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Water

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Frequently Asked Questions

Executive Summary

This chapter assesses observed and projected climate-induced changes in the water cycle, their current impacts and future risks on human and natural systems and the benefits and effectiveness of water-related adaptation efforts now and in the future.

Currently, roughly half of worlds ~8 billion people are estimated to experience severe water scarcity for at least some part of the year due to climatic and non-climatic factors (*medium confidence*[1]). Since the 1970s, 44% of all disaster events have been flood-related. Not surprisingly, a large share of adaptation interventions (~60%) are forged in response to water-related hazards (*high confidence*). {4.1, Box 4.1, 4.2.1.1, 4.2.1.2, 4.2.2, 4.2.4, 4.2.5, 4.2.6, 4.3.8, 4.6, 4.7}

Intensification of the hydrological cycle due to human-induced climate change is affecting physical aspects of water security (*high confidence*), thereby exacerbating existing water-related vulnerabilities caused by other socioeconomic factors. {4.2, 4.2.1.1, 4.2.1.2, 4.2.1.3, 4.2.2, 4.2.4, 4.2.5, 4.2.6, 4.3}

Nearly half a billion people live in unfamiliarly wet areas, where the long-term average precipitation is as high as previously seen in only about one in six years (*medium confidence*). Approximately 163 million people live in unfamiliarly dry areas now (*medium confidence*). {4.2.1.1}

The intensity of heavy precipitation has increased in many regions since the 1950s (*high confidence*). Substantially more people (~709 million) live in regions where annual maximum one-day precipitation has increased than regions where it has decreased (~86 million) (*medium confidence*). At the same time, more people (~700 million) are also experiencing longer dry spells than shorter dry spells since the 1950s (*medium confidence*). {4.2.1.1}

During the last two decades, the global glacier mass loss rate exceeded 0.5 meters water equivalent per year (*high confidence*), impacting humans and ecosystems, including cultural uses of water among vulnerable high mountain and polar communities (*high confidence*). {4.2.2, 4.3.8}

There is a clear trend of increases in streamflow in the northern higher latitudes (*high confidence*), with climatic factors being more important than direct human influence in a larger share of major global basins (*medium confidence*). At the same time, groundwater in aquifers across the tropics has experienced enhanced episodic recharge from intense precipitation and flooding events (*medium confidence*), with implications for sectoral water use. {4.2.3, 4.2.6, 4.3.1, 4.3.4}

Extreme weather events causing highly impactful floods and droughts have become more likely and (or) more severe due to anthropogenic climate change (*high confidence*). {4.2.4, 4.2.5, Cross-Chapter Box DISASTER in Chapter 4}

Anthropogenic climate change has contributed to the increased likelihood and severity of the impact of droughts (especially agricultural and hydrological droughts) in many regions (*high confidence*). Between 1970 and 2019, 7% of all disaster events worldwide were drought-related. Yet, they contributed to 34% of disaster-related deaths, mostly in Africa. {4.2.5, 4.3.1, 4.3.2, Cross-Chapter Box DISASTER in Chapter 4}

Several recent heavy rainfall events, such as in western Europe, China, Japan, the USA, Peru, Brazil and Australia that led to substantial flooding, were made more likely by anthropogenic climate change (*high confidence*). There is *high confidence* that the warming in the last 40–60 years has led to ~10 d earlier spring floods per decade. Between 1970 and 2019, 31% of all economic losses were flood-related. {4.2.4, Cross-Chapter Box DISASTER in Chapter 4}

There is increasing evidence of observed changes in the hydrological cycle on people and ecosystems. A significant share of those impacts are negative and felt disproportionately by already vulnerable communities (*high confidence*). {4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.3.6, 4.3.8}

Agriculture and energy production have been impacted by changes in the hydrological cycle (*high confidence*). Between 1983 and 2009, approximately three-quarters of the global harvested areas (~454 million hectares) experienced yield losses induced by meteorological drought, with the cumulative production losses corresponding to USD 166 billion. There is *medium confidence* that current global thermoelectric and hydropower production has been negatively affected due to droughts with ~4–5% reduction in plant utilisation rates during drought years compared to long-term average values since the 1980s. {4.3.1, 4.3.2}

Climate change and changes in land use and water pollution are key drivers of loss and degradation of freshwater ecosystems (*high confidence*), with impacts observed on culturally significant terrestrial and freshwater species and ecosystems in the Arctic and high-mountain areas (*high confidence*). In addition, precipitation and extreme weather events are linked to increased incidence and outbreaks of water-related diseases (*high confidence*). {4.3.3, 4.3.4, 4.3.5, 4.3.8}

Changes in water-related hazards disproportionately impact vulnerable populations such as the poor, women, children, Indigenous Peoples and the elderly in all locations, especially in the Global South, due to systemic inequities stemming from historical, socioeconomic and political marginalisation (*medium confidence*). {4.3.1, 4.3.3, 4.3.4, 4.3.8}

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[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Water-related risks are projected to increase with every degree of global warming (*high confidence*), and more vulnerable and exposed regions and peoples are projected to face greater risks (*medium confidence*). {Box 4.1, 4.4.1, 4.4.1.1, 4.4.4, 4.5.4, 4.5.5, 4.5.6, Box 4.2}

Climate change impacts via water availability changes are projected to increase with every degree of global warming (*high confidence*), but there are high regional uncertainties. Between 3 and 4 billion people are projected to be exposed to physical water scarcity at 2°C and 4°C global warming levels (GWL), respectively (*low confidence*). {Box.4.1; 4.4.1, 4.4.3, 4.4.5, 4.6.1}

By 2100, one third of the 56 large-scale glacierised catchments are projected to experience a mean annual runoff decline by over 10%, with the most significant reductions in central Asia and the Andes (*low confidence*). Expected impacts may be felt by roughly 1.5 billion people who are projected to critically depend on runoff from the mountains by the mid-21st century (RCP6.0 scenario). {4.4.2, 4.4.3, 4.5.8}

By 2050, environmentally critical streamflow is projected to be affected in 42–79% of the world's watersheds, causing negative impacts on freshwater ecosystems (*medium confidence*). Modified streamflow is also projected to affect inflows to urban storage reservoirs and increase the vulnerability of urban water services to hydro-meteorological extremes, particularly in less developed countries (*high confidence*). {4.4.6, 4.5.4, 4.4.5}

Future water-related impacts of climate change on various sectors of the economy are projected to lower global gross domestic product (GDP) (ranging from 0.49% of GDP by mid-century (SSP3) to less than 0.1% (RCP8.5, SSP5), with higher projected losses expected in low- and middle-income countries (*medium confidence*). {4.7.5}

Drought and flood risks and societal damages are projected to increase with every degree of global warming (*medium confidence*). {4.4.4, 4.4.5, 4.4.7, 4.5.1, 4.5.2}

Drought risks are projected to increase over the 21st century in many regions (*very high confidence*), increasing economy-wide risks (*high confidence*). With RCP6.0 and SSP2, the global population exposed to extreme-to-exceptional total water storage drought is projected to increase from 3% to 8% over the 21st century (*medium confidence*). {4.4.5}

The projected increase in precipitation intensity (*high confidence*) will increase rain-generated local flooding (*medium confidence*). Direct flood damages are projected to increase by four to five times at 4°C compared to 1.5°C (*medium confidence*). {Box 4.1, 4.4.1, 4.4.1.1, 4.4.4, 4.5.4, 4.5.5}

At 4°C global warming, by the end of the century, approximately 10% of the global land area is projected to face simultaneously increasing high extreme streamflow and decreasing low extreme streamflow, affecting roughly over 2.1 billion people (*medium confidence*). {4.4.3} The increase in extreme events is projected to compromise the efficacy of WaSH services and slow progress towards reductions in WaSH-related disease burdens (*medium confidence*). {4.5.3}

Limiting global warming to 1.5°C would reduce water-related risks across regions and sectors (*high confidence*). {4.4.2, 4.4.5, 4.5.2, 4.5.3, 4.5.4, 4.5.6, 4.5.7, 4.6.1, 4.7.2}

Projected increases in hydrological extremes pose increasing risks, with a potential doubling of flood risk between 1.5°C and 3°C of warming and an estimated 120–400% increase in population at risk of river flooding at 2°C and 4°C, respectively. Projected losses include a 1.2- to 1.8-fold increase in GDP loss due to flooding between 1.5°C and 2°C warming (*medium confidence*). {4.4.3, 4.4.4, 4.4.5, 4.5.6, 4.6.1, 4.7.2}

Over large areas of northern South America, the Mediterranean, western China and high latitudes in North America and Eurasia, extreme agricultural droughts are projected to be at least twice as likely at 1.5°C global warming, 150 to 200% more likely at 2°C warming, and over 200% at 4°C (*medium confidence*). Due to the combined effects of water and temperature changes, risks to agricultural yields could be three times higher at 3°C compared to 2°C (*medium confidence*). {4.5.1, 4.6.1}

In Mediterranean parts of Europe, hydropower potential reductions of up to 40% are projected under 3°C warming, while declines below 10% and 5% are projected under 2°C and 1.5°C warming levels, respectively.

Climate-induced hydrological changes are projected to increase migration in the last half of the century, with an almost seven-fold increase in asylum seekers to the European Union (EU) for RP4.5 compared to RCP2.6. The number of internally displaced people in sub-Saharan Africa, South Asia and Latin America increased almost five times for RCP8.5 compared to RCP2.6 (*low confidence).* {4.5.7}

Observed water adaptation responses have multiple benefits (*high confidence*), yet evidence of effectiveness of adaptation in reducing climate risks is not clear due to methodological challenges (*medium confidence*). {4.6, 4.7.1, 4.7.3}

A large share of adaptation interventions (~60%) are shaped in response to water-related hazards (*high confidence*) and involve water interventions (irrigation, rainwater harvesting, soil moisture conservation). Adaptation responses in developing countries tend to be autonomous, incremental and focused on managing water-related risks in agriculture. In contrast, responses are more policy-oriented and urban-focused in developed countries (*high confidence*). {4.6.2, box 4.3, 4.6.5, 4.7.1, 4.7.2}

Irrigation helps stabilise and increase crop yields and is often a preferred strategy for farmers and policymakers for risk reduction, but irrigation is also associated with a range of adverse outcomes, including groundwater over-extraction (*medium confidence*). In addition, large-scale irrigation also affects local to regional climates, both in terms of temperature and precipitation change (*high confidence*). {4.2.6, 4.6.2, Box. 4.2}.

