different catchments considering human impacts. They concluded that the majority of models' overestimates mean annual runoff and all indicators of upper and lower extreme runoff. To improve our understanding of changes in runoff and streamflow, hence, it seems necessary to: continue and improve streamflow measurements, particularly over the areas with poor coverage; share available records and simulated time series for improving our databases; and develop models with the least uncertainty and evaluate their performance against measurements in advance.

4.2.3.2 Projected Changes in Runoff and Streamflow

Future changes in annual runoff and/or streamflow will follow projected precipitation patterns around the world (*medium confidence*). Under RCP8.5, the largest increase in high and mean flow is projected at northern high latitudes (*high confidence* from *medium evidence and high agreement*), while the highest declines in low flow is projected across South America, Europe, and the Middle East (*very low confidence* from *limited evidence and low agreement).*

AR5 assessment of the projected changes in annual runoff at the global scale was mostly based on CMIP3 simulations and exhibited medium agreement in increase of the mean annual runoff in high latitudes and the wet tropics together with decrease in dry tropical regions (Jiménez Cisneros et al., 2014). However, there is uncertainty in the magnitude and sign of runoff changes in other parts of the world, particularly South Asia, where future changes in monsoon precipitation are highly uncertain. Similarly, the seasonal distribution of streamflow changes is dependent upon the seasonal distribution of precipitation changes, which fluctuates among different scenarios. Such future seasonal changes are generally consistent in areas currently influenced by snowfall and snowmelt in which peak annual rivers discharge will decrease and shift earlier during the year in response to global warming. The main findings of the AR5 were generally confirmed and detailed in the SR1.5 (Hoegh-Guldberg et al., 2018b) on the ground of the CMIP5-based runoff projections for global warming levels of 1.5°C and 2°C.

Present-day assessments of annual runoff/streamflow changes caused by the projected climate changes in the 21st century are derived either directly as runoff output from global climate models, participating in CMIP5 (GCMs-CMIP5) (Koirala et al., 2014; Ficklin et al., 2015; Dai, 2016b), or from global hydrological models (GHMs) and land-surface models (LSM) (Leng et al., 2016; Gosling et al., 2017; Mahat et al., 2017; Zhai et al., 2018; Zheng et al., 2018b) or from basin-scale (regional) hydrological models (RHMs) (Gelfan et al., 2017; Krysanova et al., 2017; Su et al., 2017a; Teklesadik et al., 2017; Wang et al., 2017e; Kundzewicz et al., 2018a; Islam et al., 2019). The GCMs-CMIP5 projections show a wide range of possible outcomes including both increases and decreases in runoff in most major basins, in many cases with a majority consensus on one or the other but in other cases with a roughly equal split. In agreement with both the AR5 and the SR1.5 conclusions, GCMs-CMIP5 projections are broadly consistent with the projection for precipitation increase in high latitudes of the Northern Hemisphere and precipitation decrease in sub-tropics and some mid-latitude regions; consequently, the projected runoff reflects the precipitation trends (Döll et al., 2014; Kundzewicz et al., 2018a) (*medium evidence, medium agreement*). These runoff changes confirm the findings of AR5 (Jiménez Cisneros et al., 2014) and are the result of corresponding changes in precipitation by 10–25% in these regions (Zhao and Dai, 2015). Projections are more robust for increase in runoff/streamflow in the northern high latitude of North America and Eurasia and decrease in Europe and southwestern United States (*medium evidence, high agreement*).

Under the “stronger” RCP8.5 scenarios, direction of change remains the same, while magnitude is roughly doubled. On half of the land area, the projected mean flow will primarily follow the same trends as high flow (Koirala et al., 2014). Different subsets of CMIP5 models were used for RCP4.5 and RCP8.5, leading to some differences in the sign of projected changes due to different responses of individual models.

The basin-scale RHMs give more concerted runoff projections than GHMs (Gosling et al., 2017; Hattermann et al., 2017; Krysanova et al., 2017; Kundzewicz et al., 2018a) (*high evidence, high agreement*). According to the RHMs-based projections, warming under RCP8.5 can lead by the end of the 21st century to robust positive trends in mean, high and low flows for the Lena (*high evidence, high agreement*) and mean and low flows for the MacKenzie (Gelfan et al., 2017; Pechlivanidis et al., 2017) (*limited evidence, high agreement*) and a robust negative trend in mean, high and low flows for the Tagus in relation to the reference period 1975–2004 (all trends are projected with a high certainty (Vetter et al., 2016; Krysanova et al., 2017). A robust positive trend (by 70 % by the 2080s) is projected under the RCP8.5 scenario for cold season runoff in the Fraser River Basin of British Columbia (Islam et al., 2019). With a moderate certainty, positive trends are projected for mean flow in the Ganges, for high flow in the Ganges, Rhine and Mississippi, for low flow in the MacKenzie, while negative trends for mean flow and low flows in the Rhine (Vetter et al., 2016; Krysanova et al., 2017; Pechlivanidis et al., 2017) (*medium evidence, medium agreement*). These RHM studies were forced by a subset of climate projections, namely the 5 GCMs, which were selected in the Inter-Sectoral Impact Models Intercomparison Project (ISI-MIP; e.g. (Gosling et al., 2017)). In contrast, basin-scale analysis of runoff projections derived directly from the full set of GCMs in CMIP5 show large uncertainties in projected changes, with differences in the sign of the projected change for nearly all major basins (Figure 4.6)

Utilizing multiple catchment-and global-scale models, Gosling et al. (2017) demonstrated the effects of different amount of global-mean warming (1, 2 and 3°C) on runoff in the eight large (>50,000 km^2) river catchments including the upper Amazon, Darling, Ganges, Lena, upper Mississippi, upper Niger, Rhine and Tagus. Their results determined significant changes in future runoff for the Rhine (decrease), Tagus (decrease) and Lena (increase) with global warming. However, no clear effects of such increases in global mean temperature on runoff were detected for other rivers studied. For the Tagus, Lena and Rhine Rivers, rigorous global climate change mitigation actions based on Article 2 of the Paris Agreement (Falkner, 2016) could provide significant benefits in terms of preventing some hydrological hazards due to the high magnitude of global warming.

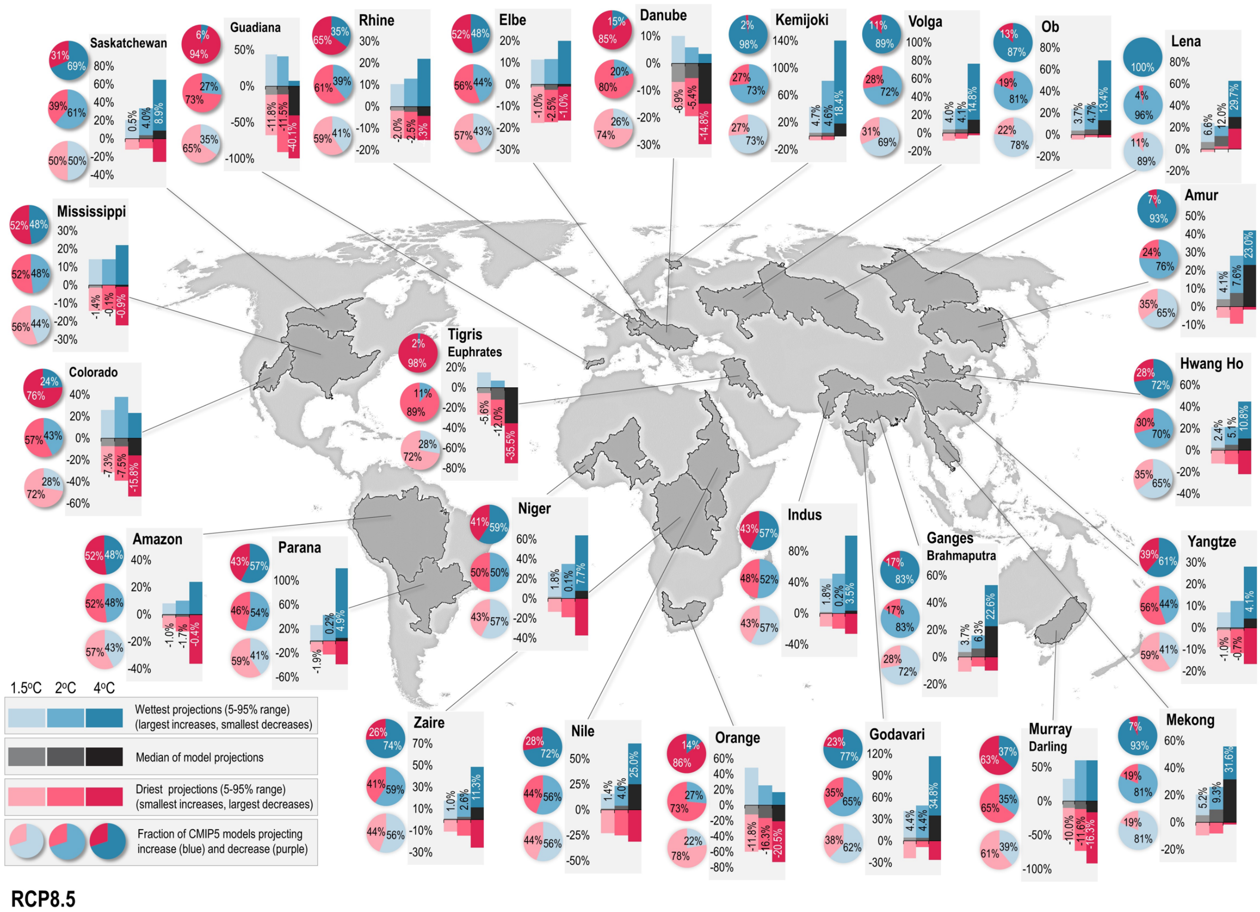


Figure 4.6: Projected changes in annual mean runoff in selected river basins at global warming of 1.5°C, 2°C and 4°C simulated by the CMIP5 multi-model ensemble of GCMs with RCP8.5. The projected runoff changes are directly from the GCM land surface schemes without bias-correction. The figure shows only results from the 54 models which reached 4°C global warming by 2100, of a total of 66 CMIP5 models used with RCP8.5. Similar results are seen when using all models and all RCPs.

4.2.3.3 Societal Impacts and Risks of Changes in Runoff and Streamflow

Socioeconomic sectors such as agriculture, industrial, food production, energy, health and urban systems will be impacted by climate change induced changes in runoff regardless of their direction. Particularly vulnerable are regions dependent on glacier runoff (*high agreement*) as well as poorer communities already experiencing vulnerability *(robust evidence, high agreement)*.

AR5 showed that the societal impacts of runoff spread throughout several socioeconomic sectors such as agriculture (4.3.1), health (4.3.3), energy production (4.3.2) and thereby affecting overall water security. AR5 estimated 8%, 14% and 17% of the global population facing water shortages and water quality issues under 1°C, 2°C and 3°C increases in temperature respectively (Jiménez Cisneros et al., 2014). Particularly vulnerable are the communities dependent on glacier runoff such as the high latitudes, the Alps, the Andes and the Himalayas (Jiménez Cisneros et al., 2014) (4.2.2.3). Runoff changes will have major impacts on the agricultural sector increasing irrigation demands and constraining irrigation especially in southern Europe, the North American Midwest, and Central Mexico (Jiménez Cisneros et al., 2014; Klein et al., 2014a).

Future changes in runoff as a consequence of 2°C increase in temperature under the RCP8.5 scenario can result in 15% of global population with severe decrease in water resources availability and 40% increase in number of people in absolute water scarcity (<500 m^3 per capita per year) (*high agreement and medium evidence*) (Schewe et al., 2014; Gosling and Arnell, 2016; McMillan et al., 2016). Particularly vulnerable are systems that depend on glacier generated runoff (*high agreement and robust evidence)* (Carey et al., 2014; Carey et al., 2017; Mukherji et al., 2019b) (4.2.2.3). Urban systems will face unprecedented challenges when managing storm water from increased runoff due to impervious surfaces (*high agreement and robust evidence)* (Vanuytrecht et al., 2014; Zahmatkesh et al., 2015; Bai et al., 2018). Rural communities will experience challenges adapting their water dependent livelihoods such as agriculture, commerce, fisheries and tourism (*medium agreement and medium evidence*) (Sherpa, 2014; Konchar et al., 2015a; Carey et al., 2017). These livelihoods could also be under pressures due to decreasing water quality and increasing sediment transport (*high agreement from medium evidence*) (Burge et al., 2014; Zabaleta et al., 2014; Riedel et al., 2017). Different hydropower generation plants can experience different effects as sites with storage-hydropower will be more resilient than run-of river plants (*high agreement from medium evidence*) (Beniston and Stoffel, 2014). Particularly vulnerable will be areas without access to other energy sources, countries diversifying for economic productivity or pursuing sustainability (*medium agreement from medium evidence*) (Bliss et al., 2014). Agriculture dependent on surface water will experience water stress (*high agreement from robust evidence*) (Schewe et al., 2014; Jurt et al., 2015; López-i-Gelats et al., 2015), and experience competition for irrigation water (*high agreement* from *medium evidence*) (Skarbø and VanderMolen, 2014).

Regions across the globe will experience both increase and decrease in runoff making local assessments essential for local decision making and policy development (*high agreement, robust evidence*) (Gosling and Arnell, 2016) (see Table 4.4).

A great shortcoming of current studies is the lack of involvement of social sciences in global change research (Carey et al., 2014; Salzmann et al., 2014; McMillan et al., 2016; Carey et al., 2017). However, opportunities for social science's engagement exist and should aid in translating mitigation, adaptation and sustainability strategies (Bliss et al., 2014; Bosch et al., 2014; Barnett et al., 2015), their feedbacks to the water system (McMillan et al., 2016), reduce discrepancy between cultural and scientific depictions (Drenkhan et al., 2015), and surpass the paradigm of stationary systems (Zahmatkesh et al., 2015; McMillan et al., 2016). Also refer to Cross-Chapter Box WATER in Chapter 3.

4.2.4 Groundwater

4.2.4.1 Observed Changes in Groundwater

Since the 1970s groundwater levels have declined in many important aquifers around the world, particularly in semi-arid environments, responding mainly to intensification of groundwater-fed irrigated agriculture (*robust evidence, high agreement*) as well as to the decline in recharge caused by climate change (*medium to low confidence* and *low agreement*). In contrast, extreme annual groundwater recharge is observed to be strongly associated with intense rainfall and flooding events mostly in arid and semi-arid regions (*medium evidence*, *high agreement*). In high altitudes, a warmer climate will change snow melt and recharge.

According to AR5, it has not yet been known to what extent groundwater abstractions are affected by climate change due mainly to lack of observation (Jiménez Cisneros et al., 2014). Occasional reports are available on spring discharge changes, e.g. the decline of the discharge of groundwater-fed spring in Kashmir (India) since 1980 in response to decreases in precipitation, and in four overexploited karst aquifers in Spain during the 20th century because of decreasing trends in precipitation (Jeelani, 2008). But there is a general lack of comprehensive study on how climate change impacts groundwater.

Even though global groundwater extraction is about one-eighth of the annual recharge (i.e., ~12,600 km^3) (Aeschbach-Hertig and Gleeson, 2012), groundwater is over-extracted in some areas of the world (Table 4.4). This has resulted severe depletion/lowering of groundwater tables, affecting all groundwater-dependent sectors.

Where recharge is predominantly influenced by precipitation, linear associations between precipitation and recharge are observed (Kotchoni et al., 2019). Precipitation-recharge relationships in humid locations over sub-Saharan Africa are found to be nearly linear reflecting the impact of local geology and soils (Cuthbert et al., 2019b). As the aridity increases from humid to semi-arid conditions, diffuse or focused recharge dominates with increasing precipitation thresholds needed to initiate groundwater recharge. Recharge becomes more episodic in semi-arid to hyper-arid locations where focused recharge dominates and infiltrations takes place via losses from ephemeral river channels, overland flows and flooding events

(Cuthbert et al., 2019b). The response of groundwater recharge to intensive rainfall suggests that groundwater may prove to be a climate-resilient source of freshwater in the dry regions (Cuthbert et al., 2019b). This emerging evidence contradicts the 'robust evidence' and 'high agreement' AR5's projection that climate change would reduce renewable surface water and groundwater resources significantly in driest subtropical regions (*robust evidence, high agreement*) (Jiménez Cisneros et al., 2014). A global-scale analysis (Shamsudduha and Taylor, 2019) from GRACE satellite measurements (2002–2016) for the 37 world's large aquifer systems reveals that trends in groundwater storage are predominantly nonlinear. In cold climate regions, however, where snowmelt dominates the hydrological process, groundwater recharge has decreased and shifted to earlier part of the year (Irannezhad et al., 2015; Irannezhad et al., 2016).

Groundwater depletion is thought to have contributed to global sea-level rise through a net transfer of freshwater from long-term groundwater storage to active circulation near the earth's surface and its eventual transfer to oceans (Taylor et al., 2012b). Groundwater depletion during the twentieth century has contributed to global sea-level rise at a rate of 0.57 (±0.09) mm $year^{-1}$ (Wada et al., 2016).

It is likely that climate change impacts on Groundwater Dependent Ecosystems (GDEs) will be influenced by changes in groundwater levels and that they would vary depending on location and land use changes (Kløve et al., 2014). Small, shallow unconfined aquifers are more sensitive to climate change than larger and confined systems (Winter et al., 2017; Havril et al., 2018). Confined and deeper aquifers are more likely to be less sensitive to the direct effects of climate variability and change (e.g. Isokangas et al. (2015)). Similarly, (Cuthbert et al., 2019a) conclude that GDEs in arid regions are more resilient to climate change compared to humid regions (see Table 4.4).

New evidence from ground-based long-term records in the Indo-Gangetic Basin reveal that sustainable groundwater supplies are constrained more by extensive contamination than depletion (MacDonald et al., 2016). Climate change, particularly rising sea levels is one of the driving forces behind salinization of shallow groundwater in the Bengal Delta (Shamsudduha and Taylor, 2019) and other Asian mega-deltas (Hoque et al., 2016). Groundwater recharge from heavy rainfall events can lead to microbial contamination of shallow groundwater and outbreaks of diarrheal diseases (Taylor et al., 2012a).

4.2.4.2 Projected Changes in Groundwater

In many regions of the globe, groundwater levels in aquifers will mainly be influenced by future irrigation and land use. However, in the tropics and semi-arid regions, with expected increase in rainfall intensity, groundwater is likely to provide future resilience through improved recharge (*low to medium evidence, medium agreement*). In regions with permafrost and seasonal snow and ice, a warmer climate will increase evapotranspiration resulting in reduced runoff and potentially also changes in recharge (*medium evidence, strong agreement*). Due to the lack of long-term observation data, future projections have *very low confidence* about how climate change will influence groundwater level and groundwater dependent ecosystems (GDEs).

AR5 concluded that the range of future changes in groundwater was large, from statistically significant declines to increases (Jiménez Cisneros et al., 2014). Changes in precipitation intensity can influence the amount of groundwater recharge in different ways. Intense precipitation episodes can reduce groundwater recharge by exceeding the soil infiltration capacity or can increase it because of faster percolation in drier soils throughout the root zone and consequently less evapotranspiration. However, change in low (high) groundwater recharge are highly (poorly) sensitive to precipitation pattern alterations. In snow-dominated environments, reductions in snowfall in response to surface air warming can decrease the groundwater recharge, even if precipitation shows no changes. Furthermore, climate change will impact coastal groundwater through saltwater intrusion induced by sea level rise which will take several centuries to recover.

Changes in groundwater are traditionally observed based on changes in groundwater levels, and for a few cases based on spring discharge or base flow. In recent years, GRACE has provided a unique way to estimate groundwater changes in large aquifers, but the length of the time series is still too short to assess climate change (Rodell et al., 2018; Shamsudduha and Taylor, 2019). However, predicting spatiotemporal changes in the magnitude, timing and mechanism of recharge is complex for most climate regions. For example, in semi-arid regions, only heavy rainfall events result in groundwater recharge, whereas in humid regions an increase in heavy rainfall events can reduce recharge rates because most water may be lost through runoff (Bates and Hughes, 2009). Over-extraction of groundwater in several watersheds in the world is negatively affecting streamflow globally. It is projected that by 2050, in 42% to 79% of world's watersheds where there is intensive groundwater pumping, environmentally critical streamflows would be affected, which will in turn affect river and groundwater dependant ecosystems (de Graaf et al., 2019).

The projected contribution of global groundwater depletion to sea-level rise is expected to increase to 0.82 (±0.13) mm year^{-1} by 2050 from 0.57 (±0.09) mm year^{-1} in 2000 that is driven by growing water demand during the twentieth century due to decreased surface water availability linked to climate variability (Wada et al., 2016).

Recent global studies of climate change impacts on freshwater resources, particularly groundwater recharge and storage change have been conducted applying a range of modelling tools from simple water-balance, soil-water balance, to hydrological models and in various parts of the world (Portmann et al., 2013; Kirby et al., 2016; Meixner et al., 2016; Zaveri et al., 2016; Hartmann et al., 2017; Mehran et al., 2017; Tillman et al., 2017; Kahsay et al., 2018; Shrestha et al., 2018). These groundwater impact studies applied projections ranging from 5 to 18 models from CMIP5 and showed changes in future groundwater recharge under different RCPs. Poor conceptual models of recharge pathways, difficulty in predicting the response of focused recharge to projected changes in the frequency and intensity of extreme precipitation events, and unconstrained feedbacks among climate, land-use and groundwater systems are highlighted by Meixner et al. (2016) in western USA. Improved conceptual models are also seen as crucial to understand climate change in GDEs (Kløve et al., 2014).

Future climate change predictions show increased temperature and drying trend in precipitation for mid latitudes (Table 4.4). For groundwater systems, drought effects can best be seen after several years of drought, when groundwater levels are lowered. The aquifer response time to changes in hydraulic forcing varies between aquifers and long response time buffer drought impacts but have long drought recovery times (Van Lanen et al., 2013).

Climate change is projected to increase salinity in coastal groundwater in low-lying deltaic environments due to increased inundation of seawater linked to storm-surges from frequent cyclones (Hoque et al., 2016). However, future recharge and sea-level rise have much less influence on the proportion of vulnerable coastal aquifers, globally as hydrogeologic properties and settings are more important factors (Michael et al., 2013), and impacts of over-abstraction on saltwater intrusion (Taylor et al., 2012a).

The relations between climate change and groundwater are more complex that those embedded in current simulation models; hence, the "high certainty" regarding the climate change-induced decline of groundwater in sub-Saharan Africa is further challenged (Cuthbert et al., 2019b).

4.2.4.3 Societal Impacts and Risks of Changes in Groundwater

There are a number of societal benefits of intensive groundwater use, however, over-exploitation significantly attenuates those benefits (*robust evidence, high agreement*). Most of these impacts are attributed to non-climatic drivers as they dominate groundwater extraction dynamics (*robust evidence; high agreement*). Societies already facing surface water variability will have more impacts of groundwater over-exploitation, leaving them without adequate access to water in future (*low to medium evidence; high agreement*).

AR5 concluded that groundwater improves resilience by supplying additional water where surface water becomes uncertain due to climate change (Jiménez Cisneros et al., 2014). However, future resiliency is already compromised at groundwater over-exploited areas such as parts of India (Fishman, 2018), Mekong Delta (Shrestha et al., 2016b), urban pockets of Nepal (Pandey et al., 2010), south western parts of USA (Russo and Lall, 2017), and in many dryland areas (Mirzabaev et al., 2019).

There are a number of societal impacts of groundwater over-exploitation in relation to irrigation, the sector that uses almost 70% of total extracted groundwater (Margat and Gun, 2013). However, the main driver is often non-climatic (Jiménez Cisneros et al., 2014; Ashraf et al., 2017), though there are indirect links to climate change For example, projected doubling of average water use by 2050 in Tunisia is attributed only partly (3.8–16.4%) to climate change and significantly to socio-economic policies (Guermazi et al., 2019); groundwater resources in South Asia in endangered due to future emphasis on food security (Kirby et al., 2016; Ritchie et al., 2018); and decline in groundwater tables in the North China Plain are attributed to extensive use (Leng et al., 2015) even before climate change impact was felt. Furthermore, marginalized poor farmers in pockets of rural areas suffer more immediate impacts from groundwater overexploitation, such as in Mexico (World Bank, 2009). And, for those whose wells dry off face persistent decline in income and wealth, cannot do any adaptations within agriculture, and rely on off-farm incomes to mitigate well drying impact (Blakeslee et al., 2019).

Overall societal impacts of intensive groundwater use have been historically positive where groundwater provides a buffer against rainfall variability and leads to food self-sufficiency and poverty reduction such as in India (Sekhri, 2014), Bangladesh (Salem et al., 2018), and Sub-Saharan Africa (Birhanu and Tabo, 2016). However, if over-exploited, most of those positive benefits are attenuated, equitable access to the resource are threatened (Sarkar, 2011), and societal dis-benefits become apparent in the form of groundwater pollution (Mas-Pla and Menció, 2019), land-subsidence (Erban et al., 2014; Shirzaei and Bürgmann, 2018), deteriorated ecosystem services (WLE, 2015), and inclusiveness (Kookana et al., 2016). Depletion of groundwater also affects some of the traditional water systems like *foggara* in Tunisia (Mokadem et al., 2018), *qanat* in Pakistan (Mustafa and Usman Qazi, 2008); *aflaj* in Oman (Remmington, 2018) and spring boxes in the Himalayas (Kumar and Sen, 2018); which are vested with cultural values, and their loss entails more than just loss of access to water. Furthermore, in many emergencies related to natural disasters, groundwater provides the safest source of drinking water and when it gets contaminated, communities become more vulnerable (Richts and Vrba, 2016).

Further, projected population growth combined with prolonged droughts and decrease in dry-season precipitation will increase the stress of these highly productive aquifers, by increasing groundwater pumping (Famiglietti, 2014), which in turn will affect future cropping patterns. Adapting to the impacts will require multiple strategies including improving agricultural water efficiency (de Coninck et al., 2018b) through shifting towards climate-resilient crops (Mo et al., 2017) and collective management interventions (Massoud et al., 2018); enhancing groundwater storage (Dillon et al., 2019); and groundwater governance (Jakeman et al., 2016). However, interventions such as improving agricultural water efficiency can be counterproductive because it can decrease non-evaporative losses that could have been available in downstream, and affects overall water availability in the basin as seen in USA (Malek and Verburg, 2018) China (Chen et al., 2018), and India (Fishman et al., 2016; Fishman, 2018). However, there is risk that farmers bring in more land under groundwater irrigation, where there is scope for expansion, resulting in either negligible or even negative "water saving" (Fishman et al., 2016).

4.2.5 Water Quality

4.2.5.1 Observed Changes in Water Quality

Climate changes mainly leads to water quality deterioration in polluted areas through extreme events such as droughts and floods and through temperature increases (*medium confidence*). Droughts reduce river dilution capacities and increase the risk of groundwater contamination (*robust evidence, medium agreement*). Serious water pollution often occurs after floods (*robust evidence, medium agreement*). Permafrost degradation has increased flux of major ions, nutrients, and organic matters into local rivers and lakes (*medium confidence)*. Increased glacial meltwater can dilute pollutants but release historically deposited pollutants (*medium confidence*).

AR5 (Jiménez Cisneros et al., 2014) stated that observed changes of water quality due to climate change were known mostly from isolated studies in high-income countries. For lakes and reservoirs, the most frequently reported change was more intense eutrophication and algal blooms at higher temperatures or increased release of contaminant due to increased storm runoff. For rivers, all reported impacts were negative. The linkages between climate and observed effects should be interpreted cautiously and at the local level.

Drought can reduce river dilution capacities, so that river basins with point sources of pollution generally show water quality deterioration (Mosley, 2015; Rice and Westerhoff, 2017; Wen et al., 2017). Reduced groundwater levels caused by droughts introduce more recharge from rivers and lakes or seawater intrusion and can increase the risk of groundwater contamination (Kløve et al., 2014; Romanazzi et al., 2015). Given the wide distribution of meteorological droughts, the impacts on water quality are global, although increasing concentrations of dissolved minerals, organic and inorganic pollutants due to droughts have been investigated mainly in high-income countries in North America, Europe, and Australia (Mosley, 2015). For example, among 14,000 studied US streams receiving wastewater discharge, 1,049 showed at least one endocrine disrupting compound exceeding safety threshold under exceptional low-flow conditions (Rice and Westerhoff, 2017).

Floods can lead to mixing of flood water with waste water and redistribution of pollutants between contaminated and uncontaminated sediments, while soil erosion by floods introduces a large number of nutrients, pathogens, and toxins into water environment with severe impacts in flood-prone regions such as South and Southeast Asia, western and central Europe, as well as parts of Africa, North America, and South America. For example, flood sediments were contaminated above guideline pollution thresholds by a factor of over 80 following a widespread flooding in west Wales (Foulds et al., 2014; Kundzewicz et al., 2014; Lynch et al., 2014; Martínez-Santos et al., 2015; Whitehead et al., 2015; Xia et al., 2015).

Permafrost degradation under global warming with associated deepening of flow pathways and melting of near-surface ground ice modify the water quality of permafrost-dominated river basins (Abbott et al., 2015; Harms et al., 2016). Increasing flux of major ions, nutrients, and organic matters are observed in high-latitude regions such as the Arctic, in which two lakes showed rapid SO_4^{2-} increase up to fivefold since 2008 to 2016 arising from permafrost thaw, while more old carbon loads are observed in high-latitude regions such as the permafrost regions of the Tibetan Plateau which may produce a positive feedback on climate warming (Abbott et al., 2015; Spencer et al., 2015; Harms et al., 2016; Qu et al., 2017; Roberts et al., 2017). The increase in temperature is also leading to increased meltwater from glaciers in mountainous and polar areas (Bliss et al., 2014; Rye et al., 2014; Yang et al., 2014). Glacial meltwater can dilute pollutants and mitigate water quality modifications (Brown et al., 2015). However, through the release of historically deposited pollutants, increased meltwater would detach and transport higher levels of persistent contaminants such as organic pollutants and toxic mercury, and reduce water quality downstream e.g., the proportion of upstream meltwater emissions of some legacy airborne pollutants compared to pollutant discharge at downstream sections in the central part of the Gangetic Plain could be as high as 200% (Hawkings et al., 2014; Sahade et al., 2015; Sharma et al., 2015; Sun et al., 2017; Zhang et al., 2017).

Although the deterioration of water quality due to climatic drivers is happening in different climate systems and land cover types, non-climatic drivers introducing higher pollutant loads or excessive water consumption reducing river dilution capacities and groundwater levels are frequently predominant (Horowitz et al., 2014; Kløve et al., 2014; Stehle and Schulz, 2015; Mekonnen and Hoekstra, 2016; Wang et al., 2017a).

4.2.5.2 Projected Changes in Water Quality

Projected warming and enhanced extreme events will increase water insecurity through water quality degradation (*low confidence from medium evidence with limited agreement*). Non-climatic drivers like land-use changes, agricultural intensification induced fertilizer and pesticide use, industrialization, urbanization etc. that increases pollutant loads and causes higher water extraction will reduce river dilution capacities and are likely to dominate over climate impacts (*robust evidence, medium agreement*).

AR5 specified that climate change was projected to reduce raw water quality and pose risks to drinking water quality with conventional treatment (Jiménez Cisneros et al., 2014).

During the last five years, projections of global water quality have been rather limited. Inorganic nutrients such as total ammonia, total phosphorus, nitrite, and total orthophosphate in big river basins are expected to respond more strongly to temperature and precipitation changes, for example, tending to result in more total phosphorus in summer but less in the other seasons (Jiang et al., 2014). According to recent studies, water scarcity pressure from water quality degradation will increase, due to the future climate change with enhanced extreme events (Arnell and Lloyd-Hughes, 2014; Dyer et al., 2014; Schewe et al., 2014; Mehdi et al., 2015; Whitehead et al., 2015; Liu et al., 2016c; Mekonnen and Hoekstra, 2016; Sjerps et al., 2017; Schyns et al., 2019). The ensemble average projects that a global warming of 2 °C above present will increase the number of people living under absolute water scarcity by 40% (Schewe et al., 2014). In addition, future climate warming will likely disrupt the historical sequestration of contaminants in permafrost in the Arctic, putting risks to nearby aquatic systems or deeper groundwater system (Bond and Carr, 2018). Moreover, as glacial runoff starts decreasing due to reduction of glacier coverage in some high mountain areas, ecosystems will be profoundly influenced, and biodiversity of microbial and algal communities, freshwater fish, and even macroinvertebrates will be affected (Fellman et al., 2014; Jacobsen et al., 2014; Muñoz et al., 2014; Milner et al., 2017). Due to the knowledge gap, local characteristics should be considered to adequately identify the influence from future climatic or non-climatic drivers on regional water quality (Drenkhan et al., 2015; Khan et al., 2017).

4.2.5.3 Societal Impacts and Risks of Changes in Water Quality

Water quality degradation caused by climatic and non-climatic drivers have profound impact on human health *(medium evidence, high agreement)*. *C*hildren, women and disabled people are more vulnerable in Africa and Asia to water quality degradation.

AR5 concluded with medium evidence and high agreement that climate change will affect raw water quality and therefore pose further risks to drinking water quality as well as human health even with traditional water treatment (Jiménez Cisneros et al., 2014).

Water quality degradation severely affects the clean drinking water availability which is a major problem during extreme climate events such as flood, storm, and typhoon in many Asian countries including Bangladesh, China, India, Indonesia, Myanmar, Nepal, Pakistan, and Vietnam making the poor water insecure and socially vulnerable (Otto et al., 2017; Abedin et al., 2018; Huynh and Stringer, 2018; Nichols et al., 2018). Studies suggest that climate change will affect the microbiological quality of water and water-related diseases and impose a severe impact on the human system and society (Levy et al., 2016; Nichols et al., 2018). As the microbiological quality of household water correlates with health outcome, changing climate will make poor more vulnerable (Benova et al., 2014; Wolf et al., 2014; Stelmach and Clasen, 2015) with women and children in developing countries being disproportionately affected (Rufat et al., 2015; Rakib et al., 2017). The limited financial and medical resources coupled with poor communication and public health education in developing countries further limit these societies' capability to combat climate-induced water-related health issues (Rakib et al., 2017).

Lower oxygen levels in freshwater and seawater caused by climate-induced increased thermal stratification degrade water quality and support the growth of disease-causing bacteria, viruses, and parasites (Melillo et al., 2014) (*medium evidence, medium agreement*). Evidence shows heavy rainfall events and warmer temperatures have been linked to diarrheal outbreaks and bacterial contamination of drinking water sources (Gamble et al., 2016; Levy et al., 2016; Otto et al., 2017). In 2015, diarrheal disease was estimated to cause 1.31 million deaths per year (Troeger et al., 2017), where nearly half a million deaths occurred in children under 5 years of age, with the highest burden of disease concentrated in sub-Saharan Africa and South Asia (Liu et al., 2016b). In addition to death, diarrhoea can harm children's growth and cognitive development, and increase exposure to other infectious and chronic illnesses, which aggravates individual and community vulnerability to climate change (Guerrant et al., 2013; Levy et al., 2016). The loss of income due to illness associated with climate change and the failure to pay for the cost of treatment can push a family further into poverty and debt (WHO, 2016; Leal Filho et al., 2018; WHO, 2018). Climate change is projected to cause approximately 250,000 additional deaths per year between 2030 and 2050 (WHO, 2018).

4.2.6 Soil Erosion and Sediment Load

4.2.6.1 Observed Changes in Soil Erosion and Sediment Load

In the areas with high anthropogenic influence, the impacts of land cover changes are much more significant in affecting soil erosion and sediment flux, compared with the influence of climate change (*robust evidence, high agreement*). In somewhat more natural conditions, such as in high latitudes and high mountains, it is possible that influence of climate change on increased sediment load is observed with some delay (*limited evidence and medium agreement*).

AR5 stated that there is limited evidence and low agreement that anthropogenic climate change has made a significant contribution to soil erosion and sediment loads, and in most cases, the impacts of land use and land cover changes are more significant than those of climate change (Jiménez Cisneros et al., 2014). SR1.5 concluded, that by 2200 or 2300, for stabilized conditions of the temperature rise by 1.5°C or 2°C, a minimum of 44% of the Bangladeshi Ganges-Brahmaputra, Indian Bengal, Indian Mahanadi and Ghanese Volta delta land area without defenses, will be exposed to destruction unless sedimentation occurs (Brown et al., 2018).

In natural conditions, climate change mainly influences soil erosion rates indirectly – through vegetation cover changes. Therefore, a response of soil erosion rates to climate change occurs with some delay in case if vegetation cover is modified and fluvial processes adapt to new landscape conditions (Micheletti et al., 2015; Carrivick and Heckmann, 2017; Beel et al., 2018). A meta-analysis of the global datasets of erosion rates concludes that only long-term measurement of water and sediment flow at the agricultural field or small catchment scales provides reasonable data for understanding the influence of climate change on erosion and sedimentation (García-Ruiz et al., 2015), but such long-term measurements are very rare.

Global rainfall erosivity based on high-temporal resolution rainfall records was estimated by Panagos et al. (2017), with the highest values in South America and the Caribbean countries, Central east Africa and South East Asia. The lowest values were assessed for Canada, the Russian Federation, Northern Europe, Northern Africa and the Middle East. In terms of climate zones, the tropics have the highest mean rainfall erosivity whereas cold regions have the lowest.

In the period of 1986–2015, sedimentation rate in dry valley bottoms of the Southern part of Russian plain has become 2–5 times lower than in 1963–1986 due to the reduction of surface runoff during spring snowmelt (Golosov et al., 2018). On the other hand, the positive trend in sediment yield in small ponds in the semi-arid climate of the south-western USA over the last 90 years was not entirely related to corresponding trends in rainfall or runoff, but reflected a complex interaction between long-term changes in vegetation, soil, and channel networks (Polyakov et al., 2017).

Detailed assessment of climate changes and the anthropogenic influence on the sediment load in regions with a high proportion of cultivated lands (Restrepo and Escobar, 2018; Tian et al., 2019) confirmed the AR5 conclusion that the effects of climate change on soil erosion and sediment load are frequently obscured by human agricultural and management activities. The results of long-term (2000–2016) monitoring of soil erosion in three different typical agricultural landscapes in Northern Germany indicated that a declining trend of erosion is mostly associated with the consequence of soil conservation management (Steinhoff-Knopp and Burkhard, 2018).

Climate change contribution to erosion and sediment load is assessed with high regional variability. Statistically significant correlation was revealed between sediment yield and air temperature for the non-Mediterranean region of Western and Central Europe (Vanmaercke et al., 2015) and Northern Africa (Achite and Ouillon, 2016), but it has yet to be found for the rivers of the rest of Europe (Vanmaercke et al., 2014; Vanmaercke et al., 2015). (Potemkina and Potemkin, 2015) demonstrate that regional warming and permafrost degradation have contributed over the last 40–70 years to increasing forested area, which has led to decreasing soil erosion in the Eastern Siberia. An increase in sediment and particulate organic carbon fluxes is already observed in the Arctic regions as a result of permafrost warming (McClelland et al., 2016; Schiefer et al., 2018), but long-term monitoring of riverbank erosion rates involving ice-rich permafrost in Northern Alaska has showed that the local river channel configuration is the main factor causing the riverbank erosion rate and climate changes do not yet affect these processes (Kanevskiy et al., 2016). Also, 15-year records of suspended sediment export in two High Arctic rivers in Canada suggests that greater sediment erosion from permafrost landscape disturbances has not yet increased downstream-suspended sediment export (Beel et al., 2018). The sediment dynamics in small rivers of the alpine zone (eastern Italian Alps) mostly depend on extreme floods with the recurrence period >100 years, according to the results of the long-term (39 years) monitoring (Rainato et al., 2017). In the northeastern Italian Alps, climate fluctuations influenced the reconstructed sediment load without any trend for two centuries (1810–2010) (Diodato et al., 2018).

A long-term global soil erosion monitoring network using a unified methodological approach is needed to correctly evaluate erosion rates and assess the proportional contribution of land-use and climate change to regional trends of soil erosion and sediment load (Evans, 2013; García-Ruiz et al., 2015; Steinhoff-Knopp and Burkhard, 2018).

4.2.6.2 Projected Changes in Soil Erosion and Sediment Load

Soil losses mainly depend on the combined effects of climate and land use changes. There is high uncertainty in soil loss projections due to influence of non-climate drivers (*robust evidence, high agreement*).

SRCCL concluded that future climate change is projected to increase, with *medium confidence*, the potential for water driven soil erosion in many dryland areas, particularly leading to soil organic carbon decline (Mirzabaev et al., 2019).

A majority of studies found different sensitivity of projections of soil losses to combinations of climate and land-cover changes (Francipane et al., 2015; Paroissien et al., 2015; Simonneaux et al., 2015; Bussi et al., 2016). In a cold environment region (Athabaska River basin, Canada), the total sediment load will increase more than two-fold due to greater riverbank and channel erosion, whereas basin sediment flux will be reduced due to increasing vegetation cover (Shrestha and Wang, 2018) (*medium confidence*). An increase in sediment load by 9–11% is projected for the period of 2041–2070 in the wet western Himalayan river basin (Azim et al., 2016). The model-based sediment load may give contradictory results (Plangoen et al., 2013; Cousino et al., 2015), particularly, because of the difficulty of evaluating connectivity between the sediment sources and river channels (Bracken et al., 2015). Increased precipitation is projected to be able to produce enough runoff to connect the system with the sources of sediment (hollows, first order stream, foothill deposits) and may generate large floods that, in turn, may be able to entrain river bed sediments and increase sediment export from local sources (Fryirs, 2013). A possible increase in soil losses, even in regions with a declining trend of total precipitation, is projected owing to the increase frequency of extreme rainfall events in Iran (Azari et al., 2016) and Morocco (Simonneaux et al., 2015).

4.2.6.3 Societal Impacts and Risks of Changes in Soil Erosion and Sediment Loads

Soil erosion and sediment loads have far reaching societal impacts in developing countries compared to developed ones; ranging from human deaths to reduced food production, water contamination, and infrastructure/settlement damages (*robust evidence; medium to high agreement).*

AR5 established potential impacts of climate change on soil erosion and sediment loads in the Global South and glacier melting regions (Jiménez Cisneros et al., 2014), however, related impacts are scarcely known (Li and Fang, 2016; Marziali et al., 2017). Since AR5, evidence of climate and water-induced soil erosion on human health, food production, water pollution, and infrastructure damages are well documented indicating heavy impacts in Africa, Asia, Caribbean, and Latin America (Alfieri et al., 2017; Issaka and Ashraf, 2017; Hewett et al., 2018; Mullan et al., 2019; Sartori et al., 2019) (*medium evidence, high agreement*). SR1.5 projects slight differences in risks posed on sediment loads under 1.5°C and 2°C of warming (Hoegh-Guldberg et al., 2018b). Increasing incidence of extreme weather events (Issaka and Ashraf, 2017) involves transportation of heavy metals, chemicals and soils and leads to eutrophication in water bodies (Bing et al., 2013).

4.2.7 Extreme Weather Events and Water-Related Hazards

4.2.7.1 Heavy Precipitation

4.2.7.1.1 Observed changes in heavy precipitation

Globally, there are more areas with significant increases in the frequency, intensity and /or amount of heavy precipitation than with decreases *(high confidence)*. Observations and simulations with climate models since the mid-20th century show that precipitation extremes intensify in response to a warming climate *(high confidence)*. However, the sensitivity of precipitation extremes to warming remains uncertain.

AR5 (Hartmann, 2013), observed trends displayed more areas with increases in the frequency, intensity and/or amount of heavy precipitation in North America and Europe. There was *medium confidence* in heavy precipitation changes in other continents due to lack of long-term observational data. In addition, for land regions where observational coverage was sufficient for evaluation, there was *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al., 2013). Regarding changes in heavy precipitation associated with global warming of 0.5°C, SR1.5 (Hoegh-Guldberg et al., 2018a) suggested that increases in precipitation extremes can be identified for annual maximum 1-day precipitation and consecutive 5-day precipitation.

Historical experiments from the Community Earth System Model (CESM) (Zhang and Villarini, 2017) reveals increases in the frequency of heavy precipitation from 1975 to 2005. The simulated increase in the frequency of heavy precipitation with the large-ensemble CESM experiments and CMIP5 data is consistent with the observations from (Fischer and Knutti, 2015; Donat et al., 2016). Schleussner et al. (2017) showed, through analyses of recent observed tendencies, that changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991–2010 period compared with those for 1960–1979, with a global warming of approximately 0.5°C occurring between these two periods *(high confidence)*. The observed tendencies over that time frame are thus consistent with attributed changes since the mid-20th century *(high confidence)*. For extreme precipitation, a robust increase was observed for both the annual maximum 1-day precipitation and consecutive 5-day precipitation. A quarter of the land mass has experienced an increase of at least 9% for extreme precipitation. Eekhout et al. (2018) constructed an extreme precipitation map from a global daily precipitation data obtained from the Global Precipitation Climatology Centre (GPCC) (Schamm et al., 2016). The GPCC dataset contains daily global land-surface precipitation data, interpolated on a regular 1 ° grid for the period 1988–2013. The extreme precipitation, defined as the 95th percentile of daily precipitation, considering only rainy days (>1 mm/day, (Jacob et al., 2014)), was found to exceed the soil infiltration capacity. (Alexander, 2016) pointed out that there remain major gaps particularly regarding data quality and availability, the ability to monitor these events consistently and the ability to apply the complex statistical methods.

Impact of the increase in heavy precipitation on related hazards is not yet attributed (*medium confidence*). For example, studies linking rainfall and landslide events show only weak relations between rainfall variations and landslide occurrences in the past (Gariano and Guzzetti, 2016).

4.2.7.1.2 Projected changes in heavy precipitation

The climate-change-related risks from extreme events such as heavy precipitation, are already moderate (*high confidence*) to high with 1°C additional warming (*medium confidence*). Projections for the 21st century show a general increase in the intensity of heavy precipitation (*medium confidence*) except in some regions in the subtropics (*low confidence*). However, there are still major uncertainties due to changes in atmospheric dynamics and regional variability.

AR5 (Hartmann, 2013) indicated that there had been more land areas with observed increases in heavy precipitation than decreases and that by the end of this century increases in heavy precipitation is likely to be observed in mid-to-high latitude land areas and over wet tropical regions in the Northern Hemisphere and SR 1.5 (Hoegh-Guldberg et al., 2018a), assessed that there are more areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation (*high confidence*). Several large regions display stronger increases at 2°C global warming, and there is a global tendency towards increases in heavy precipitation on land at 2°C compared with 1.5°C warming (*high confidence*). Overall, regions that display statistically significant changes in heavy precipitation between 1.5°C and 2°C of global warming are located in high latitudes (Alaska/western Canada, eastern Canada/Greenland/Iceland, northern Europe, northern Asia) and high elevation (e.g., Tibetan Plateau), as well as in eastern Asia (including China and Japan) and in eastern North America *(medium confidence)*. There is *low confidence* in projected changes in heavy precipitation in other regions.

Pfahl et al. (2017) used the annual maximum 1-day precipitation from 22 CMIP5 models to project a multi-model mean spatial pattern of annual maximum 1-day precipitation over the period 1950–2100 through a linear regression of Rx1day against global mean temperature. The extreme precipitation was projected to intensify with global warming in most extratropical regions and in the deep tropics, with maximum intensification rates in the tropical Pacific and the Asian monsoon regions. In contrast, there are subtropical regions with little change or even decreases. For annual maximum 5-day precipitation (Rx5day), the CMIP5 models again project an intensification with warming, and the fraction of land with increased Rx5day becomes larger at higher levels of global warming (Seneviratne et al., in preparation). With 4°C global warming, the CMIP5 ensemble mean projects increased Rx5day of 8% to 24% or higher over nearly all of the global land surface, with parts of Africa, South Asia and the Artic seeing projected changes of over 24%. Seneviratne et al. (in preparation) noted the importance of increased model resolution for the simulation of heavy precipitation: simulations with the HadGEM3 atmosphere model at N216 resolution (60km grid squares in mid-latitudes) suggest increased Rx5day over all continents (Betts et al., 2018a) (Figure 4.10; in section 4.2.7.4). At 4°C global warming, Rx5day over Asia is projected to increase by between 19% and 24% relative to the mean over 1981–2010, and over Europe by 6% to 13%.

Zhang and Villarini (2017) used CESM large ensemble experiments with the scenarios for addressing 1.5 and 2° C (Sanderson et al., 2016; Sanderson et al., 2017) to highlight the changes in the average number of heavy precipitation days. Compared to the historical period, heavy precipitation is projected to increase over the interval 2006–2035, particularly in the tropics, mid-latitudes, and polar regions. The annual frequency of heavy precipitation across the globe was found to increase in both 1.5 and 2°C experiments until around 2070, after which the increasing trend becomes much weaker or even decreasing due to the CO_2 emissions target. Overall, the projection based on the RCP8.5 is much higher than both 1.5 and 2°C experiments for 2006–2100. However, during the last 30 years of the twenty-first century, heavy precipitation is projected to be more frequent under the 2 °C experiment, likely associated with a more frequent El Niño-like state in the tropical Pacific. These projections depend a lot on the regions which are expected to experience exceptionally strong intensification of extreme precipitation, while other regions are expected to experience decreases in extreme precipitation intensity (Pfahl et al., 2017). This regional variability is due to the effects of large-scale ascent during the extreme precipitation events (extreme ascent). In some regions, extreme ascent is expected to strengthen, favoring more precipitation, and in other regions, extreme ascent is expected to weaken, favoring less precipitation (Lu et al., 2014; Pfahl et al., 2017). Tandon et al. (2018) show one of the key factors influencing extreme ascent is the horizontal scale of the ascending motion. The long-term increases in horizontal scale lead to weaker extreme ascent and decreased extreme precipitation intensity in much of the subtropics, opposite to the increased extreme precipitation intensity that is expected over most of the globe.

There are several studies projecting changes in landslide occurrence under warming climate scenarios, but modeled changes depend largely on the selection of the GCMs and local changes in precipitation, as well as, the downscaling methods to obtain rainfall and temperature in a short time scale (Gariano and Guzzetti, 2016). Overall, there is less research on projected change in land slide associated with rainfall change due to climate change.

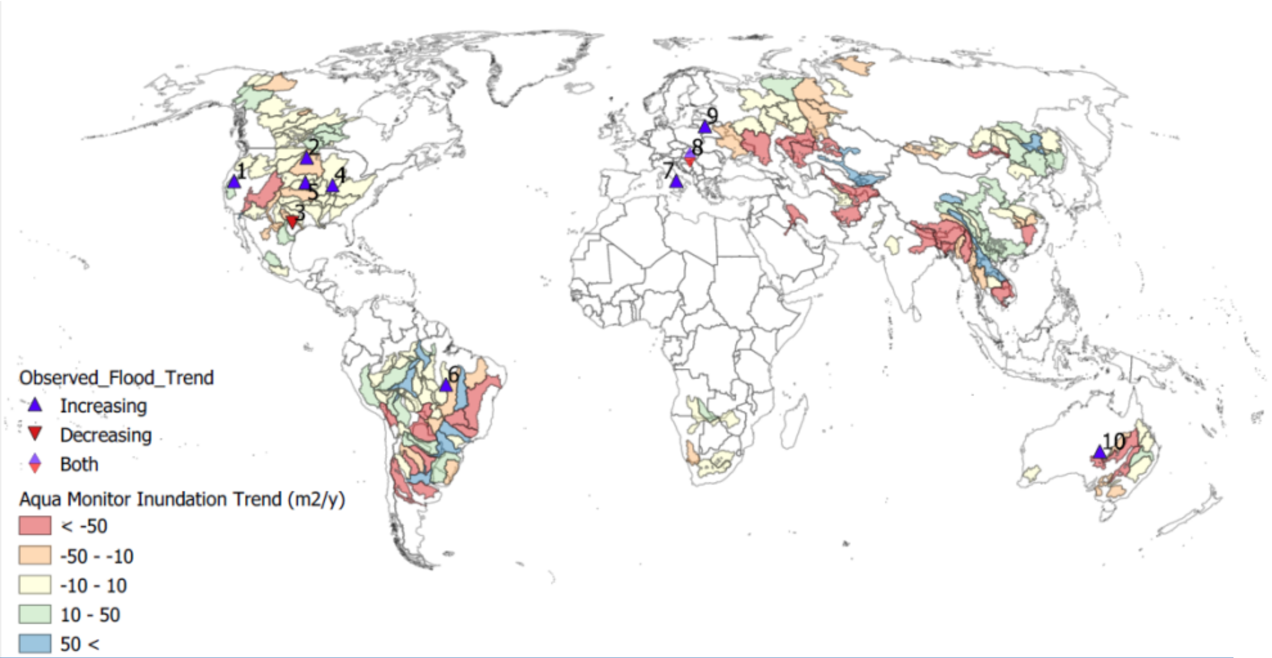
4.2.7.2 Floods

4.2.7.2.1 Observed changes in floods

There is *high confidence* that frequency and magnitude of river floods changed in the past several decades at global scale. Due to limited attribution studies, however, there is *low to medium confidence* that anthropogenic climate change has affected these changes at global scale. There is *high agreement and robust evidence* that the warming in the last decades has led to earlier spring floods, shifts in timing and magnitude of ice-jam floods and changes in frequency and magnitude of snowmelt floods. Glacial lake outburst floods are a major hazard but links between past changes and climate change remain unclear.

AR5 (Jiménez Cisneros et al., 2014) stated with *low* to *medium confidence* that observed change of river floods were attributable to anthropogenic climate change for global and regional scales, due to limitation in long-term records and difficulties in separating other sources of change. Accordingly, SR1.5 (Hoegh-Guldberg et al., 2018a) assessed with *high confidence* that river flood frequency and extreme streamflow increased in some regions since 1950. SROCC (Hock et al., 2019) summarized with *high confidence* that changes in cryosphere has lead changes in frequency, magnitude and location of related floods such as rain-on-snow floods, snowmelt floods and glacier lake outburst floods (GLOFs). Both AR5 and SROCC concluded that global mean sea level has risen (*very high confidence*) with implication for floods in coast and low-lying areas, whereas SROCC concluded it is still too early to attribute coastal flood impacts to climate change and associated sea level rise. AR6 (Seneviratne et al., in preparation) stated with *low confidence* in global trends of floods due to their high regional variabilities.

There is *high confidence* that frequency and magnitude of river floods is changed in the past several decades at global scale (Figure 4.7). For example, global flood database based on in situ measurement and satellite remote-sensing during 1985–2015 revealed that floods have increased 4-fold and 2.5 –fold in the tropics and north mid-latitudes, respectively (Najibi and Devineni, 2018). Analyses of in situ measurement showed both increase and decrease in river floods for 1980–2009 in Europe and the United States (Berghuijs et al., 2017a), overall increase in China, Brazil and Australia (Berghuijs et al., 2017a) but decrease in some areas in Australia (Ishak et al., 2013; Do et al., 2017).



	Observed change	
1-3	Flood water level (2,042 stations, USA, 1985-2015)	Slater and Villarini (2016)
4	Discharge larger than magnitude of 1/30 return period (671 stations, USA, 1980-2009)	Berghuijs et al. (2017)
5	Discharge larger than magnitude of 1/100 return period (Mississippi River, eastern USA, 1980-2009)	Munoz et al. (2018)
6	Discharge larger than magnitude of 1/30 return period (244 stations, Brazil, 1980-2009)	Berghuijs et al. (2017)
7	Frequency in flash flood (Pozzuoli town, southern Italy, between 1970-1999 and 2000-2014)	Esposito, G. (2018)
8	Flood discharge (2,370 stations, Europe, 1960–2010)	Blöschl et al., 2015
9	Discharge larger than magnitude of 1/30 return period (520 stations, Europe, 1980-2009)	Berghuijs et al. (2017)
10	Discharge larger than magnitude of 1/30 return period (309 stations, eastern Australia, 1980-2009)	Berghuijs et al. (2017)

Figure 4.7: Selected examples of the observed changes in flood attributed to observed climate change. Background colour indicates trends in inundation area (km^2/year) in river floodplain created by authors, based on water surface change map satellite (Donchyts et al., 2016).

One of the main drivers of the flood changes is changes in precipitation. However, there is *limited evidence* that observed increases in extreme precipitation (4.2.7.1) due to climate change has increased frequency and magnitude of floods, as effects of other hydrological changes is larger except for small catchments (Wakode et al., 2018).

In the snow dominated regions, the warming induced changes in timing, magnitude and frequency of snowmelt floods have been occurred for the last decades (*high agreement and robust evidence*). For example, earlier spring floods due to warmer temperature are reported in Europe (Hall et al., 2014; Morán-Tejeda et al., 2014; Kormann et al., 2015; Matti et al., 2016; Vormoor et al., 2016; Blöschl et al., 2017), the European part of Russia (Frolova et al., 2017), Canada (Yang et al., 2015a; Burn et al., 2016; Buttle et al., 2016), and the United States (Mallakpour and Villarini, 2015; Solander et al., 2017; Rokaya et al., 2018). Both positive and negative trends in magnitude of the snowmelt floods are observed in some areas of Canada (Burn et al., 2016) and the United States (Mallakpour and Villarini, 2015). However, a negative trend is observed in Scandinavia (Matti et al., 2016).

Climate change can be linked to several processes contributing to disastrous glacial lake outburst floods (GLOF) risks, however, behaviour of glacial lake systems varies between regions and types of GLOF. For example, global evaluation of reported moraine-dammed GLOFs indicate decrease in frequency since the 1970s (Harrison et al., 2018), whereas no change in frequency was found based on remote sensing in Himalaya since the late 1980s (Veh et al., 2019). Hence, despite that the number of glacial lakes has increased (Wang and Zhou, 2017; Harrison et al., 2018; Bolch et al., 2019), changes in frequency or occurrence of GLOF associated with climate change remain unclear (*medium confidence*).

The observed sea level rise, changes in numbers and magnitude of storms and cyclones (AR6 WGI) and land subsidence due to ground water intake or lower ground water level associated with increased evapotranspiration (4.2.4) can contribute to increased coastal flood (Cross-Chapter Box SLR in Chapter 3).

4.2.7.2.2 Projected changes in floods

Impacts associated with river flood will increase under all climate scenarios (*medium confidence*). Increases in river flood risks are projected at global, continental and basin scales but the regional differences are large due to the strong influence of socio-economic conditions and large uncertainty in flood hazard projections (*high confidence*). Projected increase in extreme precipitation leads to increase in flash flood and urban flooding (*medium confidence*). There is *high agreement and robust evidence* that due to projected warming, snowmelt floods will occur earlier in the year.

SR1.5 (Hoegh-Guldberg et al., 2018a) concluded with *medium confidence* that a global warming of 2°C would lead to an expansion of the area affected by flood hazard compared to conditions at 1.5°C global warming. Both AR5 (Jiménez Cisneros et al., 2014) and SROCC (Hock et al., 2019) concluded that the spring snowmelt floods will be earlier (*robust evidence, high agreement*) and the hazards from floods involving melt water will gradually diminish in particular low elevation (*medium confidence*). SROCC (Hock et al., 2019) stated that given with *limited evidence*, the magnitude and frequency of glacier lake outburst floods (GLOFs) under climate change is not clear. SROCC also stated with *high confidence* that historically rare extreme sea level events will become common by 2100 under all RCPs due to global mean sea level rise. AR6 (Seneviratne et al., in preparation) stated with *high confidence* that the flood generation is a join influence of climate, human intervention, and catchment characteristics.

There is *high confidence* that frequency and magnitude of river floods is projected to change at global scale. At the continental scale, river flood is projected to increase in middle of Africa and northern high latitude and decrease in southern of North America, southern South America, eastern part of Europe and Mediterranean both in 2050 and beyond (Koirala et al., 2014; Arnell and Gosling, 2016). These changes are due to projected changes in precipitation (4.2.1.2, 4.2.7.1.2), snow melt (4.2.2.2) and evapotranspiration (4.2.1.4). Projected increase in extreme precipitation (4.3.1.7.2) is expected to increase in flooding in relatively small river basin and urban area (*medium confidence, high agreement*) and the change leads a significant impact such as flash flood. Therefore, it is important to investigate the performance of drainage systems in a changing environment and to assess the potential urban flooding under various scenarios to achieve better adaptations (Kermanshah et al., 2017) (4.3.4.3). Projected earlier snowmelt leads earlier spring floods in all of climate scenario (*high agreement, robust evidence*), for example in northern and eastern Europe (Gobiet et al., 2014; Hall et al., 2014; Etter et al., 2017; Lobanova et al., 2018), northern part of North America (Vano et al., 2015; Musselman et al., 2018; Islam et al., 2019) and, large Arctic rivers (Gelfan et al., 2017; Pechlivanidis et al., 2017), high-altitude Asian basins (Lutz et al., 2014; Eisner et al., 2017).

Unlike flood timing, there is only *limited agreement* in projections in snowmelt flood magnitude changes. A negative trend in snowmelt flood magnitude together with an increase in rain-fed winter floods are projected with *medium confidence*, for example in mid-latitudes and low-altitude basins of Scandinavia (Hall et al., 2014; Arheimer and Lindström, 2015; Vormoor et al., 2016) and throughout Europe as a whole (Kundzewicz et al., 2017), north eastern North America (Arnell and Lloyd-Hughes, 2014). With *medium confidence*, a positive trend is projected in high-latitude basins, e.g. for large Arctic Rivers - Lena and Mackenzie (Eisner et al., 2017; Gelfan et al., 2017; Pechlivanidis et al., 2017) and high-altitude basins, such as Ganges, Brahmaputra, Salween, Mekong and the upper Indus Basin (Lutz et al., 2014), Fraser River Basin of British Columbia (Eisner et al., 2017; Islam et al., 2019), Alpine catchments (Hall et al., 2014).

The number and area of glacier lakes are projected to increase in most regions in the coming decades, and new lakes can be developed closer to steep and potentially unstable mountain walls where lake outbursts can be more easily triggered by the impact of landslides. Hence, GLOF frequencies during the next decades and into the 22nd century are projected to increase (Harrison et al., 2018). In addition to the direct impact, warming climate may affect the triggers and magnitude of GLOFs induced by non-climatic drivers such as volcanic activity and earthquakes through changes in the lake size, source glacier or stability of the lake dam and surrounding mountain slopes.

The projected sea level rise (AR6 WGI) is expected to enhance coastal inundation. For example, a 1-m sea level rise contributes an additional increase of 3–5% of annual flood exposure in the Ganges-Brahmaputra-Meghna Delta, in addition to the runoff increase associated with a warming climate (1.5–2 times) (Ikeuchi et al., 2015). In addition to the sea level rise, exposure to coastal flood will increase due to increased population and land subsidence (Neumann et al., 2015a), leading various consequences (Cross-Chapter Box SLR in Chapter 3)

There is *high confidence* that direct damage due to river flood will increase under all combination of climate and socioeconomic scenarios (Alfieri et al., 2017; Döll et al., 2018), mainly due to the socioeconomic development in inundation area, rather than increase in flood due to climate change (Kinoshita et al., 2018). Globally, human losses from flooding could rise by 70–83 % with temperature increases of 1.5°C, and by 120–188 % at 3°C warming (Dottori et al., 2018). At 4°C global warming, countries representing more than 70% of the global population and global Gross Domestic Product (GDP) will face increases in flood risk in excess of 500%. Changes in flood risk are unevenly distributed, with the largest increases in Asia, U.S., and Europe. However, changes are statistically not significant in most countries in Africa and Oceania for all considered warming levels (Alfieri et al., 2017).

In summary, the projections of flood magnitude/frequency changes at global, regional, and basin scales are still few numbers, except for regions in Europe, North America, Australia, and east Asia. There is '*medium confidence and high agreement'* that projected increases in heavy rainfall would contribute to increases in rain-generated local flooding (flash flood and urban flood) in some areas. Earlier spring peak flows in snow dominated river basins are very *likely*, but there is *'low confidence'* (due to limited evidence) in projections of changes in snowmelt flood and glacier lake outburst floods (GLOFs). The direct damage due to river flood will increase with *'high confidence'* because of increase in high flows in all continents. In addition, future anthropogenic climate change is *likely* to lead to increasing flood losses, alongside the increase in exposure linked to ongoing economic development with no adaptation.

4.2.7.3 Droughts (Meteorological, Agricultural and Hydrological)

4.2.7.3.1 Observed changes in droughts

The global long-term trend in drought frequency and severity remains inconsistent, implying there is still *low confidence* regarding drought trends at the global scale. Regional studies, however, suggest an increasing trend in the intensity and frequency of droughts in several parts of the world, such as the Mediterranean, West Africa, the Caribbean and Central China *(medium confidence)*.

AR5 stated that there was *low confidence* in drought trends since 1950 at the global scale (Jiménez Cisneros et al., 2014). Despite that, both AR5 (Hartmann et al., 2013) and SR1.5 (Hoegh-Guldberg et al., 2018a) assessed *high confidence* in observed trends in some regions, especially in the Mediterranean region (including southern Europe, northern Africa and the Near East). Hartmann (2013) also assessed with *low confidence* the attribution of droughts to climate change, due to large interannual variability and longer duration (and thus lower frequency) of drought events. (Hoegh-Guldberg et al., 2018a) agreed with this assessment, except for the Mediterranean where increased drought due to anthropogenic influence by increased greenhouse forcing was assessed as *medium confidence*.

Assessments related to global long-term trends in drought frequency and severity present a low level of agreement and the topic remains an element of debate in the literature (Dai, 2012; Sheffield et al., 2012b; Trenberth et al., 2013; McCabe and Wolock, 2015; Spinoni et al., 2019), in part owing to a lack of observations (Dutra et al., 2014) and partly due to inconsistent drought definitions (Lloyd-Hughes, 2014); as well as disparities between precipitation datasets and the fact that measuring and modelling evapotranspiration is still a challenge (Trenberth et al., 2013).

Carrão et al. (2016) developed a global drought risk map (see Figure 4.8) based on the combination of three independent determinants: hazard, exposure and vulnerability. While drought hazard was calculated using precipitation data from the Global Precipitation Climatology Center (GPCC) for the period 1901–2010, exposure is based on indicators of population and livestock densities, crop cover and water stress, and vulnerability on high level factors of social, economic and infrastructural indicators, collected at both the national and sub-national levels. Drought risk was found to be driven by an exponential growth of regional exposure, while hazard and vulnerability exhibited a weaker relationship with the geographic distribution of risk values. Drought risk is lower for remote regions, such as tundras and tropical forests, and higher for populated areas and regions extensively exploited for crop production and livestock farming, such as South-Central Asia, the Southeast of South America, Central Europe and the Southeast of the United States.

Regardless of the significant advances of drought research in the recent past, representing the risk of drought related impacts on society and particularly on ecosystems remains a difficult task mainly due to the lack of standardized data on past drought events and quantitative data on their impacts. Understanding the processes behind cascading effects that may lead to indirect impacts, affecting different sectors over large areas, sometimes distant from the drought or occurring only after the drought has ceased are among the key areas to study. High resolution data are key to understand land-atmosphere processes in small countries like the small island developing states (SIDS).

In summary, there is still *low confidence* in the assessment of changes in drought conditions at global scale. However, there is *medium confidence* in aggravating drought conditions in several parts of the world, such as the Mediterranean, West Africa, the Caribbean and Central Asia, while drought conditions have become less severe (*medium confidence)* in Northern Europe, central North America and North-West Australia.

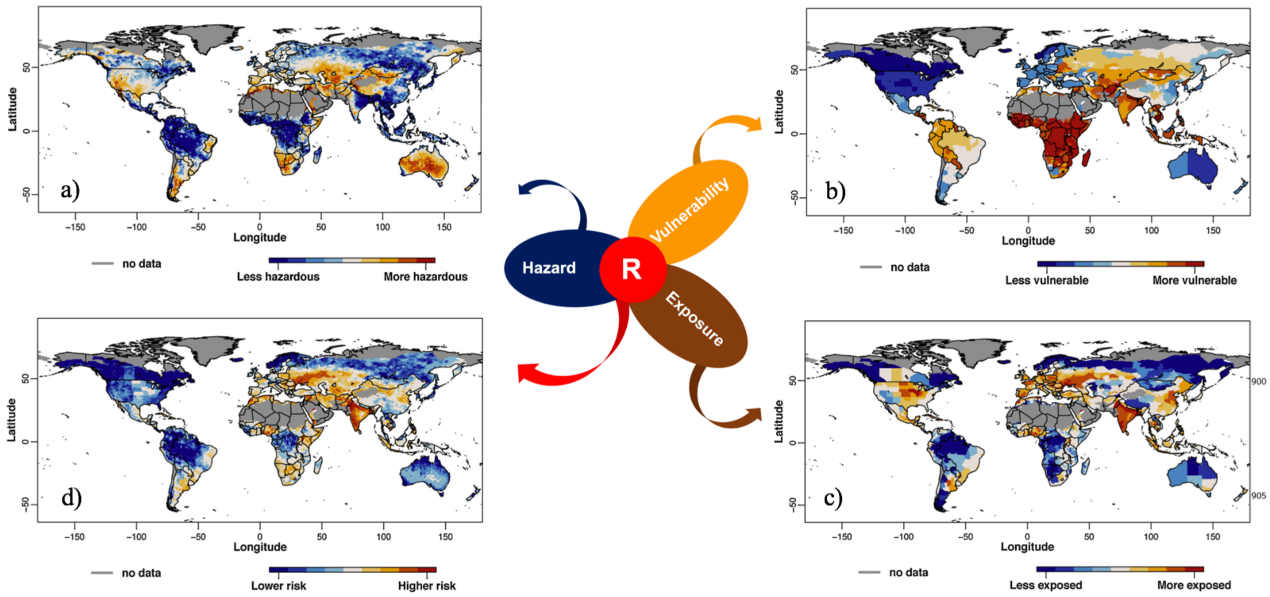


Figure 4.8: Global map of a) drought hazard computed for the events taking place between 1901–2010 by the probability of exceedance the median of global severe precipitation deficits b) drought vulnerability derived from an arithmetic composite model combining social, economic, and infrastructural factors proposed by UNISDR(2004) c) drought exposure computed at the sub-national level with the non-compensatory DEA (Data Envelopment Analysis) model (Cook et al., 2014) d) drought risk computed by scoring on a scale of 0 (lowest risk) to 1(highest risk) with the lowest and highest hazard, exposure, and vulnerability (Carrão et al., 2016).

4.2.7.3.2 Projected changes in drought

Taking into account different ways to represent drought conditions, there is *low to medium confidence* in global scale projections. However, there are some regions where drought frequency and magnitude are *likely* to increase. This is true for most of Africa, Australia, southern Europe, the southern and western United States, Central America, the Caribbean, north-west China, and parts of Southern America.

There is *medium confidence* in projections of changes in drought and dryness from the AR5 (Collins et al., 2013a). AR5 also concluded that there was *high confidence* in *likely* surface drying in the Mediterranean, southwestern USA and southern African regions by the end of this century under the RCP8.5 scenarios. However, more recent assessments have highlighted uncertainties in dryness projections for high-emissions scenarios (RCP8.5) in many regions (Orlowsky and Seneviratne, 2013; Roderick et al., 2015). SR1.5 reported substantial increases in the risk of increased dryness (*medium confidence*) in both the Mediterranean region and Southern Africa at global warming levels of 1.5°C and 2°C. There is *low confidence* elsewhere, owing to a lack of consistency in analyses with different models or different dryness indicators. For a shift from a 1.5°C to a 2°C warming level, the available studies and analyses suggest strong increases in the probability of dryness and reduced water availability in the Mediterranean region (including southern Europe, northern Africa and the Near East) and in southern Africa (*medium confidence*) (Hoegh-Guldberg et al., 2018a).

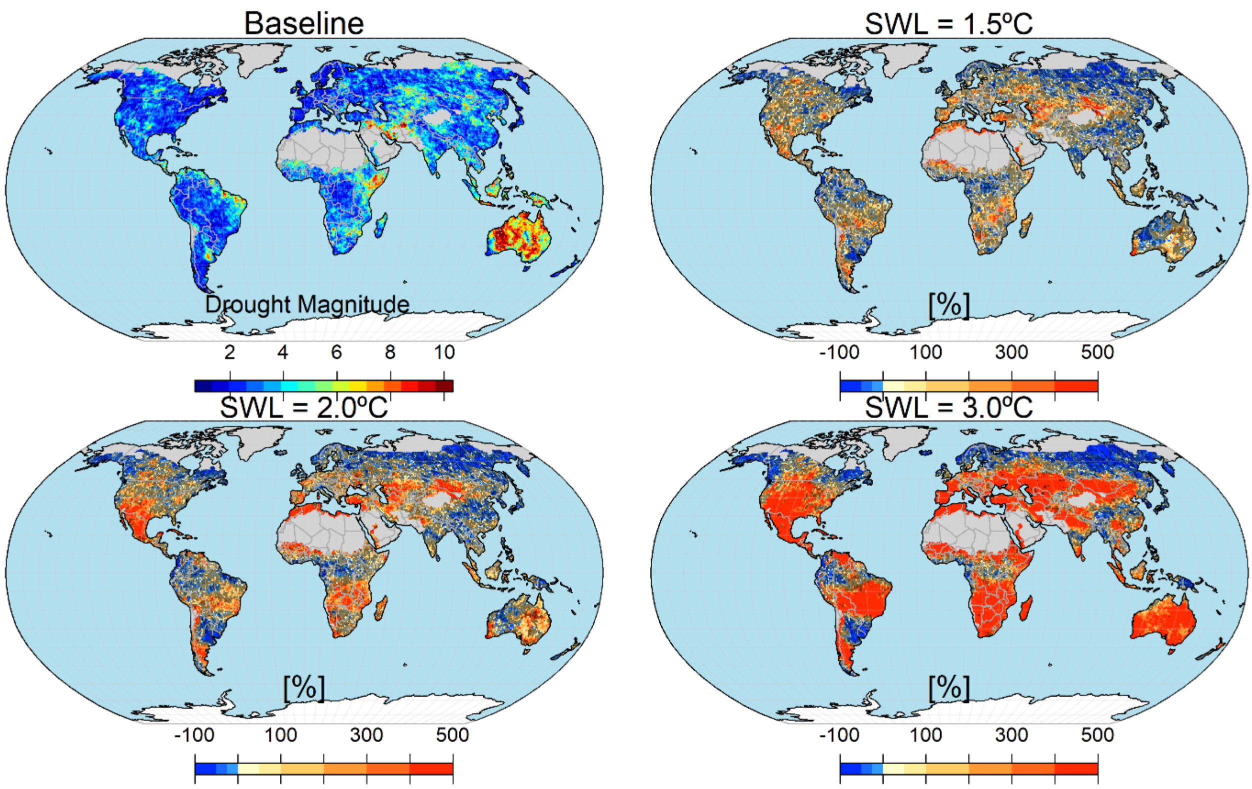
Global projections vary depending on the drought indices adopted. A drought can generally be defined as an extended period of below average natural water availability. Because droughts mostly arise from a significant deficiency in moisture supply in form of precipitation, many studies have focused on the input side (Carrão et al., 2018). Projected changes in precipitation, however, exhibit substantial spatial variation (Knutti and Sedláček, 2012; Chen et al., 2014), and in many regions, the uncertainty in precipitation projections remains high (Carrão et al., 2017), particularly at higher levels of warming. Increases are projected for most mid-latitude and high-latitude landmasses and decreases over some mid-latitude and subtropical arid and semiarid regions, following with *low-medium confidence* the paradigm of wet regions get wetter and dry regions get drier (Greve et al., 2014; Kumar et al., 2015). Notwithstanding the contribution of precipitation to worsening drought projections in the aforementioned regions, for most of them, projected changes are neither robust nor significant for the near-future (Carrão et al., 2018).

In approximately 20% of the global land surface, the increasing supply of water will outweigh the increasing evaporative demand and the water balance will, therefore not decline. Drought magnitude will likely reduce in regions like northern Europe, Southeastern South America, Central Africa, Canada, the Russian Federation, and South-eastern Asia (Koirala et al., 2014; Touma et al., 2015; Naumann et al., 2018).

Several physical processes control the incidence of droughts and dryness, and models for future projection incorporate those processes in different ways. Oceanic warming and associated climatic processes (e.g. ENSO), intensification of atmospheric patterns as well as land-atmosphere feedbacks associated with the land surface's response to climate and CO_2 change (Berga, 2016) are among the main drivers.

High evaporative losses can seriously alter natural water availability, which has led to the use of different water-balance methods (Trenberth et al., 2013; Beguería et al., 2014). However, most estimations of atmospheric evaporative demand do not account for the physiological effects of elevated CO_2 (eCO_2) on transpiration, which can be very significant (Betts et al., 2007; Swann et al., 2016). Decreasing stomatal conductance induced by eCO_2 increases canopy water-use efficiency (hence lower transpiration rates per unit leaf area), yet this mechanism is potentially offset by the enhancement of leaf area and rooting depth (Donohue et al., 2017). Models including the impact of CO_2 fertilization might present less intense drought changes (Berg et al., 2017) (Figure 4.9). However, the level of uncertainties in representing the effects of CO_2 is still very high, precluding conclusive results in a global analysis (De Kauwe et al., 2013; Prudhomme et al., 2014; Yang et al., 2016). Addressing uncertainties linked with the mentioned processes will help improving impact assessments of droughts at different levels, including ecosystems and their linked cascading effects.

Overall, there is *low to medium confidence* in global scale drought projections mainly due to divergent drought definitions. Nevertheless, driven by increased evaporative demand it is *likely* that drought frequency and magnitude will increase in most of Africa, Australia, southern Europe, the southern and western United States, Central America and the Caribbean, north-west China, and parts of Southern America. Drought or dryness will likely reduce in regions like northern Europe, Southeastern South America, Central Africa, Canada, the Russian Federation, and South-eastern Asia due to increased precipitation.



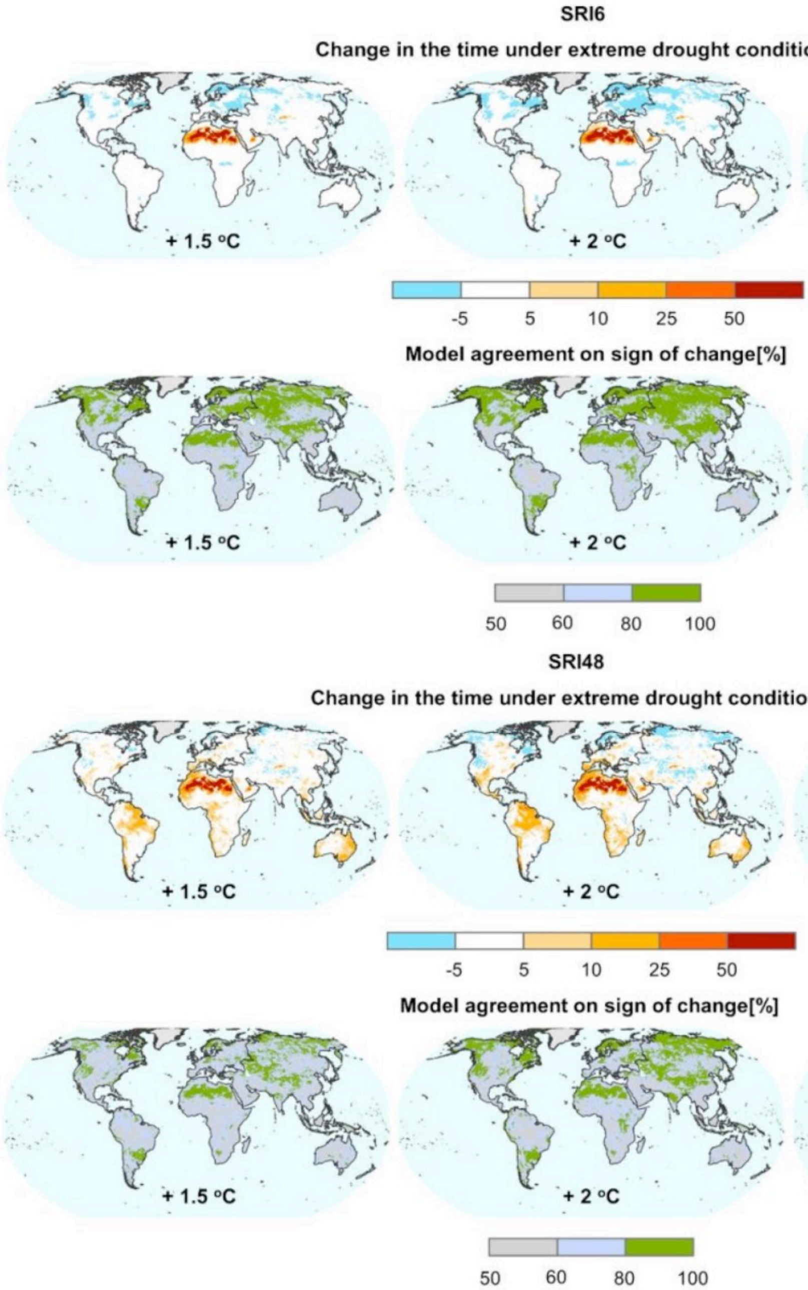


Figure 4.9: Top 2 rows: Drought magnitude (top left) and relative changes (%) in drought magnitude with respect to the baseline for the three specific warming levels (1.5, 2.0, and 3.0°C). Changes that are not statistically significant at the 10% level are shaded out in black. Territories excluded from the analysis are masked in grey (Naumann et al., 2018). Middle 2 rows: Changes in drought duration defined with the 6-month Standard Runoff Index (SRI), using a climate model and coupled vegetation-hydrological model that includes the effects of CO_2 on plant physiology. Bottom 2 rows: Changes in drought duration defined with the 48-month Stanrad Runoff Index (SRI) (Koutroulis et al., 2019).

4.2.7.4 *Societal Impacts and Risks of Extreme Weather Events and Water-related Hazards*

Extreme weather events such as heavy precipitation, floods, droughts, landslides and avalanches represent hazards to different socioeconomic sectors such as agriculture, industrial and food production, hydropower generation, fisheries, health and urban systems (*robust evidence, high agreement*). Exacerbation of these hazards can increase the vulnerability of these sectors but particularly affect selected groups such as (the poor, women, children, indigenous peoples, exposed workers and the elder (*robust evidence, high agreement*).

AR5 showed that different socioeconomic sectors such as water security, agriculture (4.3.1), health (4.3.3) and energy generation (4.3.2) will be affected in different ways by different types of hazards (Jiménez

Cisneros et al., 2014). AR5 estimated 8%, 14% and 17% of the global population facing water shortages and water quality issues under 1°C, 2°C and 3°C related to water scarcity and droughts. Floods can affect the agriculture and energy sectors however, dams might play an important role in the adaptation functioning as flood control and as irrigation storage (Arent et al., 2014). Urban systems can be vulnerable disasters such as flash floods and landslides increase in cost of property and insurance (Arent et al., 2014; Jiménez Cisneros et al., 2014; Klein et al., 2014b).

The impacts of heavy precipitation on society are varied and can be direct or indirect (Devkota and Bhattarai, 2018). Increases in frequency and intensity of heavy precipitation can result in pluvial flooding of agricultural fields (*high agreement and robust evidence*) (Bowling et al., 2018; Rokonuzzaman et al., 2018; Neset et al., 2019). Intensified convection systems may result in intense hailstorms and can damage crops and hamper agricultural productivity (*high agreement and robust evidence*) (Devkota and Bhattarai, 2018; Miya et al., 2018; Yue et al., 2019). In urban areas, unprecedented events can overwhelm drainage infrastructure (Swain et al., 2018) and impair sanitation systems increasing the risk of outbreaks of diseases such as cholera (Serdeczny et al., 2017). Seasonal and diurnal shifts in temperature at locations with seasonal temperatures close to freezing point (Ali et al., 2014) can result in snow, sleet, ice pellets or frozen rain storms in unprecedented locations without prior response experience (Schauwecker et al., 2019). The effects of heavy precipitation usually cascade through the hydrological cycle and might trigger floods and landslides causing lagged effects (Schauwecker et al., 2019).

Flood hazards, coupled with population growth and changes in land use/cover can generate vulnerability in selected groups (the poor, women, children, indigenous, exposed workers and the elder) (*high agreement and robust evidence)* (Mian et al., 2019). Projections show an increase in number of people affected by floods at different temperature increases (Figure 4.10). Effects on agriculture can be due to direct damage to crops by inundation and subsequent failure to fulfill the demand of a larger population (*high agreement and robust evidence)* (Devkota and Bhattarai, 2018). The impacts of floods also include fatalities and injuries; diseases transmittable through food, water or vector borne; escalation of prices, disruption to education, loss of employment, different degrees of psychological trauma, social insecurity and territorial displacements (*medium agreement and medium evidence)* (Devkota and Bhattarai, 2018). Increased flood frequencies could also create disruptions in urban waste management systems resulting in garbage and waste spread, clogging of drains and water ways and spreading of diseases (*medium agreement and medium evidence)* (Dewan, 2015). Floods of unprecedented magnitudes can result in overwhelmed infrastructure such as dams, spillways and drainage systems in turn affect the energy, industrial and transportation sectors (*medium agreement and medium evidence)* (Wu et al., 2019). Projected impacts by country depend on projected changes in heavy precipitation and socioeconomic projections, such as population and GDP (Figure 4.10)

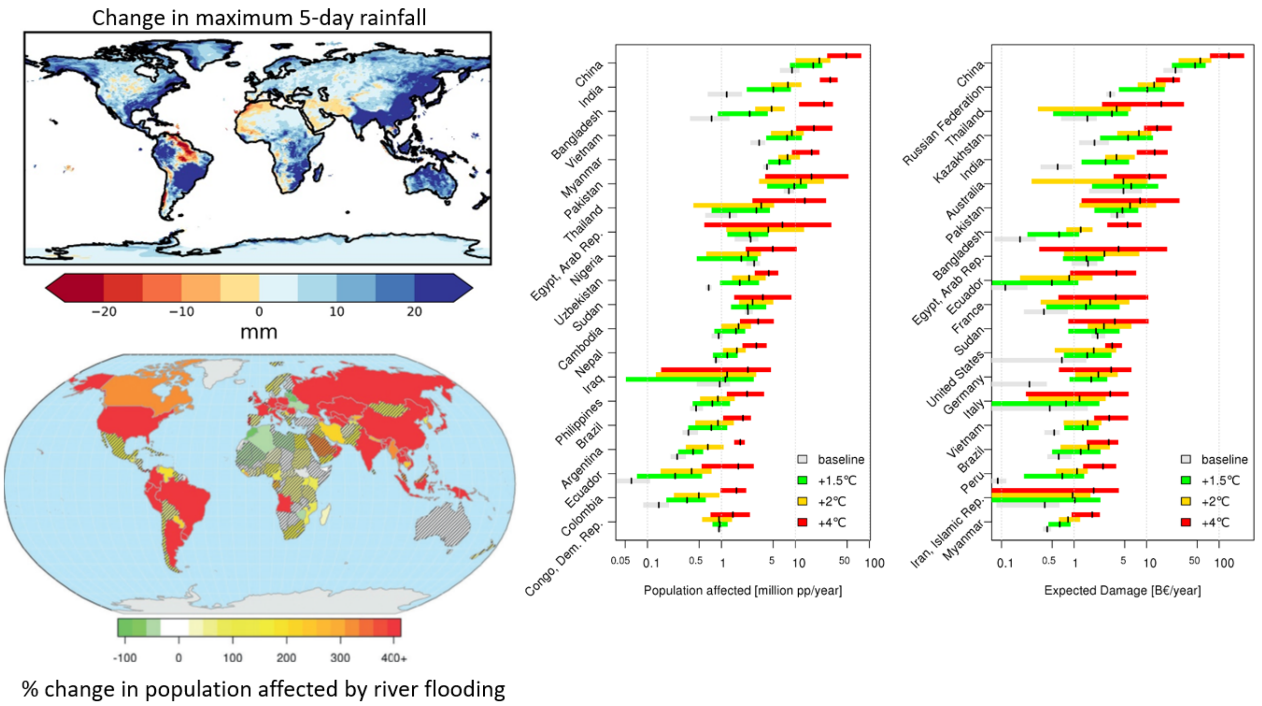


Figure 4.10: Top left: Projected change in maximum 5-day rainfall at 4°C global warming (ensemble mean, HadGEM3 atmosphere model; Betts et al. (2018a): Bottom left: projected change in number of people affected by river flooding at 4°C global warming (ensemble mean, LISFLOOD driven by EC-Earth atmosphere model). Middle: ensemble range of number of people flooded, for most impacted countries at 1.5°C, 2°C and 4°C global warming. Right: ensemble range of Expected Economic Damage, for most impacted countries at 1.5°C, 2°C and 4°C global warming (Alfieri et al., 2017)

Droughts by their own nature, their longer onset and duration times, can have longer term effects on societies (*high agreement and robust evidence)* (Van Loon, 2015). The most common societal effects of droughts are those related to agriculture and food production (*high agreement and robust evidence)* (Yan et al., 2016; Ward and Makhija, 2018; Tigkas et al., 2019). Droughts are particularly harsh for nature-based subsistence livelihoods and agriculture dependent on local biomass (*medium agreement and medium evidence)* (Serdeczny et al., 2017; Devkota and Bhattarai, 2018). Cascading effects of droughts are health issues triggered by malnutrition such as diarrhea, scabies, conjunctivitis and trachoma (*medium agreement and medium evidence*) (Serdeczny et al., 2017). Droughts and desertification can also cause human displacements often resulting in unskilled subsistence farmers moving into urban areas; loss of social ties, sense of place and cultural identity; and migration to unsafe settlements (*medium agreement and medium evidence*) (Serdeczny et al., 2017). These migrations can result in further social issues such as tensions between ethnical groups, political and legal restrictions, competition for land and additional health risk (Serdeczny et al., 2017) and transportation of diseases (*medium agreement and medium evidence*) (Semenza and Ebi, 2019). The impacts of future physical climate changes, such as changes in fresh water, depend strongly on the socioeconomic scenario (Figure 4.11)

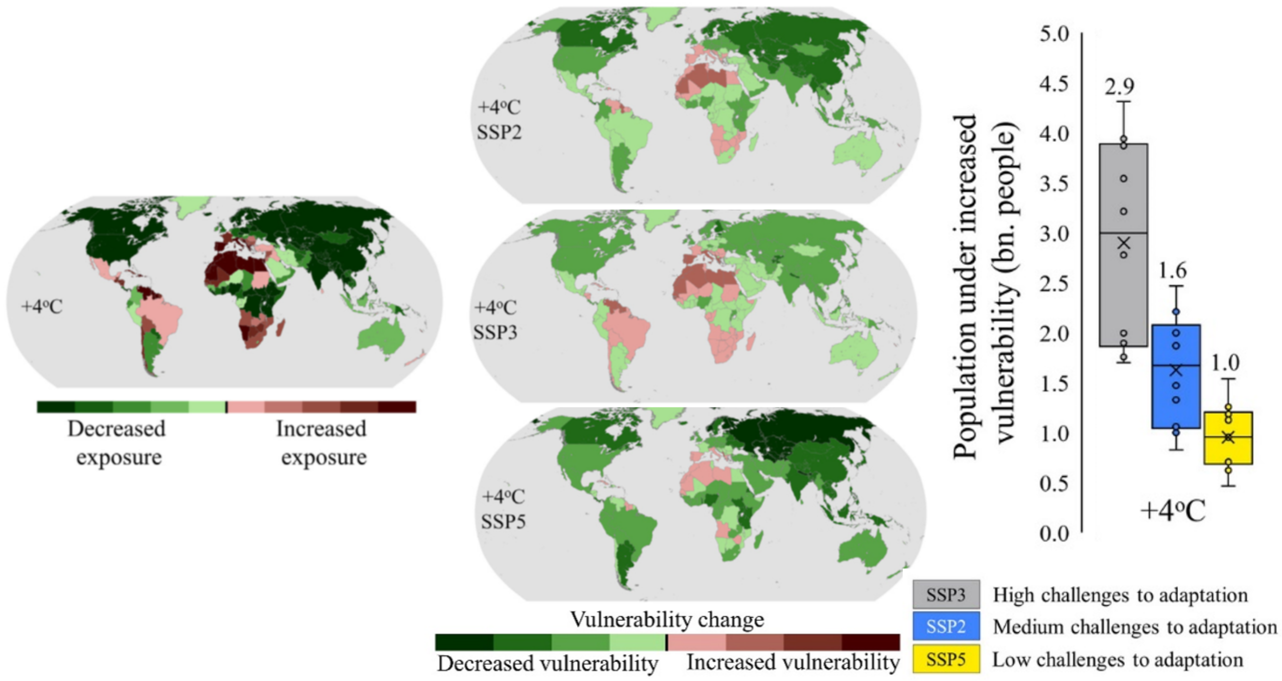


Figure 4.11: Effects of socio-economic scenario on risk of water insecurity for one climate change outcome at 4°C global warming. Left: Projected change in exposure to drought (ensemble mean). Middle column: change in "vulnerability" (risk) of water insecurity with the same projected change in hazard, with vulnerability varying according to Shared Socioeconomic Pathway (SSP). Right: ranges of global mean "vulnerability" (risk) of water insecurity at 4°C global warming, with three SSPs. Vertical range reflects uncertainty in climate hazard arising from different climate model projections. Figure panels from (Koutroulis et al., 2019).