Water adaptation measures tend to have positive economic outcomes in developing countries and positive environmental outcomes in developed countries (*high confidence*). Roughly one third and one fourth of case studies on water adaptation also documents maladaptation and co-benefits, respectively (*high confidence*). A significant knowledge gap remains in knowing if observed adaptation benefits also translate to climate risk reduction, if so, by how much and under what conditions (*medium confidence*). {4.7.1, 4.7.2, 4.7.4}

Future projected adaptations are effective in reducing risks to a varying extent (*medium confidence*), but effectiveness falls sharply beyond 2°C, emphasizing the need for limiting warming to 1.5°C (*high confidence*). {4.6, 4.7.2, 4.7.3}

Adaptations that are beneficial now (e.g., crop- and water-related ones) are also projected to effectively reduce specific future risks to a moderate to a large extent (*medium confidence*). However, residual impacts remain for some options and regions at all levels of warming, and the overall effectiveness decreases at higher warming levels (*high confidence*), further emphasizing the need for limiting warming to 1.5°C. {Box 4.2, 4.7.1, 4.7.2, 4.7.3, 4.7.4}

At warming levels beyond 1.5°C, the potential to reach biophysical limits to adaptation due to limited water resources are reported for small islands (*medium confidence*) and regions dependent on glaciers and snowmelt (*medium confidence*). {4.7.4}

Water security is critical for meeting Sustainable Development Goals (SDGs) and systems transitions needed for climate resilient development, yet many mitigation measures have a high water footprint which can compromise SDGs and adaptation outcomes (*high confidence*). {4.1, Box 4.4, 4.6, 4.6.2, 4.6.3, 4.7, 4.7.1, 4.7.4, 4.7.5.7}

Water features prominently in nationally determined contributions (NDCs) and national adaptation plans (NAPs) of most countries. SDGs cannot be met without adequate and safe water (*high confidence*), and water is fundamental to all systems transition (*high confidence*). {4.1, 4.7, 4.7.1, 4.8, 4.8.7}

Water garners a significant share of public and private adaptation funds (*high confidence*). However, barriers remain for low-income countries to access funds (*medium confidence*), and there is insufficient evidence on benefits for marginalised groups (*medium confidence*). {4.8.2}

Many mitigation measures, such as carbon capture and storage, bioenergy and afforestation and reforestation, can have a high-water footprint (*high confidence*). The water intensity of mitigation must be managed in socially and politically acceptable ways to increase synergies with SDGs, improve water security and reduce trade-offs with adaptation (*medium confidence*). {4.7.6}

A common set of enabling principles underpinned by strong political support can help meet the triple goals of water security, sustainable and climate resilient development (*high confidence*). {4.8, 4.8.3, 4.8.4., 4.8.5, 4.8.6, 4.8.7}

Many countries and social groups most threatened by climate change have contributed the least to the problem and do not have the adequate resources to adapt (high confidence). Water adaptation policies enabled through ethical co-production between holders of Indigenous knowledge, local knowledge and technical knowledge (medium confidence), through cooperation and coordinated actions among multiple actors, including women and all marginalised groups, at various levels of governance (medium confidence) is needed for effective transitions towards climate resilient development. {4.8, 4.8.3, 4.8.4, 4.8.5, 4.8.6}

4.1 Centrality of Water Security in Climate Change and Climate Resilient Development

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*' (Grey and Sadoff, 2007). Risks emanating from various aspects of water insecurity have emerged as a significant global challenge. 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; WEF, 2020). Water also features prominently in the SDGs (Section 4.8) and plays a central role in various systems transitions needed for climate resilient development. Most SDGs cannot be met without access to adequate and safe water (Ait-Kadi, 2016; Mugagga, 2016). In addition, without adequate adaptation, future water-related impacts of climate change on various sectors of the economy are projected to lower the global GDP by mid-century, with higher projected losses expected in low- and middle-income countries (World Bank, 2017; GCA, 2019).

There are at least four reasons for the centrality of water security in adapting to, and mitigating climate change.

First, approximately half the world's population (~4 billion out of ~8 billion people) are assessed as being currently subject to severe water scarcity for at least some part fo the year (*medium confidence*) due to climatic and non-climate factors (Box 4.1). Water insecurity arises from many factors, both environmental and societal. Environmental factors include too little freshwater due to drought or pollution, and too much water, due to extreme precipitation and flooding, and are being affected by climate change. Societal factors include economic and governance-related barriers to water access or protection from water-related damages. Currently, many people are experiencing climate change on a day-to-day basis through water-related impacts such as the increased frequency and intensity of heavy precipitation (*high confidence*) (Section 4.2.1.1, Seneviratne et al., 2021); accelerated melting of glaciers (*high confidence*) (Section 4.2.2, Douville et al., 2021); changes in frequency, magnitude and timing of floods (*high confidence*) (Section 4.2.4, Seneviratne et al., 2021); more frequent and severe droughts in some places (*high confidence*) (Section 4.2.5, Seneviratne et al., 2021); decline in groundwater storage and reduction in recharge (*medium confidence*) (Section 4.2.6, Douville et al., 2021) and water quality deterioration due to extreme events (*medium confidence*) (Section 4.2.7). For example, since the 1970s, 44% of all disaster events have been flood-related (WMO, 2020). With the added stressor of climate change, globally, a larger fraction of land and population are projected to face increased water scarcity due to climate change. For example, at an approximately 2°C GWL, between 0.9 and 3.9 billion people are projected to be at increased exposure to water stress, depending on regional patterns of climate change and the socioeconomic scenarios considered (Koutroulis et al., 2019).

Second, while climate change directly affects freshwater availability across space and time, it also affects water requirements for different uses, such as irrigation, potentially adding to existing societal challenges (Bijl et al., 2018). Vulnerability to water-related impacts of climate change and extreme weather are already felt in all major sectors and are projected to intensify in the future, for example, in agriculture (*high confidence*) (Sections 4.3.1, 4.5.1); energy and industry (*high confidence* for observed drought impacts and projected impacts) (Sections 4.3.2, 4.5.2); water for health and sanitation (*high confidence* about links to precipitation extremes and disease outbreaks) (Sections 4.3.3, 4.5.3); water for urban, peri-urban and municipal sectors (*medium confidence*) (Sections 4.3.4, 4.5.4) and freshwater ecosystems (*high confidence* in climate change as a driver in degradation of freshwater ecosystems) (Sections 4.3.5, 4.5.5). Agriculture and irrigation account for the most significant proportion of consumptive water use and account for 60–70% of total water withdrawals (Hanasaki et al., 2018; Burke et al., 2020; Müller Schmied et al., 2021). Globally, 10% of the most water-stressed basins account for 35% of global irrigated calorie production (Qin et al., 2019), and food production is at risk in those basins and worldwide due to changes in hydrological components of climate change. Lack of access to clean water and sanitation has been one of the leading causes of water-borne diseases. In 2017, approximately 2.2 billion people lacked access to safe drinking water, and roughly 4.2 billion people could not access safe sanitation (WHO and UNICEF, 2019). Inequities in access to safe water are being amplified during the current COVID-19 pandemic (Box 4. 5 and Cross-Chapter Box COVID in Chapter 7). The same 10% of most water-stressed basins also account for 19% of global thermal electricity generation (Qin et al., 2019), and globally, both production of hydropower and thermal power has been negatively affected by droughts and other extreme events. Globally, between 16% and 39% of cities experienced surface-water deficits between 1971 and 2000. If environmental flow requirements (EFRs) 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 are projected to face a water deficit by 2050 (Flörke et al., 2018). The situation is particularly precarious in the Global South, where most of the population lacks access to piped water (WRI, 2019).

Third, a large majority (~60%) of all adaptation responses documented since 2014 are about adapting to water-related hazards like droughts, floods and rainfall variability (Berrang-Ford et al., 2021b) (*high confidence*). Water-related adaptation action features prominently in NDC pledges by a large majority of countries in both Global North and Global South (GWP, 2018). These adaptation responses and their current benefits and effectiveness in reducing water-related risks in the future are systematically assessed in this chapter (Sections 4.6, 4.7.1, 4.7.2 and 4.7.3). These adaptation measures aim to reduce impacts of water-related hazards through responses such as irrigation, water and soil moisture conservation, rainwater harvesting, changes in crops and cultivars, improved agronomic practices, among others (Sections 4.6.2; 4.7.1). Only ~20% of all documented case studies on observed water-related adaptations measure outcomes (positive or negative), but the link between positive outcomes and climate risk reduction is unclear and remains challenging to assess (Section 4.7.1) (*medium confidence*). On the other hand, most of the future projected water-related adaptations are more effective at lower GWLs (1.5°C) than at higher GWLs, showing the importance of mitigation for future adaptations to remain effective (*high confidence*).

Finally, while limiting global warming to 1.5°C would minimise the increase in risks in the various water use sectors and keep adaptation effective, many mitigation measures can potentially impact future water security. For example, bioenergy with carbon capture and storage (BECCS) and afforestation and reforestation can have a considerable water footprint if done at inappropriate locations (Section 4.7.6, see also Canadell et al., 2021). Therefore, minimising the risks to water security from climate change will require a full-systems view that considers the direct impacts of mitigation measures on water resources and their indirect effect via limiting climate change (*high confidence*).

This chapter draws on previous IPCC reports and new methodologies (Section 4.1.1 and SM4.1, SM4.2) and assesses the impacts of climate change on natural and human dimensions of the water cycle with a particular focus on water-related vulnerabilities and adaptation responses (Figure 4.1). Section 4.2 assesses observed changes in the hydrological cycle, and Section 4.3 focuses on their societal impacts and detects which parts of these changes are directly attributable to climate change. Section 4.4 assesses projected risks of changes in the hydrological cycle on various components of the hydrological cycle, and Section 4.5 assesses the same for sectoral risks. Projections and risks assessments for future impacts are framed in terms of GWLs and time horizons, as these are useful for informing mitigation policy under the Paris Agreement and informing adaptation planning. Sections 4.6 and 4.7 assesses current and future water-related adaptation responses in reducing climate and associated impacts and risks and looks at limits to adaptations, especially in a future warmer world. Finally, Section 4.8 outlines the enabling principles for meeting water security, SDGs and climate resilient development.

4.1.1 Points of Departure and Advancements since AR5

The Fifth Assessment Report (AR5, Jiménez Cisneros et al., 2014) concluded that for each degree of global warming, approximately 7% of the global population, under a scenario of moderate population growth, was projected to be exposed to a decrease of renewable water resources of at least 20%. In addition, AR5 reported negative impacts on streamflow volumes, its seasonality (specifically in cryospheric zones), a decline in raw water quality (*medium evidence*, *high agreement*) and projected reduction in renewable surface water and groundwater in most dry tropical regions. AR5 projected an increase in meteorological, agricultural and hydrological droughts in dry regions (*medium confidence*) (Jiménez Cisneros et al., 2014).

The Special Report on Global Warming of 1.5°C (SR1.5) assessed that limiting global warming to 1.5°C is expected to substantially reduce the probability of extreme droughts, precipitation deficits and risks associated with water availability in some regions (*medium confidence*). On the other hand, higher risks to natural and human systems in a 2.0°C world would mean increased vulnerability for the poor, showing that socioeconomic drivers are expected to have a more significant influence on water-related risks and vulnerabilities than changes in climate alone (*medium confidence*) (Hoegh-Guldberg et al., 2018).