Landslides can easily damage hillside crops resulting in in decreases or stagnation in agricultural productivity (*medium agreement and medium evidence*) (Devkota and Bhattarai, 2018). Additionally, the instability of slopes can hamper agricultural activities or nature-based subsistence livestock (*medium agreement and medium evidence*) (Serdeczny et al., 2017). Landslides and avalanches can cause direct damage to structures, loss of life and injuries, and damages to roads preventing transportation important for economic activities (*medium agreement and medium evidence*) (Dewan, 2015). Avalanches resulting from deglaciation or shifts in snowmelt season can have negative impacts to snow based tourism for example in the Himalayas and the European Alps (*medium agreement and medium evidence*) (Pokharel et al., 2016; Schmucki et al., 2017).

Societal impacts will be disparate throughout the population having larger effects on developing countries and the poor in developed countries (Levy and Patz, 2015); women, children, indigenous, exposed workers and the elder (*medium agreement and medium evidence*) (Mian et al., 2019).

4.2.8 Knowledge Gaps and Regional Assessments of Various Components of Hydrological Cycle

Table 4.3 lists the existing knowledge gaps on various components of the hydrological cycle and Table 4.4 provides regional assessment of the same.

Table 4.3: Knowledge gaps on various components of the hydrological cycle

Sections	Key gaps	Scale	Reference
4.2.1 Precipitation, evapotranspiration, and soil moisture	Limited precipitation data coverage in South America, Africa and Asia.	Regional	Kumar et al. (2013)
	Lack of improved global coverage satellite remote sensing datasets before 1980s.	Global	Adler et al. (2017)
	Substantial knowledge gaps on precipitation changes in regions of sparse station coverage such	Regional	Adler et al. (2017)

	as South America, Africa and central and northern Asia before 1980s.		
	Trend analysis on root zone soil moisture are rare, even though there has been methodological development in recent years.	Global and Regional	Mao and Liu (2019)
4.2.2 Cryosphere (Snow, Glaciers, and Permafrost)	Knowledge on occurring changes in cryosphere is inadequate in High-elevated and high-latitude areas due to lack of observations.	Global and Regional	Van Dijk et al. (2016); Walvoord and Kurylyk (2016); Huang et al. (2018)
	Limited in-situ observations on permafrost and river runoff which are not compensated by the remote sensing.	Global and Regional	Van Dijk et al. (2016);Walvoord and Kurylyk (2016); Huang et al. (2018)
4.2.3 Runoff and streamflow	Impacts of anthropogenic activities on runoff and streamflow are not understood.	Global and Regional	
4.2.4 Groundwater	Inadequate knowledge on groundwater-surface water interaction and lack of understanding of groundwater ecosystem services.	Global, Regional and National	Inferred by the authors from literature
	Limited data on groundwater recharge, storage changes, location and time scales of climate-groundwater interactions and discharge at aquifer scale.	Global and Regional	Jasechko and Taylor (2015);Cuthbert et al. (2019b)
	Lack of data on the consequence of groundwater depletion and potential adaptation.	Global, Regional and National	Inferred by the authors from literature
	Lack of data to assess the impacts of future climate change on groundwater and even less so for groundwater dependent ecosystems (GDE).		Cuthbert et al. (2019b)
	Lack of geological data, hydrogeological maps on water storage, conceptual models	Global and Regional	Richey et al. (2015); Treidel et al. (2011)
	Limited data on climate-groundwater interactions including sea-level rise	Global, Regional and National	Inferred by the authors from literature
	Absence of a dedicated global network for monitoring groundwater levels.	Global	Famiglietti (2014)
4.2.5 Water quality	Inadequate knowledge on the influence of past climate on the water quality over long time scale.	Global and Regional	North et al. (2014); Henson et al. (2016)
	Local characteristics adequately considered to clearly identify the influence from future climatic or non-climatic drivers on regional water quality.	Regional and National	Drenkhan et al. (2015); Khan et al. (2017)
	Lack of comprehensive studies on the interactions among climate drivers, ecosystem changes, water quality and infectious pathogens.	Global and Regional	Trtanj et al. (2016)
	Limited knowledge gaps on the distribution of pathogens and transmission of infectious disease.	Global and Regional	Trtanj et al. (2016)
	Inadequate studies on the improved technology and effective mitigation measures to reduce the loss and risk of waterborne diseases.	Global and Regional	Inferred by the authors from literature
4.2.6 Soil Erosion and Sediment load	Absence of long-term global soil erosion monitoring network using a unified methodological approach to correctly evaluate	Global and Regional	Evans (2013); García-Ruiz et al. (2015); Steinhoff-

	erosion rates and assess the proportional contribution of land-use and climate change.		Knopp and Burkhard (2018)
4.2.7 Extreme Weather Events and Water-related Hazards	Evidence of the increase in floods associated with the increase in the frequency of heavy precipitation is limited.	Regional	Gariano and Guzzetti (2016)
	Inadequate rain gauge-based evidence for changes in the magnitude/frequency of floods.	Global and Regional	Kundzewicz et al. (2014)
	Limited knowledge on detection and attribution of climate extremes, climate-groundwater interactions and influence of climate change on erosion rate, mainly due to limited coverage of monitoring, computational limitation, complexity in drivers of change and assumptions in socioeconomic scenarios.	Global, Regional and National	Jasechko and Taylor (2015); Famiglietti (2014); García-Ruiz et al. (2015); Sharma et al. (2018)

Table 4.4: Observed and projected changes in various components of the hydrological cycle across regions

Region	Observed changes	Projected changes
Africa	*Precipitation, Evapotranspiration and Soil Moisture [Projected values are quoted for 4C global warming]*	
	Increased precipitation in southern Africa, decreased precipitation in equatorial Africa (Kumar et al., 2013; Gu and Adler, 2015; Adler et al., 2017).	Increased precipitation in southern Africa, decreased precipitation in equatorial Africa (Kumar et al., 2013; Gu and Adler, 2015; Adler et al., 2017).
	Decreased ET in central Africa (Miralles et al., 2013; Zhang et al., 2016a).	Decreased ET in central Africa (Zhang et al., 2016b) (Miralles et al., 2013).
	Increased soil moisture (approximately 10%) in Sahel, eastern and southern Africa, decreased soil moisture in Sahara (Dorigo et al., 2017; Gruber et al., 2019).	Increased soil moisture (approximately 10%) in Sahel, eastern and southern Africa, decreased soil moisture in Sahara (Dorigo et al., 2017; Gruber et al., 2019).
	Cryosphere	
	Mean annual glacier mass loss rate accelerated: −1.03 ± 0.83 m w.e. y^{-1} in low latitudes in 2006–2016 (Zemp et al., 2019) compared to mean decadal values of -0.2–0.84 m w.e. y^{-1} in 1950–2000 according to estimates with glaciological and geodetic methods (Zemp et al., 2015).	Glacier volume loss in Low latitudes between 2010 and 2100 at the level of 79±9% under RCP2.6 scenario, 92±3% under RCP4.5 (Huss and Hock, 2015), and from 98±0% to 100±0 % under RCP8.5 (Huss and Hock, 2015; Shannon et al., 2019).
	Runoff and Streamflow	
	Areas in Sub-Saharan Africa are constantly affected by runoff variability, especially by intense dry periods which affect agricultural livelihoods, cause rural-urban migration, informal settlements, spread of infectious diseases and food price increases (Serdeczny et al., 2017).	Decreases in North and South Africa, but increases in East Africa (Koirala et al., 2014; Dai, 2016b). Areas of Southern Africa will experience water scarcity under RCP8.5 at 2°C (*medium agreement from medium confidence*) (Gosling and Arnell, 2016). Increased exposure to water stress might take place in West and Eastern Africa together with increases in exposure to flood risk (*low confidence and low evidence*) (Arnell and Lloyd-Hughes, 2014). Annual runoff projections from GHMs forced by bias-corrected GCMs-CMIP5 and other related models also demonstrate a wide ensemble spread for the Upper Niger (Gosling et al., 2017; Hattermann et al., 2017; Betts et al., 2018b).
	Groundwater	
	Over extraction in MENA countries (Rodell et al., 2018).	-
	Water Quality	

	Floods can lead to mixing of flood water with waste water and redistribution of pollutants. Soil erosion by floods introduces a large number of nutrients, pathogens, and toxins into water environment with severe impacts in flood-prone regions such as parts of Africa (Kundzewicz et al., 2014; Lynch et al., 2014; Martínez-Santos et al., 2015; Whitehead et al., 2015; Xia et al., 2015). Ethiopia, Cameroon, and Tanzania experience widespread water quality induced vector and water borne infectious diseases (Leal Filho et al., 2018).	Deterioration in Africa due to higher stress of drought and climate change (Tall et al., 2017; Wen et al., 2017).
	Soil Erosion and Sediment Loss (SESL)	
	In response to climate change which resulted in an increase in temperature of around 1.1 °C between the 1970s and 2000s, rainfall has been delayed to the late warm season and the watershed of Wadi Abd (Algeria) experienced a significant change in flow regime. These changes led to a dramatic and continuous increase in sediment load over 4 decades (on average, 84 % more every decade as compared to the previous one) (Achite and Ouillon, 2016).	A possible increase in soil losses, even in regions with a declining trend of total precipitation, is projected owing to increase frequency of extreme rainfall events in Morocco (Simonneaux et al., 2015).
	Extreme Weather Events and Water-related Hazards (EWEWH)	
	Annual maximum river discharge is increased in 225 sub basins in Sahel region of Nijel (Aich et al., 2016) and decreased in parts of South Africa (Do et al., 2017). Flood increase (Epule et al., 2017), Decrease in north and increase in south (Wasko and Sharma, 2015) Floods linked to the spread of parasitic diseases in different regions in Africa (Ahmed and Suphachalasai, 2014). Regional studies suggest increasing trend in the intensity and frequency of droughts in several parts of the world, such as the West and Southern Africa (Dai, 2012; Sheffield et al., 2012a; Masih et al., 2014; Spinoni et al., 2019)	4%–18% increase in Upper Blue Nile basin. Others very high variability and disagreement among models (Aich et al., 2016); 1/100 flood has increased by 20% and 27% for short (2030s) and long (2060s) term future in Blue Nile, Ethiopia (Robi et al., 2019) 1/100 flood increase in 2050 in Africa (Arnell et al., 2016).
Australasia	*Precipitation, Evapotranspiration and Soil Moisture [Projected values are quoted for 4C global warming]*	
	Increased precipitation in northern Australia (Kumar et al., 2013; Adler et al., 2017; Gu et al., 2019).	Disagreement between models on sign of projected changes in precipitation (Collins et al., 2013b). Decreased evapotranspiration (0.2mm/day) in far northern, north-eastern and eastern Australia (Murphy et al., 2018).

Increased soil moisture (20% or more) in eastern Australia, decreased soil moisture in northern and western Australia (Dorigo et al., 2017; Gruber et al., 2019).	
Cryosphere	
No significant trend in mean annual glacier mass loss rate was detected in New Zealand in the beginning of 21st century: –0.68 ± 1.15 m water equivalent (w.e) y^{-1} in 2006 – 2016 (Zemp et al., 2019) compared to -0.7–2.4 m w.e. y^{-1} mean decadal values in 1950–2000 (Zemp et al., 2015).	Glacier volume loss in New Zealand between 2010 and 2100 at the level of 36±14% under RCP2.6 scenario, 58±10% under RCP4.5 (Huss and Hock, 2015), and from 82±8% to 88±5 % under RCP8.5 (Huss and Hock, 2015; Shannon et al., 2019).
Runoff and Streamflow	
Decreases in eastern coastal Australia (Dai, 2016b), but increases in northern and central Australia (Dai, 2016b)	Decreases in southwesten and southeastern of coastal Australia, but increases in central and northern Australia (Koirala et al., 2014)
Changes in Australia can vary across regions. Observed impacts include economic effects on business that depend on snow the Australian alps, tourism and fisheries from lakes and wetlands, and water scarcity due to drought in Central and Eastern Australia (Barnett et al., 2015).	Water scarcity in the South East Australia, particularly in the Murray-Darling Basin, where several major cities lie upon (*high agreement, medium evidence*) (Gosling and Arnell, 2016). Annual runoff projections from GHMs forced by bias-corrected GCMs-CMIP5 and other related models also demonstrate a wide ensemble spread for the Darling (Gosling et al., 2017; Hattermann et al., 2017; Betts et al., 2018b).
Groundwater	
-	-
Water Quality	
The increasing concentrations of major ions, organic and inorganic pollutants due to droughts and the recent climate warming impacted vulnerable freshwater ecosystems (Mosley, 2015; Mekonnen and Hoekstra, 2016) Water quality induced vector and water borne infectious diseases affect Malaysia and Australia (Leal Filho et al., 2018).	Rivers and reservoirs water quality projected to deteriorate (Mehdi et al., 2015; Nguyen et al., 2017).
Soil Erosion and Sediment Loss (SESL)	
-	Increased precipitation projected to produce enough runoff to connect the system with the sources of sediment (hollows, first order stream, foothill deposits) and may generate large floods that, in turn, may be able to entrain river bed sediments and increase sediment export from local sources (Fryirs, 2013).

	Extreme Weather Events and Water-related Hazards (EWEWH)	
	Annual maximum streamflow decrease in parts of east Australia (Do et al., 2017), Increase in Australia but weak (Berghuijs et al., 2017a). Annual maximum streamflow decreased in the south-east and south-west regions of Australia (Ishak et al., 2013). In north-west Australia drought conditions have become less severe (Damberg and AghaKouchak, 2014).	Annual maximum streamflow decrease in parts of east Australia (Do et al., 2017), Increase in Australia but weak (Berghuijs et al., 2017a). Annual maximum streamflow decreased in the south-east and south-west regions of Australia (Ishak et al., 2013). Severe impacts are projected in parts of Sumatra, Kalimantan, Sulawesi, Maluku Island, and Papua, while for Java the mean signal shows a decrease in flood volume in Indonesia (Muis et al., 2015).
Small Islands	*Precipitation, Evapotranspiration and Soil Moisture*	
	-	-
	Cryosphere	
	-	-
	Runoff and Streamflow	
	-	-
	Groundwater	
	Over extraction in Small Island Developing States (SIDS) (Holding et al., 2016; Gohar and Cashman, 2018)	-
	Water Quality	
	Sea level rise due contaminated coastal aquifers (Khedun and Singh, 2014).	Vulnerable freshwater resources and limit Bahamas' adaptive capacity due to future Sea level rise (Holding et al., 2016).
	Soil Erosion and Sediment Loss (SESL)	
	-	-
	Extreme Weather Events and Water-related Hazards (EWEWH)	
	During the altimetry period (1993–2017), a rise in sea level of 3–6 mm/year for the Pacific islands (Aucan et al., 2017).	Projected increase of extreme sea level events and associated severe annual wave-driven flooding events in the small island countries, during which seawater overtops the coastal berm resulting in increased inland flooding, especially for low-lying level atoll islands (Vitousek et al., 2017; Storlazzi et al., 2018). In addition, the 1/100 flood increase in 2050 in Pacific Islands (Arnell et al., 2016). Due to data resolution constraints, there remains limited evidence as to whether Small Island Developing States (SIDS) experienced

		robust drought changes. Increase in severity and frequency of drought in the Caribbean since 1950 (Herrera and Ault, 2017; Herrera et al., 2018).
Asia	*Precipitation, Evapotranspiration and Soil Moisture [Projectedl values are quoted for 4C global warming]*	
	Increased precipitation in northern Asia and South-East Asia (Kumar et al., 2013; Gu and Adler, 2015; Adler et al., 2017). Increased soil moisture (20% or more) in large parts of northern Asia and south-west Asia, decreased soil moisture (20% or more) in western Asia and parts of south Asia (Dorigo et al., 2017; Gruber et al., 2019).	Increased precipitation in northern and South-East Asia, disagreement on sign of projected precipitation change in central Asia (Collins et al., 2013b). Increased evapotranspiration (approximately 0.1 mm/day) across most of Asia, except for decreases of up to 0.4mm/day in South and South-East Asia (Murphy et al., 2018).
	Cryosphere	
	Decrease in snow water equivalent in the High mountains of Asia during 1987–2009 with an average annual rate of –0.3% and most intensive changes in mid-elevation zones (Smith and Bookhagen, 2018), though changes in snowline elevation, snow cover, and snow accumulation rates in Hindu Kush Himalaya and Tibetan Plateau-Pamir region are inconsistent. as reported (Bolch et al., 2019). Highly significant negative trends in snow-dominated duration of -3.5–6.5 weeks decade^{-1} during 1971–2014 in south-central Eurasia, the Alborz and Zagros ranges of northwestern Iran, the eastern front ranges of the Himalaya, and throughout the circumpolar regions of Russia. Positive snow-dominated duration trends in snow-dominated duration (2–3.5 weeks decade^{-1}) in northern and eastern parts of the Himalayan region, including much of the Tibetan Plateau and in Japan and near the central Pacific coast of Russia (Allchin and Déry, 2018). Losses in snow-dominated area during 1971–2014 (-5—15% decade^{-1}) are seen initially at lower latitudes of central Eurasia in March, then in North East Eurasia in April–July and up to September in the high elevated area from the Himalaya to the Hindu Kush (Allchin and Déry, 2018). The snow season now starts 8 later and 10 days earlier compared to 1970 in the Qinghai–Tibetan Plateau (Xu et al., 2018). Glaciers have been losing their mass with a mean rate of –0.15 ± 0.12 m w.e. y^{-1} in Central Asia, –0.03 ± 0.12 m w.e. y^{-1} in South-West Asia, –0.35 ± 0.12 m w.e. y^{-1} in South-East Asia and –0.37 ±	Glacier volume loss between 2010 and 2100 under RCP2.6, RCP4.5, and RCP8.5 scenario: in Russian Arctic, correspondingly, 38±16%, 51±20% (Huss and Hock, 2015), and from 70±19% (Huss and Hock, 2015) to 79±10 % (Shannon et al., 2019); in Caucasus and Middle East – 70±11%, 84±8% (Huss and Hock, 2015), and from 96±3% (Huss and Hock, 2015) to 100±0 % (Shannon et al., 2019); in High Mountains of Asia – 36±8%, 49±7%, and 64±5% (Kraaijenbrink et al., 2017); in Central Asia – 54±13%, 72±11% (Huss and Hock, 2015), and from 88±7% (Huss and Hock, 2015) to 99±0 % (Shannon et al., 2019)(Shannon et al., 2019). Maximum glacial runoff projected to be reached by 2040–2070s in High Mountains of Asia (Huss and Hock, 2015). Glacial runoff is projected to increase in High Mountains of Asia region by 10–60% in June, decrease by 5–20% in July, by 20–40% in August, by 10–40% in September by 2090 and have multidirectional trends in October (Huss and Hock, 2018). More than 50.0% of modelled 7–7.5%, 9–12% and 15–22% increase in the total runoff in 2041–2070 under RCP2.6, 4.5 and 8.5 respectively for the upstream parts of the Indus and Brahmaputra rivers, and 5–20% of modelled 4–11%, 7.5–15% and 8–22% increase in the total runoff in upstream parts of the Yangtze, Mekong and Salween rivers is estimated to be from the increased glacier-melt water (Su et al., 2016). By 2100 under the RCP8.5 scenario permafrost in Russia will remain mainly in the western part of the east Siberian Mountains (Guo and

	0.31 m w.e. y^{-1} in North Asia in 2006–2016 (Zemp et al., 2019). In West Kunlun, Eastern Pamir and the northern Karakoram there is a *high confidence* that glaciers remain stable and even have gained mass in the recent decades (Brun et al., 2017; Lin et al., 2017; Bolch et al., 2019). The enhanced glacier-melt signal is identified in the increased river runoff in the Central Tien Shan (Sorg et al., 2012; Kriegel et al., 2013; Chen et al., 2016), the upstream of the Tarim river (Duethmann et al., 2016) (Duethmann et al., 2015). Permafrost has been warming with a rate of 0.4–1.4 °C $decade^{-1}$ throughout Russian Arctic during 2007–2016 (Biskaborn et al., 2019).	Wang, 2016), almost no permafrost is expected to remain in China and the Tibetan Plateau (Chadburn et al., 2017). The permafrost area in the Qinghai–Tibet Plateau is projected to decrease by 0.15 × 106 km2 (7.28%), 0.18 × 106 km2 (8.74%), and 0.17 × 106 km2 (8.25%), respectively, in RCP2.6, RCP4.5, RCP8.5 when the global average surface temperature rises by 1.5 °C (in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively) (Kong and Wang, 2017). The snow water equivalent in winter (DJF) and spring (MAM) over the Qinghai–Tibet Plateau will decrease by 14.9% and 13.8%, respectively (Kong and Wang, 2017). The snow water equivalent is projected decrease significantly (more than 40% relative to 1986–2005) in central North America and by 0–20% in the North when the global average surface temperature rises by 1.5 °C (in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively) (Kong and Wang, 2017).
Runoff and Streamflow		
	Decreases in South and East Asia (Dai, 2016) and the north of China (Liu and Du, 2017). Human activities were responsible for more than 90% of the change in runoff in each separate sub-basin of the Yellow River between 1960 and 2012 (Kong et al., 2016).	Decreases in Central Asia, but increases in the most other parts of Asia (Koirala et al., 2014; Dai, 2016b) The Asian regions receiving water flows from glaciers in the Himalayas and the Tibetan Plateau might experience water scarcity at seasonal scale although there is a large spread in water resource stress, flood stress (Arnell and Lloyd-Hughes, 2014; Gosling and Arnell, 2016) and hydropower generation (Bliss et al., 2014; Molden et al., 2014) Water scarcity is likely to increase in the Middle East (Arnell and Lloyd-Hughes, 2014; Gosling and Arnell, 2016). Annual runoff projections from GHMs forced by bias-corrected GCMs-CMIP5 and other related models also demonstrate a wide ensemble spread for the Upper Ganges (Gosling et al., 2017; Hattermann et al., 2017; Betts et al., 2018b), for the 10 main basins in China (Zhai et al., 2018), for the entire India (Zheng et al., 2018b) (*low agreement, limited evidence*). Larger decreases in low flow are projected in the Middle East (Koirala et al., 2014).
Groundwater		

	Groundwater-level decline in Northern India (Asoka et al., 2017), and North China Plain (Yang et al., 2015b); groundwater depletion in Northern India; North China Plain.	
	Unsustainable pumping of groundwater is rapidly declining in northern India (Zaveri et al., 2016), the Barind region of Bangladesh (Shamsudduha and Taylor, 2019), the North China Plain (Liu et al., 2013b; Mao and Liu, 2019), Northwestern Saudi Arabia; Northern Middle East (Rodell et al., 2018); groundwater level increase in Central India (Rodell et al., 2018).	
	In a few regions, groundwater levels have increased due to irrigation in the lowlands such as for lower regions of Amu Darya that has led to soil salinization (Gafurov et al., 2018).	
	Groundwater level increase in Central India (Rodell et al., 2018); groundwater-level decline in Northern India (Asoka et al., 2017), and North China Plain (Yang et al., 2015b); groundwater level increase in Nile Headwaters (Rodell et al., 2018). Over extraction in MENA countries (Rodell et al., 2018).	
	A large negative trend in total water storage in the Middle East centered over western Iran and eastern Iraq (Joodaki et al., 2014), but small storage changes in large regional aquifers in the MENA region (Lezzaik and Milewski, 2018).	
	Water Quality	
	In South Asia the intensity diarrhea disease increased remarkably in 2015 (Liu et al., 2016a; Troeger et al., 2017). Water quality degradation severely affects drinking water availability during extreme climate events in Bangladesh, China, India, Indonesia, Myanmar, Nepal, Pakistan, and Vietnam (Otto et al., 2017; Abedin et al., 2018; Huynh and Stringer, 2018; Nichols et al., 2018). 70% of people in coastal Bangladesh are at risk of waterborne health diseases such as diarrhea, dysentery, and skin diseases that are linked with the climate-related safe water quality degradation (Abedin et al., 2018).	Deterioration in South Asia, especially populated regions, due to the enhanced flood potential and extended drought periods (Whitehead et al., 2015; Wen et al., 2017).
	Soil Erosion and Sediment Loss (SESL)	

	The combined impact of lower precipitation and intensive human activities, including soil conservation practices, water and sediment retention within reservoirs, water abstraction, and sedimentation in channel beds, resulted in distinct stepwise decreases in sediment loads discharged from the upper Yellow River (Tian et al., 2019). Regional warming and permafrost degradation have contributed over the last 40–70 years to increasing forested area, which has led to decreasing soil erosion in the Eastern Siberia (Potemkina and Potemkin, 2015).	An increase in sediment load by 9–11% is projected for the period of 2041–2070 in the wet western Himalayan river basin (Azim et al., 2016). A possible increase in soil losses, even in regions with a declining trend of total precipitation, is projected owing to the increase frequency of extreme rainfall events in Iran (Azari et al., 2016).
	Extreme Weather Events and Water-related Hazards (EWEWH)	
	Decrease in parts of Southeast Asia (Do et al., 2017). Overall increase in China but decrease in India and Southeast Asia (Wasko and Sharma, 2015) In Bangladesh, the societal impacts of floods include death caused by drowning, snakebites, water borne diseases, and diarrhea, while in Nepal deaths are caused by landslides (Dewan, 2015; Curtis et al., 2017). A decline in agricultural production due to crop failures and increase of water conflicts and migration in South Asia due to droughts (Koutroulis et al., 2016; Jayawardhan, 2017)	19%–25% increase (maximum 5-day rainfall at 4C global warming (range of outcomes from HELIX HadGEM3 ensemble, not bias-corrected). 1/100 flood increase in wide area in 2050 in Asia (Arnell et al., 2016). Regional studies suggest an increasing trend in the intensity and frequency of droughts in several parts of the world, such as Central China (Wang et al., 2017b).
Central and South America	*Precipitation, Evapotranspiration and Soil Moisture [Projected values are quoted for 4C global warming]*	
	Increased precipitation in equatorial South America, decreased precipitation in central and southern South America (Kumar et al., 2013; Gu and Adler, 2015; Adler et al., 2017). Decreased evapotranspitation in western Amazon (Miralles et al., 2013; Zhang et al., 2016a). Decreased soil moisture (over 20%) in central America and near western and eastern coasts of South America, increased soil moisture in Amazon (Gruber, 2012; Dorigo et al., 2017).	In northern South America, disagreement between models on sign of projected precipitation change (Collins et al., 2013b). Decreases in evapotranspiration of approximately 1.0 mm/day over most of Central and South America north of 30S, with decreases of over 1.2mm/day in northern South America (Murphy et al., 2018).
	Cryosphere	
	Mean annual glacier mass loss rate accelerated in last decades compared to the second half of 20th century: -1.18 ± 0.38 m w.e. y^{-1} in Southern Andes and –1.03 ± 0.83 m w.e. y^{-1} in low latitudes in 2006–2016 (Zemp et al., 2019) compared to mean decadal values of -0.1–0.98 m w.e. y^{-1} and -0.2–0.84 m w.e. y^{-1}	Glacier volume loss in Low latitudes between 2010 and 2100 at the level of 79±9% under RCP2.6 scenarios, 92±3% under RCP4.5 (Huss and Hock, 2015), and from 98±0% to 100±0 % under RCP8.5 (Huss and Hock, 2015; Shannon et al., 2019). In Southern Andes, correspondingly, – 10±8%,21±11% (Huss and Hock, 2015), and

correspondingly in 1950–2000 according to estimates with glaciological and geodetic methods (Zemp et al., 2015). Decrease in the glacial runoff in northern Peru (Baraer et al., 2012), the Central Andes of Chile (Casassa et al., 2009).	from 44±14% (Huss and Hock, 2015) to 98±1 % (Shannon et al., 2019). Maximum glacial runoff has been already reached in the Amazon basin and most of Southern Andes (Huss and Hock, 2018). Glacial runoff is projected to decrease by 10–60% in most of the warm period by 2090 on the continent (Jan-Apr) and either increase of decrease by 5–20% depending on the region in December (Huss and Hock, 2018).
Runoff and Streamflow	
Decreases in some parts of Brazil, but increases in Argentina and Uruguay (Dai, 2016b). Peru, Bolivia Ecuador and Colombia rely on glacier runoff for water supply are starting to experience decreases in runoff and are actively study(Wienhold et al., 2018)ing and preparing to account their effect in (*high agreement from moderate evidence*) (Bliss et al., 2014; Carey et al., 2014; Skarbø and VanderMolen, 2014; Drenkhan et al., 2015; Raoul, 2015).	Decreases in Central America as well as in the north of South America, but increases in the south-west of South America (Koirala et al., 2014; Dai, 2016b). Peru, Bolivia Ecuador and Colombia rely on glacier runoff for water supply, hydropower and irrigation. They will likely suffer from water scarcity (*high agreement from moderate evidence*) (Bliss et al., 2014; Carey et al., 2014; Skarbø and VanderMolen, 2014; Drenkhan et al., 2015; Raoul, 2015; Rasmussen, 2016; Wienhold et al., 2018). Changes in meteorologically driven runoff will also affect water scarcity in portions of North Eastern Brasil, Central Chile and Central Argentina (Arnell and Lloyd-Hughes, 2014; Gosling and Arnell, 2016). Central America is likely to have increases from 20 to 45% in population exposed to water scarcity (*medium confidence from moderate evidence*) and up to 50% increase in population exposed to flood risks (Arnell and Lloyd-Hughes, 2014). Annual runoff projections from GHMs forced by bias-corrected GCMs-CMIP5 and other related models also demonstrate a wide ensemble spread for the Upper Amazon (Gosling et al., 2017; Hattermann et al., 2017; Betts et al., 2018b). The larger decreases in low flow is projected in South America (Koirala et al., 2014).
Groundwater	
-	-
Water Quality	

	Meltwater reduction led to increased biomass of benthic algal and invertebrate herbivores by changing water temperature and water solute contents (Jacobsen et al., 2014; Milner et al., 2017). Uruguay experiencing widespread water quality induced vector and water borne infectious diseases (Leal Filho et al., 2018).	Decrease due to the glacier shrinkage and net mass (Bliss et al., 2014). The projected increase of global mean sea level and extreme weather events such as storm surges, floods, and wave setup would lead to deterioration of water quality (Reguero et al., 2015).
	Soil Erosion and Sediment Loss (SESL)	
	In the Magdalena River drainage basin (Colombian Andes) increasing trend in sediment load during the 1980–2010 period is in close agreement with trends in land use change and deforestation. During the last decade, the basin has witnessed an increase in erosion rates of 34%, from 550 t km^{-2} y^{-1} before 2000 to 710 t km^{-2} y^{-1} for the 2000–2010 period, and the average sediment load for the whole basin increased to 44 Mt y^{-1} for the same period. The rate of anthropogenic soil erosion in the Magdalena basin probably exceeds the rate of climate-driven erosion by several orders of magnitude (Restrepo and Escobar, 2018).	-
	Extreme Weather Events and Water-related Hazards (EWEWH)	
	Annual maximum streamflow decreased in eastern Brazil and increased in upper Amazon and southern Brazil (Do et al., 2017); Regions in South America, particularly those close to steep slopes have experienced losses in crops due to landslides and floods (Nehren et al., 2019). Agricultural production has been affected in the past by extended periods of droughts (Nehren et al., 2019). Some of the largest damages associated with extreme water hazards in South America are those related to landslides in urban settlements (Nehren et al., 2019).	10%–14% increase (maximum 5-day rainfall at 4C global warming (range of outcomes from HELIX HadGEM3 ensemble, not bias-corrected). Both increase and decrease in 1/100 flood (Arnell and Gosling, 2016). Changes in extreme water hazards are likely to exacerbate the effects of extreme water extremes across South America, particularly in the sectors of agriculture (Nehren et al., 2019). Damages due to landslides are likely to increase in areas particularly in urban settlements (Nehren et al., 2019). Projected vulnerability increase for 5–15 % over the central and southern part of Santa Catarina state in Brazil and decrease in vulnerability to landslide in the central region of Brazil due to declining trends of extreme rainfall events (Debortoli et al., 2017).
North America	*Precipitation, Evapotranspiration and Soil Moisture [Projected values are quoted for 4C global warming]*	
	Increased precipitation in North America from 1930 to 2004 (Kumar et al., 2013; Gu and Adler, 2015; Adler et al., 2017).	Increased precipitation in northern North America (Collins et al., 2013b).

Increased soil moisture (20% or more) in northern North America, decreased soil moisture (15–20%) in southern North America (Dorigo et al., 2017; Gruber et al., 2019).	Small increases in evapotranspiration (0.1 mm/day) in eastern and north-western North America, similarly small decreases in central North America (Murphy et al., 2018).
Cryosphere	
A negative trend of 3–9 mm y^{-1} in maximum seasonal snow depth (Kunkel et al., 2016). Decrease in snow cover extend during 1971–2014 ranges from 10% in late April to 50 % in mid-June. November and December exhibit statistically significant positive trends of (5–10% during 1971–2014) (Hernández-Henríquez et al., 2015). Highly significant negative trends in snow-dominated duration of -3.5–6.5 weeks decade-1 during 1971–2014 are characteristic of the Rocky Mountains of western North America and throughout the circumpolar regions of North America (Allchin and Déry, 2018). Decrease in snow-dominated area by 5–15% during 1971–2014 in May–August (Allchin and Déry, 2018). Mean annual glacier mass loss rate substantially increased in majority of regions of North America: -0.85 ± 0.19 m w.e. y^{-1} in 2006–2016 (Zemp et al., 2019) compared to mean decadal values of -0.081–0.75 m w.e. y^{-1} in 1950-2000 according to estimates with glaciological and geodetic methods in Alaska (Zemp et al., 2015); accordingly, -0.85 ± 0.19 m w.e. y^{-1} in 2006–2016 (Zemp et al., 2019) compared to -0.059–0.64 m w.e. y^{-1} in 1950–2000 in Northern Arctic Canada (Zemp et al., 2015); –0.83 ± 0.40 m w.e. y^{-1} in 2006–2016 (Zemp et al., 2019) compared to -0.13–0.57 m w.e. y^{-1} in 1950–2000 in Western North America (Zemp et al., 2015). Rise in glacial runoff in Alaska (O'Neel et al., 2014), decrease in British Columbia (Stahl and Moore, 2006; Casassa et al., 2009). Permafrost has been warming with a rate of 0.1–0.8 °C decade^{-1} in Alaska and Arctic Canada during 2007–2016 (Biskaborn et al., 2019). Unsustainable pumping of groundwater is now rapidly declining notably and the California Central Valley, USA (Scanlon et al., 2012).	Glacier volume loss between 2010 and 2100 under RCP2.6, RCP4.5, and RCP8.5 scenarios: in Alaska, correspondingly, 32±11%, 42±12% (Huss and Hock, 2015), and from 58±14% (Huss and Hock, 2015) to 89±2 % (Shannon et al., 2019); in Western Canada – 76±8%, 86±8% (Huss and Hock, 2015), and from 95±5% (Huss and Hock, 2015) to 100±0 % (Shannon et al., 2019); in Arctic Canada North – 14±5%, 18±7% (Huss and Hock, 2015), and from 30±12% (Huss and Hock, 2015) to 47±3 % (Shannon et al., 2019). Maximum glacial runoff has been already reached in the Western Canada and is projected to be reached by 2030-2050s in Alaska (Huss and Hock, 2018). Glacial runoff is projected to increase by 10-40% in June, decrease by 5–60% in July–August by 2090, have multidirectional trends in September and October in Western Canada; increase by 20–40% in June, by 5–10% in July, 5% in August, by 20–40% in September and 40–60% in October by 2090 in Alaska (Huss and Hock, 2018). The snow water equivalent is projected decrease significantly (more than 40% relative to 1986–2005) in central North America and by 0–20% in the North when the global average surface temperature rises by 1.5 °C (in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively) (Kong and Wang, 2017). By 2100 under the RCP8.5 scenario permafrost in Canada will retreat to the north of 65°N (Guo and Wang, 2016).

Runoff and Streamflow	
Decreases in the northwest and southeast US (Solander et al., 2017; Ficklin et al., 2018; Forbes et al., 2018) as well as in eastern and western Canada, but increases in the northeast and central US (Dai, 2016b; Ficklin et al., 2018) as well as in Canadian Arctic (Bring et al., 2016; Tananaev et al., 2016; Magritsky et al., 2018) Variations in runoff and exacerbated dry periods across Europe causing water stress across the central US and water scarcity across Western US (Hodgkins et al., 2017).	Decreases in the south-west of the USA, but increases in the most part of North America (Koirala et al., 2014; Dai, 2016b). North American regions will likely need to adapt to reduced water resources particularly from seasonal shifts in runoff (Gosling and Arnell, 2016). Annual runoff projections from GHMs forced by bias-corrected GCMs-CMIP5 and other related models also demonstrate a wide ensemble spread for the Upper Mississippi (Gosling et al., 2017; Hattermann et al., 2017; Betts et al., 2018b). GHMs-based results, grounded on higher agreement, are found for the United States, where more than 40% of land area is subject to the significant changes of summer/winter runoff (Leng et al., 2016), and water yield decrease is projected for more than 60% of this area by the end of the 21st century under the RCP8.5 scenario (Mahat et al., 2017).
Groundwater	
Groundwater-level decline in the High Plain Aquifer of USA (Haacker et al., 2016); groundwater depletion in Southern California (Rodell et al., 2018). Unsustainable pumping of groundwater is rapidly declining in the California Central Valley, USA (Scanlon et al., 2012); Western United States (Rodell et al., 2018).	Decrease in snowmelt recharge for US (Meixner et al., 2016); increase in groundwater recharge in Canada (Jyrkama and Sykes, 2007); groundwater recharge decrease in summer but increase in winter in Canada (Rivard et al., 2014). Decrease in snowmelt recharge for US (Meixner et al., 2016). Potential recharge rate can increase by approximately 100 mm/year over a period of 40 years in Canada (Jyrkama and Sykes, 2007), with a marked projected decrease in recharge during the summer and a marked increase during the winter (Rivard et al., 2014).
Water Quality	
-	Deterioration in Canadian sub-Arctic regions due to the release of radioactive contamination in permafrost (Bond and Carr, 2018). Deterioration due to the reductions in runoff volume (Liu et al., 2016a).
Soil Erosion and Sediment Loss (SESL)	
Positive trend in sediment yield in small ponds in the semi-arid climate of the south-western USA over the last 90 years was not entirely related to corresponding trends in rainfall or runoff, but	The future of sediment transfers at Linnévatnet catchment, USA where continued increases in temperature and rainfall are projected (Schiefer et al., 2018).

	reflected a complex interaction between long-term changes in vegetation, soil, and channel networks (Polyakov et al., 2017). For a glacierized catchment in the High Arctic (Linnévatnet catchment, USA) sedimentation rates through the twentieth century showed significant positive relations with spring/summer temperature, rainfall, and peak discharge conditions (Schiefer et al., 2018). 15-year records of suspended sediment export in two High Arctic rivers in Canada suggests that greater sediment erosion from permafrost landscape disturbances has not yet increased downstream-suspended sediment export (Beel et al., 2018)	In Arctic region (Athabaska River basin, Canada), the total sediment load will increase more than two-fold due to greater riverbank and channel erosion, whereas basin sediment flux will be reduced due to increasing vegetation cover (Shrestha and Wang, 2018) In the Western Basin of Lake Erie, moderate climate change scenarios reduced annual flow (up to -24%) and sediment (up to -26%) yields, while a more extreme scenario showed smaller flow reductions (up to -10%) and an increase in sediment (up to +11%) (Cousino et al., 2015)
	Extreme Weather Events and Water-related Hazards (EWEWH)	
	Annual maximum streamflow decreased for a large number of stations in western North America (Do et al., 2017); Station-based high-flow increased (Berghuijs et al., 2017a); 1/100 flood increase in Mississippi (Muñoz et al., 2014); Increased inundation in nouthern and eastern USA, decrease in southern USA (Slater and Villarini, 2016). Earlier spring floods in the most part of Canada (Burn et al., 2016; Buttle et al., 2016) and the Central and Western United States (Mallakpour and Villarini, 2015; Solander et al., 2017; Rokaya et al., 2018). Positive trend in snowmelt flood frequency in 132 watersheds of Canada (Burn et al., 2016) and for 774 stream gauge stations of the United States (Mallakpour and Villarini, 2015). Some findings indicate a decline in water availability for agriculture in Canada and California due to droughts (Yusa et al., 2015; Pathak et al., 2018).	12%–22% increase (maximum 5-day rainfall at 4C global warming (range of outcomes from HELIX HadGEM3 ensemble, not bias-corrected) 1/100 flood increase in 2050 except for middle and southern North America (Arnell and Gosling, 2016). Future flood frequencies, hazard and risk increae in 40%–60% of most populated 100 cities in Canada (Gaur et al., 2019) (Gaur et al, 2019)
Europe	*Precipitation, Evapotranspiration and Soil Moisture [Projected values are quoted for 4C global warming]*	
	Increased precipitation from 1901 to 2014 (Kumar et al., 2013; Gu and Adler, 2015; Adler et al., 2017). Increased soil moisture in northern and Eastern Europe, decreased soil moisture in southern and western Europe (Dorigo et al., 2017; Gruber et al., 2019).	Increased precipitation in northern Europe, decreased precipitation in southern Europe (Collins et al., 2013b). Increased evapotranspiration in northern Europe, decreased evapotranspiration in southern Europe (Murphy et al., 2018) Decreased soil moisture in southern Europe, and in spring in southern Europe

Cryosphere

A negative trend of 3–9 mm y^{-1} in maximum seasonal snow depth was identified for Northern Europe (Kunkel et al., 2016). Negative trend in snow-dominated duration of -2–3.5 weeks $decade^{-1}$ during 1971–2014 is observed throughout the circumpolar regions of Scandinavia and Russia, Eastern peri-Ural territories (Allchin and Déry, 2018). The snow season now starts 12 days later and ends 26 days earlier compared to 1970 in the Swiss Alps (Klein et al., 2016)

Mean annual glacier mass loss rate accelerated in last decades compared to the second half of 20th century: -0.87 ± 0.07 m w.e. y^{-1} in Central Europe and –0.90 ± 0.57 m w.e. y^{-1} in Caucasus in 2006–2016 (Zemp et al., 2019) compared to mean decadal values of 0.04–0.72 m w.e. y^{-1} and -0.04–1.26 m w.e. y^{-1} correspondingly in 1950–2000 according to estimates with glaciological and geodetic methods (Zemp et al., 2015).