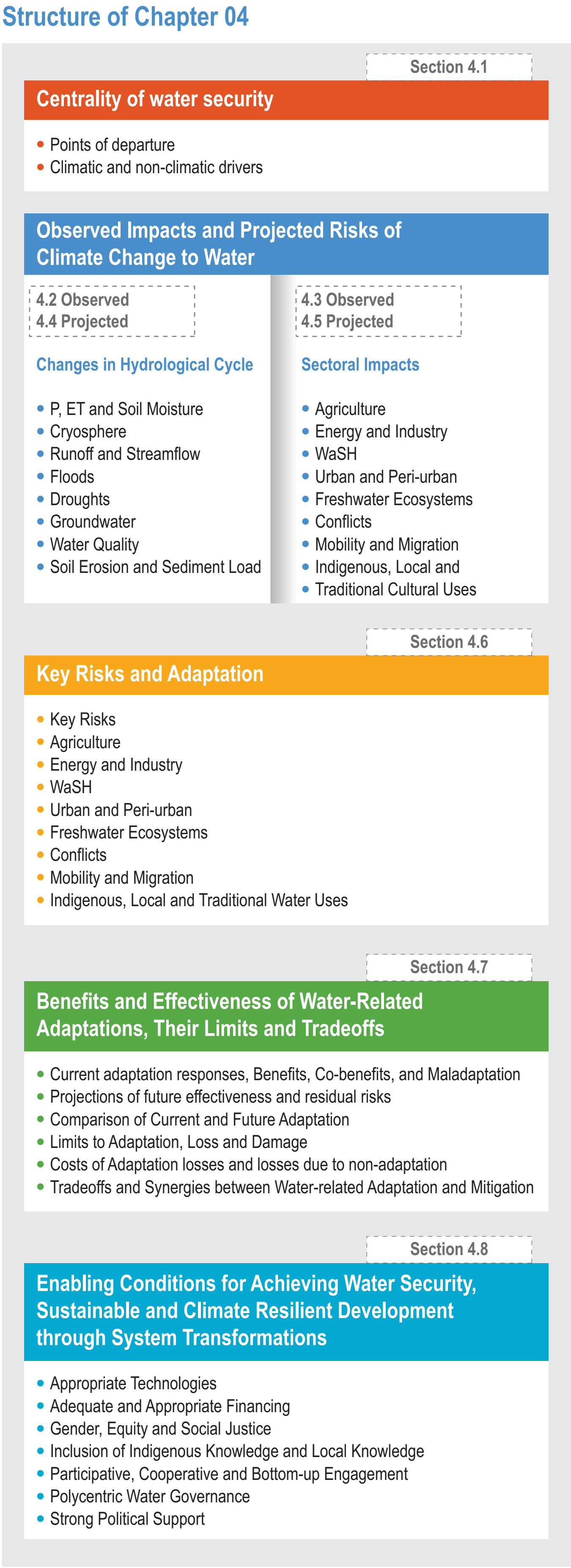

Figure 4.1 | Chapter structure.

Box 4.1 | Implications of Climate Change for Water Scarcity and Water Insecurity

Water scarcity and water insecurity are related concepts but not identical, and each has a range of interpretations leading to some overlap. Water scarcity can be broadly described as a mismatch between the demand for fresh water and its availability, quantified in physical terms. Water security/insecurity is a broader concept with definitions beyond physical water scarcity, encompassing access to water services, safety from poor water quality and flooding, and appropriate water governance that ensures access to safe water (Sadoff et al., 2020). Metrics of water security include both physical and socioeconomic components and are a tool for comparison between different locations and countries regarding relative levels of water security in the context of water-related risks. Some definitions of water scarcity also incorporate these broader issues. For example, 'economic water scarcity' has been defined as a situation where 'human, institutional, and financial capital limit access to water, even though water in nature is available locally to meet human demands' (Comprehensive Assessment of Water Management in Agriculture, 2007). Economic water scarcity can also occur where infrastructure exists, but water distribution is inequitable (Jaeger et al., 2017). Much of the literature exploring the impacts of climate change on water security, however, focuses on quantifying physical water scarcity. Discussions in this box consider physical water scarcity as a quantifiable measure of water availability compared to its demand and consider the societal elements of economic water scarcity to be part of the more comprehensive concept of water insecurity.

Physical water scarcity

Definitions of water scarcity have evolved to take account of a broader set of factors. For example, physical water scarcity indicates that an insufficient quantity of water is available to meet requirements. A commonly used measure of physical water scarcity is the Falkenmark index which measures the amount of renewable freshwater available per capita (Falkenmark et al., 1989; White et al., 2014). However, the Falkenmark index is now regarded as an incomplete measure, as it does not account for water needed for non-human needs (as quantified with EFRs). Therefore, EFRs have begun to be incorporated in recent water scarcity assessments (Liu et al., 2016; Liu et al., 2017b). Quality-induced water scarcity is an additional factor beginning to be considered (Liu and Zhao, 2020) .

Using a Water Scarcity Index (WSI) defined as the ratio of demand and availability, accounting for EFRs, it is estimated that 4 billion people live under conditions of severe water scarcity for at least one month per year (Figure Box 4.1.1a; Mekonnen and Hoekstra, 2016). Nearly half of these people live in India and China. Although regions with high water scarcity are already naturally dry (*virtually certain*[2]), human influence on climate is leading to reduced water availability in many regions. It is *very likely* that global patterns of soil moisture change are being driven by human influence on climate, and an overall global decline in soil moisture is attributable to greenhouse forcing [4.2.1.3]. Climate change patterns of streamflow change include declines in western North America, northeast South America, the Mediterranean and South Asia (*medium confidence*) [4.2.3]. However, quantification of the contribution of anthropogenic climate change to current levels of water scarcity is not yet available.

Water demand is projected to change as a direct result of socioeconomic changes. For example, the global water demand for domestic, industrial and agricultural uses, at present about 4600 $km^3\ yr^{-1}$, is projected to increase by 20–30% by 2050 (Greve et al., 2018), depending on the socioeconomic scenario. Changes in water availability and demand have been projected in several studies using climate models and socioeconomic scenarios (e.g., Arnell and Lloyd-Hughes, 2014; Gosling and Arnell, 2016; Greve et al., 2018; Koutroulis et al., 2019). In such studies, the projected changes in water availability arise from differences in precipitation and evapotranspiration (ET). However, both precipitation and evapotranspiration are also subject to very high uncertainty in key processes such as regional climate change patterns (Uhe et al., 2021) and the influence of vegetation responses to elevated CO_2 on transpiration (Betts et al., 2015).

Human factors are projected to be the dominant driver of future water scarcity on a global scale (Graham et al., 2020a). However, at regional scales, high uncertainty in climate changes means that reduced water availability is *more likely than not* in many major river basins and remains a risk in most basins even where the central estimate is for increased water availability due to climate change (Figure 4.16). Such substantial uncertainties in projected water scarcity are crucial factors causing water management policies and planning challenges in the future. Therefore, locations projected to see significant increases in water scarcity with large uncertainty can be considered to be subject to the highest challenges for water management policy (Figure Box 4.1.1b; Greve et al., 2018).

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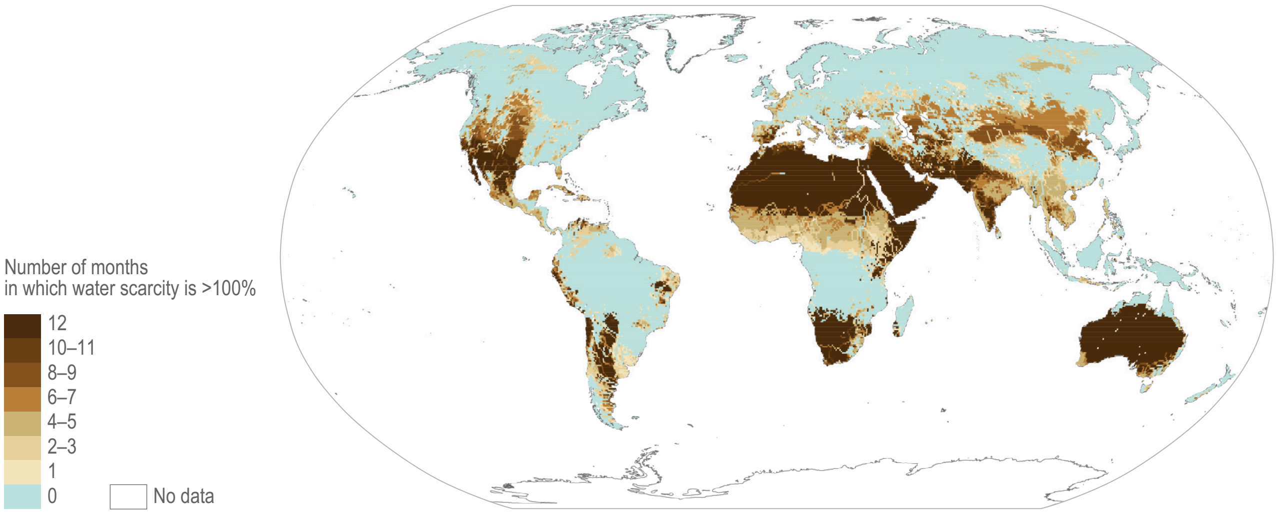
[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.

Box 4.1 (continued)

Geographical distributions of current water scarcity and levels of challenge for policies addressing future change

(a) Number of months per year with severe water scarcity



(b) Local levels of policy challenges for addressing water scarcity by 2050

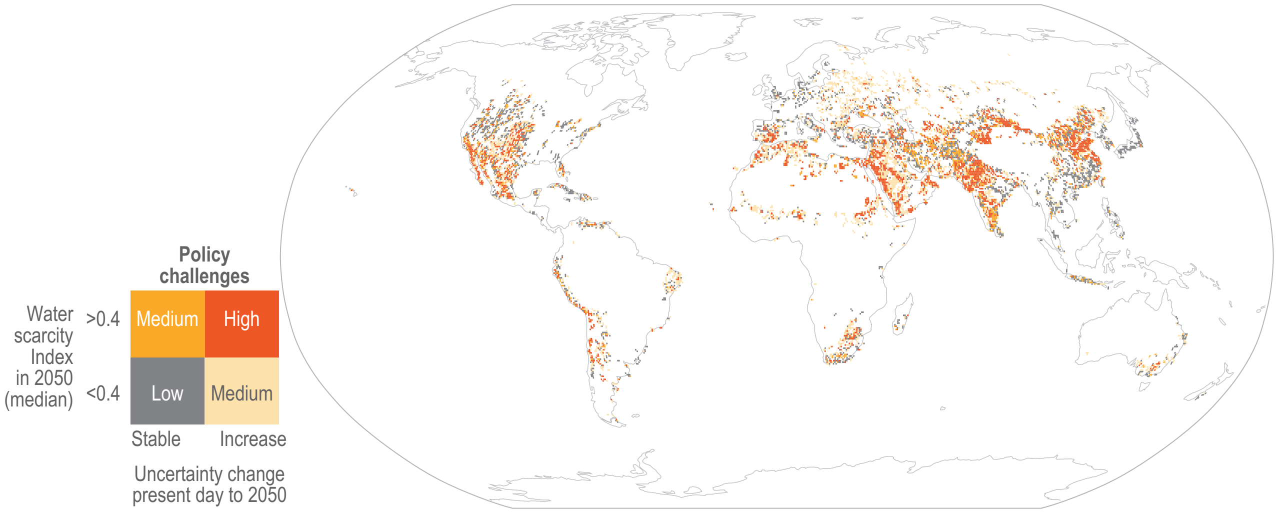


Figure Box 4.1.1 | Geographical distributions of current water scarcity and levels of challenge for policies addressing future change.