Multidirectional trends in glacial runoff in the Alps (Bard et al., 2015; Huss and Fischer, 2016), decrease in glacial runoff was identified in the Central North Caucasus (Rets et al., in preparation).

Unsustainable pumping of groundwater is now rapidly declining notably in Southern Europe (e.g. (Pulido-Velazquez et al., 2015)).

Glacier volume loss in Central Europe between 2010 and 2100 from 63±11% to 77±12% under RCP2.6 scenarios, from 79±9% to 89±8% under RCP4.5 (Huss and Hock, 2015; Zekollari et al., 2019), and from 94±4% to 99±0 % under RCP8.5 (Huss and Hock, 2015{Shannon, 2019 #885)}(Zekollari et al., 2019).

Maximum glacial runoff has been already reached in the North Caucasus and already reached or projected to be reached by 2030 in Alps, projected to be reached by 2030–2040s in Scandinavia, and by 2050–2060s in Iceland (Huss and Hock, 2018). Glacial runoff is projected to increase by 10–40% in June on the most of the territory, decrease by 10–40% in July, by 40–60% in August, by 20–60% in September, by 5–40% in October by 2090 (Huss and Hock, 2018).

The snow water equivalent is projected decrease more than 40% relative to 1986–2005 in Central and South-Eastern Europe, by 20–40% in the East, and 10–20% in the North when the global average surface temperature rises by 1.5 °C (in 2027, 2026, and 2023 under RCP2.6, RCP4.5, RCP8.5, respectively) (Kong and Wang, 2017).

Runoff and Streamflow

Decreases in the European Russia (Frolova et al., 2017) and the north of Poland (Kundzewicz et al., 2018a), but increases in northern and central Europe (Dai, 2016b) and Eurasian Arctic (Yang et al., 2015a; Bring et al., 2016; Tananaev et al., 2016; Magritsky et al., 2018) as well as in Scotland, Wales, and the UK (Hannaford, 2015)

Variations in runoff exacerbated dry periods across Europe often causing moderate water stress in North Central Europe (Hodgkins et al., 2017).

Decreases in Southern Europe, but increases in Northern Europe (Koirala et al., 2014; Dai, 2016b).

Water scarcity might affect portions of Western Europe, particularly the Iberic Penninsula, and North Central Europe (Arnell and Lloyd-Hughes, 2014; Arnell and Gosling, 2016).

GHMs-based results, grounded on higher agreement, are found for the Rhine, Tagus, Lena (Gosling et al., 2017).

Larger decreases in low flow are projected in Europe (Koirala et al., 2014).

Groundwater	
Decreases in spring discharge in Southern Italy reported by (Diodato et al., 2018). Unsustainable pumping of groundwater is rapidly declining in Southern Europe (Pulido-Velazquez et al., 2015)	-
Water Quality	
-	-
Soil Erosion and Sediment Loss (SESL)	
In the period of 1986–2015, sedimentation rate in dry valley bottoms of the Southern part of Russian plain has become 2–5 times lower than in 1963–1986 due to the reduction of surface runoff during spring snowmelt (Golosov et al., 2018). The results of long-term (2000–2016) monitoring of soil erosion in three different typical agricultural landscapes in Northern Germany indicated that a declining trend of erosion is mostly associated with the consequence of soil conservation management (Steinhoff-Knopp and Burkhard, 2018). Statistically significant correlation was revealed between sediment yield and air temperature for the non-Mediterranean region of Western and Central Europe (Vanmaercke et al., 2015) The sediment dynamics in small rivers of the alpine zone (eastern Italian Alps) mostly depend on extreme floods with the recurrence period >100 years, according to the results of the long-term (39 years) monitoring (Rainato et al., 2017). In the northeastern Italian Alps, climate fluctuations influenced the reconstructed sediment load without any trend for two centuries (1810–2010) (Diodato et al., 2018).	-
Extreme Weather Events and Water-related Hazards (EWEWH)	
Increasing floods in northwestern Europe; decreasing floods in medium and large catchments in southern Europe; decreasing floods in eastern Europe (Do et al., 2017; Blöschl et al., 2019), overall increase (Berghuijs et al., 2017b) Flood events does not show any significant trend in metropolitan area of Barcelona, Spain, due to less signal in precipitation and improvements in flood prevention measures (Cortès et al., 2018)	For example, (Stoffel et al., 2014) demonstrated that in the French, Italian and Swiss Alps, the frequency of rock slope failure is projected to increase due to glacier shrinkage, permafrost warming and thawing. In Peedmont in the European Alps, landslides are projected to occur more frequently in early spring but also to occur in smaller numbers. Rianna et al. (2014) showed that in both RCP4.5

	Increase in frequency of flash flood events (2000–2014) in the town of Pozzuoli, Italy for 1970–2014 due to variation in the rainfall regime (Esposito et al., 2018) Earlier spring floods are reported throughout the Northern Europe (Matti et al., 2016; Vormoor et al., 2016; Blöschl et al., 2017), the European part of Russia (Frolova et al., 2017), the European mountains (Hall et al., 2014; Morán-Tejeda et al., 2014; Kormann et al., 2015). Increases in floods have increased the exposed population and infrastructure making policy makers seek for different protection measures such as restoration of flood plains (Jüpner, 2018). In Northern Europe drought conditions have become less severe (Spinoni et al., 2015; Stagge et al., 2017).	and RCP8.5 scenarios, there is substantial deceleration of slope movements due to precipitation change in future in Orvieto in Italy. 6% – 13% increase (maximum 5-day rainfall at 4C global warming (range of outcomes from HELIX HadGEM3 ensemble, not bias-corrected) 1/100 flood increase in western Europe and decrease in eastern Europe and Scandinavia (Arnell and Gosling, 2016). Flood risk likely to increase. About two thirds of the population of Europe will be exposed to floods and expecting about 50 time the number of fatalities of historic records (Forzieri et al., 2017; Kundzewicz et al., 2017).
Mediterranean	*Precipitation, Evapotranspiration and Soil Moisture [Projected values are quoted for 4C global warming]*	
	Decreased precipitation (Kumar et al., 2013; Gu and Adler, 2015; Adler et al., 2017). Decreased soil moisture (Dorigo et al., 2017; Gruber et al., 2019).	Decreased precipitation (Collins et al., 2013a) Decreased evapotranspiration (Murphy et al., 2018)
	Cryosphere	
	-	-
	Runoff and Streamflow	
	-	Areas of Mediterranean Africa will experience water scarcity under RCP8.5 at 2C (*medium agreement from medium confidence*) (Gosling and Arnell, 2016). Areas of the Iberic Peninsula along the Mediterranean might be affected by Water Scarcity (*medium confidence, moderate evidence*) (Arnell and Lloyd-Hughes, 2014; Gosling and Arnell, 2016).
	Groundwater	
	-	-
	Water Quality	
	-	Future variations in sea level and sea salinity will lead to the lateral intrusion and upcoming effects of seawater intrusion and affect the coastal aquifer system (Romanazzi et al., 2015).

	Soil Erosion and Sediment Loss (SESL)	
	-	-
	Extreme Weather Events and Water-related Hazards (EWEWH)	
	The magnitude of extreme floods varies significantly over the Mediterranean region with a clear contrast between west and east. The western part of the area is much more exposed to high impact and high magnitude events. No significant trend was detected in the frequency and magnitude of extreme floods (Gaume et al., 2016). Weather disasters have been increasing across Mediterranean Europe, especially droughts (Kron et al., 2019). Regional studies suggest an increasing trend in the intensity and frequency of droughts in several parts of the world, such as the Mediterranean (Vicente-Serrano et al., 2014; Spinoni et al., 2015; Stagge et al., 2017)	1/100 flood decrease in 2050 in overall Mediterranean (Arnell and Gosling, 2016). Damages from floods and droughts are likely to progressively increase throughout the 21st century across Mediterranean Europe (Forzieri et al., 2018).
Mountains	*Precipitation, Evapotranspiration and Soil Moisture*	
	-	-
	Cryosphere	
	-	-
	Runoff and Streamflow	
	-	-
	Groundwater	
	-	-
	Water Quality	
	More old carbon loads are observed in high-latitude regions such as the permafrost regions of the Tibetan Plateau which may produce a positive feedback on climate warming (*medium confidence with medium evidence and medium agreement*) (Abbott et al., 2015; Qu et al., 2017). Through the release of historically deposited pollutants, increased meltwater would detach and transport higher levels of persistent contaminants and reduce water quality downstream (*medium confidence with*	Deterioration in high-altitude Asia due to the future decrease in runoff causing by glacier shrinkage and net mass loss (*medium confidence with medium evidence and medium agreement*)(Bliss et al., 2014; Gan et al., 2015).

	medium evidence and medium agreement) (Hawkings et al., 2014; Sharma et al., 2015; Sun et al., 2017; Zhang et al., 2017).	
Soil Erosion and Sediment Loss (SESL)		
	-	-
Extreme Weather Events and Water-related Hazards (EWEWH)		
	-	-

4.3 Sectoral Impacts (Observed and Projected) and Adaptation Interventions due to Changes in Hydrological Regimes

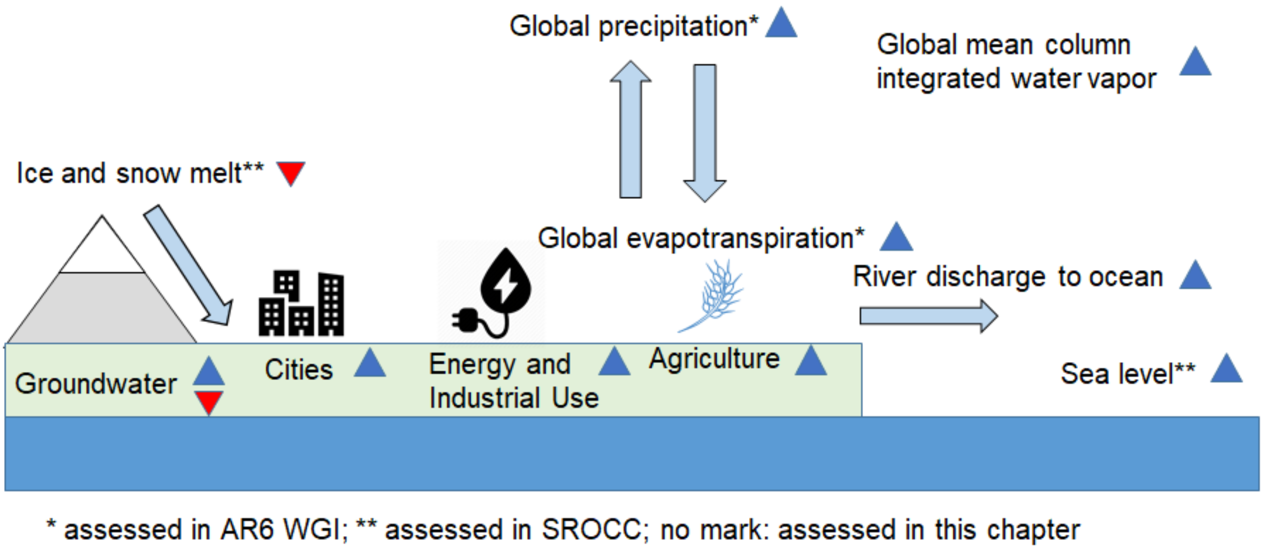


Figure 4.12: Synthesis of projected changes in natural and anthropogenic water components and their drivers. For physical changes, blue (red) refers to increase (decrease) in amount from 1986–2005 to 2080–2100 to update with findings of AR6 WGI. For human usage, blue (red) refers to increase (decrease) in projected usage of different sectors. [PLACEHOLDER FOR SECOND ORDER DRAFT: this figure will be developed as a 3D figure integrating the projected changes in the hydrological cycle and how these will affect and will be affected by sectoral water usage].

4.3.1 Agriculture

4.3.1.1 Observed Impacts in Agriculture

While direct attribution of impacts to anthropogenic climate change remains challenging, negative impacts on the agricultural sector as a consequence of drought, flood or changes in water availability have been reported across regions and crops *(strong evidence, high agreement)*. Positive effects have also been reported, partially linked to water use efficiency through the effects of higher CO_2 concentrations, however negative effects dominate at global scale *(medium evidence, medium agreement)*. The poor have been disproportionally affected, as they often rely on rain-fed agriculture in marginal areas with high exposure, high vulnerability to water-related stress and low adaptive capacity *(medium evidence, strong agreement)*.

AR5 concluded that over the last 30 years reductions in the global agricultural production in the range 1–5 % per decade globally can be linked to climate change, yet studies did not directly connected those reductions to detection and attribution (Porter et al., 2014). AR5 also stated that the increase in CO_2 since pre-industrial times contributed to an observed increase in water use efficiency and yields (*virtually certain*) (Porter et al., 2014). SR1.5 concluded that both the food and the water sectors will be negatively impacted by global warming from 1.5°C to 2°C and these risks could coincide spatially and temporally increasing hazards, exposures and vulnerabilities across people and regions (*medium confidence*) SR 1.5 reinforced AR5 conclusions in terms of projected crop yield reductions especially for wheat and rice (*high confidence*), loss of 7–10% of rangeland livestock globally (*medium confidence*) and increase of risks for small-scale fisheries and aquaculture (*medium confidence*) (Hoegh-Guldberg et al., 2018a)

Agriculture is responsible for 75–84% of consumptive water use, 84% of it comes from rainwater and the remaining 16% from irrigation which accounts for 70% of water withdrawals globally (Willett et al., 2019). Livestock related water consumption is 56% of total agricultural consumptive water use (Weindl et al., 2017).

Water stress and temperature increase are the most important climate drivers that have adversely impacted crop yield in different agro ecological zones (Troy et al., 2015). Hydro-meteorological impacts, at times associated with extremes events as drought attributed to anthropogenic influence (Cai et al., 2015; Otto et al., 2018), on agricultural yields as well as cropping area and intensity, have been reported across regions and for different crops (Iizumi and Ramankutty, 2015; Lesk et al., 2016). Fisheries and livestock have also been negatively impacted by rising temperatures and drought conditions (Naqvi et al., 2015; Islam and Wong, 2017; Weindl et al., 2017). For example, due to drought in the period 1964–2007, cereal production declined by 9–10% globally with a reduction in harvested area of 4.1%, with an increase in the severity of droughts and subsequent vulnerability since 1985 to 2007 (Lesk et al., 2016). Likewise, rice, a major contributor to calories in diets in Asia and Africa, is particularly vulnerable to water-related stress such as flood, salinity intrusion, irrigation water shortage and drought spells (Shrestha and Nepal, 2016; Islam and Wong, 2017; Stuecker et al., 2018).

Particularly the poor, who often are smallholder farmers whose first and only source of livelihood is agriculture and who are situated at low latitudes where the climate is hotter and drier, have been the most vulnerable to observed hydrological changes due to climate change (Juana et al., 2013b; Tambo and Abdoulaye, 2013; da Cunha et al., 2015; Savo et al., 2016; Castells-Quintana et al., 2018). Indigenous and local communities, often heavily reliant on agriculture, have a wealth of knowledge about observed changes. These are important because they shape farmers' perceptions which in turn shape the adaptation measures, they will be undertaking (Tambo and Abdoulaye, 2013; Savo et al., 2016). Farmers' perceived changes in climate, particularly in relation to rainfall, temperature changes and increasing and anomalous seasonal variability, are aligned with hydro-meterological data *(limited evidence, medium agreement)* (Boillat and Berkes, 2013; Esham and Garforth, 2013; Juana et al., 2013b; Nkomwa et al., 2014; Varadan and Kumar, 2014; da Cunha et al., 2015; Dumenu and Obeng, 2016; Savo et al., 2016). For instance, farmers across the globe concur that rainfall variability has a negative impact on water availability both for agricultural and domestic usage (Gandure et al., 2013; Abdullah and Rahaman, 2015; Savo et al., 2016; Su et al., 2017b). Additionally, there is a strong evidence that perceptions of the magnitude of climate induced water related hazards and their impact on agriculture are gender differentiated with women often bearing the brunt of decreased access to water and additional farm work required to sustain one's family (Caretta and Börjeson, 2015; Sujakhu et al., 2016; Su et al., 2017b).

While attribution science has made significant progress in the past years (Section 4.1.2; Chapter 16 this report), integrated studies linking hydro-climatic changes and extreme events to impacts on agriculture remain challenging, given methodological complexities in attributing observed changes in agricultural outcomes, as such outcomes are affected by a number of other factors such as level of technology application, market conditions and food and agricultural policies (Henne et al., 2018).

4.3.1.2 Projected Risks to Agriculture

Agricultural water use is projected to increase globally, as a consequence of global dietary changes, as well as increased water requirements through climate change *(strong evidence, high agreement)*. Some regions may experience increases in suitability for rain-fed production based on mean climate conditions, whoever, with increasing variability in precipitation regimes, risks to rain-fed agriculture increase globally (*strong evidence, high agreement*). CO_2 fertilisation plays an important role in determining future agricultural water demand and yield improvements, but uncertainty remains large *(strong evidence, medium agreement)*. As water restrictions are not fully resolved across agricultural models, uncertainty on limitations to yield increase through water availability remains high and differs from region to region *(limited evidence, high agreement)*.

While there are variations across regions and uncertainty across models, AR5 concluded that irrigation water demand will increase by 2080. It further recognised that vulnerability of rainfed agriculture will further increase as a consequence of climate change and increasing variability. In regions where soil does not pose a limitation to agricultural production, the effects of CO_2 fertilisation may counteract some of the negative impacts of climate change and potentially off-set some of the additional irrigation water demand through increases in water use efficiency (Jiménez Cisneros et al., 2014). SR1.5 concluded with *medium confidence* that effects of increased CO_2 will have an overall negative impact on global food security and both crop and livestock production will be negatively affected by impacts of climate extremes, such as flooding and drought as well as through increased pest attacks and diseases through change in precipitation regimes (Hoegh-Guldberg et al., 2018a). SRCCL further reflected on the potential direct impacts of changes in water availability for food security and additional risks to agricultural production through pests and diseases, which could be exacerbated by both, flood and drought conditions (Mbow et al., 2019).

With agriculture as the largest global water user (4.3.1), agricultural production is strongly linked to adequate water availability to ensure food security (Mancosu et al., 2015). Meeting growing food demand is not only dependent on water resources in terms of quantity, it is affected by and has effects on water quality (Springmann et al., 2018).

Climate change processes, including direct effects of higher atmospheric CO_2 concentrations, as well as the resultant increase in temperatures, changes in precipitation regimes and increased occurrence of extreme events like droughts and floods, affect the relationship of agriculture with water along multiple pathways. These include changes in crop water requirements (Nechifor and Winning, 2019) and crop damages at various stages of growth due to too much or too little water (Raza et al. 2019); direct impacts on crops through extreme events (Leng and Hall, 2019; Schewe et al., 2019); as well as changes in crop water productivity due to changing CO_2 concentration (Deryng et al., 2016).

Most global agricultural models project a decline in agricultural production in the absence of a CO_2 fertilization (CF) effect (Ren et al., 2018; Nechifor and Winning, 2019). Climate-induced losses are projected to both rainfed and irrigated agriculture by mid-century, with global average losses of 2.3% (2035–2065 vs. 1961–1990; A1B: -2.28%; A2: - 2.38%) (Calzadilla et al., 2013). The combined effects of changes in temperature and precipitation may reduce yields by up to 32% by 2100 (RCP8.5), while limiting warming would greatly reduce potential impacts (up 12% yield reduction by 2100 under RCP4.5) (Ren et al., 2018). Yield reductions are more pronounced at lower latitudes and are often induced by drought events (Leng and Hall, 2019).

Globally, especially higher latitude regions are likely to become more suitable for rain-fed agriculture as a consequence of temperature and precipitation increase. Increases in heat days may however counteract some of these potential increases in suitability (Bradford et al., 2017). Locally and regionally, some of those areas with current large rain-fed productions may face strong decreases in suitability, however (regional chapters, Table 4.10) (Bradford et al., 2017; Shahsavari et al., 2019).

To stabilize yields against variations in moisture availability, the most common response is the intensification of irrigation (Section 4.3.1.3). Projections indicate a potential near doubling of irrigation water withdrawals from 2330 km^3 in 2005 to 4950 km^3 in 2095, driven by various factors, including population growth, increase in irrigated agriculture and higher demand for bio-energy crops for mitigation, though development pathways, including the deployed mitigation actions, will have an important influence on these additionally needed volumes (Chaturvedi et al., 2015; Grafton et al., 2015). Increased efficiency of irrigation systems has the potential to reduce non-evaporative losses which would have otherwise flowed downstream as return flows from irrigated land (Malek et al., 2018). There is high agreement that while climate change will lead to changes in water demand in the future, most agricultural water use increase will be driven by socio-economic factors, especially in developing countries (O'Connell, 2017). Where climate impacts on yields are not a consequence of water-limitations (mainly for C4 crops), irrigation cannot offset negative yield impacts (Levis et al., 2018).

There are limitations to a further increase water use, as many regions are already facing water limitations under current climatic conditions (Rockström et al., 2014; Steffen et al., 2015; Kummu et al., 2016). In the light of the volume of irrigated agriculture globally and the projected increase in water requirements for food production, increasing water productivity, thus improving the ratio of water used per unit of agricultural production, is an essential component in order to meet agricultural water demand globally (see also Section 4.3.1.3) (Jägermeyr et al., 2015; Jägermeyr et al., 2017; Zheng et al., 2018a). Assuming a doubling of global maize production by 2050, Zheng et al. (2018a) find that increasing water productivity could reduce total water consumption compared to a BAU scenario by 20 to 60%, for example. Under economic optimization assumptions, shifts towards less water intensive and less climate sensitive crops would be optimal in terms of water use efficiency and absolute yield increases, however this could pose risks to food security as production shifts away from main staple crops (Nechifor and Winning, 2019).

CF has the potential to offset the negative impacts on yields to some extent, partly through increasing water efficiency (Calzadilla et al., 2013; Deryng et al., 2016; Ren et al., 2018; Nechifor and Winning, 2019). Rain-fed C3 crops benefit more strongly from this effect (Levis et al., 2018). Combined results from field experiments and global crop models show that CF could reduce consumptive water use by 4–17% (Deryng et al., 2016). While there is *medium agreement* about the positive impact of CF on crop yields, and water use efficiency, there are divergent estimates about the magnitude of this effect (Calzadilla et al., 2013; Wesseh and Lin, 2017).

Large uncertainties remain with regard to the representation of water supply on crop yield, with only few models being able to fully represent agricultural management and physical processes relevant to assessing irrigated yield (Elliott et al., 2014; Frieler et al., 2017; Winter et al., 2017). Models also currently largely fail to account for potential water-saving mechanisms and increases in water efficiency of C4 plants under higher CO_2 concentrations, thus potentially underestimating yield responses under drought conditions (Fodor et al., 2017). Models currently also do not differentiate crop responses to elevated CO_2 under temperatures and hydrological extremes (Deryng et al., 2016).

Risks to livestock production manifest through changes in the availability of as well as increasing requirements for drinking water for livestock and through changes in the overall availability as well as reduced nutritional value of forage and feed crops (Zougmoré et al., 2016; Henry et al., 2018).

In addition to global trends in water and agriculture, regional risks and trends are diverse (see regional chapters). Climate change and increasing variability will affect agricultural production in all world regions, leading to yield loss along several lines of impact pathways. Strong increases in irrigation water demand are projected, both as a consequence of climate change as well as socio-economic development. Large uncertainties remain with regard to changing water requirements for agricultural production, stemming from uncertainties of pathways and associated climate outcomes, effects of CF on water use as well as from limitations of agricultural models to fully represent available water resources and associated limitations.

4.3.1.3 Water-related Adaptation in the Agricultural Sector

Water-related adaptation in the agricultural sector is widely documented, with irrigation expansion and agricultural water management among the most common adaptation measures adopted (*robust evidence, high agreement*. A number of constraints limit further implementation, including threat of surface and groundwater overexploitation that limits further irrigation intensification (*robust evidence; high agreement*).

AR5 reported on a range of available hard and soft adaptation with regard to water-related adaptation, including technological as well as local and indigenous response options, however there was a strong focus on potential options as well as modelling studies and documented implementation is limited (Noble et al., 2014a; Porter et al., 2014). Assessing the feasibility of different irrigation measures as adaptation, SR1.5 (de Coninck et al., 2018a) found mixed evidence across feasibility dimensions.

There is robust evidence that water related adaptation is occurring in the agricultural sector. Observed adaptation measures are highly contextual, flexible, incrementally adjusted and based on perceived hydrological changes by the farmers (Boillat and Berkes, 2013; da Cunha et al., 2015; Rey et al., 2017). As many adaptation-related decisions are taken at the local and community level due to the immediacy and magnitude of experienced climatic changes, implementing community-based adaptation strategies and designing future local adaptation measures can heighten the chance of positive societal outcomes while also decreasing vulnerability and risk (Ajani et al., 2013; Calzadilla et al., 2013).

Among documented measures, the most commonly reported include irrigation; rainwater harvesting and contour agriculture (Caretta and Börjeson, 2015; da Cunha et al., 2015; Lebel et al., 2015). Further frequently implemented measures include diversifying crops e.g. planting drought-resistant varieties, intercropping, shortening of growing seasons, manipulating planting dates; agricultural intensification – by boosting yields over space and time; investing in irrigation technology, conserving soil and water (e.g. mulching, small-scale water harvesting and management); seasonal and permanent migration; diversifying one's livelihood with off-farm employment; agroforestry and afforestation (Ajani et al., 2013; Boillat and

Berkes, 2013; Calzadilla et al., 2013) (Caretta and Börjeson, 2014; Lasco et al., 2014; Sujakhu et al., 2016; Altieri and Nicholls, 2017; Shinbrot et al., 2019).

Approximately 40% of global yields come from irrigated agriculture, with irrigated areas having doubled over the last 50 years and now constituting around 20% of total harvested area (FAO, 2018; Meier et al., 2018). Further expansions of irrigated areas over the coming century are projected, both due to expanding agricultural areas and shifting from rain-fed to irrigated practice (Malek and Verburg, 2018; Nechifor and Winning, 2019). Different types of irrigation techniques are associated with a large spread in irrigation water productivity. Replacing inefficient systems has the potential to reduce average non-beneficial water consumption by up 76%, while maintaining yield production (Jägermeyr et al., 2015). A number of adjustments can improve water use efficiency, including extending irrigation intervals, shortening the time of watering crops or reducing the size of the plot being farmed (Caretta and Börjeson, 2015; da Cunha et al., 2015; Dumenu and Obeng, 2016). Deficit irrigation has been shown to be an important contribution to improving water productivity (Zheng et al., 2018a). For the Mediterranean, significant improvements in irrigation efficiency will be needed to counteract projected drying trends and ensure future food security; especially drip and deficit irrigation can contribute to increasing regional crop production under drying conditions (Malek and Verburg, 2018). Further technical improvements of irrigation techniques have the potential to reduce water consumption (Deligios et al., 2019), yet, overreliance on irrigation can deplete groundwater and trigger food insecurity, once water resources fall below required levels (Zaveri et al., 2016).

The use of non-conventional water sources, i.e. desalinated and treated wastewater, is emerging as an important component of increasing water availability for agriculture (DeNicola et al., 2015; Martínez-Alvarez et al., 2016; Martínez-Alvarez et al., 2018) (DeNicola et al., 2015; Martínez-Alvarez et al., 2016; Martínez-Alvarez et al., 2018; Morote et al., 2019). Such practices come with risks to water quality and consequent potential impacts on soils and production, however, which need to be closely monitored (Martínez-Alvarez et al., 2016; Martínez-Alvarez et al., 2018).

Further measures aimed at using limited available water more efficiently include rainwater harvesting, which can improve soil fertility and prevent soil erosion by enhancing soil moisture (Juana et al., 2013b; Altieri and Nicholls, 2017); contour agriculture (paddy farming) which supports the retention of soil moisture and concomitantly promotes better drainage (Ajani et al., 2013; Altieri and Nicholls, 2017). Such measures may limited by reductions in rainfall below critical values (Haque et al., 2016), as well as access to funding for implementation, especially storage tanks (Ajani et al., 2013; Lebel et al., 2015; Sujakhu et al., 2016). Moreover, success over large areas and under changing climatic conditions is yet to be documented (Lebel et al., 2015). Further changes in agriculture management such as adjusting crop type, growth season and planting time are also potential adaptation measures to hydrological change (Cai et al., 2015; Mo et al., 2017).

To ensure sufficient freshwater availability for livestock production, both improved management as well as technological investments, for example in storage and dams will be required (Henry et al., 2018). Specific options include diversification towards more resilient animals; agroforestry and crop-livestock mix approaches; as well as relocation/retreat (Rojas-Downing et al., 2017). Improving livestock productivity has a large potential to reduce livestock production water footprints to adapt to reductions in water availability (Rojas-Downing et al., 2017; Weindl et al., 2017).

4.3.2 Energy

4.3.2.1 Observed Impacts on Energy Sector

Hydropower is a largely a non-consumptive use of water and long regarded as a low emission source of renewable energy. Hydropower costs are being affected by multiple climate impacts such as floods, flash flood (including GLOFs); droughts, rising water temperature, and heatwaves (*medium evidence and medium agreement)*. However, climate change is not the only reason for escalating costs – other reasons include improper planning and execution of projects, lack of climate consideration in hydropower plant design and not adequately budgeting for social costs of mitigation such as rehabilitation of displaced population and sharing hydropower benefits with local people *(robust evidence; medium agreement)*.

AR5 found that climate change hampers hydropower generation through changes in the mean annual streamflow, shifts of seasonal flows, and increases of streamflow variability (including floods and droughts), as well as by increased evaporation from reservoirs and changes in sediment fluxes (Jiménez Cisneros et al., 2014). AR5 suggested that as hydropower can play a key role in ending energy poverty, it is important to ensure the environmental and social sustainability and climate resilience of water storage and energy generation infrastructure of hydropower (Niang et al., 2014). SR1.5 stated that construction and operation of hydropower plants can fragment rivers and alter natural flows reducing water and ecosystem quality and create water disputes in basins with up- and down-stream users (Roy et al., 2018). If further specified that hydropower plays an important role in energy access for water supply in developing regions, can contribute to water security, and has the potential to reduce water demands if used without reservoir storage to displace other water-intensive energy processes (Roy et al., 2018). SROCC stated with *high confidence* that changes in the terrestrial cryosphere in the Arctic and high mountain regions have distressed human societies through mostly adverse effects on freshwater supply, hydropower, and food security since the mid-20th century (Hock et al., 2019). SROCC revealed that hydropower facilities have experienced changes in seasonality, and water availability from high mountain areas of Central Europe, Iceland, Western US/Canada, and Low Latitude Andes (Pörtner et al., 2019).

Large volumes of water are used throughout the energy sector (Fricko et al., 2016), making it one of the most vulnerable sectors to constraints in the water supply (Tan and Zhi, 2016; Williams et al., 2019). In 2016, 98% of total electricity worldwide came from thermoelectric power and hydropower, which are the most vulnerable to water stress (van Vliet et al., 2016b). Hydropower is the largest source of renewable electricity globally with relatively low maintenance costs and is preferred as a climate-friendly investment in many countries (WEC, 2016). While reducing emissions relative to fossil fuel-based energy production in most world regions, emerging evidence suggests that hydropower dams, especially in tropical regions, may be associated with substantial GHG emissions (*medium evidence; medium agreement*) (Wang et al., 2017c; Räsänen et al., 2018; Song et al., 2018). Though hydropower is a low carbon technology, investments in the hydropower sector fell to their lowest level in over a decade, a trend which may continue (IRENA, 2019).

In last decade, climate change-induced drought, falling water level, and water scarcity substantially affected hydropower and electricity generation across the globe (Bartos and Chester, 2015; Wang et al., 2017c; Eyer and Wichman, 2018; Huber, 2019; UNDRR, 2019). Climate variability is affecting major hydropower dependent countries such as Brazil, Norway and sub-Saharan Africa (Conway et al., 2017). Though truncated river discharge, decreased precipitation and increased evapotranspiration make hydropower generation vulnerable (van Vliet et al., 2016a), the majority of power producers does not account for climate change impacts making them susceptible to climate-induced water stress and direct them to overestimate their ability to meet future electricity needs (Bartos and Chester, 2015; Cherry et al., 2017).

4.3.2.2 Projected Risks to Energy Sector

Change in temperature, precipitation and river discharge will make hydropower susceptible to changing climate and reduce hydropower generation and production potential globally which has a substantive social and economic cost (*medium evidence, medium agreement*).

AR5 stated with high confidence that hydropower production is likely to decrease in all sub-regions except Scandinavia which will affect future renewable energy production and transmission (Kovats et al., 2014). SR1.5 revealed that climate change will positively affect the hydropower production of Baltic and Scandinavian countries while Greece, Spain, and Portugal will see approximately 10% reduction in hydropower potential under 2C warming which can be reduced by half by limiting the global warming to 1.5C (Hoegh-Guldberg et al., 2018a). SROCC stated with medium confidence that projected changes in the terrestrial cryosphere will affect water resources and their uses, such as hydropower, irrigated agriculture, and water quality in high mountain areas and downstream regions and food security and livelihoods in the Arctic (Hock et al., 2019). SROCC concluded with high confidence that altered amount and seasonality of water supply from snow and glacier melt will increasingly distress hydropower production (Pörtner et al., 2019). AR6 WG I finds that reduction in precipitation will have an adverse impact on the total regional water resources as well as hydropower generation (Douville et al., in preparation).

Though the potential of hydropower is noteworthy in reducing emission and attaining green growth, the susceptibility of hydropower to climate change is found to be increasing at the global and regional scale (Tarroja et al., 2016; Turner et al., 2017; Savelsberg et al., 2018). It is anticipated that climate change will alter water supply and water temperature, which increase the thermoelectric plants' vulnerability to water shortage (Koch et al., 2014; Ranzani et al., 2018; Zhang et al., 2018). Insufficiency for cooling is projected as a consequence of changes in river flow regimes, particularly a general decrease in low flow levels, and to increased water requirements for thermoelectric power generation and other sectors. Grid insecurity can impede smooth and equitable (i.e., with climate justice and environmental justice principles informing policies and actions) transition in the energy sector, thus further impeding our ability to mitigate either the climate crisis or the water crisis (Fricko et al., 2016; Zhou et al., 2018; Burillo et al., 2019).

Emerging studies suggest that hydropower is significantly vulnerable to changes in rainfall, water discharge, heating and cooling degree day and sunshine duration (Fan et al., 2018; Savelsberg et al., 2018). A coupled hydrological–electricity modeling framework with data on 24,515 hydropower power plants shows reductions in usable capacity for 61–74% worldwide for 2040–2069 (van Vliet et al., 2016b). Most hydropower plants are currently situated where mean annual streamflow is declining and where water temperatures are projected to be increased in the days to come (Cronin et al., 2018). It is likely that potential increases in the severity of streamflow droughts (Trenberth et al., 2013; Prudhomme et al., 2014) and heatwaves (Christidis et al., 2014) under changing climate will directly impact energy security at global and regional level (van Vliet et al., 2016a). Modeling studies suggest that climate change will cause to fall global hydropower generation capacity of up to 6.1% under RCP8.5 in 2080 (van Vliet et al., 2016c). Nevertheless, the impacts of climate change on hydropower production will differ and progressively increase along with temperature change (Koch et al., 2014; Zheng et al., 2016; Totschnig et al., 2017; Tobin et al., 2018) (*medium confidence, medium agreement*).

The future impacts of climate change have the potential to jeopardize hydropower investments and green jobs if there is a shortfall of adaptation innovation and climate-resilient technology (Cervigni et al., 2015; Conway et al., 2017; IRENA, 2019) (*medium evidence, medium agreement*). As the power sector accounts for 10% of total global water withdrawals and projected to reach more than double by 2040 (IEA, 2016), Indian subcontinent, Northern China, Spain, the West of the US, Australia and several basins in Africa will be in the risks of water shortages (Gaupp et al., 2015) which will adversely impact the power sector as well *(medium evidence, medium agreement)*. Hydropower reservoirs also supply water for non-power uses such as flood control, drought management, and water supply for municipalities and food production; it is projected that climate change will challenge the future hydropower potential (IHA, 2018). Diversion of water for irrigation and hydropower upstream may affect water availability for energy generation and agriculture downstream (Zhang et al., 2018).

4.3.2.3 Water-related Adaptation in Energy Sector

In some regions, hydropower plants could be adapted to decreased water availability to some extent by increasing efficiency and technological up-gradation (*medium evidence, medium agreement*). The seasonal weather forecast, modernization of turbines and generators, artificial intelligence, blockchain technology, machine learning, and cyber-physical systems can enhance adaptation by improving the performance of turbines, plants and equipment, increasing flexibility and operational efficiency (*limited evidence, medium agreement*).

The incorporation of information from climate and water models into current and future hydropower planning and development is essential to ensure a resilient energy sector (Bekoe and Logah, 2016; Carvajal et al., 2017; de Jong et al., 2018; Eyer and Wichman, 2018; Arango-Aramburo et al., 2019; Carvajal et al., 2019; Tarroja et al., 2019). As electricity generation is vulnerable to climate change, design changes, dam management, improved cooling systems, power plants efficiency, and technological upgrade can provide necessary adaptation solutions and build resilience (Mo et al., 2014; Byers et al., 2016; Cronin et al., 2018) (*medium evidence, medium agreement*). The more efficient the power plants use of water, the less they will be faced with climate-induced water scarcity (Byers et al., 2016). For instance, higher concentration on resource-efficient and climate-smart hydropower plant design, construction, management, and technology can mitigate the future impacts of climate change on hydropower (Byers et al., 2016; van Vliet et al., 2016b; Cronin et al., 2018).

A modelling study (van Vliet et al., 2016c) suggested that increasing the efficiency of hydropower plants by up to 10% could offset the impacts of decreased water availability in most regions such as North America, Europe, Africa and Asia in the 2020s and 2050s under RCP2.6 and RCP8.5, although power outputs reductions were still projected on monthly scales. A 10% increase in efficiency did not completely offset reduced water availability in South America and Australia, although this is in the context of large uncertainties projected changes in power production due to streamflow changes.

Thermoelectric production systems require water as a coolant, so where this is provided by rivers, these may also need to adapt to changes in streamflow. Adapting power plant cooling technology can considerably slash the global freshwater withdrawals and thermal pollution (Fricko et al., 2016). A modeling study (van Vliet et al., 2016c) suggested that a 20% increase in efficiency of thermal power plants would not be enough to offset the impacts of decreased flows and that changing fuel from coal to gas may be a more effective form of adaptation. Efficiency enhancement is projected to be most effective in Africa and Australia, where a relatively high number of coal-powered plants could be substituted for gas, but insufficient to offset the impacts of decreased flows in North America, Europe, and Asia under RCP8.5 by 2050 (van Vliet et al., 2016c). Changing the source of coolant from river water to sea water may also be an effective adaptation in coastal power plants (van Vliet et al., 2016c). Other alternative methods of cooling include recirculation of water used for extracting coal, oil or gas, the use of treated sewage water, and the use of methods that do not use or lose water, such as dry cooling towers, regenerative cooling and heat pipe exchangers (Siebert et al., 2010; US Department of Energy, 2013).

Conservation of surplus water in the wet season can be one of the most effective adaptations for hydropower to climate change (Hasan and Wyseure, 2018). Hydropower projects can be treated as a financing instrument for multipurpose reservoirs which can be a promising adaptation to climate-induced water availability, and support food and energy production and navigation service in the dry season (Berga, 2016). A slight increase in installed capacity and modernization of turbines and generators can help to prevent the reduction of hydropower generation due to change in water temperature and river flow (Koch et al., 2015). Installation of closed-circuit cooling systems in the thermal power plants can help to alleviate the negative impacts of climate change on power production (Koch et al., 2014). To increase resilience, implementation of protection against flooding at power plant sites can provide adaptation to increased heavy precipitation (Siebert et al., 2010; Energy UK, 2015).

Because hydropower often faces social resistance, benefit sharing has been practiced in different parts of the world (Balasubramanya et al., 2014; Suhardiman et al., 2014; Wichelns, 2014; Shrestha et al., 2016a) to enhance its social acceptability as an adaptation measure. For existing plants, improved hydro-metrological data, early warning systems, low-cost protective structures, better sedimentation management, turbine recoating, insurance can be a beneficial adaptation option. For planned hydropower plants climate-smart design considering the trade-off between early adaptation costs and future benefits can be useful (NDRI, 2017). Further, there are several barriers to adaptation such as economic, social and institutional factors, including market-policy-governance failures and behavioral barriers which is critical to effective adaptation in hydropower (Cimato and Mullan, 2010; NDRI, 2017). However, uncertainties in future climate also affect the scope of adaptation needed during the hydropower design phase (NDRI, 2017).

The insufficient integration of climate change in the planning and design of power and water infrastructure could imply drastic hydropower revenue cuts between 5% to 60% in Africa under drying climate conditions; and as a consequence, increase the consumer expenditure for energy up to 3 times compared to baseline values (Cervigni et al., 2015). The differences in hydrological conditions, topography, financial capability, project size, climate nexus interconnections, and environmental impacts require integrated adaptation strategies during hydropower planning can build hydropower resilience to climate change impacts (Cervigni et al., 2015; Berga, 2016; van Vliet et al., 2016c).

4.3.3 Water, Health, and Sanitation (WaSH)

4.3.3.1 Observed Impacts on WaSH

Climate change, through its impact on water availability and quality, affects WaSH and human health by increasing the risk of diseases, directly or indirectly *(robust evidence,high confidence)*.

AR5 concluded that the health effects of climate change were relatively small, yet not well quantified. However, an increase in heat-related mortality and decrease in cold-related mortality in some regions as a result of warming was indicated (*medium confidence*). Additionally, local changes in temperature and rainfall altered the distribution of some waterborne illnesses and disease vectors (*medium confidence*) (Smith et al., 2014).

Increasing variability in rainfall, increasing temperatures, and likely higher than average sea-level rise are impacting freshwater, livelihood and household security by polluting available surface freshwater and destroying sanitation infrastructures, mainly in developing countries (Hadwen et al., 2015). Temperate regions are increasingly experiencing the spread and transmission of diseases usually associated with warmer climates including waterborne and water related diseases like cholera, malaria and schistosomiasis (Davies et al., 2014; Gbalégba et al., 2017; M'Bra et al., 2018; Walker, 2018). Due to increasing droughts, rainwater collection for household usage has become more common. Tanks where water is stored however, contain pathogens such as *Salmonella spp., Campylobacter jejuni, Pseudomonas aeruginosa* and more others have been identified indicating an increasing future risk of infections (Walker, 2018). In water scarce areas or periods, wastewater has become an option to address water scarcity in the agricultural sector and to conserve water resources (Dickin et al., 2016; Faour-Klingbeil and Todd, 2018), creating a risk for farmers' and consumers' health (Contreras et al., 2017; Jaramillo and Restrepo, 2017; Lam et al., 2017; Adegoke et al., 2018; Faour-Klingbeil and Todd, 2018; Khalid et al., 2018). Wastewater contains potentially toxic elements such as chromium, lead, mercury, and parasitic worms, which induce severe risks to human health (Hu et al., 2017; Khalid et al., 2018). Increased exposure to water related hazards and drought has repercussions on mental health and has been linked to violence and suicides (Padhy et al., 2015).

There is strong evidence that Indigenous concepts of health and wellness fundamentally differ from Western conceptions of health. Relationship to traditional lands and waters is regarded as fundamental to indigenous peoples' physical, mental and spiritual wellbeing (Bowles, 2015; Ford et al., 2016; Belfer et al., 2017; Jones et al., 2019). Recognition of this relationship is essential to understanding climate-related impacts on freshwater to indigenous peoples' health and to the notion of risk (Bowles, 2015; Nursey-Bray and Palmer, 2018) *[high confidence, medium evidence]*. Freshwater has particular significance for Indigenous communities not only for physical health but also because it is often held in deep, genealogical and spiritual relationship by indigenous groups. In Aotearoa-New Zealand, Whanganui River tribes express this as "ko au te awa, ko te awa, au". "I am the river; the river is me." (Te Aho, 2010; Salmond et al., 2019). Hence when water bodies are unwell, so also are the people.

The impact of WaSH deficiency on health and wellbeing is differentiated along gender lines with women, elderly and children being more negatively affected than others *(very high confidence)* (Davies et al., 2014; Sekhri and Storeygard, 2014; Hutton and Chase, 2016; Tong et al., 2016; Abid et al., 2018; Mpandeli et al., 2018; Kher and Aggarwal, 2019). For instance, women are the most exposed to wastewater usage in agriculture as they are in direct contact with chemical and microbiological contaminants used for irrigation, organic pollutants and pesticides that particularly affect pregnant and lactating women. In India for example, where women are facing enormous social gender abuse, water deficiency increase their dowry deaths (Sekhri and Storeygard, 2014). Table 4.5 below synthetizes findings from different review papers for gender dimension of vulnerability to different climate change outcomes and impacts on WaSH.

Table 4.5: Gender differentiated vulnerability to water induced disasters and its impacts on WaSH.

Climate change outcome/impact on WaSH	Region-Country	Gender dimension of vulnerability	References
Wastewater use in agriculture due to water scarcity	Developing countries	In developing countries, especially in Africa, most farmers are women and work on less fertile land than their male counterparts, due to gender imbalance/prejudice. They are then the most exposed to wastewater pollutants and pesticides used	Abid et al. (2018)

Water supply change	Global; India sub-Saharan Africa,	Water scarcity mostly affects women, as they must collect, transport and store water. Every day, 200 million hours are spent by women around the world carrying water to their homes. 63% of women in sub-Saharan Africa collect water compared to 11% of men in rural areas and about 29% of women collect water compared to 10% of men in urban areas. For the household water supply, women must work tirelessly at the expense of their health, time and education, depriving them of socioeconomic and political power, as well as opportunities for advancement in India, a decline in annual rainfall increases reported dowry deaths of women.	Kher and Aggarwal (2019); Sekhri and Storeygard (2014); Abid et al. (2018)
Increase of floods events	Global; Africa, Asia	Women and children are the main victims of climate change related disasters, being floods events or drought. They face many social, educational and employment, privacy and health problems. Women face poverty more than men in the aftermath of disasters. Mortality rate for women and children is 14 times higher than that of men in natural disasters. Flooding increases the prevalence of waterborne diseases. It also increases mortality and morbidity rates and increases women's care responsibilities. In the event of a flooding, women are more vulnerable to the effects of migration. In least developed countries, the number of female deaths is higher during migration due to cultural, social, religious and behavioral restrictions, insufficient or non-existent access to information and precarious socio-economic status.	Kher and Aggarwal (2019); Abid et al. (2018)
Decrease of Sanitation and health risk	Global; Africa; Asia	Women are involved in the daily disposal of household waste. In regions such as sub-Saharan Africa where there are no appropriate disposal methods and where disposal is done by primitive burning and burial methods, many waterborne and airborne diseases are prevalent among women. In areas where droughts are frequent, HIV cases are more frequent because people living in these areas suffer from malnutrition and develop a weak immune system that makes them more vulnerable to HIV/AIDS. Pregnant women are more likely to get malaria. These women easily develop anemia and their infants are more likely to be born with low birth weight and a weak immune system. In many rural and socio-economically disadvantaged areas, where groundwater is contaminated with arsenic, several health problems appear in women, such as lesions, brown spots on hands and feet, hardening of the skin, loss of sensation and swollen limbs Sanitation practices include also carrying water, washing, bathing, menstrual management, and changing clothes. It is during these activities that rural women encounter three broad types of stresses; environmental, social and sexual. These stresses may be exacerbated by climate-induced increase in water scarcity.	Abid et al. (2018), Kher and Aggarwal (2019)

4.3.3.2 Projected Risks to WaSH

The incidence rate of WaSH related diseases is projected to increase in most part of the world mainly in the developing world due to climate change *(Medium to robust evidence, medium to high agreement)*.

Based on AR5, globally over the 21st century, the magnitude and severity of negative impacts of climate change on WaSH are projected to increasingly outweigh positive impacts (*high confidence*) and climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Evidence is growing that projected climate change will lead to more water scarcity or overflow and related WaSH deficiencies. Much of the impact on WaSH is likely to occur by amplifying existing risks related to exposure (Smith et al., 2014).

The incidence rate of WaSH related diseases is projected to increase in most part of the world mainly in the developing world due to climate change *(Medium to robust evidence, medium to high agreement)* (Hodges et al., 2014; Asante, 2015; Ebi and Nealon, 2016; Baylis, 2017; Kohlitz et al., 2017; Ryan et al., 2019). Increased hydrological impact of climate-change induced droughts will lead to water flow decrease that may create water ponds for diseases vectors breeding (Boucher et al., 2015; Williams et al., 2015; Aloysius et al., 2016; Haarsma et al., 2016; James et al., 2017; Sarr and Camara, 2017). All of these projected impacts of climate change on WaSH affect differently gender lines with women, elderly, children and poor countries being more negatively affected than men and developed countries (Sekhri and Storeygard, 2014; Hutton and Chase, 2016; Abid et al., 2018; Kher and Aggarwal, 2019).

According to future climate projections, many WaSH related diseases will increase in the regions of the world where they were already prevalent (see Table 4.10).

4.3.3.3 Water-related Adaptation in WaSH

The poor have been disproportionally affected by hygiene and Sanitation deficiencies, as they often rely on rain-fed agriculture or live in marginal areas with high exposure, high vulnerability to water-related stress, and because of their limited access to resources and services they have low adaptive capacity (*medium evidence, strong agreement*)

AR5 indicated that the most effective vulnerability reduction measures for health in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*) (Smith et al., 2014).

The sustainable development goal (SDG) number 6 focuses on the need to address the issue of water called for the essence of access to drinking water and sanitation by the year 2030 (Howard et al., 2016). In response to the threat posed by climate change induced water hazards on sanitation and health systems globally, numerous countries have directed their efforts towards improvement of water quality and supply as it is paramount to avoid the break out and spread of waterborne diseases due to reduced water availability for hand washing after defecation and before eating (Bain and Luyendijk, 2015; Dey et al., 2019). Some observed adaptation strategies to WaSH deficiencies in Africa, Asia and Pacific Island are related to holistic management and efficient use of available water resources and population migration (Islam et al., 2014; Hadwen et al., 2015; Alhassan and Hadwen, 2017). All of these are gender imbalanced with more threats on women (Abid et al., 2018; Kher and Aggarwal, 2019). While the use on wastewater in agriculture appear to be an adaptation strategy to water shortness, it is important that such activities been accompanied by communities' information and sensitization on the related health risk in order to decrease exposition and risk (Jaramillo and Restrepo, 2017).

4.3.4 Urban, Peri-Urban, and Municipal Sector

4.3.4.1 Observed Change in Urban, Peri-urban and Municipal Sectors

Given that more than half of the world population is living in cities, urban water systems are crucial for safe water provision. Rapid population growth, urbanisation, ageing infrastructure, and changes in water use are more likely to be responsible for increasing the vulnerability of municipal water services to shortage or excess than climate change (*medium confidence, medium evidence*). Hence, while this sector is vulnerable to climate change, observed changes in water supply, sewage and drainage cannot be solely attributed to climate change (*high confidence, medium evidence*).

AR5 found that urban climate change risks are increasing; however, the report was focused on projected rather than observed impacts on water supply, sanitation and drainage in urban areas (Revi et al., 2014).

SR1.5 was similarly concerned with projected impacts but noted that urban areas are at risk of variability in precipitation, as well as indirect risks from interactions between urban and natural systems (Hoegh-Guldberg et al., 2018a). SRCCL concluded that urbanisation increases extreme rainfall events over or downwind of cities, where paving results in high surface runoff of water (de Noblet-Ducoudre et al., 2019).

Globally, nearly all net population growth is taking place in cities and the world is becoming increasingly urbanised, created new and difficult challenges for urban water management. Over half (54%) of the global population currently lives in cities (WWAP, 2018). The extension of public water services does not always keep pace with rapid urbanization, in part because water infrastructure is the most expensive infrastructure in cities (Koop and van Leeuwen, 2017), leading to a variety of water-related problems, such as inadequate water supply, lack of sanitation, failing stormwater management, and ecosystem degradation (van Ginkel et al., 2018).

In developing countries, there are significant discrepancies in service provision between formal and informal areas in cities (WWAP, 2018; Makarigakis and Jimenez-Cisneros, 2019). Although the overall population living in urban slums worldwide fell from 28% in 2000 to 23% in 2014, in absolute terms, the number of dwellers living in slums rose from 792 million to an estimated 880 million over the same period. In Least Developed Countries (LDCs), nearly two-thirds (62%) of urban dwellers live in slum conditions. Slums remain most pervasive in Sub-Saharan Africa (WWAP, 2018), where some cities in Kenya, Tanzania, Zambia and Zimbabwe have regressed in access to improved water sources between 1990 and 2015 (Dos Santos et al., 2017). In peri-urban areas of South Asia and Mexico, peri-urban water sources often become major providers of groundwater and surface water for growing urban needs, and dumping sites for solid urban waste and polluted water, further diminishing the water security of residents (Roth et al., 2019; Soto-Montes-de-Oca and Alfie-Cohen, 2019).

People living in informal settlements tend to pay a much higher price for water than those who receive water from a piped network (WWAP, 2018; Makarigakis and Jimenez-Cisneros, 2019; WRI, 2019). Among slum populations, women tend to be responsible for water collection – for example, a study in the informal settlements of Ougadougou in Burkina Faso found women are responsible for water collection in 84% of sampled households (Dos Santos et al., 2017). In such settlements, women are therefore more vulnerable to climate-linked water insecurities (e.g. (Kher et al., 2015; Gambe, 2019).

In most of the cases outlined in Table 4.6, rapid population growth, urbanisation, ageing infrastructure, and changes in water use are more likely to be responsible for increasing the vulnerability of municipal water services to shortage or excess than climate change (*medium confidence, medium evidence*). For example, the 2014/15 drought event in Sao Paulo, Brazil, was more likely to have been driven by water use changes and population growth, than climate change, according to a multimethod approach (Otto et al., 2018). A literature review found that the severity of urban pluvial flood disasters in Beijing, China could be attributed to management failure, and rapid urbanisation, as well as climate change (Jiang et al., 2018). Water insecurity in peri-urban settlements in South Asia arose from governance, demographic, and economic problems, and was only partly attributed to climate change (Roth et al., 2019). Water reallocation projects appear to be focused in regions with high levels of urbanization (North America) and rapidly urbanizing population centres (Asia) (Forino et al., 2017).

Table 4. 6: Examples of observed changes in the urban, peri-urban and municipal sector since AR5 (city, country)

Region	Water Supply	Sewage	Drainage
Africa	Cape Town, South Africa: Shortages (Otto et al., 2018)	-	Warri, Nigeria: Flooding (Odemerho, 2015)
Asia	Hyderabad, India: Shortages (Roth et al., 2019)	-	Beijing, China: Flooding (Jiang et al., 2018)
Australasia	Melbourne, Australia: shortages (Henley et al., 2019)	-	-
Central and South America	Lima, Peru: Rural-urban water transfers (Hommes and Boelens, 2017)	-	Sao Paulo, Brazil: Shortages (Otto et al., 2018)

Europe	Istanbul, Turkey: Water conservation (Buurman et al., 2017)	-	Birmingham, United Kingdom: Flooding (Adedeji et al., 2019)
North America	Mexico City, Mexico: Declining groundwater levels (Chelleri et al., 2015)	Milwaukee, Wisconsin, USA: Faecal pollution(Templar et al., 2016; McLellan et al., 2018)	-
Small Islands	Funafuti, Tuvalu: Reliance on rainwater harvesting (Gheuens et al., 2019)	-	Georgetown, Guyana: Flooding (Mycoo, 2014)

Given the vulnerability to water-stress of slums and peri-urban areas, further research is necessary to determine the climate impacts on these areas where a growing proportion of the world's population live (e. g., (Roth et al., 2019). Also see Cross-Chapter Box ILLNESS in Chapter 3.

4.3.4.2 Projected Exposure to Climate Change in Urban, Peri-urban and Municipal Sectors

Projected future hydrological changes – both in terms of increase and decrease of stream flows will threaten existing water infrastructure in most regions *(very high confidence)*. For instance, projected increased rainfall intensity will impact sewage systems that lack capacity to process the additional load *(Dettinger et al., 2015; Neumann et al., 2015b; Shahid et al., 2015; Howard et al., 2016)*. In both developed and developing countries, faecal sludge management systems will be vulnerable to climate impacts, particularly in urban areas that are at risk of flooding *(Howard et al., 2016)*.

AR5 reported that climate change will impact residential water demand and supply, and its management (Revi et al., 2014). According to AR5, water utilities are also confronted by changes to the availability of supplies; water quality; and saltwater intrusion into aquifers due to higher ambient and water temperatures, altered streamflow patterns, drier conditions, increased storm runoff, sea level rise, and more frequent forest wildfires in catchments (Jiménez Cisneros et al., 2014). SR1.5 found that constraining warming to 1.5°C instead of 2°C might mitigate the risks for water availability, but socioeconomic drivers could affect water availability more than variations in warming levels (Hoegh-Guldberg et al., 2018a).

The United Nations estimates that 55% of all people live in cities, and by 2050, this will increase to 68% (UN, 2018). Urban water demand is projected to increase by 50–80% by 2050 (Flörke et al., 2018). This trend is already spurring competition between cities and agricultural users for water, which is expected to continue (Garrick et al., 2019).

Globally, climate change will exacerbate existing challenges for municipal water services, which include population growth, urbanisation and inadequate investment, particularly in less diversified economies with limited government effectiveness (Ceola et al., 2016; Van Leeuwen et al., 2016; Reckien et al., 2017; Tapia et al., 2017; Veldkamp et al., 2017). Global urban land expansion forecasts show that almost half of global urban expansion by 2030 will take place in high-frequency flood zones, while the global percentage of urban land within drylands will not change (Güneralp et al., 2015).

Modified streamflows will affect the amount and variability of inflow to storage reservoirs. A study of urban water supply vulnerability in 71 surface-water supplied cities, which did not account for climate change, estimated that by 2040, without additional measures 45% of cities will be vulnerable to increased agricultural and urban water demands (Padowski and Gorelick, 2014). Changing flow regimes may exacerbate existing challenges to reservoir capacity, such as sedimentation, water quality degradation, and toxins (Goharian et al., 2016; Howard et al., 2016; Yasarer and Sturm, 2016). Elevated stream temperatures combined with increased concentration of pollutants during low flow periods and increased sediment, nutrient and pollutant loadings from heavy rainfall, may affect drinking water quality, and may require wastewater facilities to increase treatment to meet quality standards (Dettinger et al., 2015; Howard et al., 2016).

Existing urban stormwater infrastructure might not withstand more frequent and intense rainfall events as well as urbanisation and deforestation (Thakali et al., 2016; Van Leeuwen et al., 2016). Likewise, increased rainfall intensity will impact sewage systems that lack capacity to process the additional load (Dettinger et al., 2015; Neumann et al., 2015c; Howard et al., 2016; Shahid et al., 2016). In both developed and developing countries, faecal sludge management systems will be vulnerable to climate impacts, particularly in urban areas that are at risk of flooding (Howard et al., 2016).

In many places around the world, urbanization seems to be the major dynamic behind increasing exposure and vulnerability of people and assets to various natural hazards (Güneralp et al., 2015). As the examples from Table 4.7 show, projected climate change will pose a substantial challenge to urban water management, which necessitates the further refinement of urban climate models and downscaling methods to more closely determine the nature and scale of the future exposure of this sector to climate change (Jaramillo and Nazemi, 2018; Szewrański et al., 2018; Akhter et al., 2019).

Table 4.7: Examples of exposure to climate change in urban, peri-urban and municipal water sector in 2030

Region	Water Supply	Sewage	Drainage
Africa	Addis Ababa, Ethiopia: Increased water demand (Kifle Arsiso et al., 2017)	-	-
	Windhoek, Namibia: Reduced rainfall (Shikangalah and Mapani, 2019)	-	-
Asia	Jakarta, Indonesia: Increased water demand (Kumar et al., 2017)	Jakarta, Indonesia; Lucknow, India: Increased wastewater production (Kumar et al., 2017)	Jakarta, Indonesia: Increased flooding (Budiyono et al., 2016)
Australasia	Perth, Australia; Melbourne, Australia: Reduced winter rainfall (Andrys et al., 2017; Fiddes and Timbal, 2017)	-	-
Central and South America	El Alto, Bolivia: Increased water demand (Kinouchi et al., 2019)	-	Sao Paulo, Brazil: Increased flooding (Da Silva et al., 2018)
Europe	-	-	Cardiff, Wales: Increased flooding (Murray et al., 2017)
North America	-	-	New York City, United States: Increased flooding (Lu et al., 2017)
Small Island States	Belize; Papua New Guinea: Increased water demand and aridity (Karnauskas et al., 2018)	-	-

4.3.4.3 Water-related Adaptation in Urban, Peri-urban and Municipal Sectors

Although water-related adaptation is underway in the urban, peri-urban and municipal sectors of some nations, governance, technical, and economic barriers remain in the implementation of locally informed strategies more widely, particularly in developing countries (*high agreement, robust evidence*).

AR5 reported that case studies of the potential effectiveness of adaptation measures are growing. Although such studies demonstrated that it is technically feasible in general to adapt to projected climate changes, not all considered how adaptation would be implemented in practice (Jiménez Cisneros et al., 2014). Furthermore, AR5 concluded that more attention has been given to adaptations that help ensure sufficient water supplies than to increasing the capacity of sewage and drainage systems, or adapting them to allow for the impacts of heavier rainfall or sea level rise (Revi et al., 2014).

Climate change adaptation in this sector can involve 'hard'-engineering structures (grey), managed or restored biophysical systems (green and blue), or hybrid approaches that combine these strategies (Depietri and McPhearson, 2017). Green, blue and hybrid approaches are variously classified in terms of circular economy, water sensitive urban design, nature-based solutions, integrated urban water management, and ecological infrastructure, for example (Fletcher et al., 2015). Grey approaches can be expensive and inflexible, while green, blue and hybrid methods offer potentially cost-effective and multi-functional forms of adaptation (Brink et al., 2016). In most regions, urban water managers are implementing hybrid adaptation approaches, particularly for drainage, which aim to reduce the ecological and infrastructural impacts of runoff (*medium confidence*, *medium evidence*, Table 4.8).

One example of the hybrid approach is the Sponge Cities strategy in China, which has been undertaken since 2014 to address urban pluvial flooding and stormwater. By seeking to preserve or restore the capacity of the landscape to absorb and store rainwater, this top-down holistic strategy for urban development attempts to alleviate flood-risk, reduce run-off pollution, and augment water supply for different uses (Jiang et al., 2018).

Table 4.8: Examples of urban, peri-urban and municipal water adaptation

Region	Water Supply	Sewage	Drainage
Africa	-	-	Cape Town, South Africa: Maintenance of drainage systems; plans for upgrading stormwater infrastructure (Pasquini et al., 2015) Durban, South Africa: Ecological infrastructure (Martel and Sutherland, 2019)
Asia	Seoul, South Korea: Rainwater harvesting (Maksimović et al., 2015); Singapore: Stormwater recycling (Liu and Jensen, 2018)	-	Beijing, China: Sponge Cities (Jiang et al., 2018); Singapore: Ecological or green infrastructure (Liao, 2019)
Australasia	Perth, Australia: Groundwater replenishment (Bekele et al., 2018)	-	Melbourne, Australia: Ecological or green infrastructure (Schuch et al., 2017)
Central and South America	-	-	Sao Paulo, Brazil: Floodplain restoration scheme (Henrique and Tschakert, 2019)
Europe	Berlin, Germany: Stormwater recycling (Liu and Jensen, 2018)	-	Madrid, Spain: Sustainable Urban Drainage Systems (Rodríguez-Sinobas et al., 2018)
North America	-	Philadelphia, USA: Green infrastructure (Maksimović et al., 2015; Liu and Jensen, 2018)	Philadelphia, USA; Toronto, Canada: Green infrastructure (Maksimović et al., 2015; Liu and Jensen, 2018; Johns, 2019)
Small Island States	Funafuti, Tuvalu: Rainwater harvesting (McCubbin et al., 2015)	-	-

It is difficult to differentiate climate change adaptation from general water security planning in the context of rapid urbanisation and infrastructure maintenance. These challenges vary according to existing infrastructure, economic development, urban planning, population size, and geographic location (Koop and van Leeuwen, 2017). For example, a survey of wastewater systems in Connecticut in the United States found that most wastewater managers were not adapting to future climate change, rather efforts to build resilience were based on past storms (Kirchhoff and Watson, 2019).

Although Integrated Urban Water (see Box 4.3) Management and Integrated Water Resource Management (IWRM) (section 4.5.1.3.1) have emerged as a strategy to deliver both essential and non-essential services (Kirshen et al., 2018), studies of their application in cities in Australia (Furlong et al., 2017) and Turkey (Van Leeuwen et al., 2016) found that neither climate variability and change have been incorporated into long term plans. These studies use the City Blueprint Framework to evaluate the state of a city's IWRM and compare cities accordingly (Koop and van Leeuwen, 2016).

Among the barriers to adaptation is uncertainty, in terms of climate variability, future greenhouse gas emissions, population growth, and water demand (Walsh et al., 2016). To counter this, 'no regrets' or 'low regrets' strategies that minimise risk have been adopted (Stults and Larsen, 2018). In Australian capital cities, water planning has focused on securing new supplies that will withstand climate change, including the use of storm water and sewage recycling, managed aquifer recharge of non-potable water, and seawater desalination plants (Bekele et al., 2018; Horne, 2018). Residential water demand management measures, such as education, water pricing, outdoor water restrictions, metering, efficiency labelling, have also been introduced in Australia, as well as European and North American cities (Hornberger et al., 2015; Moglia et al., 2018; Stavenhagen et al., 2018).

Barriers to adaptation in this sector also relate to information, uncertainty, costs and willingness to pay, political will, stakeholder engagement, and community acceptance (Vicuña et al., 2018). Currently, decision makers lack basic data on existing water resources and patterns of use in low income countries (Howard et al., 2016) and face the challenge of downscaling global climate models to the catchment level (Lehmann et al., 2015). The lack of precipitation data at local scales is especially problematic for adaptation planning (Carter et al., 2015; Gooré Bi et al., 2017). In addition, new and existing infrastructures are expensive investments and require costly maintenance, which can limit the adaptation options available to water managers (Smid and Costa, 2018). Adaptation planning also competes with immediate development needs, particularly in low-income countries (e.g. (Long and Ziervogel, 2020)), and can perpetuate environmental and social injustice (Anguelovski et al., 2016). Some water sector adaptation measures potentially conflict with mitigation measures because they have high energy demand. For example, Perth's urban water supply system, which includes desalination and groundwater recharge, is the most energy-intensive in Australia (Lam et al., 2017; Lindsay et al., 2017).

[START BOX 4.3 HERE]

Box 4.3: Urban Water Crises

Since AR5 many cities in the Global North and Global South have experienced crises in water supply. Cities in southeastern Brazil, such as Sao Paulo, Rio de Janeiro, and Belo Horizonte, experienced water shortages during the drought of 2013–2015, which was the worst in over 50 years (Nobre et al., 2016; Milano et al., 2018). The severity of the 2013–2015 drought in California, USA led to the implementation of the first state-wide mandatory water restrictions (Manago and Hogue, 2017). The 2015–17 drought in the Western Cape region of South Africa was unprecedented and led to water shortages and the fear of 'Day Zero' in Cape Town in 2018 (Otto et al., 2018). Significant events in the decade prior to AR5 included the complete closure of piped supplies in Chennai, India in 2003 (Krueger et al., 2019), and the implementation of demand management measures in response to the 1997–2012 Millennium Drought in Melbourne, Australia (Rogers and Xue, 2015).

Climate change is only one of the contributors to water scarcity in urban and peri-urban areas, particularly in the Global South. For example, the 2014/15 drought event in Sao Paulo was more likely to have been driven by water use changes and population growth, than climate change (Otto et al., 2015). Other challenges include infrastructure and governance issues, impaired water quality, and a lack of community adaptive capacity (Hoekstra et al., 2018; Krueger et al., 2019).

These urban water crises have worrying implications for a 1.5C and 2C warmer world. Globally, nearly all net population growth is taking place in cities and the world is becoming increasingly urbanised, created new and difficult challenges for urban water management.

These global statistics likely underestimate current access to water at the local scale, particularly in the Global South where there are significant inequalities in service provision between formal and informal areas in cities (WWAP, 2018; Makarigakis and Jimenez-Cisneros, 2019; Mitlin et al., 2019; WRI, 2019). Households without access to municipal water must self-provide (a gendered responsibility), or purchase water from private sources, which can be costlier than piped water (Mitlin et al., 2019).

The focus on achieving SDGs by 2030, particularly increasing access to clean water and sanitation, raises questions of equity, health, and water justice in terms of water service provision in cities and peri-urban areas, as well as for users in catchments where water is extracted for urban use (Hoekstra et al., 2018; Mitlin et al., 2019; Zhang et al., 2019).

[END BOX 4.3 HERE]

4.3.5 Freshwater Ecosystems

4.3.5.1 Observed Impacts on Freshwater Ecosystems

The loss and degradation of freshwater ecosystems and unprecedented decline and extinction of many freshwater dependent populations is well documented (*high agreement, robust evidence*) and climate change is known to be one of the key drivers of this change (*high agreement, robust evidence*).

The loss and degradation of freshwater ecosystems has been widely documented. The Global Wetland Outlook (Ramsar Convention, 2018) reported that between 1970 and 2015 the area of freshwater wetlands declined by approximately 35% (Davidson and Finlayson, 2018) (*high agreement, robust evidence*). Where long term data are available, only 13% of the wetlands recorded in and around the year 1700 remained by the year 2000 (Davidson, 2014) **(***medium agreement, limited evidence***).** Many populations of wetland-dependent species have seen long-term unprecedented decline and threatened with extinction (Davidson and Finlayson, 2018; Darrah et al., 2019; Díaz et al., 2019) (*high agreement, robust evidence*).
A global systematic review of studies published since 2005 shows that climate change is one of the key direct drivers of change impacting freshwater ecosystems (Bustamante et al., 2018; Díaz et al., 2019), other drivers being, water pollution, extraction of water, drainage and conversion, and invasive species (Ramsar Convention, 2018). The link between air and water temperatures and ecological processes in freshwater ecosystems well recognized (Dell et al., 2014; Miller et al., 2014; Scheffers et al., 2016; Szekeres et al., 2016; Myers et al., 2017; Pecl et al., 2017; FAO, 2018) **(***high agreement, robust evidence***).** Temperature changes are leading to changes in the distribution patterns of freshwater species, including migratory water birds (Bussière et al., 2015) and keystone species such as the beaver (*Caster Canadensis)* in North America (Jung et al., 2016).

In all parts of the world without exception, freshwater species are threatened, with high levels of overall percentage of threatened species recorded in the Madagascar and Indian Ocean Islands (43%); in Europe (36%); in tropical Andes (35%) and New Zealand (41%) according to the composite analyses provided by the Global Wetland Outlook (Ramsar Convention, 2018). Apart from the loss and degradation of freshwater ecosystem and species, there have been other climate change induced changes. For example, increased temperature is known to have altered the sex of hatchlings of reptiles (Urban et al., 2014) and drying of peatlands has led to acidification and fires, further impacting the ecosystems and their species (Lane et al., 2017).

Indigenous models of freshwater management have existed for millennia yet have only begun to be recognized in recent years. There is now increasing recognition of the important role of indigenous peoples cultural and ecological knowledge in observing and assessing climate change impacts (Alessa et al., 2016), in developing disaster reduction strategies (Hiwasaki et al., 2014), and in freshwater management (Miltenberger, 2014) Indigenous perspectives of freshwater differ markedly from Western market-oriented and pragmatic approaches to water der(Te Aho, 2010; von der Porten et al., 2016; Castleden et al., 2017; Bishop, 2019; Groenfeldt, 2019) (*strong evidence, high confidence*). Indigenous models of freshwater management are recognized as embedded in traditional bioethical knowledge, values and practices (Harmsworth et al., 2016). In Aotearoa – New Zealand where freshwater systems are vital to the wellbeing of native biodiversity and also to Maori, projected impacts on Maori health are strongly related to cultural relationships to freshwater. Climate change-related impacts on precipitation and evapotranspiration include disruption of traditional food supplies e.g. risk and contamination of seafood, a primary food source (Royal Society Te Aparangi, 2017)and the disruption of the natural-resource-based Maori economy (Lawrence et al., 2016; Ministry of Environment, 2019) (*strong evidence, high confidence*).

4.3.5.2 Projected Risks to Freshwater Ecosystems

Changes in precipitation and temperatures are projected to affect all types freshwater ecosystems and their species. Under all scenarios, except the one with lowest GHG emission scenario, freshwater biodiversity is expected to decrease proportionally to the degree of warming and precipitation change (*medium agreement, limited evidence).*

Increased water temperatures could lead to shifts in the structure and composition of species assemblages following changes in metabolic rates, body size, timing of migration, recruitment, range size and destabilization of food webs (Woodward et al., 2010; Mantyka-Pringle et al., 2014; Scheffers et al., 2016; Comte and Olden, 2017; Myers et al., 2017; Pecl et al., 2017). Decreases in water availability and changes to flow regimes will reduce both habitat size and heterogeneity and increase the probability of species extinctions (Tedesco et al., 2013; Knouft and Ficklin, 2017).

Changes in the seasonality of flow regimes, floods and variability (Blöschl et al., 2017) and more intermittent flows (Pyne and Poff, 2017) are also projected and could result in decreased food chain lengths through the loss of large-bodied top predators, changes in nutrient loadings and water quality (Woodward et al., 2010). The situation in drylands is expected to be more severe (Jaeger et al., 2014; Gudmundsson et al., 2017b). Changes to snow and glacier melting, including disappearance of some glaciers (Lutz et al., 2014; Kraaijenbrink et al., 2017) will lead to reduced water availability and declines in biodiversity in high altitudes through local extirpations and species extinctions in regions of high endemism. The impact of the melting of the permafrost in high latitudes could have major impacts on water flows and the survival of many species (Malhotra and Roulet, 2015).

These impacts are expected to be most noticeable where large temperature increases are projected, such as those by 2050 for eastern North America, Europe, Asia, southern Africa and Australia. Climate change has and will continue to affect freshwater fisheries worldwide with the relative impact varying over time and geographically (FAO, 2018), as expected for other species whether sedentary or migratory (Junk et al., 2013).

4.3.5.3 Water-related Adaptations for Freshwater Ecosystems

Adaption measures to cope with changes in ecosystems including to freshwater ecosystems, encompass both Community-based adaptation (CBA) and Ecosystem based Adaptation (EbA) interventions and these have been implemented in many locations around the world, yet, challenges such as improving the evidence base of their effectiveness, scaling up of these interventions, mainstreaming across sectors and receiving more adaptation finance remain (*medium agreement, limited evidence*).

CBA and EbA interventions to climate change have gained wide recognition at the global policy level (Schipper et al., 2015; Reid, 2016; UNFCCC, 2017; Barkdull and Harris, 2019; Piggott-McKellar et al., 2019) as being integral components of an integrated set of adaption measures to cope with changes to ecosystems, including freshwater systems.

In Aotearoa-New Zealand cultural monitoring by indigenous communities has gained increased recognition by local communities and governance bodies. While Maori freshwater management models vary across tribal areas, they share culturally-determined values, principles and practices underpinned by genealogical relationships to water (Rainforth and Harmsworth, 2019). While these models may not translate well into Western environmental management frameworks, their effectiveness has been rigorously assessed and affirmed (Hikuroa et al., 2011; Faaui et al., 2017; Clapcott et al., 2018; Bishop, 2019). Contemporary Indigenous-led initiatives do indeed elucidate complex and dynamic human-environmental interactions and are applied in Aotearoa-New Zealand alongside science and technical approaches to guide policy and at local, regional, and national scale (strong evidence, high confidence) (Rainforth and Harmsworth, 2019).

A systematic review of 132 academic papers and 32 articles from grey literature by (Doswald et al., 2014) provided a comprehensive global overview of EbA, which showed that EbA interventions were used in a range of ecosystems, including inland wetlands (linked to 30 publications). An assessment of the potential for EbA in three sub-basins of the Murray-Darling Basin, Australia, concluded that EbA can augment catchment management practices but that there were also institutional challenges (Lukasiewicz et al., 2016). In urban settings, EbA has been associated with ecological structures for reducing risks, including by using urban wetlands (Barkdull and Harris, 2019).

4.3.6 Inland Navigation and Transportation

4.3.6.1 Observed Impacts on Inland Navigation and Transportation

It is about as likely as not that climate change has impacted inland navigation and transportation systems (*limited evidence, high agreement*).

AR5 found that studies of climate change and transportation have focused more on mitigation, than vulnerability, impacts and adaptation. In addition, assessments of the impact of climate change have tended to take a global or urban perspective, leaving the impacts on rural infrastructure to be inferred (Dasgupta et al., 2014). SR1.5 concluded that much of the published research on the risks of climate change for the transportation sector has been more qualitative than quantitative (Hoegh-Guldberg et al., 2018a).

The extent to which the impact of climate events and water-related hazards can be attributed to climate change remains unclear in many regions (*limited evidence, medium confidence*). Further research is necessary to determine the extent to which inland navigation and transportation systems in regions beyond the Arctic have been impacted by climate change (Du et al., 2017; Hori et al., 2017; Melvin et al., 2017; Zheng and Kim, 2017).

4.3.6.2 Projected Risks to Inland Navigation and Transportation

By affecting precipitation patterns, increasing the likelihood and intensity of water-related hazards, and raising temperatures, climate change will result in negative impacts on inland navigation and transportation systems (*medium evidence, high agreement)*.

AR5 concluded that climate change may negatively affect transport infrastructure. The projected impacts will not be uniform, pertaining to geographic area, transport mode, time frame, and issues such as technology and economic development. For example, AR5 found that unpaved roads and bridges are especially vulnerable to precipitation extremes. Likewise, transport infrastructure on ice or permafrost is especially vulnerable to rising temperatures (Arent et al., 2014). SR1.5 found that risks to transportation are expected to be lower at 1.5°C than at 2°C of global warming, and the extent of this risk depends on human vulnerability and the effectiveness of adaptation in the sector (Hoegh-Guldberg et al., 2018a).

Although climate change will impact inland navigation and transportation systems to differing degrees, further research is needed to determine the extent and nature of these impacts in rural areas, as well as in less developed countries.

4.3.6.3 Water-related Adaptation on Inland Navigation and Transportation

Although adaptation planning and implementation are necessary for the inland navigation and transportation sector (*high agreement*), few strategies have been implemented (*limited evidence*).

AR5 highlighted four different aspects of adaptation strategies for transport in urban contexts: maintain and manage; strengthen and protect; enhance redundancy; and where needed, relocation. The report found cities with adaptation plans usually included attention to more resilient transport systems (Revi et al., 2014).

A study of the adaptation actions being undertaken by 117 parties to the UNFCCC found adaptation was notably underreported in the transportation sector (Lesnikowski et al., 2017). Literature reviews showed that adaptation was limited in the European Union, Singapore and South Africa (Vajjarapu et al., 2019), and that few countries have adopted strategies at a national level, such as the United Kingdom, United States, the Netherlands, and Finland (Wang et al., 2019b). In the United States, land and transport managers at some sub-national levels pursued 'no regrets' approaches to changes in climate (Strauch et al., 2015), while others prioritised short term responses to extreme weather events over long term mitigation (Miao et al., 2018).

Despite recognition of the importance of adaptation strategies, barriers to implementation exist at both national and sub-national levels. A literature review of adaptation strategies identified political reluctance as well as shortfalls in inter-agency coordination, funding, and information as key barriers, all of which were especially evident in developing countries (Vajjarapu et al., 2019).

4.3.7 Knowledge Gaps

Table 4.9 presents the main knowledge gaps in our understanding of sectoral uses of water and how that use is being impacted by climate change. Table 4.10 presents the regional assessment of sectoral use of water in various regions of the world.

Table 4.9: Knowledge gaps in sectors impacts of climate change and adaptation interventions

Sections	Key gaps	Scale	Reference
4.3.1 Agriculture	Lack of integrated studies linking hydro-climatic changes and extreme events to impacts on agriculture.	Global, Regional and National	Henne et al. (2018)
	Inadequate knowledge on the direct link between farmers' perceptions and hydro-meteorological data.	Global, Regional and National	Savo et al. (2016)
	Uncertainties with regard to future crop water requirements due to model limitations as well as gaps in fully understanding effects of elevated CO_2 on crop water requirements.	Global, Regional and National	Elliott et al. (2014); Frieler et al. (2017); Winter et al. (2017); Fodor et al. (2017)
	Limited understanding on how to increase water use efficiency of different irrigation as well as water storage and saving techniques across regions and within changing climatic conditions.	Global, Regional and National	Section 4.3.1.2 and 4.3.1.3; and Inferred by the authors from literature
4.3.2 Energy	Limited literature on scale (e.g., national, regional, or plant-wise) and problem specific (e.g., reservoir operation, risk assessment, or resource planning) climate change impacts on hydropower.	Global, Regional and National	Kao et al. (2015); Ehsani et al. (2017)
	Causal linkages between climate and electricity supply and the economic impacts of associated energy supply disruption are mostly unknown.	Global, Regional	Conway et al. (2017)
4.3.3 Water, Health, and Sanitation (WaSH)	Quality and accuracy of model to predict tangible climate change impact on health outcomes.	Global and Regional	Inferred by the authors from literature
	Insufficient longitudinal data	Developing countries	Inferred by the authors from literature
	Limited availability of studies	Europe, North America, South America	Inferred by the authors from literature
4.3.4 Urban, Peri-Urban, and Municipal Sector	Limited research to determine the climate change impacts on urban, peri-urban, and municipal areas where a growing proportion of the world's population live.	Global, Regional and National	Roth et al. (2019)
	Poor knowledge on the effectiveness of adaptation in informal and peri-urban settlements.	Global, Regional	Saraswat et al. (2016); Yazdanfar and Sharma (2015)

4.3.5 Freshwater Ecosystems	Research is limited on the observed impacts of climate change on resident and migratory species in tropical or warm arid regions.	Regional	(Mitsch and Hernandez, 2013)
	Insufficient understanding of processes, impacts and risks associated with increasing salinity in freshwater ecosystems because of sea level rise.	Global and Regional	
	Understanding of climate change impact on lower taxonomic orders is inadequate.	Global and Regional	Bustamante et al. (2018)
	Lack of understanding on how individual ecosystems or individual populations of freshwater species' basic biological responses. E.g the establishment of novel ecosystems with new assemblages of species, including invasive alien species, irreversible changes in freshwater ecosystems	Global and Regional	Moomaw et al. (2018).
	More evidence is needed on the effectiveness of CBA and EbA.	Global	Doswald et al. (2014); Milman and Jagannathan (2017); Newsham et al. (2018); Piggott-McKellar et al. (2019).
4.3.6 Inland Navigation and Transportation	Knowledge is limited to determine the extent to which inland navigation and transportation systems in regions beyond the Arctic have been impacted by climate change.	Regional	Du et al. (2017); Hori et al. (2017); Melvin et al. (2017); Zheng and Kim (2017)
	Climate change impact on inland navigation and transportation systems in rural areas, as well as in less developed countries are less understood.	Regional and National	Chinowsky et al. (2015); Daniel et al. (2018)

Table 4.10: Sectoral impacts of climate change and adaptation interventions across regions

Region	Observed changes	Projected changes
Africa	*Agriculture*	
	Yield decline and economic loss: The 2017/18 drought of the Western Cape led to an average yield decline of 14%, loss of 30,000 jobs and $ 400,000 USD in export income; likelihood of drought occurrence was increased at least by a factor of 3 through in the influence of climate change (Otto et al., 2018; Pienaar and Boonzaaier, 2018). Yield decline in Tunisia since 1970s cereals and date production negatively affected by inconsistencies and decrease of rains associated with temperature increases during growing season (Ben Zaied and Ben Cheikh, 2015). Yield Decline: in Tanzania farmers trace declines to a decrease in number of rainy days and an increase in extreme temperatures – both heat and cold (Below et al., 2015). Harvest Failure and Famine: in Malawi drought years, erratic rainfall and increased temperatures from 1970s to 2010s. (Nkomwa et al., 2014)	Yield reduction of rain-fed agriculture: Rain-fed maize yields are projected to decline in all over Sub Sahara Africa: Malawi up to 33% by 2100; up to -20% by 2065 in Nigeria; up to -28% by 2050 in Ethiopia (Kassie et al., 2015; Mereu et al., 2015; Msowoya et al., 2016). Similarly, 50% to 95% of sequential rain-fed cropping area in Benin could be reduced to single-cropping area (Duku et al., 2018). Limitations to irrigation expansions and irrigated yield loss: Irrigation potential projected to be reduced by at least 50% in Benin by 2100 (Duku et al., 2018)
	Energy and Industrial Uses	
	Diminished annual hydropower production during droughts in Africa (Bekoe and Logah, 2016). Sub-Saharan Africa facing multifaceted challenges in the hydropower generation capacity (Conway et al., 2017).	By 2030 Eastern and southern Africa which will experience climate-related energy supply obstruction (Conway et al., 2017). Without adaptation, blackouts and disruptions to power plant operations due to insufficient cooling water to become more frequent (Zhou et al., 2018).
	Water, Health, Sanitation, and Hygiene (WASH)	
	Low prevalence and seasonal variation of *S. haematobium* among school-aged children in Kaedi (Mauritania) (*High confidence*, (Gbalégba et al., 2017)) Lack of rainfall associated with higher temperatures, compounded with growing population, decreased yields and has led to the increasing use of wastewater in agriculture in the Middle East and North Africa (MENA) countries (*High confidence*, (Faour-Klingbeil and Todd, 2018)) In Côte d'Ivoire an incremental increase in monthly precipitation and temperature has been linked to an increase in malaria incidence (M'Bra et al., 2018)	Baseline model output compared to prevalence data indicates suitable temperatures are necessary but not sufficient for both *S. mansoni* transmission and high infection prevalence. All else being equal, infection risk may increase by up to 20% over most of eastern Africa over the next 20 and 50 years. Increases may be higher in Rwanda, Burundi, south-west Kenya and eastern Zambia, and *S. mansoni* may become newly endemic in some areas. (*Medium confidence*, (McCreesh et al., 2015)) Combined with human population density projections, with temperatures suitable for year-round, highest-risk transmission areas for malaria will shift from coastal West Africa to the Albertine Rift between the Democratic Republic of Congo and Uganda, whereas areas with seasonal transmission

Larger area of Africa currently experiences the ideal temperature for disease transmission than previously projected (*High confidence*, (Ryan et al., 2015)) Temperature is increasing in all areas of Ghana and rainfall is decreasing. These changes make the country agriculture very vulnerable (*High confidence*, (Asante, 2015) In Botswana maximum temperature increase had a positive influence on diarrheal disease. (*Medium confidence*, (Alexander et al., 2018)) Microbiological contaminants in specific regions such as sub-Saharan Africa and Southeast Asia remain the main health risk factors despite growing chemical risks associated with rapid urbanization and industrialization that may change the types and distribution of wastewater contaminants (*medium confidence*, (Dickin et al., 2016)) In Africa, in the flood plain system of the Chobe River of Botswana, a strong seasonal diarrheal disease pattern was identified, with two outbreaks occurring regularly in the wet and dry seasons. Rainfall, weekly average minimum air temperature, and river height were predictive of E. coli concentration, and increases in E. coli in the river were positively associated with diarrheal cases (Alexander et al., 2018).	suitability will shift toward sub-Saharan coastal areas.(*Medium confidence*, (Ryan et al., 2015))
Urban, Peri-Urban, and Municipal Sector	
-	Nearly 30% of urban land in mid-latitudinal Africa will face high-frequency flood risk ((Güneralp et al., 2015) Increased water demand in Ethiopia (Kifle Arsiso et al., 2017) Reduced rainfall in Namibia (Shikangalah and Mapani, 2019)
Freshwater Ecosystems	
The large biodiversity-rich lakes in Africa are sensitive to climate change as their water balances are dominated by direct rainfall and evaporation (Junk et al., 2013; IPBES. 2018a)	In parts of Africa changes in precipitation could further limit water availability while in the Horn of Africa, greater rainfall could increase groundwater levels (Thangarajan and Singh, 2016; IPBES, 2018a). In Africa temperatures are expected to rise faster than the global average (James and Washington, 2013; Belle et al., 2016) with areas such as the Kalahari basin warming at close to double the global mean (Li et al., 2015a). The consequences for freshwater species is likely to be severe with local extinctions as freshwater ecosystem dry (Myhre et al., 2013) or the species need to contend with warmer water and air temperatures. Rainfall variability is projected to increase with models suggesting fewer, but higher intensity rainfall events (Myhre et al., 2013; IPBES, 2018a)