(a) The number of months per year with severe water scarcity (ratio of water demand to availability > 1.0). Reproduced from Mekonnen and Hoekstra (2016).

(b) Local levels of policy challenges for addressing water scarcity by 2050, considering both the central estimate (median) and the change uncertainty in projections of a Water Scarcity Index (WSI) from the present day to 2050 (Greve et al., 2018). Projections used five CMIP5 climate models, three global hydrological models from ISIMIP and three Shared Socioeconomic Pathways (SSPs). Levels of policy challenges refer to the scale and nature of policies to address water scarcity and range from monitoring and reviewing risks ('low') through transitional changes in water systems ('medium') to transformational changes ('high'). Low policy challenges arise when the projected water scarcity in 2050 is lower (<0.4), and the level of uncertainty remains relatively stable in future projections. Medium policy challenge arises when either the central estimate of water scarcity remains low but uncertainty increases, or the uncertainty is stable but the central estimate of water scarcity for 2050 is higher (>0.4). High policy challenges arise when the central estimate of water scarcity is higher and the uncertainty increases. White areas show grid points defined as non-water-scarce (75th quantile of the WSI < 0.1 at all times) or very low average water demand. Reproduced from Greve et al. (2018).

Box 4.1 (continued)

Water security and insecurity

Unlike physical water scarcity, water security or insecurity cannot be quantified in absolute terms. However, relative levels of water security in different places can be compared using metrics representing critical aspects of security (Gain et al., 2016; Young et al., 2019), ideally with thresholds for secure/insecure compared with local experience to assess validity (Young et al., 2019).

Gain et al. (2016) define a Global Water Security Index (GWSI) metric on a scale of 0 to 1 combining indicators of relative levels of availability of freshwater, accessibility to water services, water management and water quality and safety (including flood risk, which can affect water quality as well as being a direct physical hazard). Global application of this index indicates large worldwide differences in water security arising from different combinations of reasons (Figure Box 4.1.2a). In North Africa, the Middle East, large parts of the Indian sub-continent and north China, low water security arises predominantly from low water availability. However, many areas with relatively high water availability have relatively low levels of water security due to other factors. In 2015, 29% of the world's population did not have access to safe drinking water (Ritchie and Roser, 2019). In large parts of South and Southeast Asia, significant contributions to water insecurity came from increased flood risk and deteriorated water quality (Burgess et al., 2010; Ward et al., 2017; Farinosi et al., 2018). Water availability is relatively high across most of Africa, but water security is relatively low due to low accessibility, management and safety/quality standards. Most people in Africa do not have access to safe drinking water and improved sanitation (Marson and Savin, 2015; Naik, 2017; Armah et al., 2018).

In contrast, some areas with high physical water scarcity, such as some parts of the USA, Australia and southern Europe, show relatively high water security levels due to good governance, safety/quality and accessibility. Nevertheless, marginalised groups such as Indigenous Peoples experience reduced access to water even within regions in the Global North. For example, in both Canada and the USA, many Indigenous Peoples living on reserves lack access to piped water (Collins et al., 2017; Hanrahan, 2017; Marshall et al., 2018) and (or) are on boil water advisories (Patrick et al., 2019). In Australia, 25–40% of Aboriginal people live in remote rural areas with poor access to clean water (Bowles, 2015; NCCARF, 2018).

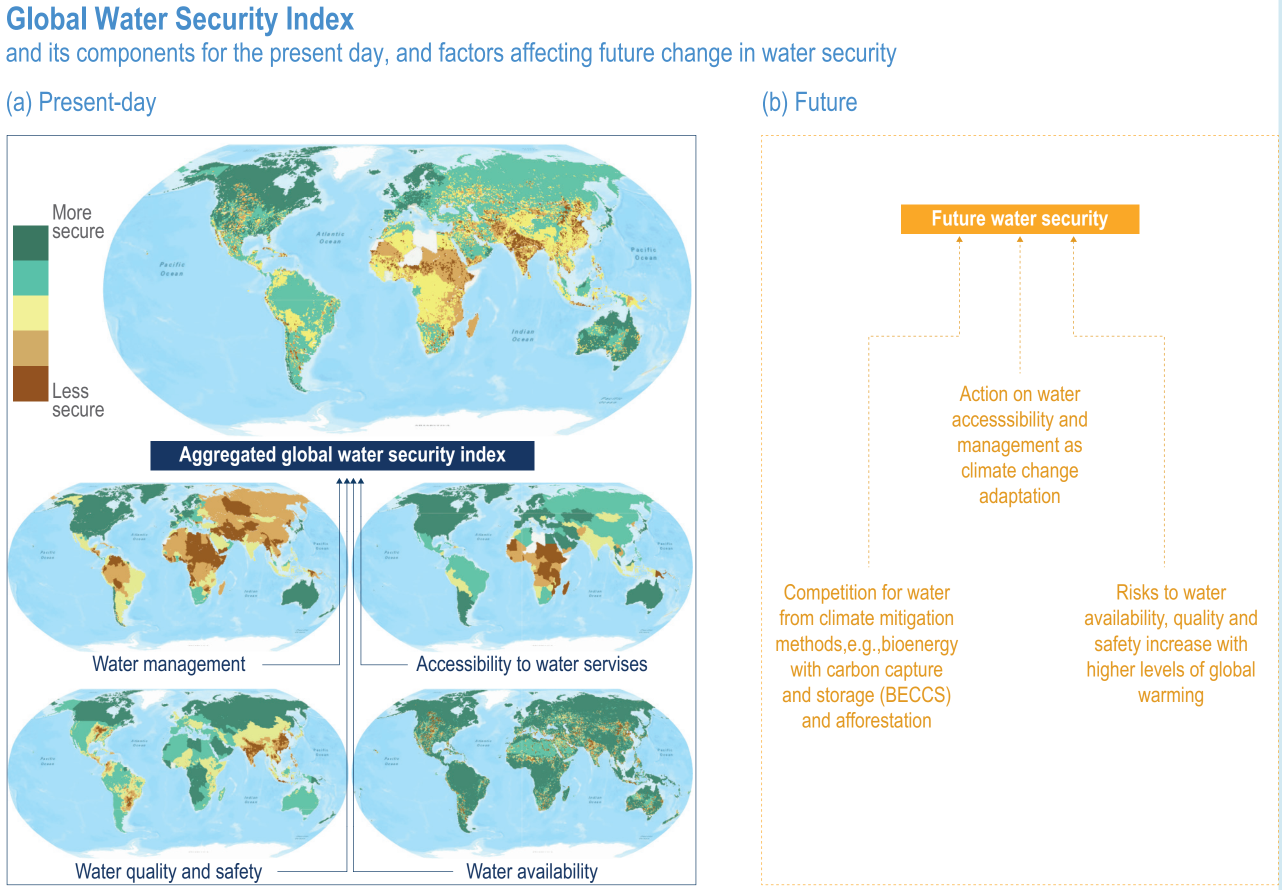


Figure Box 4.1.2 | Global Water Security Index (GWSI) and its components for the present day, and factors affecting future change in water security.

Box 4.1 (continued)

(a) Top: a global map of local values of GWSI constructed from the following components with their subjectively weighted contribution to the combined metric indicated in brackets. Middle left: relative effectiveness of water management (15%), comprising a World Governance Index at country scale (itself representing six components: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law and control of corruption) and indicators of transboundary legal frameworks and political tensions at a river-basin scale. Middle right: relative accessibility to water services (20%), including drinking water and sanitation. Bottom left: relative water quality and safety (20%), including a Water Quality Index and Flood Frequency Index. Bottom right: relative availability of fresh water (45%), comprising a Water Scarcity Index, Drought Index and the groundwater depletion rate. Data for the components do not apply to the same set of dates but are generally applicable to recent decades up to 2010. White areas indicate no data available for at least one component. For further details, see Gain et al. (2016).

(b) Factors through which climate change or action on mitigation or adaptation could influence water security.

The discrepancy between physical water scarcity and overall water insecurity is a function of socioeconomic vulnerabilities and governance gaps. Therefore, improving societal aspects of water management will be key in adapting to climate change-driven increases in water scarcity in the future (*high confidence*).

Future water security will depend on the magnitude, rate and regional details of future climate change and non-climatic factors, including agricultural practices, water demand and governance. In many cases, climate change may not be the dominant factor affecting water security. Nevertheless, climate change poses clear risks to water security in many regions through potential impacts on water availability, quality and flooding. The range of possible outcomes is extremely large, and assessing the likelihood of particular outcomes depends on consideration of uncertain regional climate changes and uncertain socioeconomic futures. Uncertainty in future water scarcity projections makes climate change risks to water security and planning for adaptation challenging. Limiting climate change to lower levels of global warming would reduce the risks to water security arising from climate change, partly because uncertainties in regional climate change are smaller at lower levels of warming.

In summary, roughly half of the world's population are assessed as currently subject to severe water scarcity for at least some part of the year due to climatic and non-climatic factors, and this is projected to be exacerbated at higher levels of warming (*medium confidence*). General water insecurity issues are seen worldwide, particularly in South Asia, North China, Africa and the Middle East, due to high population densities often coupled with low water availability, accessibility, quality and governance (*high confidence*). Areas with high water availability can also be water-insecure due to increased flood risk, deteriorated water quality, and poor governance (*high confidence*). Future water security will depend on the evolution of all these socioeconomic and governance factors and future regional climate change (*high confidence*). The main climate change contribution to water insecurity is the potential for reduced water availability, with a secondary contribution from increased flooding risk (*medium confidence*). Future socioeconomic conditions are a crucial driver of water insecurity, implying the need for further adaptation to some level of future climate change (*medium confidence*). However, policy challenges are high in many regions, with uncertainty in the regional climate outcomes being a key factor (*high confidence*).

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

The Special Report on Climate Change and Land (SRCCL) stated that groundwater over-extraction for irrigation is causing depletion of groundwater storage (*high confidence*). The report also noted that precipitation changes, coupled with human drivers, will have a role in causing desertification, and water-driven soil erosion is projected to increase due to climate change (*medium confidence*). The population vulnerable to impacts related to water is projected 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) could increase farmers' adaptive capacity (*high confidence*) (Mirzabaev et al., 2019).