	Inland Navigation and Transportation	
	Impacts of increased frequency of extreme rainfall and other climate-related events cannot be specifically attributed to climate change (Twerefou et al., 2015; Nyarieko et al., 2019).	Climate change may combine with land use changes and lack of maintenance to contribute to the deterioration of transport infrastructure (Hearn, 2016; Duy et al., 2019)
Australasia	*Agriculture*	
	Economic Losses: in Australia severe drought between 2002 to 2010 led to around 18% reduction in agricultural total factor productivity (Sheng and Xu, 2019)	-
	Energy and Industrial Uses	
	-	-
	Water, Health, Sanitation, and Hygiene (WASH)	
	Australia is vulnerable to the impacts of climate change on health and that policy inaction in this regard threatens Australian lives (Zhang et al., 2018)	-
	Urban, Peri-Urban, and Municipal Sector	
	Water shortages in southern and eastern Australia may be partially attributed to climate change (*high confidence*) (Cai et al., 2014; Henley et al., 2019)	Reduced streamflow (Andrys et al., 2017; Fiddes and Timbal, 2017) Increased urban extent in drylands (Güneralp et al., 2015)
	Freshwater Ecosystems	
	-	-
	Inland Navigation and Transportation	
	Difficulties in determining climate attribution due to localized nature of damage and degradation (Balston et al., 2017).	-
Small Islands	*Agriculture*	
	-	-
	Energy	
	-	-
	Water, Health, Sanitation, and Hygiene (WASH)	

	Pacific island countries (PICs) are reported as among those most vulnerable to the health impacts of a changing climate (McIver et al., 2016).	Predicted and observed effects of climatic change include food security and salinization of freshwater (Kim et al., 2015b).
	Urban, Peri-Urban, and Municipal Sector	
	-	Freshwater stress due to rising aridity, growing demand, and decreasing groundwater recharge (*high confidence*) (Holding et al., 2016; Karnauskas et al., 2018)
	Freshwater Ecosystems	
	-	-
	Inland Navigation and Transportation	
	Coastal flooding and increased intensity of heavy rainfall impacting transport infrastructure but not specifically attributed to climate change (Cashman and Nagdee, 2017)	-
Asia	*Agriculture (Including aquaculture)*	
	Yield Decline: Decreased rainfall made farmers food insecure and forces them to purchase food. Higher mean temperatures cause for declines in yields of wheat, maize, mustard, summer and winter vegetables in the Hindu Kush Himalayas. (Juana et al., 2013a; Varadan and Kumar, 2014; Sujakhu et al., 2016) Yield Declines and Failures: in Nepal farmers in the Makawanpur district reported numerous floods between 1985 and 2009 and changes in the monsoon and rainfall pattern (Shrestha and Nepal, 2016)	Yield reduction of rain-fed agriculture: in India between 15% and 40% of current rice producing areas could become less suitable or unsuitable for rain-fed rice production by 2050 (Singh et al., 2017) Limitations to irrigation expansions and irrigated yield loss: Amu Darya Basin (Afghanistan, Tajikistan, Turkmenistan, Uzbekistan) could 35 to 55% loss of irrigated area by 2100 (White et al., 2014). A review shows potential decreases in irrigated production in Iran in the majority of studies and across scenarios and timeframes (Karimi et al., 2018) Changes in crop water requirements: Temperature increase may reduce growing seasons for boro rice in Bangladesh, reducing overall crop water requirements and shortening of crop growing periods could significantly reduce crop water requirements in the North China Plain, a main crop growing region (Mo et al., 2013; Acharjee et al., 2017; Sun et al., 2018b) Groundwater depletion as a consequence of increasing irrigation demand: Combined pressures of climate change and development are likely to drive major increases in irrigation water demand, further depleting already stressed groundwater tables in China (Leng et al., 2015; Wang et al., 2017b)
	Energy	

Southwest China accounted 50% reduction in hydropower generation due to drought in 2011(Wang et al., 2017c) Power stations accentuate water scarcity in regions of China; (Qin et al., 2015; Zhang et al., 2016b; Zhang et al., 2018).	China will experience climate shock in hydropower plants due to water scarcity under all emission scenarios in its Northern region (Gaupp et al., 2015; Zheng et al., 2016). Reductions in energy production due to cooling water shortage in China (Zheng et al., 2016; Zhou et al., 2018). Beijing–Tianjin–Hebei region is under high water stress, in part due to the high water demand of the coal-dominated electricity sector:2017-2030 baseline water stress projections (Sun et al., 2018a): RCP4.5: unmet demand 15.3m3; RCP8.5: unmet demand 21.1 m3 Coal-fired plants magnify water insecurity in Pakistan; by 2055, climate change-induced water stress in Pakistan projected to increase by 36–92% compared to current levels (Alkon et al., 2019)
Water, Health, Sanitation, and Hygiene (WASH)	
In Oceania, there is a high agreement that increasing variability in rainfall, increasing temperatures, and likely higher than average sea-level rise are impacting freshwater, livelihood and household security by polluting available surface freshwater and destroying sanitation infrastructures (Hadwen et al., 2015). A study on the impacts of climatic change on freshwater found seasonal shifts and prolonged drought resulting in reduced availability of clean freshwater to be the most commonly identified condition affecting livelihoods, with negative implications for agriculture, livestock and human health. (Pearce et al., 2015). In Southeast Asia, available evidence suggested that possible occupational health risks of wastewater and excreta management practices include diarrhea, skin infection, parasitic infection, bacterial infection, and epilepsy (*Medium confidence) (Lam et al., 2015)*. Floods and droughts increase the frequency and intensity of waterborne diseases in Cambodia (*High confidence*, (Davies et al., 2014)) Microbiological contaminants in specific regions such as sub-Saharan Africa and Southeast Asia remain the main health risk factors despite growing chemical risks associated with rapid urbanization and industrialization that may change the types and distribution of wastewater contaminants (*Medium confidence*, (Dickin et al., 2016)) In India rainfall shocks have a significant effect on dowry deaths (*High confidence*, (Sekhri and Storeygard, 2014))	In China it is projected that increase temperatures and temperature sensitivity of diarrheal diseases and three vector-borne diseases will have an adverse impact in the success of WaSH-infrastructure in reducing the spread of infectious diseases (*Medium confidence*, (Hodges et al., 2014)) The overall effects of climate change, land conversion and reduced water availability could reduce Chinese food production substantially. Climate change will probably have substantial impacts on water resources – e.g. changes in rainfall patterns and increases in the frequencies of droughts and floods in some areas of China. Such impacts would undoubtedly threaten population health and well-being in many communities. In the short-term, population health in China is likely to be adversely affected by increases in air temperatures and pollution. In the medium to long term, however, the indirect impacts of climate change – e.g. changes in the availability of food, shelter and water, decreased mental health and well-being and changes in the distribution and seasonality of infectious diseases – are likely to grow in importance. (*medium confidence*, (Tong et al., 2016))

	In India, climate change affects physical health (Farmer suicide; stress related; agricultural work less productive psychiatric disorders) (*High confidence*, (Padhy et al., 2015))	
	Urban, Peri-Urban, and Municipal Sector	
	Flooding in southeast China can be partially attributed to climate change (Burke et al., 2015; Jiang et al., 2018).	Almost three-quarters of urban land will be under high-frequency flood risk by 2030 (Güneralp et al., 2015)
	Climate change is not solely responsible for peri-urban water insecurity in South Asia (Roth et al., 2019).	Increased water demand and wastewater production in Indonesia and India (*low confidence*) (Kumar et al., 2017)
		Increased flooding in Indonesia and China (*low confidence*) (Budiyono et al., 2016)
	Freshwater Ecosystems	
	Across Central Asia, lakes, ponds and streams have disappeared following agricultural intensification, irrigation and urban development combined with climate change (IPBES, 2018b)	Flooding hazards is projected to change with more frequent flooding and increased runoff to streams and wetlands in South, South-East, and North-East Asia, in contrast to Western Asia where runoff is projected to decrease (ADB, 2017; IPBES, 2018b)
		In regard to freshwater ecosystems, there are some trends suggesting shifts in monsoon regimes, rainfall or precipitations, and seasonality of dry and wet season, which may vary across sub-regions and countries (Hasson et al., 2016; Trang et al., 2017; Wang et al., 2017d; IPBES, 2018b). These climate change-related reductions and modifications of river flow and water supply will have large adverse consequences for the biodiversity, livelihood, food production, and water availability to the millions of people in the Asia-Pacific who are dependent on the major rivers for their water and food supply ((Ferraro et al., 2013; Quinn et al., 2013; Elliott et al., 2014; Hejazi et al., 2014; IPBES, 2018b)
	Inland Navigation and Transportation	
	Disruption of transport due to flash floods in India and China not specifically attributed to climate change (Yin et al., 2016; Singh et al., 2018).	Changing precipitation patterns will impact roads (Duy et al., 2019)
Central and South America	*Agriculture*	
	-	Yield reduction of rain-fed agriculture: Suitability for rain-fed maize production is projected to decrease across important maize producing regions in Mexico and Brazil (López-Blanco et al., 2018; Martins et al., 2019).
	Energy	

	Hydropower generation capacity is being affected in Brazil due to climate stress (Conway et al., 2017). Diminished annual hydropower production during droughts in the Amazon (Carvajal et al., 2017; de Jong et al., 2018; Arango-Aramburo et al., 2019; Carvajal et al., 2019)	Latin American hydropower production will be diminished in the years ahead due to climate extremes such as floods, droughts and glacial retreat (IRENA, 2016; Zhang et al., 2018).
	Water, Health, Sanitation, and Hygiene (WASH)	
	-	-
	Urban, Peri-Urban, and Municipal Sector	
	Water shortages cannot be directly attributed to climate change (*medium confidence*) (Otto et al., 2015; Nobre et al., 2016; Martins et al., 2019)	Increased flooding in Brazil (*low confidence*) (Da Silva et al., 2018)(Da Silva et al. 2018) Increased water demand in Bolivia (*low confidence*) (Kinouchi et al., 2019)
	Freshwater Ecosystems	
	-	In the Americas under all scenarios that have been examined the risk of extinction of freshwater species is expected to increase above that already occurring as a consequence of biodiversity loss due to pollution, habitat modification, over exploitation, and invasive species (IPBES, 2018d). Freshwater ecosystems are also at risk of abrupt and irreversible change, especially those in the higher latitudes and at higher altitudes with significant changes in species distributions, including the melting of the permafrost systems (IPBES, 2018d; Moomaw et al., 2018).
	Inland Navigation and Transportation	
	-	-
North America	*Agriculture (Including aquaculture)*	
	Irrigated Areas: in the USA between 1978 and 2012, 11–21% of the total irrigated acreage in the southwest of cotton, stone fruit and grapes yields declined due to climate-induced irrigation water shortage (Elias et al., 2016) Irrigated Areas: In NY state 2015/2016 rainfall and streamflow decreased. Farmers reported rainfed field crop and pasture yield losses greater than 30%, with some loses over 90%. They planned to increase irrigation to off-set these negative consequences. (Sweet et al., 2017)	Groundwater depletion as a consequence of increasing irrigation demand: The combined effects of groundwater depletion and consequent limitations to irrigation as well as temperature increase are projected to reduce corn yields in the Central High Plains of the US (Cotterman et al., 2018)
	Energy	

	Hydropower generation in USA reduced severely by CC impacts (Bartos and Chester, 2015) (*medium confidence, medium agreement*). Due to water scarcity hydroelectricity generation dropped approximately 27% in the USA between 2001-2012 (Bartos and Chester, 2015). In 2010, the Hoover Dam experienced a 23% drop in its power generating capacity due to falling water levels (Wang et al., 2017c). Power stations accentuate water scarcity in regions of the US (Colton et al., 2016).	Hydropower in USA is projected to shrink 1 to 2 TWh per year due to hydro-climatic (temperature, precipitation, and runoff) changes (Kao et al., 2015). Los Angeles County (US) generators, substations, and transmission lines could lose up to 20% of safe operating capacities (MW) due to lack of cooling water (Burillo et al., 2019).
	Water, Health, Sanitation, and Hygiene (WASH)	
	-	-
	Urban, Peri-Urban, and Municipal Sector	
	Water shortages in Canada (Herring et al., 2016)	Increased flooding in the United States (Lu et al., 2019) Increased urban extent in drylands (Güneralp et al., 2015)
	Freshwater Ecosystems	
	-	-
	Inland Navigation and Transportation	
	Independent events yet to be attributed directly to climate change (Douglas et al., 2017)	Winter roads: reduced viability and longevity in the Canadian and US Arctic (Du et al., 2017; Hori et al., 2017; Scheepers et al., 2018). Airports: changing precipitation patterns precipitation (Thompson, 2016) Roads and bridges: changing precipitation patterns (Neumann et al., 2015b)
Europe	*Agriculture (Including aquaculture)*	
	Yield Loss and Gain: in Switzerland from 1983-2010 maize yields have benefited from increasing temperatures ; area suitable for winter wheat decreased slightly because of higher temperature and excess water (Henne et al., 2018) Changes in Irrigation Frequency and Crops Planted: in England since the mid-1970s droughts are more common in eastern England. Farmers restrict water for irrigation and modify their agricultural practices to increase soil and water conservation and to include in their farming routines crops that are more drought resistant. (Rey et al., 2017) Climate change contributes to the emergence of certain diseases in the United Kingdom (*Medium confidence*, (Baylis, 2017))	Risks to agriculture and food security through extremes (droughts, floods): Irrigated agriculture in England is projected to face increasing water abstraction restrictions with increasing drought conditions (2071-2098) (Rio et al., 2018). Similarly, spring cereal, potato and maize, increases in soil moisture deficits are projected across models and scenarios for Poland, with potential consequences for crop failure (Kundzewicz et al., 2018b). A wider scale infestation of Aedes aegypti in Europe and other locations is projected by 2100 (*Medium confidence*, Liu-(Liu-Helmersson et al., 2019)

	Energy	
	Hydropower production declined in Europe (Germany, Romanian, Norway) and electricity price experienced negative shock due to climate change impacts (Germany) (medium confidence, medium agreement) (McDermott and Nilsen, 2014; Bartos and Chester, 2015; Wang et al., 2017c). Power stations accentuate water scarcity in regions of Europe (Behrens et al., 2017). Climate-induced water availability will leadis projected to decrease in hydropower generation in between 17% and 41%, leading to potentially increasing Portuguese soaring the electricity prices by Portuguese up to 17% by 2050 (Teotónio et al., 2017).	Hydropower potential of Europe will see 15–20% reduction under 3°C warming, 10% reduction under 2°C warming and 5% reduction under 1.5°C warming (Tobin et al., 2018). Baltic and Scandinavian countries will experience a 15% uplift in hydropower potential under 3°C (Tobin et al., 2018). In Portugal, climate-induced water availability will lower the hydropower generation in between 17% and 41%, potentially increasing Portuguese electricity prices by up to 17% by 2050 (Teotónio et al., 2017). Climate change will cause price hike in the Swiss energy sector in the years ahead (Savelsberg et al., 2018) Mean annual hydropower generation will decline in Austria and Germany by 5.5% during 2051–2080 due to change in runoff (Totschnig et al., 2017).
	Water, Health, Sanitation, and Hygiene (WASH)	
	-	-
	Urban, Peri-Urban, and Municipal Sector	
	Urban flooding cannot be directly attributed to climate change (Miller and Hutchins, 2017)	Increased flooding, especially in cities in the United Kingdom (Murray et al., 2017; Guerreiro et al., 2018)
	Freshwater Ecosystems	
	In the European Union the spatial coverage of freshwater ecosystems with a good ecological quality, has decreased from 42% to 32% (IPBES, 2018c) Across Europe and Central Asia, lakes, ponds and streams are disappearing as a consequence of agricultural intensification, irrigation and urban development combined with climate change (well established). The extent of wetlands in Western, Central and Eastern Europe has declined by 50% from 1970 (Dixon et al., 2016), while 71% of fish and 60% of amphibians with known population trends are declining (well established) (IPBES, 2018c)	Climate change is expected to intensify the hydrological cycle and alter evapotranspiration, with implications for ecosystem services but also feedback to regional and global climates. As a result, increased stress on freshwater ecosystems is expected in the coming decades. (IPBES, 2018c) Under business-as-usual scenarios of future global change, Climate change is also expected to further increase the stress on freshwater ecosystems, not only by changing species distribution but also by exacerbating the symptoms of eutrophication due to loss of planktivorous species through warming and salinization (inconclusive) (IPBES, 2018c)
	Inland Navigation and Transportation	
	-	-
Mediterranean	*Agriculture (Including aquaculture)*	

-	-
Energy	
-	Hydropower generation will be reduced approximately 40% on average in the Mediterranean countries in southern Europe, northern Africa and the Middle East by end of the century under a high emissions scenario (Turner et al., 2017)
Water, Health, Sanitation, and Hygiene (WASH)	
-	-
Urban, Peri-Urban, and Municipal Sector	
-	Urban land cover in hyper-arid Northern Africa is expected to increase 6 times in 30 years (Güneralp et al., 2015) Southern European cities are expected to have intensified drought conditions (*low confidence*) (Guerreiro et al., 2018)
Freshwater Ecosystems	
-	-
Inland Navigation and Transportation	
Drought impacts on inland navigation but not specifically attributed to climate change (*low confidence*) (Van Lanen et al., 2016)	Inland navigation: droughts (Forzieri et al., 2018). Rail and road infrastructure: landslides (Scholes, 2016; Matulla et al., 2018); changing precipitation (Coles et al., 2017) Airports: changing precipitation patterns (Burbidge, 2016; Thompson, 2016) Changing customer demand (Christodoulou and Demirel, 2017)

4.4 Cross-Sectoral Impacts (Observed and Projected) and Adaptation Interventions Due to Changes in Hydrological Regimes

4.4.1 Water-Induced Disasters (WIDs)

4.4.1.1 Observed Impacts on Water-Induced Disasters

Despite the observed changes in extreme weather events and associated water-related hazards (4.2.7.4), changes in their impacts are not clearly detected because water security is affected by several anthropogenic and natural factors (*high confidence due to high evidence*).

According to AR5, water security and, as they are associated with it, food and energy security, are threatened by climate change (Jiménez Cisneros et al., 2014). SR1.5 stated that there is *low confidence* due to *limited evidence* that anthropogenic climate change has affected the frequency and the magnitude of floods, and growing population and economy are the main drivers to increase exposure of people and assets to flooding (Hoegh-Guldberg et al., 2018a).

Water-related disasters are the result of very complex interactions between the ocean, the atmosphere and the land (Dimri et al., 2016), but they also result from the exposure and vulnerability of human and natural systems (Aerts et al., 2018). Data remains insufficient to demonstrate that the magnitude and frequency of floods have been modified due to anthropogenic climate change. However, it is clear that socio-economic losses due to floods increased during the second half of the 20th century as a result of higher vulnerability (Winsemius et al., 2015; Zhou et al., 2017; Mondal, 2019). Model-based estimation of average global economic damage due to flood in the past several decades is US$ 52–351 billion annually (Alfieri et al., 2016; Muis et al., 2017; Dottori et al., 2018). Regarding droughts, the situation is similar: although it is not clear whether they have increased in the past because of climate change, they are affecting more people than before (Nobre et al., 2016). Warmer temperatures and increased population generate a higher water demand and consumption which adds onto water scarcity induced by prolonged dry periods (Nobre et al., 2016). Damages related to heavy rain, pluvial flooding and fluvial flooding related to tropical cyclones have been increasing due to a surge in cyclone intensity despite a decrease in number of cyclones (Cinco et al., 2016). Despite the lack of evidence of an existing connection between particular water induced disasters and climate change; there is strong evidence between water related disasters and health through impacts on pathogens, vectors and transmission (Wu et al., 2016). Floods and droughts both have extensive effects on agriculture as they damage crops or reduce crop yields (Gu et al., 2019). The pressures that water related disasters pose into a population and the sectors that sustain them can ultimately result in complex social processes like forced migration (Marino and Lazrus, 2015).

4.4.1.2 Projected Risks to Water-Induced Disasters

Drought and flood risks are projected to increase globally, as a consequence of the combined increases in hazards and exposed population (*medium evidence, strong agreement*). All studies show that in all world regions, some increases in water related hazards are projected and these consistently outweigh reductions in hazard.

AR5 concluded with *medium confidence* that flood hazards will increase over half of the globe and decrease in other regions, with large variability within catchments (Jiménez Cisneros et al., 2014). SRCCL corroborated previous AR5 and SR1.5 findings in which droughts, both from meteorological and hydrological types will increase in frequency and magnitude throughout the 21st century over much of the world but particularly on the Mediterranean and South African regions (*medium evidence*), high latitudes (*high confidence*), the Arabian Penninsula (Arneth et al., 2019). These changes in droughts can exacerbate water scarcity and compromise water security affecting sectors such as agriculture and energy hampering sustainable development (Arneth et al., 2019).

Modelling of climate extremes and consequent disasters remains a challenge as models tend to under – or overestimate the severity of extreme impacts across sectors (Schewe et al., 2019). While the occurrence of droughts or floods can have severe impacts on societal systems, compound events (concomitant occurrence of several extremes within a short time window or at the same time) have the potential for major disruptive effects (Toreti et al., 2019). In the near term (2021–2050), increases in drought risk are projected for most regions under all RCPs for some CMIP5 models, however these are not robust or significant, posing challenges in terms of informing adaptation decisions. In the long term (2051–2100), larger increases in drought risk emerge across RCPs with significantly increased drought risk across the Mediterranean and Amazon region (Carrão et al., 2018). Drought risks to agricultural production are projected across regions (Section 4.3.1.2).

Overall drought risks are projected to increase in terms of area, intensity, duration as well as the share of population affected with different degrees of intensity and severity across the continent (Gizaw and Gan, 2017; Ahmadalipour et al., 2019). Emissions as well as development pathways will have a major influence on these determinants of drought risk, with a mean of 22% to 26% of area affected under RCP4.5 and RCP8.5, respectively, by 2100 (Ahmadalipour et al., 2019). The risk of increasing aridity associated with prolonged periods of drought is projected to increase substantially at higher levels of warming, which will affect an increasing percentage of the population: at a warming level of 3°C above pre-industrial, 170 million people are estimated to be affected by extreme drought. The number of exposed population could be reduced to 120 million by limiting warming to 1.5°C (Samaniego et al., 2018). In higher end scenarios (CMIP5; RCP8.5; 90th percentile of ensemble), cities are projected to be negatively affected by droughts up to 14 times more by 2100 than the most severe droughts in the historical record (Guerreiro et al., 2018). The effects of droughts can be exacerbated in regions that are dependent on glacier runoff as glaciers might disappear and with them an important water source (Bae et al., 2015). Sectoral impacts of droughts can be compounded as the drought phenomena trickles through different sectors (Van Loon, 2015), starting off from a hydrological drought and progressively expanding through the agricultural sector (Aboulnaga et al., 2019) and ultimately affecting real GDP, industry output, employment, trade and household consumption (Kilimani, 2018).

Flood risk displays more ambiguous trends as it increases due to population growth; although the hazard itself might decrease or increase following changes in mean annual precipitation (Guerreiro et al., 2018). Increases in flood hazard can yield an increase in infrastructural flood protection works as the probability of high flows increases (Devkota and Gyawali, 2015). Dam operation rule, especially those of multipurpose dams will require further adaptation, both, to withstand increases in floods and to fulfil their goal during extended periods of drought (Fluixá-Sanmartín et al., 2018). The effects of global warming are also likely to exacerbate floods in regions with glacier dependent runoff, as higher glacial melt increases river channel storage (Bae et al., 2015). Landslides, sinkholes and avalanches also threaten infrastructure, crops and agricultural development (Bajracharya et al., 2018). Heavy precipitation, floods and mass movements can affect the agricultural sector by damaging crops and crop yields.

The impacts of droughts can produce migration from rural to urban areas and more developed regions (Aboulnaga et al., 2019). Migration that can be partially due to or accentuated by climate change can result in further impacts, e.g. on health (public and mental) (Shultz et al., 2019), socioeconomic (competition for resources), or on social conflict (racial or ethnical struggles) (Serdeczny et al., 2017). Sectoral impacts of Water Induced Disasters will be disparate throughout the population having larger effects on developing countries and the poor in developed countries (Levy and Patz, 2015); women, children, indigenous peoples (Norton-Smith et al., 2016), exposed workers and the elder *(medium agreement and medium evidence)* (Mian et al., 2019). Governments and policy makers will encounter larger difficulties attaining socio-economic development and will need extensive development plans that include climate change adaptation in order to fulfil societal necessities (Schwan, 2018).

4.4.1.3 Adaptation Measures to Cope with Water-Induced Disasters

Adaptation measures to water induced disasters are already taking place (*very high confidence*) in both developed and developing countries (*high confidence*).

AR5 reported that case studies of the potential effectiveness of adaptation measures are increasing. To reduce the impact of water-related disasters, the report listed options such as the implementation of monitoring and early warning systems; the development of contingency plans; improved flood defences and planning; diversifying water supplies; improving efficiency of water use; and the adoption of more resilient crops. Although generally it is technically feasible to adapt to projected climate changes, AR5 found that not all studies considered how adaptation would be implemented in practice (Jiménez Cisneros et al., 2014). AR5 also concluded that many adaptation measures build on examples of responses to past variability and disasters, as it has been suggested that the ability to cope with current climate variability is a prerequisite for adapting to future change. The report cautioned, however, that it cannot be assumed that past response strategies will be sufficient to deal with the range of projected climate change (Dasgupta et al., 2011).

More frequent and extreme flood events have prompted changes to planning, the built environment, infrastructure, and agriculture. In delta cities that have a local history and experience of flood management, adaptation strategies build on past practices (Francesch-Huidobro et al., 2017). Flood protection policy is shifting or strengthening their policies for inclusion of flooding information on urban planning (Barros et al., 2015). New technologies for levee or dyke design and multipurpose flood protection/recreational areas are being developed around the (Barros et al., 2015). Early warning systems have become important mechanisms to reduce the impact of flooding while increasing communitarian preparedness (Barros, 2015) (Trinh et al., 2018; Tang, 2019) and are found to have one of the most highest returns to adaptation investments (GCA, 2019). Though, the complexity of flood phenomena, mainly through its propagation through the hydrological cycle demands rigorous developments on technology to monitor storm systems, soil saturation, water level on different water bodies, and flood discharge and therefore create comprehensive hydrometeorological warning systems (Funk et al., 2015). Transferability of such technology, especially that related to remote sensing should be exchange from developed to developing countries (Funk et al., 2015). Urban planners are also adjusting peak flow estimates to ensure the risk of flood and coastal erosion are better adapted to climate change (Kuklicke and Demeritt, 2016).

Elevated homes (both indoors and outdoors) have been adaptation systems that have been used as adaptation to floods, specifically in coastal systems around the (Schaer, 2015; Forino et al., 2017; Marfai and Triyanti, 2018). Maintenance of drainage infrastructure is also an effective adaptation technique against pluvial floods in urban systems (Marfai and Triyanti, 2018). Some agricultural communities are using versatile farming techniques that allows them to shift to short-season crop varieties, which help reduce the impact of floods that tend to occur during harvest time (Trinh et al., 2018) or shift livelihood, for example to fisheries in order to sustain an income during the flood season (Juarez-Lucas et al., 2019). To alleviate the impact of landslides, planners are using mixtures of conventional protective walls mixed green nature based solutions (Rahman and Alam, 2016).

Farmers are adapting their practices in response to more frequent and severe droughts through the adoption of more drought-tolerant crop varieties, use of organic fertilizers, introducing crop rotation, farming calendar, as well as investing in water storage and irrigation (Chalise et al., 2015; Arunrat et al., 2017; Masud et al., 2017; Gentle et al., 2018). Seasonal migration has emerged in some locations as a useful adaptation strategy that enables farmers to supplement and diversify their incomes (Gentle et al., 2018). These strategies are not without their problems, as they may be detrimental for health, wellbeing, family and personal relationships (Bryant and Garnham, 2015; Tschakert et al., 2017).

In general, adaptation measures should diversify through several facets of society (Biagini et al., 2014) to generate a less vulnerable redundancy across sectors and ensure resilient backups in case past strategies fail (Dasgupta et al., 2011). Adaptation strategies should include capacity building, management and planning, practice and behaviour, policy, information, physical infrastructure, warning or observing systems, "green infrastructure and nature-based solutions, financing, and technology (Biagini et al., 2014). Insurance at different scales, for distinct sectoral assets (crops, infrastructure, etc.), for different directly to climate change, or to different types of water induced disasters can increase the resilience of communities providing an effective adaptation measure (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Surminski et al., 2016). Adaptive capacity has been found to be the largest factor that reduces vulnerability to water induced disasters and its exacerbation due to climate change (Krishnamurthy et al., 2014).

4.4.2 Water-related Conflicts

4.4.2.1 Observed Changes in Water-related Conflicts

There is *low* agreement as to the causality between climatological change in the hydrological cycle and the risk of a conflict. However, there is *high agreement* that climatic changes, coupled with other socio-economic and political exacerbating factors, multiply tensions at both the intra-state and the inter-state level.

According to AR5 violent conflict increases vulnerability to climate change (Field et al., 2014).

Recent research (Mach et al., 2019) estimated that climate change influenced 3–20% of conflict risk over the past century. However, only few studies focused specifically on the association between observed changes in the hydrological cycle linked to climate change and conflicts (Zografos et al., 2014; Dinar et al., 2015), and particularly on the role of drought in the Syrian civil war (Gleick, 2014; Kelley et al., 2015; Selby et al., 2017). Some studies associate conflicts to water abundance, mainly because of political mobilization around abundant waters and the need for developing new rules of allocation among competing users (Salehyan and Hendrix, 2014; Selby and Hoffmann, 2014; De Juan, 2015). But the large majority acknowledge water variability due to climate change as having the potential to increase the risk of conflict (De Stefano et al., 2017; Waha et al., 2017), particularly in regions dependent on agriculture for food production (Koubi, 2019). A reverse association from conflict to climate impacts has also been observed by some (Buhaug, 2016), arguing that conflict-affected societies are unable to address climate-change related impacts.

With respect to transboundary waters, the probability of inters-state conflict can increase or decrease depending on both climatic variables (e.g. less precipitation) and others socio-economic and political factors (Koubi, 2019). Although global analyses of transboundary tensions and cooperation are still limited (Link et al., 2016), there is (*medium-high*) evidence that when hydrological conditions change in transboundary river basins, especially in presence of water variability, formal agreements (such as water treaties or river basin organizations) can enhance cooperation (Dinar et al., 2015; De Stefano et al., 2017). Still, more cooperation not necessarily reduce the risk of conflict (Dinar et al., 2019), particularly when water variability increases beyond a certain threshold (Dinar et al., 2015).

4.4.2.2 Projected Risks to Water-related Conflicts

There is *low evidence/ medium agreement* that climate change and the projected increase in water variability has the potential to affect the risk of conflict both within and between states.

AR5 concluded that hydrological changes may increase the risks of violent conflicts and nation-state instability (Jiménez Cisneros et al., 2014). Further research since AR5 supports the conclusion that the impact of climate change on shared water resources might increase tensions among states, particularly in the absence of robust institutional capacity (Petersen-Perlman et al., 2017; Dinar et al., 2019).

Yet, vulnerability to climate change, climate variability and water scarcity is expected to be alleviated/aggravated by human intervention (e.g. land use change, man-made reservoirs, etc.) (Veldkamp et al., 2017). Indeed, whether conflict arises or increases depends on several contextual factors, not necessarily linked to climate change, including land use (Froese and Schilling, 2019); the lack of stable, well-functioning political institutions (Zografos et al., 2014; Petersen-Perlman et al., 2017) and social services to the citizenry (Koubi, 2019). Important uncertainties remain about the mechanisms through which climate change may cause conflict, particularly when other contextual factors, such as low levels of economic development, are in place, or current knowledge/available evidence is limited (Hendrix, 2017; Adams et al., 2018).

At the intra-state level, several experts agree on the fact that additional climate change will increase the probability of conflict risk, in particular in a 2°C warming scenario (Mach et al., 2019). Yet, to date, low socio-economic development, low capabilities of the state, intergroup inequality and recent history of violent conflict are considered more influential drivers of conflict (Mach et al., 2019). Recent studies indicate that, both at the intra-state and inter-states level, climatic change multiplies tensions in regions dependent on agriculture and when coupled with other socio-economic and political factors (Koubi, 2019); while policies that improve good governance and societal development reduce the risk of conflict associated with the challenges to adaptation to climate change (Hegre et al., 2016; Witmer et al., 2017).

Conflicts between agricultural and urban water needs are projected to arise in several river basins, especially in South Asia and in the West of the United States, due to increased demand for urban water supply, climate change and socio-economic developments, including urbanization (Flörke et al., 2018). Future climatic conditions and population growth are expected to exert additional pressures on the management of already stressed basins such as the Nile, the Indus, the Colorado, the Feni, the Irrawaddy, the Orange and the Okavango (Farinosi et al., 2018).

4.4.2.3 Adaptation Measures to Cope with Water-related Conflicts

Water adaptation measures can both contribute to conflict risk reduction and have side effects on the risk of conflicts (*low evidence/medium agreement*).

Although climate-conflict linkages are disputed, potential for synergies between conflict risk reduction and adaptation to climate change exists (Mach et al., 2019). Some adaptation options, such as water conservation, storage, infrastructure, voluntary migration, planned relocation as response to flood risk/sea-level rise, and international water treaties/organizations can reduce vulnerability to both climate change and conflicts, especially where exposure to climatic hazards is higher. Yet, they can also have side effects on the risk of conflicts, by favouring, for example, some groups, such as urban communities over rural communities (Iglesias and Garrote, 2015; Iglesias et al., 2018) or countries (rich countries over less-developed countries) (Shackleton et al., 2015); or by displacing climate hazards to more vulnerable and marginalized groups (Milman and Arsano, 2014; Mach et al., 2019), such as certain ethnic groups and livelihoods, e.g. pastoralist (Zografos et al., 2014). Water adaptation measures, as climate adaptation in general, are constrained by economic, institutional, political, and competing development considerations (Anguelovski et al., 2014), which need to be taken into account in designing adaptation plans/measures.

[START BOX 4.4 HERE]

Box 4.4: Water Law and Transboundary Agreements

Law plays a key role in the context of climate-related water adaptation. Water law dictates structure, rules and processes within which governmental actions take place (e.g. in the European Union, the Water Framework Directive, 2000) and encourages the efficient management of water resources and water-related services at the national and regional levels (Tortajada, 2016).

Several legal sources (e.g. international river treaties) and tools (adjudication, enforcement, etc.) exist that aim at resolving disputes among riparian states, or preventing them from arising (Mitchell and Zawahri, 2015; Petersen-Perlman et al., 2017). Others, e.g. water property rights or licences, respond to the need of the states to enhance their adaptive capacity in the face of the challenges (e.g. drought) posed by the impact of climate change on water resources (Cosens et al., 2017). Recent studies (Craig et al., 2017; DeCaro et al., 2017; Honkonen, 2017) and IPCC special reports (Agus et al., 2019; Hock et al., 2019) suggest that adaptation to climate change can be favoured by legal tools and regulations that enhance the ability of state and non-state actors (e.g. farmers, indigenous groups, homeowners) to flexibly respond to the challenges created by climate change.

A variety of legislative mechanisms (e.g. law governing water use rights in times of water scarcity and/or variability) already exist to address adaptation challenges related to current level of climate change impacts on freshwater resources. However, many of these mechanisms might not be suitable to cope with/manage irreversible changes associated with greater levels of warming, such as depletion of groundwater aquifers (Hill Clarvis et al., 2014). This can be partly attributed to the difficulty of reconciling scientific uncertainties with the necessity of predictability of any legal system, which postulates clear, precise, and stable norms and rights (Honkonen, 2017).

Legal frameworks that encourage the efficient management and allocation of water resources, in a way that takes account of future shifts/expected changes in water resources, exist at various level of governance. For example, the Convention on the Protection of the Rhine (1999) requires the International Commission to be competent in all possible matters delegated by the riparian states, thus empowering it to deal with climatic change-induced flow variability without becoming arbitrary (Art. 8.1.e). Yet, even when laws and regulatory mechanisms are specifically designed to support adaptive water governance, fragmentation and lack of coordination - e.g. among state and federal government agencies in federal systems, or supra-national and national authorities in regional organizations (e.g. the European Union) - can pose a barrier to adaptation (DeCaro et al., 2017). Subsidiarity, transparency and effective participation play a key role in the context of climate adaptation (Tortajada, 2016; Craig et al., 2017; Honkonen, 2017). But these principles should be supported by stable institutions, flexible governance systems and substantial legal standards (i.e. legislation), which ensure equal participation of the public - including women (Fauconnier et al., 2018) - consultation, access to information (Cosens et al., 2017).

[END BOX 4.4 HERE]

4.4.3 Impacts on Human Mobility and Migration

4.4.3.1 Observed Changes on Human Mobility and Migration

There is robust empirical evidence that climate induced hydrological changes have both increased and decreased the likelihood of migration, depending on the socio-economic, political, and environmental context. Overall, empirical research shows some agreement between studies, but the complexity of migration processes makes it difficult to generalize broadly. There is much evidence linking observed migration with climate induced changes in the hydrological cycle, but evidence on future migration estimates, particularly in relation to migrant destinations is weak (*medium evidence; medium agreement*).

AR5 noted that migration is complex, and that migration decisions and outcomes are influenced by a combination of social, demographic, economic, environmental and political factors and contexts (Adger et al., 2014a).

International migration linked to climate induced hydrological changes have been observed, through studies of bilateral flows (Backhaus et al., 2015) and refugee movement (Missirian and Schlenker, 2017; Abel et al., 2019). Sea level rise and floods negatively affect people in coastal areas, which may directly or indirectly lead to migration (Chen and Mueller, 2018; Islam, 2018; Bernzen et al., 2019). Drought has been found to influence both internal (Afifi et al., 2015; Mastrorillo et al., 2016; Thiede et al., 2016) and international (Obokata et al., 2014; Nawrotzki and Bakhtsiyarava, 2017) migration decisions, often through adverse agricultural conditions (Backhaus et al., 2015; Mastrorillo et al., 2016; Nawrotzki and Bakhtsiyarava, 2017). Droughts may increase or decrease migration risk, depending on the nature of the drought event as well as the socio-economic factors of the affected households/communities (Afifi et al., 2015; Ocello et al., 2015; Koubi et al., 2016; Mastrorillo et al., 2016; Thiede et al., 2016; Nawrotzki and Bakhtsiyarava, 2017).

More synthesizing research is needed to better understand the contexts in which climate induced hydrological changes lead to increased or decreased likelihood of migration (Obokata et al., 2014; Gray and Wise, 2016). Future research also needs to combine large sample studies with local case studies to better understand environmentally influenced migration patterns at different scales (Obokata et al., 2014).

In summary, climate induced hydrological changes can both increase and decrease the likelihood of migration and the outcome is largely determined by the socio-economic, political, and environmental context.

4.4.3.2 Projected Risks to Human Mobility and Migration

There is high uncertainty about how climate induced hydrological changes will influence migration in the future. Evidence is weak on migration estimates, particularly in relation to migrant destinations and alternative adaptation options *(weak evidence, low agreement)*.

Projections of future migration due to environmental change have largely been focused on the number of people who will migrate or become displaced.

The projected rapid population growth in at-risk areas is expected to increase migration and displacement in the future (McLeman, 2018; Rigaud et al., 2018). A model incorporating water, agriculture, and sea level rise together with SSPs, projects between 31 (RCP2.6) and 143 (RCP8.5) million people internally displaced by 2050 in Sub-Saharan Africa, South Asia and Latin America (Rigaud et al. 2018). Another estimate, combining climate and statistical models, project that asylum applications to the EU could increase by between 98000 (RCP4.5) and 660000 (RCP8.5) by 2100 (Missirian and Schlenker, 2017).

More research is needed on detailed projections of future migration patterns, for example where people will go (Abel et al., 2019). More local and regional models, incorporating contexts, are needed (specifically in Africa, Central and South America, and the Mediterranean) to complement global models (Rigaud et al., 2018). Projections need to include immobility and non-migratory adaptation strategies (Zickgraf, 2018) (Cross-Chapter Box MIGRATE in Chapter 7).

There is limited evidence on the future impacts of climate induced hydrological changes on migration patterns, but studies agree that migration will increase with climate induced hydrological changes.

4.4.3.3 Adaptation Measures for Human Mobility and Migration

Human mobility is viewed as one of many adaptation measures to hydrological changes. Both migration and resettlement have been however, also found to increase vulnerability among affected populations *(medium evidence, strong agreement).*

Migration is generally regarded as an adaptation strategy in response to climate change (Gemenne, 2011). While migration has the potential to improve the situations for migrants and communities, it may also lead to e.g. impoverishment (Wilmsen and Webber, 2015), increased vulnerability (Adger et al., 2018) and even exposure to violence (Linke et al. 2018). Women migrants may improve their economic situation but still face insecurity with regards to land ownership, welfare, and eviction threats (Patel and Giri, 2019). Climate related changes in seasonal migration patterns might also create food insecurity and vulnerability through loss of agricultural labor (Rademacher-Schulz et al., 2014). Migration requires economic and social capital, and vulnerable populations who are unable migrate may become trapped (Adams, 2015; Nawrotzki and Bakhtsiyarava, 2017; Zickgraf, 2018).

Adaptation includes strategies to avoid displacement as well as measures that facilitate successful migration and resettlement (Adger et al., 2018). Governments may facilitate migration in areas exposed to climate risk, by supporting poor and marginalized communities, and thereby decrease the risk of populations becoming trapped (Black and Collyer, 2014; Adger et al., 2018). Managed retreat, including planned realignment and resettlement, is an adaptation measure in coastal areas vulnerable to floods and sea level rise (Hino et al., 2017; Maldonado and Peterson, 2018; Tadgell et al., 2018).

More research is needed to understand what constitutes successful adaptation and how to avoid increased vulnerability among migrating and resettled populations (McLeman, 2018; Tadgell et al., 2018). Impacts on women and marginalized groups need to be better understood (McLeman, 2018). The issues of immobility and trapped populations need more research attention (Zickgraf, 2018).

Adaptation to climate change induced hydrological change constitute both non-migratory and migratory strategies. Migration may lead to increased vulnerability; therefore, research need to better understand how to ensure migration becomes a successful adaptation strategy.

4.4.4 Impacts on Cultural Uses of Water

4.4.4.1 Observed Changes on Cultural Uses of Water

Climate change is impacting cultural uses of water among communities in the Arctic and high mountain areas (*robust evidence, high agreement*), as well as First Nations and Indigenous peoples elsewhere (*limited evidence, high agreement,* these impacts are exacerbated by historical, socioeconomic and political marginalisation (*robust evidence, high agreement*).

AR5 reported that religious and sacred values inform perceptions of climate change and risk (Adger et al., 2014a; Adger et al., 2014b). Although neither AR5 nor SR1.5 assessed the impacts of climate change on cultural uses of water, AR5 concluded that the livelihoods of Indigenous peoples in the Arctic have been altered by climate change through impacts on traditional and cultural values (Adger et al., 2014a).

As climate change is already impacting the cryosphere are strong (*robust evidence, high agreement*), studies on the consequences of these impacts for cultural uses largely pertain to societies who live in the vicinity of cryospheric components such as glaciers, ice, snow, permafrost, and glacier lakes (Carey et al., 2017; Mukherji et al., 2019b). In the Peruvian Andes and the Hindu Kush Himalaya, elderly women and monks attribute the changing ice to a lack of spiritual devotion (Drenkhan et al., 2015; Konchar et al., 2015b; Scoville-Simonds, 2018; Mukherji et al., 2019b). Literature reviews of cryospheric change in the Peruvian Andes found communities interpreted climate impacts in a wider context of socioeconomic and political injustice and inequality (Drenkhan et al., 2015).

Climate impacts on cultural water uses are also evident among First Nations and Indigenous peoples elsewhere. These impacts on cultural uses arise from their effects on relationships of reciprocity with biota and ecosystems that shape culture and cultural identity. For example, a synthesis of climate impacts on Indigenous peoples in the United States found disruption of access routes to traditional hunting grounds, and exacerbated stresses to culturally-important species (Norton-Smith et al., 2016). Given the ongoing structural impacts of colonialism on First Nations and Indigenous peoples, there is limited evidence that environmental change can be attributed solely to climate change (*medium evidence, strong agreement*).

4.4.4.2 Projected Risks to Cultural Uses of Water

Climate change will negatively impact cultural uses of water, especially for Indigenous societies, but the exact extent and scope of such change is not well understood (*limited evidence, high agreement*).

SR1.5 concluded that constraining global warming to 1.5C, rather than 2C, will strongly benefit terrestrial and wetland ecosystems and their services, including the cultural services provided by these ecosystems to humans (Hoegh-Guldberg et al., 2018a).

There is growing evidence that climate change will directly and indirectly impact cultural uses of water (*medium evidence, medium agreement*). Ethnographic research in northern Canada showed that changing access to Inuit hunting grounds and the sea ice itself would be detrimental to their culture and health (Durkalec et al., 2015). A literature review of the possible impacts of climate change on Indigenous peoples in the United States found that changes in streamflow and water temperature will exacerbate declines of culturally important species, reduce water quality, and lead to changes or the loss of culturally important places and subsistence practices (Norton-Smith et al., 2016).

Further work is necessary to discern the projected impacts of climate change on cultural uses of water.

4.4.4.3 Adaptation on Cultural Uses of Water

Adaptation to climate change related to cultural uses of water is already underway but most of it is unplanned and ad hoc. The efficacy, therefore, of such adaptation is limited (*limited evidence; high agreement*).

AR5 reported that religious and sacred values inform the actions taken to adapt to climate change (Noble et al., 2014b). Neither AR5 nor SR1.5 reviewed adaptation related to cultural uses of water.

Local peoples have responded and adapted to glacier retreat and decline in snow cover. In the Peruvian Andes, concerns regarding the capacity to produce sufficient water for ritual purposes has led to the prohibition of Catholic pilgrims from removing ice; guards allow only small bottles of meltwater to be taken (Paerregaard, 2013). Ethnographic research in the Andes found local peoples undertook rituals to summon rainfall in response to greater water scarcity (Stensrud, 2014; Stensrud, 2016). In the Canadian Arctic, Inuit hunters are adapting to changing sea ice conditions and using boats to access hunting areas that were previously accessible only by crossing the sea ice, either on foot or using a dog team or snowmobile (Pearce et al., 2015). Furthermore, Inuit hunters increasingly anticipate the possibility of encountering hazards when traveling and hunting on the land and ice as a result of climate change impacts. These adaptation strategies are the product of Indigenous knowledge systems that perceive the Arctic environment as being in a constant state of flux (Ford et al., 2016).

Although a growing number of studies demonstrate significant adaptive capacity among communities in the Arctic and high mountain areas, as well as First Nations and Indigenous peoples (Golden et al., 2015; Bunce et al., 2016; Anderson et al., 2018; Eira et al., 2018; Huntington et al., 2019), there are many structural conditions that hamper the ability of local peoples to adapt cultural uses of water to climate change. In addition to institutional and jurisdictional barriers, a literature review of adaptations taking place in the Arctic found limited evidence of anticipatory thinking about future risks (Ford et al., 2016).

Given the limited literature on climate change impacts cultural uses of water, additional studies are needed to identify how cultural values influence the perception of climate impacts.

4.4.5 Key Risks Related to Water

[PLACEHOLDER FOR SECOND ORDER DRAFT: This section as well as the figure serve as an extended giving an impressions of the aim of this subsection – the actual transition levels for the burning embers (this is only a mock-up), as well as the details in the text are still being assessed based on available literature and papers in preparation; figure and text will also be adapted based on discussions and findings with Chapter 16]

Water is one of the most fundamental components for the functioning of human and environmental systems and direct as well as indirect impacts and risks, which manifest through a multitude of pathways have the potential to fundamentally disrupt these systems. The preceding sections have outlined the various pathways along which climate affects water resources and water-using sectors. In synthesis, fundamental shifts in risks levels are likely to manifest at different levels of warming. This section summarises the emerging evidence of impacts and risks at different levels of GMT increase across the three dimensions outlined in this section: a) biophysical risks of hydrological change (4.2); b) sectoral risks of hydrological changes (4.3) and c) cross-sectoral risks of hydrological change (4.4).

Projected increases in hydrological extremes pose increasing risks to societal systems globally, with a potential doubling of flood risk between 1.5°C and 3°C of warming (4.2.7.2) (Dottori et al., 2018) and a near-doubling of drought duration (Naumann et al., 2018). Increasing sectoral risks are reported across regions and sectors with increasing temperatures. Risks to agricultural yields, for example, could be three times higher at 3°C compared to 2°C (Ren et al., 2018), with additional risks as a consequence of increasing climate extremes (Leng and Hall, 2019); with higher levels of warming, impacts on water-dependant energy production increase substantially across regions (van Vliet et al., 2017; Tobin et al., 2018); the regional potential infestation areas for disease carrying vectors could be five times higher at 4°C than at 2°C (Liu-Helmersson et al., 2019). Also refer to Cross Sector Box on Key Risks by Systems and Regions; Chapter 16.

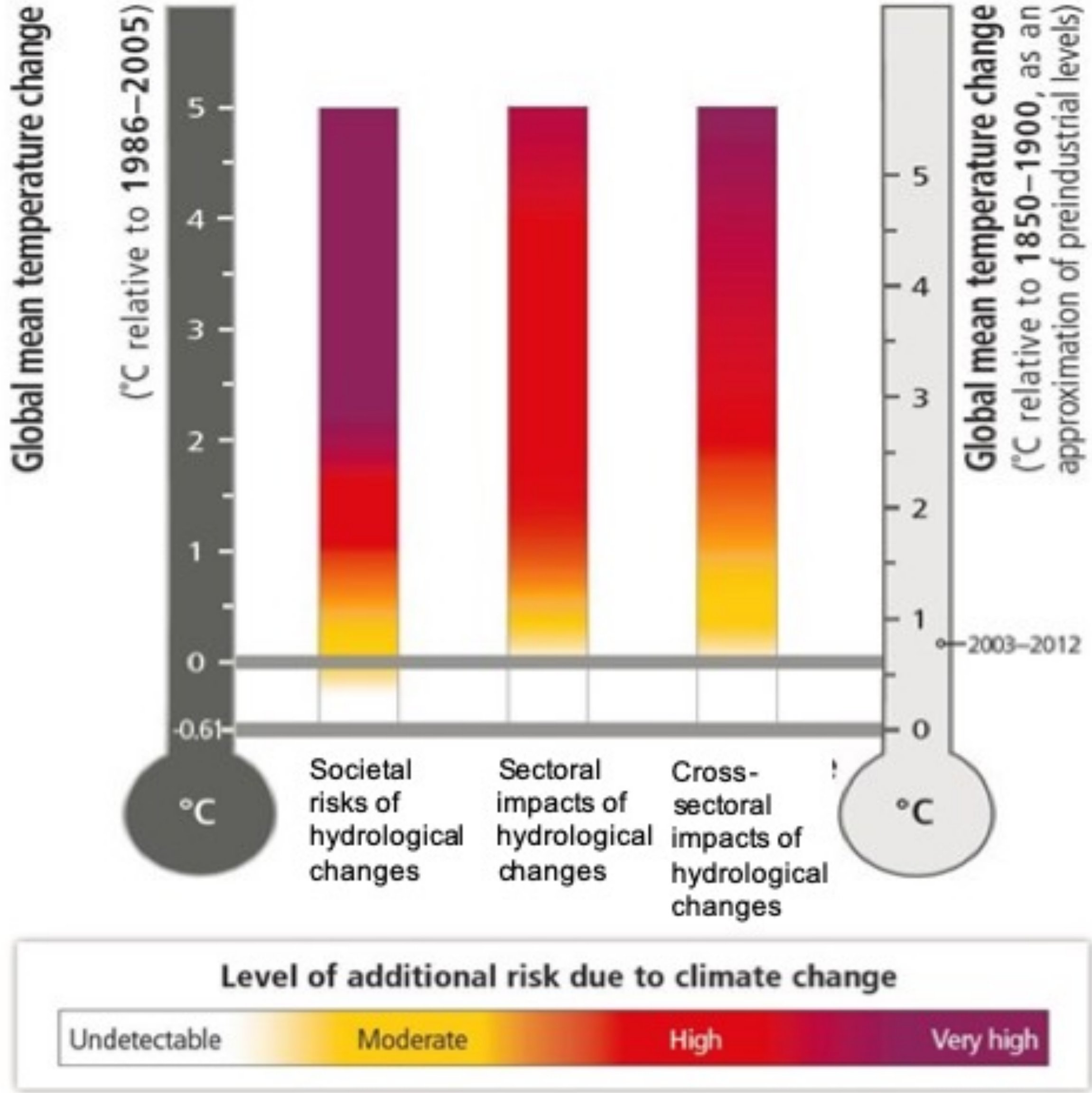


Figure 4.13:[PLACEHOLDER FOR SECOND ORDER DRAFT: synthesis of key risks related to water figure and does not show actual risk levels based on analyses of this chapter]

4.4.6 Knowledge Gaps

Table 4.11 captures current knowledge gaps related to those impacts of changes in hydrological cycle that affects several sectors (cross-sectoral impacts), and table 4.13 captures regional trends in cross sectoral impacts and risks.

Table 4.11: Knowledge gaps in sectors impacts of climate change and adaptation interventions

Sections	Key gaps	Scale	Reference
4.4.1 Water-Induced Disasters	Insufficient data to link increase in floods and droughts due to climate change.	Global, Regional and National	Inferred by the authors from literature
	Lack of local data in developing countries not only on observations of water induced disasters and on their effect in different socio-economic sectors.	Developing countries	Inferred by the authors from literature
	Lack of localized studies on how water induced disasters are projected to affect different socio-economic sectors.	Global, Regional and National	Inferred by the authors from literature

	Lack of evidence on the effects of water induced disasters on migration and conflicts.	Global, Regional and National	Inferred by the authors from literature
4.4.2 Water-related Conflicts	Transferability and global comparison of adaptation measures are lacking.	Global, Regional and National	Inferred by the authors from literature
	The mechanisms through which climate change may cause conflict are still understudied.	Global, Regional and National	Inferred by the authors from literature
	Limited evidence on how/why adaptation options may vary at different spatial and societal scales.	Global, Regional and National	Inferred by the authors from literature
4.4.3 Human Mobility and Migration	How climate induced hydrological changes lead to increased or decreased likelihood of migration is not well understood.	Global, and Regional	(Obokata et al., 2014; Gray and Wise, 2016)
	The issue of trapped populations and immobility were unrevealed by the studies.	Regional and National	(Zickgraf, 2018)
	Large sample studies and local case studies are not well integrated to better understand environmentally influenced migration patterns at different scales.	Regional and National	(Obokata et al., 2014)
	Future migration patterns in the context of climate induced hydrological changes is largely unknown (i.e where people will go).	Global, Regional and National	(Abel et al., 2019)
	Limited understanding on the future immobility and non-migratory adaptation strategies, and how adaptive capacities might change in the years ahead.	Regional and National	(Zickgraf, 2018)
	What constitutes successful adaptation and how to avoid increased vulnerability among migrating and resettled populations are unknown.	Regional and National	(McLeman, 2018; Tadgell et al., 2018)
4.4.5 Cultural Uses of Water	Projected impacts of climate change on cultural uses of water is limited.	Regional and National	Carey et al. (2017);Huntington et al. (2019)
	How cultural values influence the perception of climate impacts is not well understood.	Regional and National	Carey et al. (2017); Vuille et al. (2018); Rasul and Molden (2019)

Table 4.12: [PLACEHOLDER FOR SECOND ORDER DRAFT: to be further developed, particularly in relation to the adaptation options]. Synopsis of hydrological changes, human and climate drivers and adaptation/management option

ISSUE/SYNDROME	HUMAN DRIVER	CLIMATE DRIVER	MANAGEMENT/ADAPTATION OPTIONS (placeholder for SOD)
Increase in frequency and magnitude of droughts	Agriculture, Cities	Hydrological Process, Temperature	Seasonal outmigration; improved efficient irrigation; short season crop varieties
Increase in frequency and magnitude of floods	Agriculture		Early warning systems; improved urban planning
Shortening of snow/frost season and snow pack volume		Hydrological Process, Temperature, Cryosphere	Efficient irrigation; short season crop varieties; outmigration
Decrease in glacier runoff	Agriculture, Cities	Hydrological Process, Cryosphere	Efficient irrigation; short season crop varieties; outmigration
Groundwater depletion	Agriculture	Hydrological Process	Changes in livelihood; efficient irrigation
Seasonal shift in peak flows	Cities, Health/WASH	Hydrological Process, Temperature, Cryosphere	Efficient irrigation; short season crop varieties;seasonal outmigration
Decreased water quality	Agriculture	Hydrological Process, Temperature	Changes in livelihood
Increased erosion and sediment transport	Agriculture, Cities, Health/WASH	Hydrological Process, Temperature	Nature based solutions
Degradation of Lakes or other major water bodies	Agriculture, Cities, Navigation	Hydrological Process, Temperature	Changes in livelihood, outmigration
Increased stream water temperature		Temperature, Cryosphere	

Agriculture Health/WASH Temperature Hydrological Process

Cities Navigation Cryosphere

Table 4.13: Cross-sectoral impacts of climate change and adaptation interventions across regions

Region	Observed changes	Projected changes
Africa	*Water-Induced Disasters (WIDs)*	
	South Africa is affected by prolonged droughts of prolonged dry periods that cause issues across agriculture and energy sectors (Elum et al., 2017).	Problems related to droughts include exacerbation of water scarcity (Derrick Ngoran et al., 2015), exacerbation of undernutrition, poverty (Tirado et al., 2015) and damage to crops (Adhikari et al., 2015).
	Water Related Conflicts	
	Conflict associated to water abundance (Sudan/South Sudan → (Selby and Hoffmann, 2014))	Additional pressures on the management of already stressed basins (Nile, Orange, Okavango → (Farinosi et al., 2018))
	Conflict associated to maladaptation to water variability (Ethiopia → (Milman and Arsano, 2014) (Northern Africa → (Waha et al., 2017))	Growing population and rising temperatures are expected to lead to higher levels of violence (sub-Saharan Africa → (Witmer et al., 2017))
	Impacts on Human Mobility and Migration	
	Temperature anomalies may both increase and decrease the risk of migration depending on the context (Gray and Wise, 2016). The relationship between precipitation and migration has been described as weak and inconsistent (Gray and Wise, 2016), with both positive and negative effects on (international) migration and displacement (Ocello et al., 2015; Nawrotzki and Bakhtsiyarava, 2017; Owain and Maslin, 2018). Climate induced hydrological changes are often less important in influencing migration decisions than economic or social factors (Afifi et al., 2015; Neumann and Hermans, 2017), individual characteristics, and structural conditions (Ocello et al., 2015; Mastrorillo et al., 2016; van der Land et al., 2018).	Sea Level Rise and changes in resource availability is expected to lead to increased migration in Sub-Saharan Africa in the future (Serdeczny et al., 2017). In a worst-case scenario, Rigaud et al. (2018) predicts around 86 million internal climate migrants in Sub-Saharan Africa by 2050. Just as observed changes show complexity and context dependency, future changes cannot be generalized across the African continent (Gray and Wise, 2016).
	Impacts on Cultural Uses	
	-	-
Australasia	*Water-Induced Disasters (WIDs)*	
	Extreme weather events such as droughts have had detrimental effects on the agricultural sector for instance on wheat yield (Feng et al., 2019).	Extreme weather events such as droughts can be exacerbated in the future impacting the agricultural sector for instance on wheat yield (Feng et al., 2019).
	There has been an increase in volatility of the hydrological cycle across Australia, increasing both floods and droughts affecting energy production and agriculture (Xie et al., 2016).	Damages to water resources infrastructure such as dams is expected to increase with increases in extreme water hazards such as droughts (Burritt and Christ, 2018).
		Increases in flood protection due to increases of extreme floods are likely to take place across major Australian cities (Horne, 2018).

	Water Related Conflicts		
		-	-
	Impacts on Human Mobility and Migration		
		In Australia, migration is seen as one of many adaptation strategies during floods and droughts, but few have actually migrated due to such hydrological changes (King et al., 2014).	Research on migration in Australasia focuses mainly Australia and New Zealand as future destinations for migrants from Pacific Islands (Campbell et al., 2014). In New Zealand, models found negligible future impacts of climate change on internal population distribution, indicating other adaptation measures will be more important (Cameron, 2018).
	Impacts on Cultural Uses		
Small Islands	*Water-Induced Disasters (WIDs)*		
		Increase in heavy precipitation due to hurricanes affecting urban centers across small Islands in the Caribbean (Shultz et al., 2019). Floods and droughts increasing impacts on agriculture, energy, transport, tourism, health and fisheries in the Pacific Islands (Edmonds, 2018). Increased convection mixed with high urbanization has increased pluvial flooding in cities across small islands in the Caribbean and the Pacific (Mycoo and Donovan, 2017).	Increases in floods and droughts are likely to have detrimental effects on agriculture, energy, transport, tourism, health and fisheries in the Pacific Islands (Edmonds, 2018; Mycoo, 2018). Increased heavy precipitation and increased droughts can add up to social stresses caused by sea level rise in small islands in small island developing states and enhance migration (Shultz et al., 2019).
	Water Related Conflicts		
		Climate change impacts in small island states provide challenges for sustainability and may, in the long run, threaten the habitability of entire islands (Betzold, 2015; Connell, 2016). There is, however, limited research showing that forced migration due to climate change has occurred in Pacific Islands (Campbell et al., 2014). Planned resettlement has been initiated in e.g. Fiji (Piggott-McKellar et al., 2019). Existing evidence show that migration decisions are context dependent and that there are often multiple reasons for migrating (Kelman, 2015; Stojanov et al., 2017; Kelman et al., 2019).	Sea level rise is expected to lead to increased international migration due the limited terrestrial space in such nations (Kelman, 2015; Stojanov et al., 2017). However, the strong focus on international migration as an adaptation strategy might be unjustified, since "virtually all of the present atoll islands will be there at the end of the 21st century if present trends continue" (McLean and Kench, 2015). There is potential for forced migration from Small Island states, but other adaptation strategies exist (ibid).
	Impacts on Human Mobility and Migration		
		-	-
	Impacts on Cultural Uses		
		-	-

Asia	*Water-Induced Disasters (WIDs)*	
	Regions in the middle east are constantly affected with prolonged droughts which damages crops and crop yields contributing to food insecurity (Waha et al., 2017). The agricultural sector can also be affected by secondary effects induced by floods like soil degradation due to increase in nutrient transport (Hafeez et al., 2019). Countries in the Indian sub-continent are likely to experience losses to agriculture due to increased floods and reduced domestic and drinking water due to droughts (Lacombe et al., 2019).	Changes in disasters such as floods will increase damages to crops in China (Gu et al., 2019). Regions in the middle east are likely to be affected with greater droughts which possibly could affect food security and water availability (Waha et al., 2017). South Asia, a region that already has stresses in the energy, water-stressed, and food production sectors and these problems might intensify with high population and changing climate (Rasul and Molden, 2019).
	Water Related Conflicts	
	Conflict associated to water variability in presence of other contextual factors (Middle east→ (Waha et al., 2017))	Conflicts between agricultural and urban water needs (in several river basins in South Asia → (Flörke et al., 2018)) Additional pressures on the management of already stressed basins (Indus, the Feni, the Irrawaddy→(Farinosi et al., 2018))
	Impacts on Human Mobility and Migration	
	The migration outcome of hydrological changes varies over different contexts and cases. It is difficult to separate environmental drivers of migration and displacement from economic drivers (Bernzen et al., 2019) and hydrological changes may both increase and decrease migration risk. In Vietnam, droughts were found to decrease migration risk while floods increased migration risk (Koubi et al., 2016). Increases in soil salinity, caused by SLR, had adverse effects on agricultural production in Bangladesh, and led to increases in internal migration, but decreased international migration (Chen and Mueller, 2018). Research on climate induced hydrological changes in Asia is dominated by case studies from Bangladesh, where floods, sea level rise, increases in soil salinity, drought and riverbank erosion in areas with economically vulnerable populations are generally associated with increased migration and displacement (Chen and Mueller, 2018; Islam, 2018; Kabir et al., 2018; Rakib et al., 2019).	Climate change impacts is expected to become an important driver of migration in Asia, due to the combination of population pressures, projected climate change impacts (e.g. changing monsoon patterns, sea level rise), and poverty rates (Hugo and Bardsley, 2014). A model focusing on Bangladesh found that by 2100, as many as 2.1 million people might have been forced to migrate due to sea level rise (Davis et al., 2018). This study also modelled migrant destinations and increased job, housing and food needs in those places. In Yemen, future climate effects on net migration are expected to be small (Wodon et al., 2014).
	Impacts on Cultural Uses	
	-	-
Central and South America	*Water-Induced Disasters (WIDs)*	
	South Brazil has experienced a major drought reflected as water shortages across sectors such as domestic use and energy production (Nobre et al., 2016).	Changes in water induced disasters are likely to exacerbate the effects of extreme water extremes across South America, particularly in the sectors of agriculture (Nehren et al., 2019).

	Regions in South America, particularly those close to steep slopes have experienced losses in crops due to landslides and floods (Nehren et al., 2019). Agricultural production has been affected in the past by extended periods of droughts (Nehren et al., 2019). Some of the largest damages associated with extreme water hazards in South America are those related to landslides in urban settlements (Nehren et al., 2019).	Damages due to landslides are likely to increase in areas particularly in urban settlements (Nehren et al., 2019). Vulnerability to Food insecurity is likely to increase particularly in Brazil and Central America (Betts et al., 2018b) with changes being exacerbated with a more extreme scenario due to floods and droughts.
	Water Related Conflicts	
	-	-
	Impacts on Human Mobility and Migration	
	In South America climate variability, and specifically temperature shocks, were found to generally increase the likelihood of migration, though there were large differences between demographic groups and countries, highlighting the complexity and context dependency of the climate-migration relationship (Thiede et al., 2016). Climate-related migration was generally directed towards urban areas (ibid). Higher-than normal rainfall in rural Mexico have been found to both increase (Nawrotzki et al., 2015) and decrease (Barrios Puente et al., 2016) US bound migration. Evidence also points to immobility in the face of climate induced hydrological changes, due to residential satisfaction, lack of resources, or low mobility potential (Adams, 2015). In the Bolivian Andes, despite concerns about glacial retreat and future livelihoods, no strong effects on migration have been recorded (Raoul, 2015).	-
	Impacts on Cultural Uses	
	-	-
North America	*Water-Induced Disasters (WIDs)*	
	Declines in water availability for agriculture have been identified in Canada and California due to droughts (Yusa et al., 2015; Pathak et al., 2018). Water Sanitation Systems in metropolitan areas across North America are vulnerable to waterborne disease outbreaks if affected by floods (Exum et al., 2018).	Water Sanitation Systems in metropolitan areas across North America are vulnerable to waterborne disease outbreaks if affected by floods (Exum et al., 2018). Vulnerability to floods is likely to increase across the eastern US (Toomey et al., 2019).
	Water Related Conflicts	

	-	Conflicts between agricultural and urban water needs (West of the United States → (Flörke et al., 2018)) Additional pressures on the management of already stressed basins (Colorado → (Farinosi et al., 2018))
	Impacts on Human Mobility and Migration	
	The main migration driver in North America is economics, and few hydrological stressors are grave enough to lead to migration at a larger scale (Adamo and de Sherbinin, 2014). There is empirical evidence of drought causing large scale migration in the 1930s, an event known as the Dust Bowl (Whitley et al., 2018). In some cases, hydrological changes have affected migration from Mexico to the United States (Nawrotzki et al., 2015).	Sea Level Rise is projected to, by 2100, affect between 4.2 and 13.1 million people in the United States (Hauer et al., 2016), however the migration outcomes of such changes are unknown (Aerts, 2017). In Alaska, despite showing little observed migration from hydrological changes, future migration caused by climate change is expected (Hamilton et al., 2016).
	Impacts on Cultural Uses	
	A synthesis of climate impacts on Indigenous peoples in the United States found disruption of access routes to traditional hunting grounds, and exacerbated stresses to culturally-important species (Norton-Smith et al., 2016).	A literature review of the possible impacts of climate change on Indigenous peoples in the United States found that changes in streamflow and water temperature will exacerbate declines of culturally important species, reduce water quality, and lead to changes or the loss of culturally important places and subsistence practices (Norton-Smith et al., 2016).
Europe	*Water-Induced Disasters (WIDs)*	
	Increases in floods have increased the exposed population and infrastructure making policy makers seek for different protection measures such as restoration of flood plains (Jüpner, 2018).	Flood risk in Europe is likely to increase projecting that about two thirds of the population of Europe will be exposed to floods and expecting about 50 time the number of fatalities of historic records (Forzieri et al., 2017; Kundzewicz et al., 2017).
	Water Related Conflicts	
	-	Conflicts among users in rural areas (Iglesias and Garrote, 2015)
	Impacts on Human Mobility and Migration	
	The drivers of migration in Europe are largely political, economic, social and cultural, factors that may be influenced by environmental change (Mulligan et al., 2014). No post-AR5 literature on observed European migration due to hydrological changes can be found.	Future hydrological changes, both inside and outside of Europe, can be expected to play a more important role in European migration patterns (Mulligan et al., 2014). Quantitative estimates show increased number of asylum seekers to the EU as an effect of temperature anomalies elsewhere (Missirian and Schlenker, 2017).
	Impacts on Cultural Uses	
	-	-

Mediterranean	*Water-Induced Disasters (WIDs)*	
	Weather disasters have been increasing across Mediterranean Europe, especially those related to droughts (Kron et al., 2019).	Damages from floods and droughts are likely to progressively increase throughout the 21st century across Mediterranean Europe (Forzieri et al., 2018).
	Water Related Conflicts	
	-	Conflicts among users (Iglesias et al., 2018)
	Impacts on Human Mobility and Migration	
	Climate induced hydrological changes are not the main drivers of migration in the Middle East and North Africa (MENA) region, but extreme events like droughts and floods appear to influence both temporary and permanent migration patterns (Wodon et al., 2014). A severe drought struck the eastern Mediterranean between 2006 and 2010, which affected migration patterns in Syria by increasing the number of migrants in and from rural areas (De Châtel, 2014; Fröhlich, 2016).	-
	Impacts on Cultural Uses	
	-	-
Mountains	*Water-Induced Disasters (WIDs)*	
	-	-
	Water Related Conflicts	
	-	-
	Impacts on Human Mobility and Migration	
	-	-
	Impacts on Cultural Uses	
	In the Peruvian Andes and the Hindu Kush Himalaya, elderly women and monks attribute the changing ice to a lack of spiritual devotion (*medium confidence*) (Drenkhan et al., 2015; Konchar et al., 2015b; Scoville-Simonds, 2018; Mukherji et al., 2019b). Literature reviews of cryospheric change in the Peruvian Andes found communities interpreted climate impacts in a wider context of socioeconomic and political injustice and inequality (*medium confidence*) (Drenkhan et al., 2015).	-

4.5 Global Frameworks and Local Initiatives for Enabling Water Related Adaptation

4.5.1 Global Policies and Frameworks

A number of global policies and frameworks are propelling action and enhancing our understanding for the needs and challenges of water adaptation and water resilient pathways. We divide these frameworks into political frameworks for action, and analytical frameworks and frameworks for action based on the justifications that informs these frameworks.

4.5.1.1 Political Frameworks for Action: Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs)

Nationally Determined Contributions and National Adaptation Plans are high-level policy instruments communicating climate change mitigation and adaptation ambitions and plans by parties (countries) to the United Nations Framework Convention on Climate Change (UNFCCC). 92% of countries which mention adaptation in NDCs also include water.

Nationally determined contributions (NDCs) are considered as a heart of the Paris Agreement which demonstrates pledges of each country to reduce national GHG emissions and adapt to the impacts of climate change. Several countries have highlighted that climate change induced water cycle change might have an impact on economic, social, and political areas and water accessibility and food security situation. The most vulnerable sectors referred to the NDCs by the parties are: water, agriculture, biodiversity, and health. Out of the top 13 climate hazards, water-related hazards such as flood and drought are identified as a topmost extreme events in the NDCs by the countries (UNFCCC, 2016). NDC provides evidence that water vulnerability is much higher on the agenda on lower income countries than the upper-income countries and as such 52.0% of developing countries indicated water-related target/measures in their NDCs (Amponin and Evans, 2016). Parties UNFCCC are expected to produce National Adaptation Plans (NAPs) which are periodically updated to inform their national-level adaptation strategies. Water-related impacts and adaptation often feature prominently in NAPs (DEFRA, 2018), addressing adaptation to flooding, water supplies and other issues which are additionally affected by water-related impacts such as human health.

There is a *robust evidence* that enhancement of high-level political support, institutional coordination and engagement with the private sector and vulnerable communities can enhance the integration process of adaptation into development planning in Africa (NAP-GSP, 2017). There is a *robust evidence* that most countries in Asia-Pacific have conducted sectoral and national level vulnerability and impact assessments, which support informed adaptation planning. Further, more than half of European countries have made progress in identifying and assessing adaptation options, and 13 countries are in the implementation or the monitoring and evaluation stages of the adaptation policy process (EEA, 2014). The water, agriculture and forestry sectors have received major priority for adaptation actions in EU (EEA, 2014).

4.5.1.2 Analytical Frameworks for Problem Diagnosis

4.5.1.2.1 Water-Energy-Food (WEF) nexus approach for integrated solutions to interconnected inter-sectoral problems

WEF nexus is a paradigm that recognizes that water, energy, and food are linked in a complex web of relationships in the hydrological, biological, social, and technological realms (D'Odorico et al., 2018; Märker et al., 2018). For instance, agricultural production requires significant energy inputs due to intensive groundwater pumping (Shah, 2009; Siddiqi and Anadon, 2011; Wang et al., 2012) and use of energy-intensive fertilizers (Woods et al., 2010). Similarly, hydropower production, even though a largely non-consumptive user of water, often has tradeoffs with irrigation, thereby affecting food production (Zeng et al., 2017a). New technologies such as desalination plants, that are viewed as an insurance policy for urban water supply against future climate change and drought, or water to energy units – thought critical for mitigation in urban spaces, are also very energy intensive (Haraguchi et al., 2019).

The nexus approach is inherently about capturing true efficiency gains instead of simply displacing or masking increased resource use (Scott, 2013). A number of studies have focused on the water-energy-food nexus at global and regional scales (Bazilian et al., 2011; Siddiqi and Wescoat, 2013; Rasul, 2014; Mercure et al., 2019) and discussed implications of climate change and adaptation (Conway et al., 2015; Gondhalekar and Ramsauer, 2017). A key benefit of the nexus paradigm is that it allows for widening the set of salient stakeholders and hence solution possibilities, that may otherwise not be possible in single domain efforts and helps connect these stakeholders to achieve synergistic goals (Ernst and Preston, 2017). For example, energy and water utility joint collaborations have yielded more successful outcomes than what was possible with single-sector utility programs. For example, in Texas, water, gas, and energy utilities have collaborated for 'tri-resource' conservation of water, electricity, and gas with home improvement upgrades resulting in approximately 4.7 million kilowatt-hours of energy and 10 million gallons of water savings per year (Young and Mackres, 2013). In India, several states have tinkered with their agricultural electricity policies with profound possible impacts on groundwater use (Shah et al., 2012; Mukherji and Das, 2014; Fishman et al., 2016), though much of these impacts are nullified due to implementation failures arising from a strong farmers' lobby in states where groundwater is over-exploited.

The WEF nexus paradigm thus opens up possibilities for strategic intervention in linked elements to achieve effects on another connected element. If the specific types and extent of WEF linkages in a region are well understood, it becomes possible to intervene through one element with the aim to cause an effect on another connected element that may have proven difficult for direct intervention. However, the opportunities that can be opened up for innovative and strategic policy making have yet to be fully explored and we need to move beyond viewing WEF nexus as a way of problem identification to a way of seeking integrated solution to interconnected problems (See Cross-Chapter Box NEXUS in Chapter 17).

4.5.1.2.2 Hydro-social cycle and socio-hydrology

Water is not solely a physical element, but it has been conceptualized as a component of the social cycle. Access to water and water quality for instance are two factors that affect and shape power relations in societies. The role that water plays in influencing social dynamics has been defined in the hydro-social cycle by numerous social scientists who have studied through qualitative methodologies the coupling of human-environment relations. Socio-ecological relationships are dynamic and changing over space and time, this is the focus of the hydro-social cycle approach that has been mostly applied at the case study level (Bakker, 2003; Budds, 2008; Linton, 2008; Linton and Budds, 2014). For instance, (Swyngedouw, 2009) outlines how water management for productive means has triggered social privilege and exclusion of certain groups in modern Spain. In his study he stresses that water is more than a material resources, that it has ideological and representational ramifications e.g. water efficiency policy, water as symbol of purity. Hence, the argument made by social scientists is that conceptualizing water as only part of the hydrological cycle is reductive, but water should be intended as the main component of couple human-environment dynamics pertaining to the hydro-social cycle (Linton, 2008; Linton and Budds, 2014; Boelens et al., 2015).

Hydrologists have approached the issue of socio-ecological relationships and the role that water plays in it from the angle of modelling. Human-induced drivers are conceptualized as external forcing the water cycle to explore how water and societies co-evolve (Sivapalan et al., 2012). The approach of socio-hydrology is quantitative and as such human behavior is parametrized to predict interactions and feedbacks between the hydrological cycle and society (Di Baldassarre et al., 2013; Pande and Sivapalan, 2017; Wesselink et al., 2017). While Integrated Water Resource Management (IWRM) is a scenario-based approach (see section 4.5.1.3.1), socio-hydrology computes human behavior into models to test hypothesis and project coupled human-water co-evolutionary dynamics, comprising unprompted or unforeseen behaviors (Sivapalan et al., 2012). Floods have been a focus of study for socio-hydrologists. For instance, four fabricated examples were created to develop a comparative historical framework analyzing water and people's behaviors when flooding happens in a highly developed infrastructural systems and less developed non-protected systems (Di Baldassarre et al., 2013; Di Baldassarre et al., 2015).

These two analytical approaches that while aiming at the same goal – understanding couple human-environmental behavior in the context of hydrological and social change – build on two very different methodological and epistemological premises. While they have proven challenging to reconcile, examples are emerging of how these two approaches can fruitfully come together to more cohesively assess and understand human and natural systems interactions in the context of water induced disasters.

4.5.1.3 Frameworks for Policy Action

4.5.1.3.1 Integrated Water Resources Management (IWRM) for connecting all water use sub-sectors

Recent adaptation literature (Kahn, 2016) supports the AR5 view that cross-sectoral adaptation options are more effective than standalone efforts to reduce climate-related risks. IWRM provides an umbrella concept to achieve the SDGs (Smith and Clausen, 2018; UNDP, 2019) and is considered as one of the effective holistic approach for increasing an adaptive capacity of water sector to climate change (Gain et al., 2013; Cosgrove and Loucks, 2015; Upadhyaya, 2016; Benson and Lorenzoni, 2017; Giupponi and Gain, 2017). After the approval of Agenda 2030 by the United Nations, IWRM and climate change adaptation are considered complementary elements of the global activity towards sustainable development (UN, 2015).

Following this, some 80% of 172 countries laid foundations to achieve at least medium to low levels for IWRM implementation nationally by 2030 (UN Environment, 2018). However, while the main IWRM principles remain quite general, it is becoming more evident that specific features of its practical implementation and climate change adaptation pathways are widely varied depending on diversity and regional peculiarities of climate change and water demand/supply relationship, physiographic conditions, spatial scales, transboundary issues, etc. (Crabbé et al., 2014; Vega et al., 2015; Benson and Lorenzoni, 2017; Rouillard and Spray, 2017; Roy et al., 2017; Sebesvari et al., 2017).

Recent examples include:

- “top-down” and “bottom-up” approaches to IWRM may be differently inter-related across scales within one river basin (e.g. Tweed River Basin in Scotland, (Rouillard and Spray, 2017);
- ecosystem-based solutions focused on biodiversity and ecosystem services as well as the transboundary issues may be differently addressed in the IWRM practice e.g. in the Mekong River basin (Sebesvari et al., 2017); Pangani River basin in Africa (Overton et al., 2014);
- combination of two or more integrated approaches can be recommended, e.g. IWRM combined with Integrated Coastal Zone Management (ICZM) approaches to manage sustainability of the coastal ecosystems in Bangladesh (Roy et al., 2017), IWRM combined with water resources conservation and institutional strengthening approaches to reduce the current level of risk and vulnerability caused by climate change in La Ceiba city region, Honduras (Vega et al., 2015).

The combination of IWRM and adaptive management may be considered a promising regional-level approach for adapting ecological systems, and particularly hydrological systems, to climate changes (Giupponi and Gain, 2017). Despite the main focus of IWRM is on current and historic issues compared to the long-term focus of adaptation (Ludwig et al., 2014), both IWRM and adaptation share the same goal of promoting sustainable development and both of them require some identical key elements (e.g. public participation, information sharing and disclosure, and concern for social justice) (Giupponi and Gain, 2017).

4.5.1.3.2 Nature-based solutions

Nature-based solutions (NBS) are increasingly recognized as an important adaptation measure for meeting the complex challenges of water management and building resilience to climate change (*robust evidence, medium agreement*). NBS must now be fully integrated into climate change and water management plans from the global to the local level to achieve the 2030 Agenda for sustainable development *(high agreement, low evidence)*.

Neither AR5 (Revi et al., 2014) nor SR1.5 (IPCC, 2018) mentioned NBS directly. However, both the reports discussed climate-resilient pathways, including strategies, choices, and actions needed to reduce climate change impacts on human societies. AR5 provided *strong evidence* that ecosystem-based adaptation, an important component of NBS, is a key contributor to urban resilience (*medium confidence*). SR1.5 noted that urban green infrastructure improvements through increased use of NBS could reduce the impacts of climate extremes in urban centers.

NBS mimics natural processes to enhance water availability, to increase water quality, and to decrease risks associated with water-related disasters. NBS include green infrastructure as soil moisture retention, groundwater recharge, natural and constructed wetlands, riparian buffer strips, floodplain restoration, and green roofs, among others (UN-Water, 2018).Traditional water management often relies on human-made engineered structures, e.g. dams, dykes, irrigation cannels, and water diversion projects (Liu et al., 2013a). These structures are often called "gray infrastructure". Although gray infrastructure has supported the evolution of all human societies (Muller, 2018), they also bear many negative environmental and ecological consequences (Palmer et al., 2015). Dams often lead to fragmentation of river ecosystems (Nilsson et al., 2005) and results in biodiversity losses (Vörösmarty et al., 2010). Irrigation is often claimed to be a main cause of groundwater decline (Wada et al., 2012), and coupled with the use of fertilizers, it leads to aquatic pollution (Liu et al., 2010; Lun et al., 2018).

There is a call for NBS to guarantee water security worldwide (Palmer et al., 2015). Green infrastructure uses natural or semi-natural structures e.g. wetlands, healthy forest ecosystems, and alike to supply clean water, regulate flooding, enhance water quality, and control erosions. Compared with gray infrastructure, green infrastructure is often more flexible, more cost-effective, and can provide more ecosystems services (UN-Water, 2018; WWAP, 2018; Hu et al., 2019). Hence, restoring natural ecosystems, e.g., peatland is an important approach to safe potable water supply (Xu et al., 2018). Integrating green infrastructure with the built gray infrastructure is thought to be a key to guarantee future water security (Palmer et al., 2015).

Despite the numerous benefits, ensuring inclusion of NBS in options assessments for water management remains a challenging task, NBS is still a relatively new concept, involving complex natural process. However, sufficient technical guideline and cost-benefit data are still lacking. Yet, NBS is believed to be central to achieving the 2030 Agenda for Sustainable Development.

Green infrastructure and other NBS will play an important role for future water security. There is a need, with *high confidence*, to generate more knowledge on the ecosystem services and cost-benefit analysis of green infrastructure to address sustainability challenges; and in the process, move from disciplinary linear model to interdisciplinary model with stakeholder participation (Palmer et al., 2015; UN-Water, 2018; Liu et al., 2019b).(Palmer et al., 2015; Programme, 2018; WWAP, 2018; Liu et al., 2019a).

4.5.2 Local Adaptation Initiatives – What Works? What Does Not? And Why?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

4.5.2.1 Meta Review of Case Studies on Local Adaptation

- Local case studies from previous sections (on sectoral and cross sectoral adaptation) will be synthesized using an adapted methodology from IPCC SR1.5C (methodology explained in Supplementary Material Chapter 4, SR1.5C)
- Looks at six axes of feasibility – these are: economic, technological, institutional, socio-cultural, environmental/ecological and geo-physical
- Then rank adaptation interventions in terms of suitability and carry out further analysis to understand contextual issues that affects suitability.
- Alternatively, meta reviews of existing water adaptation in various sectors and cross sectors (Sections 4.2 and 4.3) will be commissioned (through journal special issue) and insights from those meta reviews will be presented in this section.
- We envisage meta reviews of anything between 30-100 water-adaptation case studies per sector (e.g. agriculture, WaSH, ecosystems, energy, water induced disasters etc.)

Based on our assessment so far, the main adaptation interventions we have identified so far are the following. We will assess as many of these options as possible, based on availability of literature.

Agricultural water usage:
Supply side interventions:
1. Expansion in irrigation – either area, or intensity
2. Increasing local water supply – rainwater harvesting, groundwater recharge
3. Drought and flood resistant seeds/technologies, and agronomic practices
4. Re use of urban waste water for peri urban agriculture

Demand side interventions:
1. Efficient irrigation systems – including precision irrigation
2. Improved on farm agricultural water management in rainfed and irrigated areas
3. Better green water (soil moisture) management
4. Growing low water consuming crops
5. Reducing food waste
6. Better weather prediction systems

Mixed – Combination of supply and demand side; and policy institutional
1. Virtual water trade – growing water intensive crops in areas with relative water abundance and exporting them to water scarce areas
2. Managing irrigation systems better through participatory irrigation management
3. Capacity building and trainings for farmers to improve their skills and knowledge
4. Incorporating traditional and indigenous knowledge within "modern" extension services
5. Insurance – flood and drought insurance
6. Outmigration from rural areas – reducing depndance on water intensive agriculture

Water for energy:
1. Changing dam design to cope with changing hydrological regimes
2. Sharing benefits with local communities
3. Water efficient alternative energy sources – e.g. more efficient cooling systems in nuclear power plants

Water for WaSH:
1. Hygiene measures, e.g hand washing to reduce water borne diseases
2. Depuration systems

Urban and municipal water systems:
1. Urban re-design to help water percolate, e.g sponge cities
2. Roof top rainwater harvesting
3. Reuse and recycling of water
4. Management of storm water drains

Water induced disasters:
1. Early warning systems for floods, drought etc.
2. Insurance
3. Trainings and capacity building
4. Infrastructural investments such as embankment and dykes
5. Nature based investments such creating space for rivers to flow and flood

Human mobility and water:
1. Managed retreat
2. Stilt housing

4.5.2.2 What Works (Good Adaptation) vs. What Does not Work (Maladaptation)

- Will follow from the previous section (4.5.2.1) and list interventions that had desired impacts, and those which did not.
- Will contextualise good adaptation and mal adaptation within a broader socio-economic-political context.
- Will tease out broad principles that facilitates "good" adaptation. Some of those broad principles are already discussed in Section 4.6.

This section also draws from Cross-Chapter Box ADAPT in Chapter 1 and Cross-Chapter Box on Crafting solutions for and governing climate change adaptation; to be placed in Chapter 1 or 18.

4.5.3 Limits and Constraints to Adaptation

Institutional constraints, including path dependency, are amongst the most important factors hindering effective adaptation generally and in the water sector *(high agreement, robust evidence)*. For some regions, such as SIDS, insufficient water availability has the potential to become a hard limit to adaptation, as water is no longer sufficient to meet socio-economic needs *(limited evidence, medium agreement)*.

The core constraints identified in AR5 for freshwater related adaptation refer to governance, financial as well as information constraints (Klein et al., 2014b). Some hard limits were identified with regard to water supply in fossil aquifers, for example in Small Island. Water availability was also singled out as a constraint to diversifying options for water-dependent sectors, where water availability can become a constraint. Klein et al. (2014b) also reported that trade-offs could be associated with different options, for example with regard to water supply and consequent impacts of water quality. Table 4.14 categorises constraints and limits to adaptation.

The need for adaptation as a response to observed and projected changes and their societal impacts (section 4.3) is becoming increasingly clear. Information on successful adaptation and enabling conditions and success factors, also specific to the water sector is emerging, but large knowledge gaps remain (sections 4.4.5, 4.6.7). Further understanding the constraints and limits that exist with regard to adaptation to climate change impacts in the water sector is becoming urgent in the light of increasing slow and rapid onset impacts associated with climate change.