The Sixth Assessment Report (AR6) Working Group I (WGI) (Douville et al., 2021) concluded that anthropogenic climate change has increased atmospheric moisture and precipitation intensity (*very likely* by 2–3% per 1°C) (*high confidence*), increased terrestrial ET (*medium confidence*) and contributed to drying in dry summer climates including in the Mediterranean, southwestern Australia, southwestern South America, South Africa and western North America (*medium to high confidence*), and has caused earlier onset of snowmelt and increased melting of glaciers (*high confidence*) since the mid-20th century. The report also stated with *high confidence* that the water cycle variability and extremes are projected to intensify, regardless of the mitigation policy. The share of the global population affected by water-related hazards and water availability issues is projected to increase with the intensification of water cycle variability and extremes. They concluded with *high confidence* that strong and rapid mitigation initiatives are needed to avert the manifestation of climate change in all components of the global water cycle.

Building on these previous reports, this chapter advances understanding climate change-induced hydrological changes and their societal impacts and risk in several key ways.

First, since AR5, the methodology of climate change impact studies has advanced and these methodological advances are described in SM4.1. AR6 uses new projections (CMIP6) based on the SSPs and other scenarios, and we assess those results in this chapter alongside those using other projections and scenarios.

Second, this chapter follows the developments set in motion by SR1.5, SRCCL and SROCC to incorporate Indigenous knowledge (IK), traditional knowledge (TK) and local knowledge (LK). SR1.5 stated that disadvantaged and vulnerable populations, including Indigenous Peoples and certain local communities, are at disproportionately higher risk of suffering adverse consequences due to global warming of 1.5°C 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). SROCC found adaptation efforts have benefited from the inclusion of IK and LK (IKLK) (Abram et al., 2019). In this chapter, we engage directly with Indigenous contributing authors and use multiple evidence-based approaches, as undertaken by the IPBES (Tengö et al., 2014; Tengö et al., 2017). This approach is guided by the understanding that the co-production of knowledge (between scholars and local communities) about water and climate change vulnerability, impacts and adaptation has the potential to lead to new water knowledge and context-specific governance strategies (Arsenault et al., 2019; Chakraborty and Sherpa, 2021). Additionally, 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 IKLK (Section 4.8.4) (Stefanelli et al., 2017; Wilson, 2019; Chakraborty and Sherpa, 2021).

Finally, grounded in the AR6 goal to expand the solution space, this chapter advances the understanding of adaptation in the water sector since AR5 by deploying a meta-analysis of adaptation measures. The meta-analysis focuses on both current adaptation responses (Section 4.7.1) and future projected adaptation responses, which have been modelled (Section 4.7.2). The meta-review assesses the outcomes of current adaptation responses and effectiveness of future projected adaptations in reducing climate and associated risks. Studies derived from the Global Adaptation Mapping Initiative (GAMI) database (Berrang-Ford et al., 2021a) (see Chapter 16) were coded systematically following a meta-review protocol developed specifically for this assessment (Mukherji et al., 2021; SM4.2). A similar meta-review protocol was also developed to assess effectiveness of adaptations to reduce projected climate risks (Section 4.7.2; SM4.2).

4.1.2 Climatic and Non-Climatic Drivers of Changes in the Water Cycle

The water cycle is affected by both climatic and non-climatic factors (Douville et al., 2021). Radiative forcing by changes in greenhouse gas (GHG) concentrations, aerosols and surface albedo drives global and regional changes in evaporation and precipitation (Douville et al., 2021). A warmer atmosphere holds more moisture, increasing global and regional mean precipitation, and more extreme precipitation (Allan et al., 2014; Giorgi et al., 2019; Allan et al., 2020). Regional precipitation responses vary according to changes in atmospheric circulation. Geographical variation in aerosols drives changes in atmospheric circulation, affecting precipitation patterns such as the Asian monsoon (Ganguly et al., 2012; Singh et al., 2019). (Section 4.2.1)

Warming increases glacier melt and is expected to decrease snowfall globally and lead to shorter snow seasons with earlier but less rapid snowmelt. It can also lead to local increases in snowfall intensity (Allan et al., 2020). These changes affect the seasonality of river flows in glacier-fed or snow-dominated basins. (Section 4.2.2)

Rising atmospheric CO_2 generally decreases plant transpiration, affecting soil moisture, runoff, stream flows, the return of moisture to the atmosphere and surface temperature (Skinner et al., 2017). However, 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 (Zhu Z. et al., 2016; Zeng Z. et al., 2018). Increased ozone can impact plant functioning, reducing transpiration (Arnold et al., 2018). (Section 4.2.1)

Direct human interventions include abstraction of surface water and groundwater for drinking, irrigation and other freshwater uses, as well as streamflow impoundment behind dams and large-scale inter-basin transfers (Zhao et al., 2015; Donchyts et al., 2016; McMillan et al., 2016; Shumilova et al., 2018). The consequences of these interventions are substantial and are discussed below briefly. In addition, these direct human interventions can change due to various societal and economic factors, including changes in land use and urbanisation (Sections 4.3 and 4.5).

Irrigation can reduce river flows and groundwater levels via abstraction and increase local precipitation (Alter et al., 2015; Cook et al., 2015), alter precipitation remotely through moisture advection (de Vrese et al., 2016) and change the timing of monsoons through land–sea temperature contrasts (Guimberteau et al., 2012) (Box 4.3). Land cover change affects ET and precipitation (Li et al., 2015; Douville et al., 2021), interception of precipitation by vegetation canopies (de Jong and Jetten, 2007), infiltration (Sun et al., 2018a) and runoff (Bosmans et al., 2017). Land cover impacts on the hydrological cycle are of similar magnitude as human water use (Bosmans et al., 2017).

Urbanisation decreases land surface permeability (Choi et al., 2016), which can increase fast runoff and flooding risks and reduce local rainfall by decreasing moisture return to the atmosphere (Wang et al., 2018). But urbanisation can also increase the sensible heat flux driving greater or more extreme precipitation (Kusaka et al., 2014; Niyogi et al., 2017). (Section 4.3.4)

The water cycle, including direct human interventions

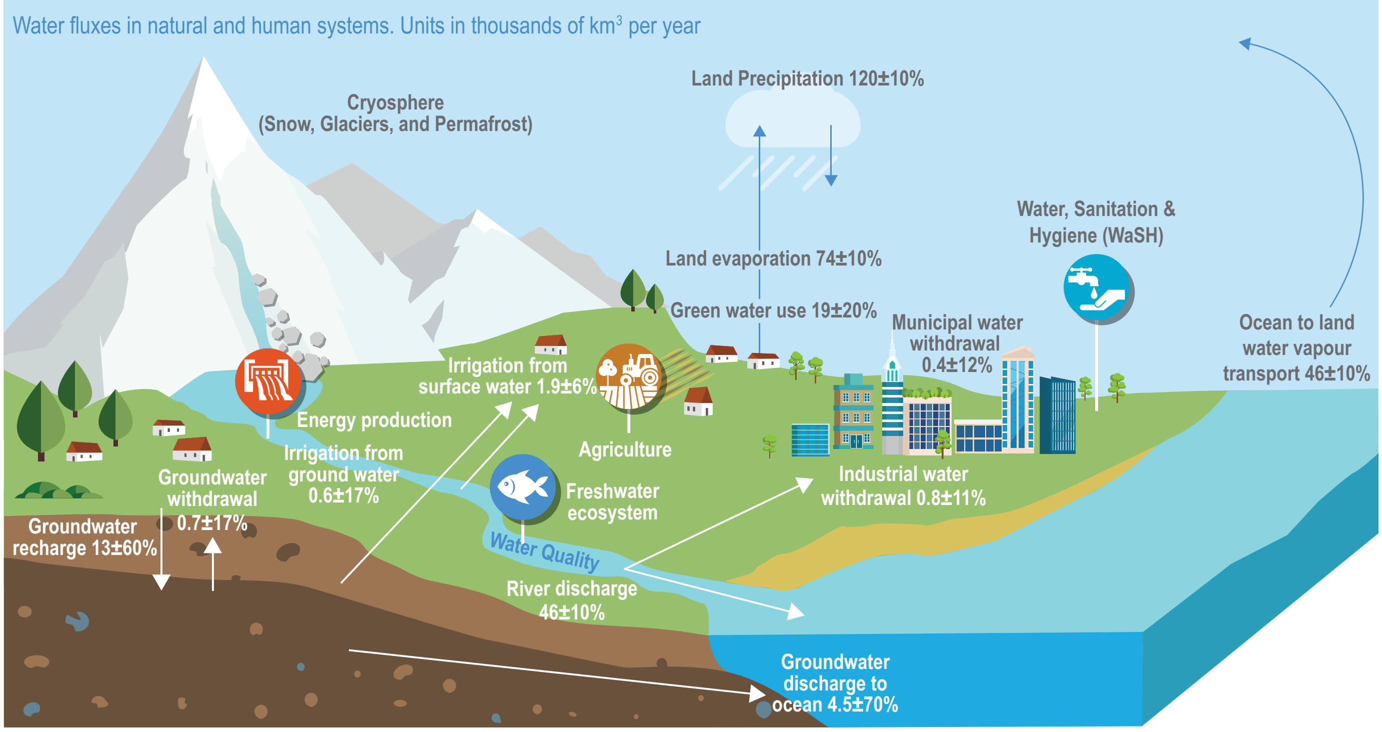


Figure 4.2 | The water cycle, including direct human interventions. Water fluxes on land precipitation, land evaporation, river discharge, groundwater recharge and groundwater discharge to the ocean from Douville et al. (2021). Human water withdrawals for various sectors are shown from Hanasaki et al. (2018), Sutanudjaja et al. (2018), Burek et al. (2020), Droppers et al. (2020) and Müller Schmied et al. (2021). Green water use (Abbott et al., 2019) refers to the use of soil moisture for agriculture and forestry. Irrigation water use (called blue water) is not included in green water use.

In summary, radiative forcing by GHG and aerosols drives changes in ET and precipitation at global and regional scales, and the associated warming shifts the balance between frozen and liquid water (*high confidence*). Rising CO_2 concentrations also affect the water cycle via plant physiological responses affecting transpiration, including via reduced stomatal opening and increased leaf area (*high confidence* regarding the individual processes; *medium confidence* regarding their net impact). Land cover changes and urbanisation affect both the climate and land hydrology by altering the exchanges of energy and moisture between the atmosphere and surface (*high confidence*) and changing the permeability of the land surface. Direct human interventions in river systems and groundwater systems are non-climatic drivers with substantial impacts on the water cycle (*high confidence*) and have the potential to change as part of societal responses to climate change (Figure 4.2).

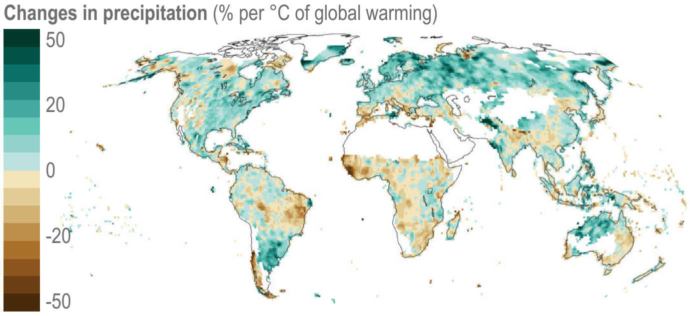
4.2 Observed Changes in the Hydrological Cycle Due to Climate Change

All components of the global water cycle have been modified due to climate change in recent decades (*high confidence*) (Douville et al., 2021), with hundreds of millions of people now regularly experiencing hydrological conditions that were previously unfamiliar (Sections 4.2.1.1, 4.2.4, 4.2.5). Extensive records from weather stations, satellites and radar clearly show that precipitation patterns have shifted worldwide. Three major shifts documented are (a) some regions receiving more annual or seasonal precipitation and others less, (b) many regions have seen increased heavy precipitation, and many have seen either increases or decreases in dry spells and (c) some regions have seen shifts towards heavier precipitation events separated by more prolonged dry spells (Section 4.2.1.1). Observationally based calculations suggest that ET has changed in response to changes in precipitation and increasing temperatures, resulting in changing patterns of soil moisture worldwide which are now detectable by satellite remote sensing (Sections 4.2.1.2, 4.2.1.3). Rising temperatures have caused profound and extensive changes in the global cryosphere, with mountain glaciers, land ice and snow cover shrinking, causing substantial, permanent impacts on the ways of life of people in these regions, particularly Indigenous Peoples with strong cultural links to long-term or seasonally frozen environments (Sections 4.2.2, 4.3.8). Groundwater recharge in spring may have been reduced due to shorter snowmelt seasons, although the dominant impact on groundwater has been non-climatic and through intensification of irrigation (Section 4.2.6). The global-scale pattern of streamflow changes is now attributable to observed historical climate change, with human land and water use insufficient by themselves to explain the observed streamflow changes at global scales (Section 4.2.3). Numerous examples of extreme hydrometeorological events, including heavy precipitation, flooding, drought and wildfire events causing deaths, high levels of economic damage and extensive ecological impacts, have been shown to have been made more *likely* by human influence on climate through increased GHG concentrations in the atmosphere (Sections 4.2.1.1, 4.2.4, 4.2.5). Overall, there is a clear picture of human alteration of the global water cycle, which is now affecting societies and ecosystems across the

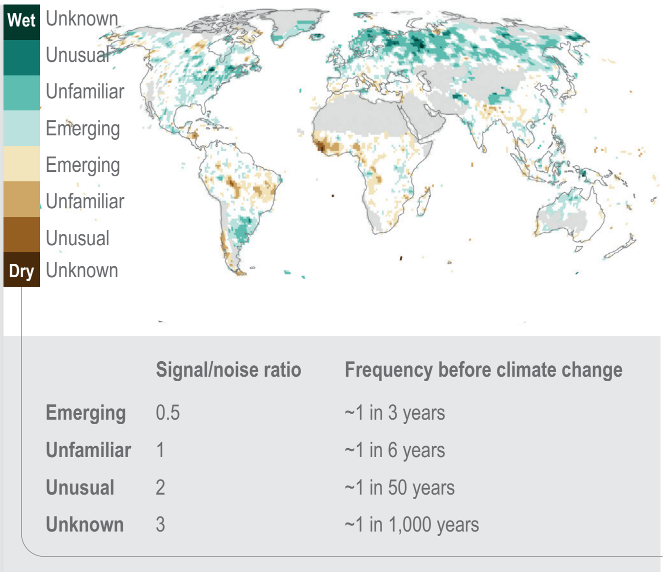
Observed mean and extreme precipitation changes

and people experiencing the emergence of historically unfamiliar precipitation and changes in extreme precipitation

(a) Trend in annual precipitation

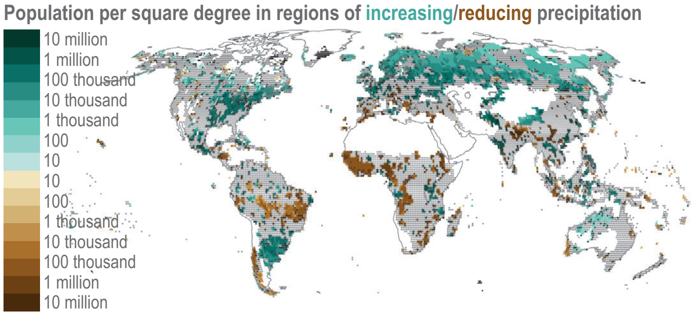


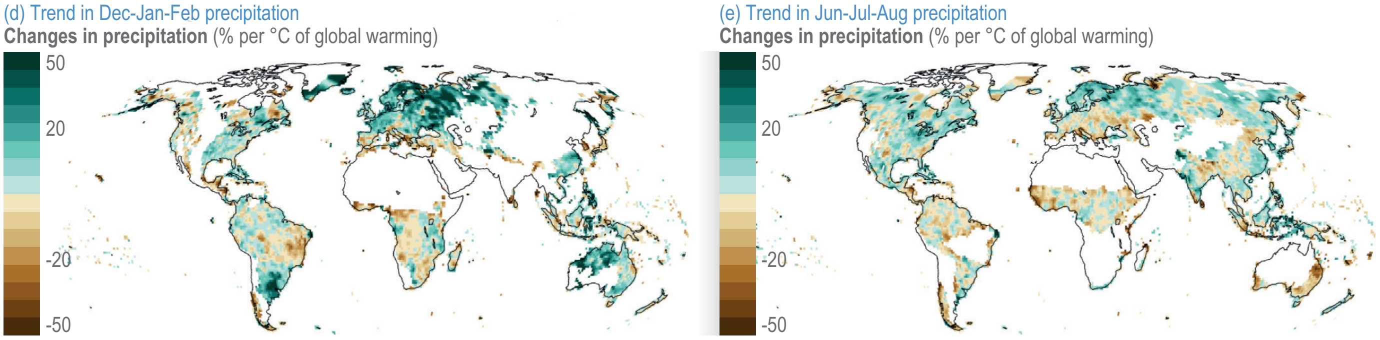
(b) Level of unfamiliarity of annual precipitation



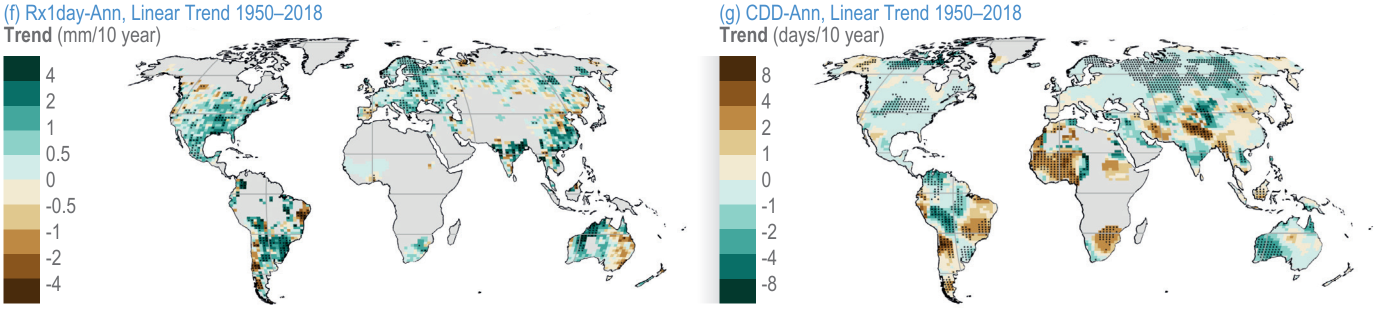
	Signal/noise ratio	Frequency before climate change
Emerging	0.5	~1 in 3 years
Unfamiliar	1	~1 in 6 years
Unusual	2	~1 in 50 years
Unknown	3	~1 in 1,000 years

(c) Population density in regions of emerging precipitation changes

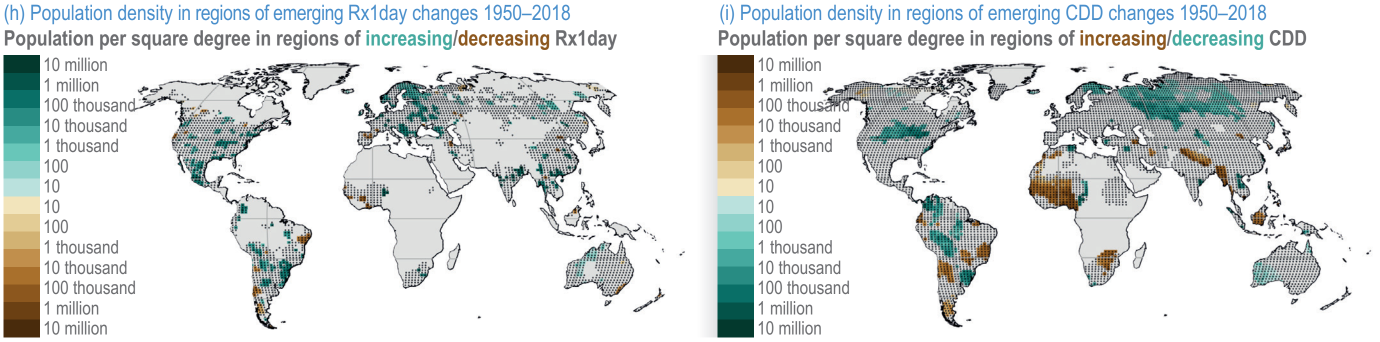



(d) Trend in Dec-Jan-Feb precipitation

(e) Trend in Jun-Jul-Aug precipitation


(f) Rx1day-Ann, Linear Trend 1950–2018

(g) CDD-Ann, Linear Trend 1950–2018


(h) Population density in regions of emerging Rx1day changes 1950–2018

(i) Population density in regions of emerging CDD changes 1950–2018

Figure 4.3 | Observed mean and extreme precipitation changes and people experiencing the emergence of historically unfamiliar precipitation and changes in extreme precipitation.

(a) Percentage changes in annual mean precipitation over land (1891–2019) per °C global warming in the Global Precipitation Climatology Centre (GPCC) v2020 data set (Schneider et al., 2017; Schneider et al., 2020). Green shows increasing precipitation; orange shows decreasing precipitation.

(b) Levels of unfamiliarity of wetter and drier climates, classified in terms of the ratio of the signal S of change to the noise N of variability, where the latter is defined as one standard deviation in annual data with the trend removed, that is, occurs approximately one in 6 years. Grey regions are either unobserved (oceans) or deserts (<250 mm year^{-1}). Stippling indicates where the signal of change is not significant. See Hawkins et al. (2020) for further details.

(c) Population densities in regions with annual precipitation classified as "emerging".

(d) Precipitation trends from the GPCC data set in December, January and February (mm day^{-1} decade^{-1}).

(e) As (d) for June-July-August.

(f) Changes in annual maximum 1-day precipitation (Rx1day) in the HadEX3 data set (Dunn et al., 2020).

(g) Trend in annual mean consecutive dry days (CDD), 1950–2018, in HadEX3.

(h) Population densities per grid box where the trend in Rx1day is significantly different from zero.