Table 4.14: Categories of constraints and limits to adaptation in the water sector

Constraints	Example(s)	Hard/soft	Literature
Institutional	Lack of inter-sectoral communication limits the potential for water-energy-food-nexus approaches	Soft	Rasul and Sharma (2016); Ernst and Preston (2017)
Informational	Lack of precipitation data at the local level is problematic for adaptation planning	Soft	Carter et al. (2015); Gooré Bi et al. (2017)
Financial (and technological)	Lack of financial and technical resources to adapt (e.g. establishment and maintenance of infrastructure)	Soft and hard	Castells-Quintana et al. (2018); Smid and Costa (2018)
Biophysical	Aridity increases as a consequence of climate change can limit management options (e.g. Small Islands or Mediterranean)	Soft and hard	Karnauskas et al. (2016); (Schleussner et al., 2016); Karnauskas et al. (2018)
	Soil moisture loss poses limits to food production and ecosystem services	Hard	van der Geest et al. (2019)

Institutional constraints remain a challenge to adaptation implementation: path-dependency of institutions and the speed at which these allow for changes in the decision-making process, remain a major limitation globally (Barnett et al., 2015; Oberlack, 2017) as well as for the water sector (Kingsborough et al., 2016; Azhoni and Goyal, 2018). A lack of inter-sectoral coordination and communication within institutions limits the potential for integrated policies, such as water-energy-food-nexus approaches (section 1.5.1.2.1) (Rasul and Sharma, 2016; Ernst and Preston, 2017). Trade-offs between different policy goals need to be considered to ensure wider implications of adaptation strategies are considered, for example in the case of water quality implication of agricultural adaptation (Fezzi et al., 2015).

Limitations in knowledge and understanding of the complex processes, feedback effects and interconnections in the water sector pose additional challenges to effective adaptation and adaptation decision-making (Kundzewicz et al., 2018a). For tropical and mountainous regions, and the African continent in particular, a lack of reliable climate projections and large uncertainties in available data remain one of the biggest obstacles in long-term adaptation planning (Antwi-Agyei et al., 2015), especially in the water sector (Azhoni et al., 2017b; Watson et al., 2017; Hirpa et al., 2018; González-Zeas et al., 2019).

The lack of financial and technological resources poses another constraint on adaptation in the water sector (Castells-Quintana et al., 2018). In Spain, for example, financial constraints have been identified as a main barrier to modernization of irrigation system, an important water-saving measure (Esteve et al., 2018), while (Iglesias et al., 2018) find that financial barriers are a common element, materializing in conjunction with technological, socio-economic and climatic barriers in the Mediterranean.

Water, as a central resource to all human activity, is also a biophysically finite resource at specific points in time and space (4.2) (Rockström et al., 2014; Kummu et al., 2016). For some regions of the world, such as SIDS (Karnauskas et al., 2016; Karnauskas et al., 2018) and the Mediterranean (Cross-Chapter Paper on Mediterranean) (Schleussner et al., 2016), aridity increases as a consequence of climate change have the potential to limit management options. Constraints on water availability have the potential to place hard limits to adaptation in some world regions, for example through increases in soil moisture loss and consequent limits to food production, as well as provisioning ecosystem services (van der Geest et al., 2019). SR1.5 clearly shows that such risks can be reduced substantially by limiting warming to 1.5°C (Hoegh-Guldberg et al., 2018a).

Integrated approaches, such as linking land-use and water policies (Mehdi et al., 2015), inter-institutional networks (Azhoni et al., 2017b), nexus approaches (Conway et al., 2015) as well as consideration of linkages to the SDGs (Gunathilaka et al., 2018) are crucial to overcoming constraints in water adaptation. Monitoring and evaluating the effectiveness of adaptation measures, policies and actions can contribute to knowledge, learning and data to support adaptation implementation in the future (4.6) (Klostermann et al., 2018).

4.5.3.1 Loss and Damage

Especially for the poor, loss and damage from water-induced events has been reported, even where some adaptation has occurred *(limited evidence, high agreement)*. Irreversible loss of glaciers has been reported for all mountain regions *(strong evidence, high agreement)*.

AR5 did not specifically mention loss and damage, van der Geest and Warner (2015), however, in Chapter 19 of AR5 acknowledged that "losses accelerate with greater warming" (Oppenheimer et al., 2014). SR1.5 was the first IPCC report to formally define loss and damage (IPCC, 2018) and noted for the water sector, that in conjunction with rising sea-levels, increasing aridity and decreased freshwater availability may contribute to posing hard limits to adaptation for SIDS (Roy et al., 2018) (Chapter 5;). While the concept of loss and damage remains an area of active research, progress has been made since the AR5 in attributing climate change impacts to anthropogenic forcing (4.3 and Chapter 16), providing an important basis towards better understanding loss and damage in practice. Water is reported as both, a driver of loss and damage though hydro-meteorological events such as droughts, floods and slow-onset processes such as changes in river runoff, surface, and underground water availability (Huggel et al., 2019; Mukherjee et al., 2019), as well as a resource that is impacted and requires adaptive responses (Handmer and Nalau, 2019).

Losses and damages in the water sector occur as a consequence of different processes and circumstances and have been documented also where some adaptation measures have been implemented (Table 4.15). Climate impacts, such as droughts in East Africa or glacier melt in the cryosphere, underline that there are biophysical limits to adaptation, even under current climate conditions, leading to loss and damage (Warner and van der Geest, 2013; Huggel et al., 2019; van der Geest et al., 2019). Nevertheless, a lack of investment in critical infrastructure and maladaptive measures can increase existing risks and exacerbate impacts (Mukherjee et al., 2019; van der Geest et al., 2019).

Table 4.15: Examples of regional studies on loss and damage in the water sector

Climate impact	Losses and damages	Location	Adaptation measures implemented/mentioned	Literature
Drought and climate variability	Loss of food security	Sahel and semi-arid drylands of East Africa	Pastoralism (moving cattle to regions with abundant pasture)	van der Geest et al. (2019)

Salinity intrusion from Sea level rise	Loss of food security and loss of drinking water	Bangladesh	Reduce dependence on crop cultivation, plant salt-resistant rice cultivars, on-farm measures to salinity	Warner and van der Geest (2013)
Freshwater scarcity, aridity, severe storms and tropical cyclones; El Nino	Loss of homes, loss of livelihoods (subsistence farming and fishing), contamination of drinking water	Pacific Small Island States	Seasonal work and voluntary relocation	Handmer and Nalau (2019)
Changes in glacier runoff, permafrost thawing, glacier mass loss; GLOFs	Loss of cultural heritage, loss of water availability, loss of income, loss of lives, damages to assets	Cryosphere	Outmigration, changes irrigation systems; new livelihoods such as tourism	Hock et al. (2019); Huggel et al. (2019); Mukherji et al. (2019b); Rasul and Molden (2019)
Increasing temperatures, permafrost thawing	Accelerating melting rates, loss of habitability and livelihoods, loss of food security, extinction of species	Arctic	Outmigration	Landauer and Juhola (2019)
Floods and landslides; typhoons	Loss of lives and livelihoods, loss of production and infrastructure, psychological damages, loss of ecosystems	Philippines	Food relief, temporary shelter and loaning money	Acosta et al. (2016)

With higher levels of warming, loss and damage as a consequence of transformational adaptation is may occur, as further limits to adaptation emerge. Relocation, driven partially by water scarcity for example, may develop into a more frequent response, as early as the 2040s (Nalau and Handmer, 2015). In conjunction with further socio-economic development and urbanization, projected increases in the frequency and intensity of heavy rainfall may lead to increasing flood impacts and thus associated loss and damage (Rözer et al., 2018).

As a consequence of their lower adaptive capacity and general lack of access to adequate infrastructure, housing and other basic needs, immediate loss and damage from extremes like flooding are higher for vulnerable groups, while the relative magnitude of losses places a disproportionate burden on vulnerable households (Rufat et al., 2015; Patankar and Patwardhan, 2016).

Nature-based solutions, including ecosystem-based adaptation, can reduce the risk of maladaptation in some cases (section 4.5.1.3.2), however there are limits to the effectiveness of such approaches when climate change accelerates (Handmer and Nalau, 2019; van der Geest et al., 2019). Nevertheless, ecosystems play an essential role in buffering climate impacts, also at higher levels of warming (Mukherjee et al., 2019; van der Geest et al., 2019).

While understanding of loss and damage associated with climate change has improved, attribution of impacts to anthropogenic forcing remains a key area of research. Disentangling the multiple drivers of impacts and risks persists as a challenge, but understanding the underlying drivers of change will be essential in order to avoid and manage risks (Rözer et al., 2018; Handmer and Nalau, 2019; Huggel et al., 2019). Careful assessment of adaptation measures needs to take into account the potential of mal-adaptation, as structural measures, such as drainage systems or flood protection, can have unintended consequences on other parts of the system and are designed for several decades and present a risk of lock-in, if not designed flexibly to respond to changing conditions (Mukherjee et al., 2019). Research has focused on documenting tangible losses, yet in-tangible losses, such as cultural heritage (4.4.5) or psychological impacts remain insufficiently documented in the water sector and as a consequence of water-related disasters (Acosta et al., 2016; Mukherjee et al., 2019). See Cross-Chapter Box LOSS in Chapter 17.

4.5.3.2 Costs of Adaptation and Losses due to Non-Adaptation

Impacts of climate change on water resources is projected to lower GDP in several low- and middle-income countries (LMICs) in the absence of any adaptation or mitigation measures (*high agreement, high evidence*). The costs of adaptation are large but could generate very high total net benefits (*high agreement, high evidence*).

Estimating the costs of adaptation for impacts of climate change on water is important for informing decision-making, budgeting and resource allocation (Chambwera et al., 2014). In AR5, adaptation costs for impacts on water were deemed to have 'limited coverage' and were mostly focused on 'isolated case studies'; while adaptation costs in the agriculture, heavily dependent on water, were deemed to have 'extremely limited or no coverage' (Chambwera et al., 2014). In contrast, adaptation costs in coastal zones, susceptible to sea-level rise, were deemed 'comprehensive' (Chambwera et al., 2014).

Global estimates of losses due to climate change impacts on water are few, due to regional differences in the impacts of climate change on water (Bank, 2016; Rozenberg and Fay, 2019) (*medium agreement, low-medium evidence*). Inadequate water supply and sanitation are estimated to generate global damages of US$260 billion annually (WHO, 2012); and global annual flood damages are expected to be US$120 billion per year from damage to urban property alone (Sadoff et al., 2015). The 2013-2015 drought in south central Brazil was reported to have caused losses of over USD 5 billion, while 2010-2011 drought in Horn of Africa caused up to a quarter million deaths and left up to 13 million people reliant on humanitarian aid (GCA, 2019).

Regionally, in South Asia, the impact of climate change on water resources is projected to lower GDP in 2050 by 2.2% in Bangladesh, 2.1% in India, 7.7% in Nepal and 4.3% in Sri Lanka if no additional adaptation and mitigation measures are undertaken to limit temperature rise below 2°C (Ahmed and Suphachalasai, 2014). Climate change impacts on water is expected to reduce GDP by 2.7% in low-income Asian countries, and by 0.9% in high-income Asian countries by 2050 (Ahmed and Suphachalasai, 2014). In Sub-Saharan Africa, the damages from floods in 2080 are projected to be between US$62.2-US$223.1 billion, with damages not uniformly spread between countries (Markandya).

The costs of water-related infrastructure in adaptation to climate change has received considerable attention, especially in LMICs to bridge the large 'adaptation gap', which requires committed expenditures over extended periods of time (Jenkins, 2013; (UNEP), 2016; Dellink et al., 2017; (UNEP), 2018; Hallegatte et al., 2018; GCA, 2019) (*medium agreement, high evidence*). For example, subsidizing capital costs (including maintenance) to extend irrigated land to its full potential would cost about 0.13% of the GDP per year of LMICs between 2015 and 2030; the cost of coastal and riverine protection ranges between 0.06% to 1% of LMICs' GDP per year over the same period (Rozenberg and Fay, 2019). In Sub-Saharan Africa, increasing the capacity of surface reservoir storage, rainwater harvesting and desalination comprises 25% of the average annual costs of adaptation between 2010 and 2050 assuming a 2°C warming (Schaeffer et al., 2013). GCA (2019) reported that investing USD1.8 trillion globally in five areas – early warning systems, climate-resilient infrastructure, improved dryland agriculture crop production, global mangrove protection and investments in making water resources more resilient could generate USD 7.1 trillion in total net benefits. Water investments are central part of all these five areas.

Less attention has been paid to the role of low-regret options, use of economic instruments for water management, and understanding autonomous adaptation. Options such as climate-smart agriculture, early-warning systems, restoration of wetlands, and zoning are postulated to have lower investment costs than engineering-based options (Agrawala, 2011; Linquiti and Vonortas, 2012; Cartwright et al., 2013). However, they require maintenance and regulation, and high technical and human capacity, the costs of which are more uncertain under adaptation and are likely to vary considerably by scale, location and context (McCarthy et al., 2011; de Bruin et al., 2014; ECONADPT, 2015; Faust et al., 2015; Watkiss et al., 2015) (*low-medium agreement, low evidence*). Better water management using economic instruments such as water pricing and regulation can improve returns on adaptation investments and interventions by delivering better services, or reducing losses (Papadaskalopoulou et al., 2015; Bank, 2016; Damania et al., 2017; Bhave et al., 2018; Khalid et al., 2018). For example, under scenarios SSP 1 and SSP 3 (O'Neill et al., 2017; Riahi et al., 2017), water pricing and regulation is expected to reverse losses in expected global GDP of 0.49% to gains of

0.09%, with damages in GDP drastically reduced in the Middle East, almost eliminated in the Sahel and Central Africa, and reversed into gains in Central Asia and East Africa, with benefits concentrated in those regions that are worst affected (Bank, 2016). A gap in the role of improving equity in access to water as an adaptation option also exists (*low evidence*). Lastly, while most estimates of the costs of adaptation focus on planned, publicly-financed adaptation; autonomous and private adaptation costs are often ignored ((UNEP), 2016; Bank, 2017) (*high agreement)*.

Autonomous responses of private actors can be substantial; but are often not incorporated into policy or monetized, as they are localized and data is limited (e.g. see Leclère et al. (2013); Bawakyillenuo et al. (2015); Thorn et al. (2015); Mersha and van Laerhoven (2018); Khanal et al. (2019) (*high agreement, high evidence*). If no autonomous adaptation took place, climate impacts may be higher by approximately a third, both regarding GDP and welfare losses (ECONADPT, 2015) (*low evidence, low-medium agreement*). An improved understanding of autonomous and private adaptation may increase linkages with planned adaptation, produce benefits for more people (Thorn et al., 2015; Bonzanigo et al., 2016; (UNEP), 2018), reduce crowding-out of autonomous adaptation measures (Mersha and van Laerhoven, 2018); and limit perverse outcomes that may exacerbate climate change (Leclère et al., 2013) (*low-medium agreement, low evidence)*.

The impacts of climate change on water resources are large, and adaptation measures are needed to stem losses. Generating better evidence on the costs and benefits of all options including low cost, low regret solutions such as water pricing, water saving technologies for efficient water use, and enhanced support for autonomous adaptation is needed for informed decision-making (GCA, 2019).

4.5.4 Trade-offs and Synergies between Water-related Adaptation and Mitigation

Many adaptation and mitigation measures have a considerable water footprint (*high agreement, high evidence*), which needs to be managed proactively in order to reduce negative feedback loops while at the same time increasing synergies with other sustainable development initiatives (*high agreement, medium evidence*).

SR1.5 reiterated the challenge of trade-offs or mal adaptations, in which adaptation activities may actually increase greenhouse gas emissions and water use, reduce other options for adaptation, e.g., in agriculture, and undermine sustainable development. Alternately, adaptation activities can have synergistic effects of increasing mitigation of emissions and enhancing sustainable development. SR1.5 also recognizes the substantial land and water footprint of growing bio energy crops with carbon capture and storage (BECCS) and afforestation and reforestation efforts (AR) (Hoegh-Guldberg et al., 2018a). In AR5 there was *medium evidence* and *high agreement* that maladaptation due to lack of understanding or consideration of trade-offs and synergies in adaptation and mitigation action due to greater emphasis on short-term outcomes is a cause of concern for adaptation planners (Noble et al., 2014b).

The interdependence of adaptation with climate change and its mitigation has been recognized for decades (Goklany, 1995; Magnan et al., 2016) with early approaches to make these often-divergent activities more synergistic, as identified for urban infrastructure (McEvoy et al., 2006), agriculture (Rosenzweig and Tubiello, 2007) and ecosystem management (Pittock et al., 2008).

A number of interventions such as use of solar pumps for groundwater pumping, reuse of wastewater, desalination, BECCS, and AR have important implications for water and energy use.

Solar pumps for groundwater extraction are increasingly introduced where conventional energy sources -- typically diesel or electrical power -- are not available (Burney et al., 2010) or supply is intermittent or expensive (Shah et al., 2018). They are found to be suitable in Africa (Schmitter et al., 2018) as well as Europe (Rubio-Aliaga et al., 2016) and South Asia (Sarkar and Ghosh, 2017) and can reduce emission of short-lived climate pollutants by replacing diesel use while also leading to better productivity outcomes for farmers (Gupta, 2019). Concern is mounting that, although solar pumps generate essentially zero emissions, they do not replace existing pumps using diesel or carbon-based electricity, and moreover, they may exacerbate groundwater depletion in places where groundwater is already over-exploited (Closas and Rap, 2017). Regulations and incentives that support solar-powered replacement of conventional pumps, not additionally, are recommended (Mukherji et al., 2017; Bassi, 2018).

The collection, treatment, and reuse of wastewater -- mostly from residential and industrial sources in urban areas -- are energy intensive practices (Tram Vo et al., 2014). While these recover often-valuable nutrients and may capture energy as methane while saving water, reuse of water that contains heavy metals may have negative impacts on land and water quality, and in semi-arid regions, salinization may be a challenge. Treatment and remediation measures to make reuse suitable for agriculture and other uses have been described; however, these can be costly (Qadir et al., 2014). Separation and treatment of especially poor-quality wastewaters will increasingly be necessary.

Desalination of seawater or brackish inland water is seen as an adaptation measure, especially in water-scarce regions (Jones et al., 2019). Yet, the practice is energy intensive (Craig, 2010), it rejects brine that can be extremely high in salinity and may contain other constituents, and its adoption can be socially and politically contentious (Wilder et al., 2016). Solar desalination is a rapidly developing technology with increasing market-based adoption (Pouyfaucon and García-Rodríguez, 2018).

Carbon capture and storage (CCS) is recognized as crucial for climate mitigation and will be required for negative-emissions strategies (Gibbins and Chalmers, 2008; Bui et al., 2017). BECCS involves the sequestration of CO_2 via biofuel field crops or forest bioenergy crops (Azar et al., 2010; Creutzig et al., 2015) and has profound water implications. Alternately, carbon can be recovered as methane from municipal waste facilities (Pour et al., 2018) or carbon dioxide can be ‘scrubbed’, including from thermo-electric power-plant emissions, and injected for storage in deep subterranean geological strata (Rubio-Aliaga et al., 2016; Turner et al., 2018). Both BECCS and conventional (non-bioenergy) CCS can have major implications for food production (Muratori et al., 2016) and water resources through increased water use for irrigated biofuels crops (Scott and Sugg, 2015a) as well as negative impacts on groundwater quality resulting from CO_2 injection underground, a process that uses modified wells. Bui et al. (2018) identify potential alternatives to the storage of CO_2 by reusing it to produce marketable compounds.

While AR is thought to be one of the most cost effective ways of storing carbon, and additional 0.9 billion ha of canopy cover in places amendable to supporting more forests and woodlands could potentially store additional 205 gigatonnes of carbon (Bastin et al., 2019), it is recognized that aggressive AR interventions can present tradeoffs between biodiversity, carbon sequestration and water use, and is purported to have higher land footprint per tonne of CO_2 removed compared to other CCS interventions (Smith et al., 2018). At the same time, AR also offers multiple additional benefits beyond CCS, including several water quality and quantity related benefits. A recent global assessment of forest-water interactions clearly showed forests and water are an integrated system and forests influence the complete water cycle, including water availability both downstream via rainfall-runoff dynamics and downwind via recycled rainfall effects (Creed and Noordwijk, 2018). While the downstream impacts of forests on water resources are well understood (Bruijnzeel, 2004), downwind impacts are only now being addressed (Ellison et al., 2017; van der Ent and Tuinenburg, 2017). This knowledge can be used to concentrate AR activities in locations where water supply is abundant (to offset downstream impacts) and where transpired water can potentially be captured via precipitation downwind (Creed and Noordwijk, 2018). (Cross-Chapter Box MITIG in Chapter 2)

Dilling et al. (2015) demonstrate that climate change adaptation must reduce societal vulnerability and enhance sustainable development. Significant opportunities for adaptation-mitigation synergies have been described within the WEF nexus (section 4.5.1.2.1) framework (Scott et al., 2015). Although climate change-induced drought may drive increased carbon emissions in some regional contexts (Shadman et al., 2016), more broadly, greenhouse gas mitigation measures can have positive impacts for water resources (Strzepek et al., 2015).

Technological, adoption, and policy innovations are required to minimize trade-offs between adaptation and mitigation measures and water-use intensity and quality degradation while also supporting sustainable development.

4.6 Enabling Principles of Sustainable and Resilient Water Adaptation Solutions

[PLACEHOLDER FOR SECOND ORDER DRAFT: Enabling principles discussed in this section derive from a meta-analysis of adaptation measures in major water use sectors (4.5.2). We have started looking at a large number of adaptation initiatives, in various sub sectors (agricultural water use; WasH; energy; freshwater ecosystems; cultural uses; navigation etc.) coding them; develop/or refine an existing metrics for measuring good adaptation and distinguish it from mal-adaptation; and distil common enabling principles that facilitates good adaptation. Since our meta-analysis is only partially completed so far, the enabling principles presented here are a result of our chapter team's collective wisdom]. Also refer to Cross-Chapter Box on Enabling Equitable adaptation for poverty reduction and strengthening sustainable development, Chapter 8.

4.6.1 Participative, Cooperative and Bottom up Engagement

Participation, cooperation and bottom-up engagement are critical for optimal adaptation in the water sector *(medium evidence-high agreement)*. There is *robust evidence/high agreement* that many of the countries and social groups most threatened by climate change are those that have contributed least to the problem and do not have access to enough resources to adapt. Effective participation of these actors in climate change adaptation planning in the water sector can contribute to more just adaptation actions *(high confidence)*.

AR5 concluded that institutions that promote participation of and collaboration between stakeholders tend to encourage adaptation in the water sector (Jiménez Cisneros et al., 2014). SR1.5 and SRCCL reports pointed out that increased participation is necessary for effective adaptive (co) management (de Coninck et al., 2018b) and the success of decentralised natural resource management (Mirzabaev et al., 2019).

There is *medium evidence*, *high agreement* on the fact that optimal adaptation depends critically on inter-state cooperation (Banda, 2018), which in turns requires trust and norms of reciprocity among all those involved (Ostrom, 2014). Reciprocity is key to international cooperation on climate change, where actors are more inclined to cooperate when they perceive that the expected outcome will be fair, in terms of costs and benefits of implementation (Keohane and Victor, 2016). Research shows that cooperation at the international level is less likely to occur if participants do not trust each other (Hamilton and Lubell, 2018).

In climate related water adaptation, transboundary cooperation is particularly necessary, as 60% of global freshwater resources are shared between countries (Timmerman et al., 2017). Yet, 158 of the world 263 international basins lack any type of cooperative framework (UN Watercourses Convention, 2018). SDG 6 on water and sanitation includes a specific indicator (6.5.2) to assess cooperation over transboundary waters. While the methodology for measuring this indicator is debated, it is clear that its composition will influence international water policy and law (McCracken and Meyer, 2018), e.g. by including explicit reference to transboundary cooperation in national water policies and legislations and thus building and sustaining a climate of trust among riparian states. Moreover, although the 2030 Agenda for Sustainable Development (UN, 2015) makes it clear that without participation of local communities (e.g. SDG 6, target 6.B) and women (e.g. SDG5, target 5.5.) the SDGs will not be met, the involvement of these actors in formal water governance processes and water management is still limited (Fauconnier et al., 2018). This is due partly to the absence, in many regions of the world, of adequate legal, regulatory and institutional frameworks for effective stakeholder's participation (i.e. their ability to make their voices heard and considered during decision-making processes), partly to the influence of local social and cultural contexts, which can discourage inclusive water governance (Andajani-Sutjahjo et al., 2015; Dang, 2017).

Yet, inclusion and effective participation in bottom-up decision-making processes of those disproportionately most affected by climate change – including women and indigenous people - is particularly important to ensure the legitimacy and inclusiveness of the decision-making process and the design of socially just adaptation actions (Shi et al., 2016). Incentives for bottom-up and participative decision-making in the water sector, such as the establishment of stakeholder advisory groups at the appropriate level of government, or informal mechanisms (e.g. internet-based platforms), can facilitate effective engagement (OECD, 2015), which in turn helps to build public confidence and trust in water governance.

4.6.2 Polycentric (Nested) Governance

Governance ensuring interconnectedness from global to local levels, with multiple actors, bottom up and top-down linkages, well-coordinated and enhanced efforts to adapt to climate induced water challenges and hazards, can lead to effective results (*medium evidence, high agreement*)**.**

SR1.5 concluded with *high confidence* that cooperation and coordinated actions at various governance levels are key factors to ensure participation, transparency, capacity building and learning among different players (IPCC, 2018). Polycentric sources of climate action that link efforts undertaken at multiple levels of governance offer the opportunity to experiment and learn from different approaches, thus accelerating the global response to climate change (de Coninck et al., 2018b). According to SRCCL, adaptive governance builds on multi-level and polycentric governance (Hurlbert et al., 2019).

Although polycentric governance has become more authoritative and legitimate over the time, questions remain about the extent to which polycentrism can result in greater climate justice or otherwise exacerbate existing inequalities, for example, because multiple sites of governance have been created by actors with greater resources (Okereke, 2018). Inequalities in the political power of those collaborating within a polycentric system may also affect the effectiveness of the system (Hamilton and Lubell, 2018).

In the water sector, polycentric governance can derive legitimacy from formal and informal participation of multiple stakeholders, procedural fairness (Baldwin et al., 2016) and the processes through which outcomes are derived (Boelens et al., 2016; Kellner et al., 2019; Pahl-Wostl, 2019), e.g., multi-actor and evidence-based approach instead of centralised modes of command and control (Boelens et al., 2015; Arriagada et al., 2018). Advantages of polycentric approaches to climate governance have been emphasized by several studies (Ostrom, 2014; Keohane and Victor, 2016; Tormos-Aponte and García-López, 2018), including in terms of increased communication, inclusiveness and better outcomes (Cole, 2015). However, in order to work, polycentric governance systems require information sharing and aligning interventions across different scales (Carlisle and Gruby; Biesbroek et al., 2018a). This is especially true for the implementation of groundwater governance in transboundary contexts, where several institutions need to be directed toward effective and efficient solutions and avoid high costs of transactions (Albrecht et al., 2017).

Few empirical studies, which have specifically examined the potential of polycentric governance in addressing water challenges in the face of climate change (Baldwin et al., 2018; Aubin et al., 2019; Kellner et al., 2019), show that polycentric systems can encourage and support deliberative initiatives that produce better environmental outcomes and improve good governance.

4.6.3 Gender, Equity and Social Justice

There is *high confidence* that climate induced water changes are not equally felt across gender, class, age and physical ability. Robust evidence indicates that successful adaptation will not take place with the continued marginalization and silencing of women and other disadvantaged groups during the stage of community consultation and implementation.

There is strong confidence that the effects of decreasing water quality and quantity due to climate change are not felt evenly across populations. Equity issues are central to climate change and sustainable development, as the world's poorest people and countries feel the adverse impacts of a changing climate most acutely (Levy and Patz, 2015; Forum, 2019). Particularly vulnerable groups are women, children and indigenous people, whose ability to have access to adequate water is limited and can be threatened by adaptation actions that are not equitable (GCA, 2019). Understanding the implications of climate related water adaptation policies in terms of equity, is a prerequisite for ensuring their legitimacy and inclusiveness, and promote social justice (Cartwright et al., 2013; Carr and Thompson, 2014; Djoudi et al., 2016; Jost et al., 2016; Sultana, 2018).

Globally, there exists a strong gender divide along the lines of water usage: when water is used for productive purposes it is most often controlled by men, when it is used for households' purposes it is most often in the hands of women (Kher et al., 2015; Alda-Vidal et al., 2017; Das, 2017; Zwarteveen, 2017; Sinharoy and Caruso, 2019). Numerous studies substantiate a male bias in information access, employment opportunities, resource availability, and decision-making in water related adaptation measures (Huynh and Resurreccion, 2014; Meinzen-Dick et al., 2014; Njuki et al., 2017; Sultana, 2018; Sinharoy and Caruso, 2019). Women's water rights are hampered by societal patriarchal norms that prevent women from accessing water and participating in water management. Gender power relations effectively limit women's decision-making power, mobility and access to resources, including water, making them more vulnerable to climate related hazards (Karim et al., 2012; Caretta and Börjeson, 2014; Carr and Thompson, 2014; Meinzen-Dick et al., 2014; Djoudi et al., 2016; Jost et al., 2016; Sellers, 2016; Sultana, 2018; Yadav and Lal, 2018; Sinharoy and Caruso, 2019). Additionally, water scarcity is a trigger for domestic violence and for gender-based violence in the context of lacking WASH (Karim et al., 2012; Stevenson et al., 2012; Sommer et al., 2015).

In the vast majority of societies in developing countries, women and girls are in charge of fetching water. The necessity of water collection takes away precious time from income-generating activities and education (Truelove, 2011; Crow et al., 2012; Stevenson et al., 2012; Fontana and Elson, 2014; Kookana et al., 2016; Yadav and Lal, 2018). The distances women and girls will have to walk as a result of growing water scarcity due to climate change will increase (*limited evidence, strong confidence*) (Becerra et al., 2016; Sellers, 2016).

While often depicted as victims of climate change induced water scarcity (Arora-Jonsson, 2011; Huynh and Resurreccion, 2014; Djoudi et al., 2016; Gonda, 2017; Yadav and Lal, 2018), women are proactive adaptation actors (Wutich, 2012; Gabrielsson and Ramasar, 2013; Moraes and Rocha, 2013; Moraes, 2015; Singh and Singh, 2015) (Cross-Chapter Box GENDER in Chapter 18). Notably, women are not a homogenous group and local gender roles are not immutable (Carr and Thompson, 2014; Djoudi et al., 2016; Gonda, 2017; Sultana, 2018). For instance, lack of gender sensitive analysis prior to the implementation of agricultural water management projects to remediate water scarcity due to climate change has led to maladaptation and has increased gender vulnerability (Cartwright et al., 2013; Figueiredo and Perkins, 2013; Carr and Thompson, 2014; Djoudi et al., 2016; Njuki et al., 2017; Phan et al., 2019). Integrating the principle of gender inclusivity in adaptation is not only morally and ethically proper, but it is also advantageous because women hold much of the local and traditional knowledge in agricultural communities and can fruitfully provide insights on how to design and implement adaptation (Figueiredo and Perkins, 2013; Fauconnier et al., 2018; James, 2019). Also see Cross-Chapter Box GENDER in Chapter 18.

4.6.4 Inclusion of Indigenous Knowledge

Indigenous Knowledge and Local Knowledge (IK/LK) are dynamic and have incrementally evolved to adapt to climate and environmental change (*robust evidence, high agreement*). The effectiveness of adaptation measures and strategies will improve when they are ethically co-produced by holders of IK/LK and technical knowledge (*medium evidence, high agreement*).

Although AR5 had increased reference to IK/LK than AR4, the report received criticism as it could have engaged more critically with IK/LK and focused more closely on the historical and contextual complexities of the experiences of Indigenous and local peoples (Ford et al., 2016). SR1.5 emphasised the high vulnerability of Indigenous peoples to climate change, and stated that disadvantaged and vulnerable populations, including Indigenous people and certain local communities, are at disproportionately higher risk of suffering adverse consequences with global warming of 1.5C or more (Roy et al., 2018). SRCCL highlighted the enhanced efficacy of decision-making and governance with the involvement of local stakeholders, particularly those most vulnerable to climate change such as Indigenous peoples (Arneth et al., 2019).

IK/LK do not rely simply on ancient, past or static techniques and practices. Instead, there is strong evidence that this knowledge is dynamic and have incrementally evolved to adapt to climate and environmental change (e. g. (Pearce et al., 2015; McMillen et al., 2017). Strong evidence shows some traditional practices are responding to climate change-induced water hazards, e.g. planting of traditional drought resistant crop varieties (Boillat and Berkes, 2013; Gómez-Baggethun and Reyes-García, 2013; Ford et al., 2016). In Norway and Finland, Skolt Sámi have taken steps to alleviate climate change impacts to rivers and lakes by initiating large-scale ecological restoration of degraded habitats (Pecl et al., 2017), (Brattland and Mustonen 2018); (Mustonen and Kontkanen, 2019). Community-led decisions among the nomadic herders of Siberia led to alternative routing, pasture areas, and shifts in nomadic cycles in response to changing flood and permafrost events (Mustonen, 2015).

The co-production of knowledge (between scholars and local communities) of climate change vulnerability, impacts and adaptation with regard to water has the potential to lead to new water knowledge and governance strategies that are context-specific (Arsenault et al., 2019). Shifting beyond the exclusive use of technical knowledge and Western viewpoints redresses the shortcomings of resource- and security-oriented understandings to water and acknowledges the more holistic and relational approaches common to IK/LK (Table 4.16) (Stefanelli et al., 2017; Wilson et al., 2019).

Table 4.16: Examples of findings arising from water-related climate research that is inclusive of IK/LK

Region	Findings
Africa	-
Asia	Bangladesh: reappraisal of rainfall indicators and impacts (Bremer et al., 2018)
Australasia	Murray Darling Basin, Australia: identification of traditional water values, sources and uses of water (Jackson et al., 2015)
	Waipā River, New Zealand: freshwater management and river restoration (Parsons et al., 2017)
Central and South America	-
Europe	"Eurasian North", Finland and Russia: observations of hydrologic change at local scales (Mustonen and Mustonen, 2016)
North America	Yukon, Canada; Alaska, United States: observations of hydrologic change at local scales (Wilson et al., 2015; Wilson et al., 2019)
	Nunavut, Canada - gendered impacts of climate change and the gendered nature of adaptive capacity (Bunce et al., 2016)
Small Island States	Marshall Islands, Palau, Yap, Kosrae, Chuuk, Pohnpei, and Papua New Guinea: gendered impacts of climate change and gendered nature of adaptive capacity (McLeod et al., 2018).
Mountains	-

In contrast to top-down adaptation strategies, ongoing and direct engagement with Indigenous and local communities aligns knowledge production with local cultural contexts and the preferred adaptation measures of local peoples (e. g., (Leonard et al., 2013; Bardsley and Wiseman, 2016). There is strong evidence that relationships with local community and governance may assist in fostering 'two-eyed seeing' and decolonizing collaborative approaches to freshwater management (Arsenault et al., 2019; Wilson et al., 2019). There is also a high level of consensus that indigenous-led freshwater models are well-positioned to promote relational approaches to water management at the level of local governance (Somerville, 2014) and national policy. Accordingly, there is considerable evidence that market -based models of water rights regimes impede the ability of indigenous societies to exercise their rights and traditional ecological knowledge regarding freshwater protection (Nursey-Bray and Palmer, 2018). There is a *high confidence* that the effectiveness of such adaptation measures and strategies will improve when, for instance in the case agriculture, traditional and technical knowledge can be combined in responding and adapting to climate change-induced water hazards (Gandure et al., 2013; Sujakhu et al., 2016). There is evidence (Mustonen et al., 2018) that community-led actions and restoration measures to address anthropogenic damage may help ameliorate climate impacts, and provide "safe havens" to the species suffering from them (Mustonen and Kontkanen, 2019).

An area for future research is the role of IK/LK as potential sources of ethics, morals and well-being for human behaviour. Studies of IK/LK that focus on the relationship between humans and the cosmos find that climate change is the product of spiritual and aesthetic crisis, rather than science or economy alone (Davydov and Mikhailova, 2011; Mustonen and Mustonen, 2016).

Knowledge co-production between users of IK/LK and technical knowledge is not without challenges. Among these are structural and institutional problems, such as water rights, language, and research practice (Ford et al., 2016; Simms et al., 2016; Stefanelli et al., 2017; Arsenault et al., 2019), as well as extractives and colonial uses of IK/LK (Castleden et al., 2017), which can produce distrust and research or consultation fatigue (David-Chavez and Gavin, 2018). In addition, some IK/LK is sacred and cannot be shared with outsiders (Sanderson et al., 2015).

In sum, knowledge co-production is a vital and developing approach to climate change and water that recognises the culture, agency and concerns of Indigenous and local peoples, and is critical to the development of effective, equitable and meaningful strategies for addressing the impacts of global warming. Also see Cross-Chapter Box INDIG in Chapter 11.

4.6.5 Strong Political Support

There is *strong evidence* that the design and the implementation of climate adaptation planning in the water sector can be constrained by the lack of a strong political support. There is *high agreement* that adaptation failure in the water sector reflects political myopia and the lack of political support towards adaptation measures.

Climate adaptation planning approaches can be constrained by several economic, institutional, developmental and political barriers (Anguelovski et al., 2014; Eisenack et al., 2014), including the lack of strong political support (i.e. the collective willingness to take action). Despite scientific evidence about the seriousness of the impact of climate change continues to accumulate, states have taken little effective action to address it. The Paris Agreement, for example, although making a significant impact on the status quo - with almost all the world's states agreeing on the global goal of limiting the global warming to 2°C – it is *unlikely* to make significant changes, without the states' political will to take actions (Keohane and Victor, 2016), including costly actions (*high confidence*).

In order to work, adaptation policies agreed at the international level must be strongly supported by the political will of government to act accordingly at the national and local level, and reshape sectoral policies, including water sectors policies, from the perspective of climate change adaptation (Hjerpe et al., 2015). As evidence suggests, adaptation failure, or minimal adaptation, to the impacts of climate change on water is a governance failure (Oberlack and Eisenack, 2018; Javeline et al., 2019), reflecting political myopia (Muller, 2018; Empinotti et al., 2019), and the lack of political support towards adaptation measures that, although costly, may improve community resilience (Pralle, 2019).

The lack of political will is a major obstacle to stakeholder engagement in the water sector, and affects the determination of political actors to reform and adjust water governance systems in order to make them adaptive (OECD, 2015; Nava et al., 2016; Azhoni et al., 2017a; Phuong et al., 2018). There is, in general, a low level of commitment on the part of political actors to legislate in this policy area (Biesbroek et al., 2018b), which is only partly due to the fact that elected officials have little political incentive to commit resources to adaptation (Vogel and Henstra, 2015).

International donors and supranational/transnational legislation (e.g. EU law) can support/ be a driver for the capacity of national governments to act and remove possible barriers to the effective implementation of climate change adaptation policies at the national level (Massey et al., 2014; Biesbroek et al., 2018a; Rahman and Tosun, 2018). Yet, where the capacity to drive adaptation exists, the political will to make use of this capacity remains crucial (Tilleard and Ford, 2016).

4.6.6 Adequate and Appropriate Financing

Water garners a major share of both public and private adaptation funds (*robust evidence, high agreement),* yet several barriers remain for least developed countries to access these funds (*high agreement, medium evidence*) and there is insufficient evidence on how these funds, when available, are deployed for the benefit of marginalised groups (*high agreement, low evidence*).

AR5 considered the important role of financing for urban adaptation (Revi et al., 2014) and risk financing (Arent et al., 2014); financing for adapting to climate change impacts on water was not explicitly considered. SR 1.5 (de Coninck et al., 2018b) mentioned that governance and finance challenges made sustainable water supply more challenging, while SRCCL mentioned the role of finance in adapting to disasters, including water related disasters like floods and droughts (Hurlbert et al., 2019).

In 2015-16, water and wastewater received 51% of global public adaptation financing (~US$ 11 billion), decreasing slightly from 57% in 2013-2014 (Buchner et al., 2017). Public financing for disaster risk management interventions increased from 7% in 2013-2014 to 11% in 2015-2016 (~$2.4 billion per year (Buchner et al., 2017). Vulnerability is central to allocating public funds (Ciplet et al., 2013; Persson and Remling, 2014); as of 2018, around 13% of The Adaptation Fund's investments were in water management; 12% in coastal zone management and 10% in disaster risk reduction (Fund, 2018). The report from Global Commission on Adaptation (GCA, 2019) provided cost benefit analysis for five main streams of adaptation, including water and also emphasized the need for inclusion of indigenous knowledge for implementing appropriate adaptation.

Private financing remains a relatively minor source of adaptation financing and is more important regionally (Bank, 2019). Around 39% of green bonds issued for adaptation finance in 2017 were in water, wastewater and solid waste management (Bank, 2017). In 2018, while US$ 100.5 billion worth of water-themed bonds (excluding US municipalities) were issued, these were mostly in Europe (63%), Asia Pacific (19.6%) and North America (14.9%) (Filkova et al., 2018; Bank, 2019).

Accessing public adaptation financing can be challenging for developing countries (Bank, 2019), but they offer autonomy and support capacity building, policy reform, and management activities, essential for adaptation in water (Biagini et al., 2014; Sovacool et al., 2017) (*medium agreement; low-medium evidence*). In contrast, private and blended financing in water are likely to remain focused on developed and large emerging economies (Atteridge, 2011; Buchner et al., 2011; Byiers and Rosengren, 2012; (UNEP), 2016; Bank, 2019) (*medium evidence, medium agreement*).

Private sector adaptation activities integrated into business to manage risks to profits and market share are insufficiently understood (Smit and Wandel, 2006; Christiansen et al., 2012; (UNEP), 2016) (*low-medium agreement; low evidence*). Remittances, which especially help poor households fund productive assets or post-disaster needs are also understudied (Banerjee et al., 2011; Bendandi and Pauw, 2016) (*medium agreement; low evidence*).

Public financing faces fluctuations, which can challenge the achievement of financing $100 billion per year by 2020, and leveraging private financing (Fridahl and Linnér, 2016; Cui and Huang, 2018). A better understanding of the gaps in adaptation financing could enable public funds to more effectively deployed. Also see Cross-Chapter Box FINANCE in Chapter 17.

4.6.7 Appropriate Technology and Innovations

[PLACEHOLDER FOR SECOND ORDER DRAFT]

4.6.8 Knowledge Gaps

Table 4.17 captures our current knowledge gaps related to the enabling principles of sustainable and resilient water adaptation solutions.

Table 4.17: Knowledge gaps in enabling principles in adaptation solutions

Sections	Key gaps	Scale	Reference
4.5.3.1 Loss and Damage	Knowledge on in-tangible losses, such as cultural heritage or psychological impacts in the water sector because of water-related disasters is inadequate.	Regional and National	Acosta et al. (2016); Mukherjee and Hastak (2018)

	Robust evidence on the costs and benefits of non-infrastructure options and autonomous adaptation for informed decision-making is lacking.	Regional and National	Inferred by the authors from literature
4.6.2 Polycentric (Nested) Governance	Insufficient knowledge on how can polycentric governance be increased and scaled up to include ground water resources.	Regional and National	Inferred by the authors from literature
	How polycentric governance of water can be organized and coordinated with enhanced technology and financial flow with equity and harmonized partnership has not been studied.	Global, Regional and National	Ostrom (2014); Cole (2015); Albrecht et al. (2017); Jordan et al. (2018)
4.6.4 Indigenous Knowledge	Studies covered less geographic representation of areas where indigenous knowledge systems and communities may not yet be included in research on water-related climate change impacts, such as low-lying islands, drought and flood-prone regions, and coastal regions.	Global, Regional and National	David-Chavez and Gavin (2018)
	Lack of evidence on the appropriate scale of decision-making for different climate change-related issues to ensure that local and national policy responses are aligned and equitable.	Global, Regional and National	Rahman and Tosun (2018); McLeod et al. (2018)
	Lack of studies on: critical historical analysis of sustainable development; inter-generational and gender issues, outcomes of knowledge co-production, and on how Indigenous peoples themselves define and frame environmental concerns.	Global, Regional and National	Petrov et al. (2016); Lepenies et al. (2018)
4.6.6 Adequate and Appropriate Financing	Private sector adaptation activities integrated into business to manage risks to profits and market share are inadequately understood.	Regional and National	Banerjee et al. (2011); Christiansen et al. (2012); Begum and Pereira (2015); Dougherty-Choux et al. (2015); UNEP (2016) ;
	Contribution of remittances on poor household's fund and productive assets or post-disaster needs is not well documented by the literature.	Regional and National	
	Weak understanding of the gaps in adaptation finance which obstruct public funds to more effectively deployed.	Regional and National	Inferred by the authors from literature

Frequently Asked Questions

FAQ4.1: How will climate change affect water security?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

FAQ 4.2: How is climate change impacting extreme weather and the severity of water-related disasters?

FAQ 4.3: Globally, agriculture is the largest user of water. How will climate change impact this sector?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

FAQ 4.4: What is the relationship between climate change, conflicts over water, and human migration?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

FAQ 4.5: How can we adapt to the ways that climate change is impacting water supplies?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

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