(i) Population densities per grid box where the trend in CDD is significantly different from zero. Stipples in (h) and (i) show where HadEX3 data is available. Population data in (c), (h) and (i) are for 2020 from CIESIN (2018a; 2018b).

world. This section describes changes in the hydrological cycle through a lens of societal impacts.

4.2.1 Observed Changes in Precipitation, Evapotranspiration and Soil Moisture

4.2.1.1 Observed Changes in Precipitation

AR6 WGI (Douville et al., 2021) concluded that GHG forcing has driven increased contrasts in precipitation amounts between wet and dry seasons and weather regimes over tropical land areas (*medium confidence*), with a detectable precipitation increase in the northern high latitudes (*high confidence*). GHG forcing has also contributed to drying in dry summer climates, including the Mediterranean, southwestern Australia, southwestern South America, South Africa and western North America (*medium to high confidence*) (Figure 4.3). AR6 WGI (Seneviratne et al., 2021) also concluded that the frequency and intensity of heavy precipitation events have *likely* increased at the global scale over most land regions with good observational coverage. Heavy precipitation has *likely* increased on the continental scale over North America, Europe and Asia. Regional increases in heavy precipitation frequency and (or) intensity have been observed with at least *medium confidence* for nearly half of the AR6 WGI climatic regions (Figure 4.3). Human influence, in particular GHG emissions, is *likely* the main driver of the observed global-scale intensification of heavy precipitation in land regions

Large numbers of people live in regions where the annual mean precipitation is now 'unfamiliar' compared to the mean and variability between 1891 and 2016 (Figure 4.3c). "Unfamiliar" is defined as the long-term change being greater than one standard deviation in the annual data (Figure 4.3b). In 2020, approximately 498 million people lived in unfamiliarly wet areas, where the long-term average precipitation is as high as previously seen in only about one in 6 years (*medium confidence*) (Figure 4.3c). These areas are primarily in mid and high latitudes (Hawkins et al., 2020). On the other hand, approximately 163 million people lived in unfamiliarly dry areas, mostly in low latitudes (*medium confidence*). Due to high variability over time, the signal of long-term change in annual mean precipitation is not distinguishable from the noise of variability in many areas (Hawkins et al., 2020), implying that the local annual precipitation cannot yet be defined 'unfamiliar' by the above definition.

Notably, many regions have seen increased precipitation for part of the year and decreased precipitation at other times (*high confidence*) (Figure 4.3d,e), leading to small changes in the annual mean precipitation. Therefore, the numbers of people seeing unfamiliar seasonal precipitation levels are expected to be higher than those quoted above for unfamiliar annual precipitation changes (*medium confidence*). Still, quantified analysis of this is not yet available.

The intensity of heavy precipitation has increased in many regions (*high confidence*), including much of North America, most of Europe, most of the Indian sub-continent, parts of northern and southeastern Asia, much of southern South America, parts of southern Africa and parts of central, northern and western Australia (Figure 4.3 f) (Dunn et al., 2020; Sun et al., 2020). Conversely, heavy precipitation has decreased in some regions, including eastern Australia, northeastern South America and western Africa. The length of dry spells has also changed, with increases in annual mean consecutive dry days (CDD) in large areas of western, eastern and southern Africa, eastern and southwestern South America, and Southeast Asia, and decreases across much of North America (Figure 4.3g). Precipitation extremes have changed in some places where annual precipitation shows no trend. Some regions such as southern Africa and parts of southern South America are seeing increased heavy precipitation and longer dry spells. Many regions with changing extremes are highly populated, such as the Indian sub-continent, Southeast Asia, Europe and parts of North America, South America and southern Africa (Figure 4.3h,i). Substantially more people (~709 million) live in regions where annual maximum one-day precipitation has increased than in regions where it has decreased (~86 million) (*medium confidence*). However, more people are experiencing longer dry spells than shorter dry spells: approximately 711 million people live in places where annual mean CDD is longer than in the 1950s, and ~404 million in places with shorter CDD (*medium confidence*) (Figure 4.3i).

In summary, annual mean precipitation is increasing in many regions worldwide and decreasing over a smaller area, particularly in the tropics. Nearly half a billion people live in areas with historically unfamiliar wet conditions, and over 160 million in areas with historically unfamiliar dry conditions (*medium confidence*). Over 700 million people experience heavy precipitation significantly more intense than in the 1950s, but less than 90 million experience decreased heavy precipitation. Compared to the 1950s, 711 million people now experience longer dry spells and 404 million experience shorter dry spells.

Table 4.1 | Trends in global evapotranspiration for different periods between 1981–1982 and 2009–2013.

Trend (mm yr^{-2})	Period	Data source	Author(s)
+0.54	1981 to 2012	Observations	(Zhang Y. et al., 2016)
+1.18	1982 to 2010	Observations	(Mao et al., 2015)
+0.93 ± 0.31	1982 to 2010	LSMs	(Mao et al., 2015)
+0.88	1982 to 2013	Remote-sensing data	(Zhang K. et al., 2015)
+1.5	1982 to 2009	Remote-sensing and surface observations	(Zeng et al., 2014)

4.2.1.2 Observed and Reconstructed Changes in Evapotranspiration

WGI (Douville et al., 2021) conclude with *high confidence* that global terrestrial annual ET has increased since the early 1980s, driven by both increasing atmospheric water demand and vegetation greening (*medium confidence*), and can be partly attributed to anthropogenic forcing (*high confidence)*.

Regional changes in ET depend on changes in both the climate and the properties of the land surface and ecosystems. The latter also responds to changes in climate and atmospheric composition. For example, a warming climate increases evaporative demand (Huang M et al., 2015; Berg et al., 2016), although seasonal rainfall totals (Hovenden et al., 2014) affect the amount of soil moisture available for evaporation. Since transpiration accounts for much of the land-atmosphere water flux (Good et al., 2015), vegetation changes also play a significant role in overall changes in ET.

With higher CO_2, the increase in evaporative demand can, to some extent, be counteracted by reduced stomatal conductance ('physiological effect'), which reduces transpiration and increases leaf-level water use efficiency (WUE), but is highly species-specific. There is evidence for recent increases in leaf-scale WUE from tree rings (14 ± 10%, broadleaf to 22 ± 6%, evergreen over the 20th century: (Frank et al., 2015)), carbon isotopes (30 to 35% increase in 150 years: (van der Sleen et al., 2014)), and satellite-based measurements (1982–2008) combined with data-driven models (Huang M et al., 2015). 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), and ozone pollution (King et al., 2013; Frank et al., 2015).

Higher CO_2 also increases photosynthesis rates, though this may not be maintained in the longer term (Warren et al., 2015; Adams et al., 2020), particularly where temperatures exceed the thermal maxima for photosynthesis (Duffy et al., 2021). Higher photosynthesis increases leaf area index (LAI) ('structural effect') and therefore transpiration; 55 ± 25% of observed increases in ET (1980–2011) have been attributed to LAI change (Zeng Z. et al., 2018). Increases in ET driven by increased LAI (from satellite observations 1982–2012) are estimated at 0.32 ± 0.07 mm $month^{-1}$ per decade, generating a climate forcing of –0.31 $Wm{-}^{2}$ per decade (Zeng et al., 2017).

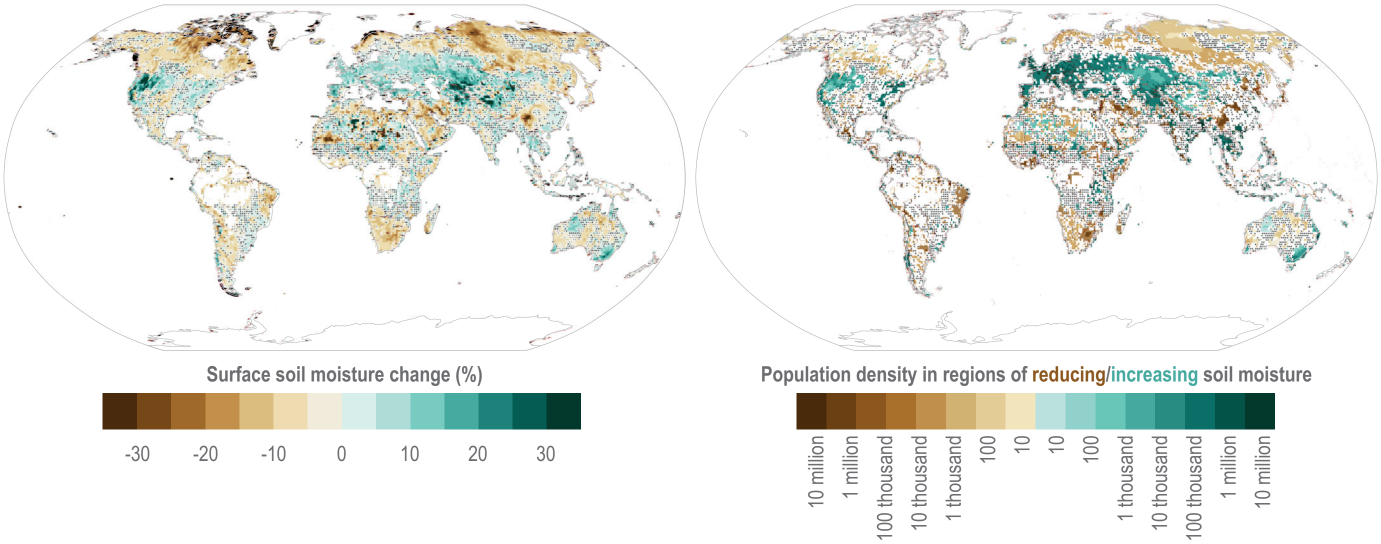
Overall regional transpiration change depends on the balance between the physiological and structural effects (e.g., Tor-ngern et al., 2015; Ukkola et al., 2015). In dry regions, ET may increase due to increasing LAI (Huang M et al., 2015), but in some densely vegetated regions, the stomatal effect dominates (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; Mankin et al., 2019). Other factors modulate the transpiration effect both temporally and spatially, for example, additional vegetation structural changes (Kim et al., 2015; Domec et al., 2017), vegetation disturbance and age (Donohue et al., 2017) and species (Bernacchi and VanLoocke, 2015).

Recent studies report global ET increases from the early 1980s to 2009 and 2013 (Table 4.1). Calculations informed by observations suggest that ET has increased in most regions, with statistically significant ($p<0.05$) trends of up to 10 mm yr^{-2} observed in large parts of North America and northern Eurasia. Larger increases in ET are also observed in several regions, including northeast Brazil, western central Africa, southern Africa, southern India, southern China, and northern Australia. Decreases of around 10 mm yr^{-2} are reported for western Amazonia and central Africa (Miralles et al., 2014), although not across all data sets (Zeng et al., 2018). In estimates of past changes in long-term drying or wetting of the land surface driven by climate, uncertainties in ET observations or reconstructions make a more substantial contribution to the overall uncertainty than observed changes in precipitation (Greve et al., 2014). Other changes in ET are also driven strongly by land cover changes and irrigation (Bosmans et al., 2017).

The contribution of changes in WUE to observed changes in ET is a key knowledge gap. WGI assigned *low confidence* to this contribution. Estimating large-scale transpiration response to increased CO_2 based on leaf-level responses of WUE is not straightforward (Bernacchi and VanLoocke, 2015; Medlyn et al., 2015; Tor-ngern et al., 2015; Walker et al., 2015; Kala et al., 2016) and new methodological approaches are needed.

In summary, there is *high confidence* that ET increased by between approximately 0.5 and 1.5 mm yr^{-2} between the 1980s and early 2010s due to warming-induced increased atmospheric demand worldwide and greening of vegetation in many regions. Increases in many areas are 10 mm yr^{-2} or more, but in some tropical land areas, ET has decreased by 10 mm yr^{-2}. Plant stomatal responses to rising CO_2 concentrations may play a role, but there is *low confidence* in quantifying this. Changes in land cover and irrigation have also changed regional ET (*medium confidence*).

Global patterns of changes in soil moisture and people in regions with significant changes



(a) Observed change in surface soil moisture 1978–2018

(b) Population density in regions of surface soil moisture changes

Figure 4.4 | Global patterns of changes in surface soil moisture and people in regions with significant changes.

(a) Percentage changes in annual mean surface soil moisture (0–5 cm) for 1978–2018 from satellite remote sensing: the "COMBINED" product of European Space Agency Climate Change Initiative Soil Moisture (ESA CCI SM v03.2), which blends data products from two microwave instruments, a scatterometer measuring radar backscattering and a radiometer measuring brightness temperature (van der Schalie et al., 2021).

(b) The population density in 0.25° grid boxes with trends of significantly increasing and decreasing soil moisture from (a). Stippling indicates where changes are not significant.

4.2.1.3 Observed and Estimated Past Changes in Soil Moisture and Aridity

AR6 WGI (Douville et al., 2021) find that a global trend in soil moisture is detectable in a reanalysis and is attributable to GHG forcing, and conclude that it is *very likely* that anthropogenic climate change affected global patterns of soil moisture over the 20th century.

Changes in soil moisture and land surface aridity are due to changes in the relative balance of precipitation and ET. Soil moisture is also affected by irrigation. Regional trends derived from satellite remote sensing products show increases and decreases in annual surface soil moisture of up to 20% or more between the late 1970s and late 2010s (Figure 4.4). For example, using the ESA CCI SM v03.2 COMBINED products (van der Schalie et al., 2021), approximately 0.9 billion people live in regions with decreasing surface soil moisture, and 2.1 billion people live in regions with increasing surface soil moisture (Figure 4.4, b). However, there are disagreements between data sets on the direction of change in some regions (Seneviratne et al., 2010; Feng and Zhang, 2015; Feng, 2016), so quantification is subject to *low confidence*.

Analysis of changes in P–ET estimates for 1948–2005 (Greve et al., 2014) suggests that geographical variations in soil moisture trends are more complex than the 'wet get wetter, dry get drier' (WGWDGD) paradigm. This is also supported by remote sensing data, with ESA CCI data for 1979–2013 showing only 15% of land following the WGWDGD paradigm for soil moisture (Feng and Zhang, 2015). Defining arid, humid and transitional areas according to precipitation and temperature regimes, all three classes of regions see more widespread trends of declining soil moisture than increasing soil moisture (Feng and Zhang, 2015). In the ESA CCI product, increasing soil moisture trends are mainly seen in humid or transitional areas and are rare in arid regions (Table 4.2)

Reconstructions of historical soil moisture trends with data-driven models and process-based land surface models indicate drier dry seasons predominantly in extratropical latitudes, including Europe, western North America, northern Asia, southern South America, Australia and eastern Africa, consistent with climate model simulations of changes due to human-induced climate change (Padrón et al., 2020). Furthermore, reduced water availability in the dry season is generally a consequence of increasing ET rather than decreasing precipitation (Padrón et al., 2020).

While observationally based data for soil moisture are now more widely available, regional trends remain uncertain due to disagreements

Table 4.2 | Proportions of arid, transitional and humid areas with drying and wetting trends in surface soil moisture from remote sensing, 1979–2013 (Feng and Zhang, 2015).

Areas	% of the area with a drying trend	% of the area with a wetting trend
Arid	38.4	2.9
Transitional	13.0	10.5
Humid	16.3	8.1

between data sets, so confident assessments of soil moisture changes remain a knowledge gap.

In summary, global mean soil moisture has slightly decreased, but regional changes vary, with both increases and decreases of 20% or more in some regions (*medium confidence*). Drying soil moisture trends are more widespread than wetting trends, not only in arid areas but also in humid and transitional areas (*medium confidence*). Reduced dry-season water availability is driven mainly by increasing transpiration (*medium confidence*)

4.2.2 Observed Changes in the Cryosphere (Snow, Glaciers and Permafrost)

AR5 reported a decrease in snow cover over most of the Northern Hemisphere, decreases in the extent of permafrost and increases in its average temperature, and glacier mass loss in most parts of the world (Jiménez Cisneros et al., 2014). SROCC (IPCC, 2019c) stated with *very high* or *high confidence* (a) reduction in seasonal snow cover (snow cover extent decreased by 13.4% per decade for 1967–2018); (b) glacier mass budget of all mountain regions (excluding the Canadian and Russian Arctic, Svalbard, Antarctica, Greenland) was 490 ± 100 kg m^{-2} yr^{-1} in 2006–2015; (c) warming of permafrost (e.g., permafrost temperatures increased by 0.39°C in the Arctic for 2007–2017). Tourism and recreation activities have been negatively impacted by declining snow cover, glaciers and permafrost in high mountains (*medium confidence*).

Recent studies confirmed with *high confidence* that snow cover extent continues to decrease across the Northern Hemisphere in all months of the year (see Douville et al. (2021); Eyring et al. (2021); Fox-Kemper et al. (2021) for more details). From 1922 to 2018, snow cover extent in the Northern Hemisphere peaked in the 1950s to 1970s (Mudryk et al., 2020) and has consistently reduced since the end of the 20th century (Hernández-Henríquez et al., 2015; Thackeray et al., 2016; Mudryk et al., 2017; Beniston et al., 2018; Hammond et al., 2018; Thackeray et al., 2019; Mudryk et al., 2020). The consistently negative snow-mass trend of approximately 5 Gt yr^{-1} in 1981–2018 for all winter-spring months (Mudryk et al., 2020), including 4.6 Gt yr^{-1} decrease of snow mass across North America and a negligible trend across Eurasia, has been observed (Pulliainen et al., 2020). Negative trends in snow-dominated period duration of 2.0–6.5 weeks per decade was detected from surface and satellite observations during 1971–2014 (Allchin and Déry, 2017), mainly owing to earlier seasonal snowmelt (Fox-Kemper et al., 2021). The observed decrease of snow cover metrics (extent, mass, duration) led to changes in runoff seasonality and has impacted water supply infrastructure (Blöschl et al., 2017; Huss et al., 2017), particularly in southwestern Russia, western USA and central Asia. In these regions, snowmelt runoff accounts for more than 30% of irrigated water supplies (Qin et al., 2020). Negative impacts on hydropower production due to changes in the seasonality of snowmelt have also been documented (Kopytkovskiy et al., 2015).

During the last two decades, the global glacier mass loss rate exceeded 0.5-meter water equivalent (m w.e.) per year compared to an average of 0.33 m w.e. yr^{-1} in 1950–2000. This volume of mass loss is the highest since the start of the entire observation period (*very high confidence*) (Zemp et al., 2015; Zemp et al., 2019; Hugonnet et al., 2021) (also see Douville et al. (2021; Fox-Kemper et al. (2021; Gulev et al. (2021) for more details). Regional estimates of glacier mass balance are also mostly negative (Dussaillant et al., 2019; Menounos et al., 2019; Zemp et al., 2019; Douville et al., 2021; Fox-Kemper et al., 2021; Hugonnet et al., 2021), except for West Kunlun, eastern Pamir and northern Karakoram (Brun et al., 2017; Lin et al., 2017; Berthier and Brun, 2019). Changes in glacier metrics estimated in post-SROCC publications are summarised in Figure 4.5.

Regional and global decreasing trends in glacier mass loss are about linear until 1990, after which they accelerated, especially in western Canada, the USA, and the southern Andes (WGMS, 2017). There is a worldwide growth in the number, total area and total volume of glacial lakes by around 50% between 1990 to 2018 due to the global increase in glacier melt rate (Shugar et al., 2020) (Shugar et al., 2020) that can potentially increase risks of glacial lake outburst floods (GLOFs) with significant negative societal impacts (Ikeda et al., 2016). A drop in glacier runoff has happened in the regions where the glaciers have already passed their peak water stage, for example, in the Canadian Rocky Mountains, European Alps, tropical Andes and North Caucasus (Bard et al., 2015; Hock et al., 2019b; Rets et al., 2020). There is *medium confidence* that the accelerated melting of glaciers has negatively impacted glacier-supported irrigation systems worldwide (Buytaert et al., 2017; Nüsser and Schmidt, 2017; Xenarios et al., 2019). Varying impacts on hydropower production (Schaefli et al., 2019) and tourism industry in some places due to cryospheric changes have also been documented (Hoy et al., 2016; Steiger et al., 2019).

Permafrost changes mainly refer to changes in temperature and active layer thickness (ALT) (Hock et al., 2019b; Fox-Kemper et al., 2021; Gulev et al., 2021). Permafrost temperature near the depth of zero annual temperature amplitude increased globally by 0.29 ± 0.12°C during 2007–2016, by 0.39 ± 0.15°C in the continuous permafrost and by 0.20 ± 0.10°C in the discontinuous permafrost (Biskaborn et al., 2019). Thus, permafrost has been warming during the last 3–4 decades (Romanovsky et al., 2017) with a rate of 0.4°C–1.4°C per decade throughout the Russian Arctic, 0.1°C–0.8°C per decade in Alaska and Arctic Canada during 2007–2016 (Biskaborn et al., 2019) and 0.1°C–0.24°C per decade in the Tibetan plateau (Wu et al., 2015). The ALT has also been increasing in the European and Russian Arctic and high-mountain areas of Eurasia since the mid-1990s (Hock et al., 2019b; Fox-Kemper et al., 2021; Gulev et al., 2021). Unfortunately, unlike glaciers and snow, the lack of *in situ* observations on permafrost still cannot be compensated for by remote sensing. Still, some methodological progress on this front has been happening recently (Nitze et al., 2018).

There is *high confidence* that degradation of the cryospheric components is negatively affecting terrestrial ecosystems, infrastructure and settlements in the high-latitude and high-altitude areas (Fritz et al., 2017; Oliva and Fritz, 2018; Streletskiy et al., 2019). Similarly, communities in the north polar regions and the ecosystems on which they depend for their livelihoods are at risk (Mustonen, 2015; Pecl et al., 2017; Mustonen and Lehtinen, 2020) (Figure 4.6).

In summary, the cryosphere is one of the most sensitive indicators of climate change. There is *high confidence* that cryospheric components

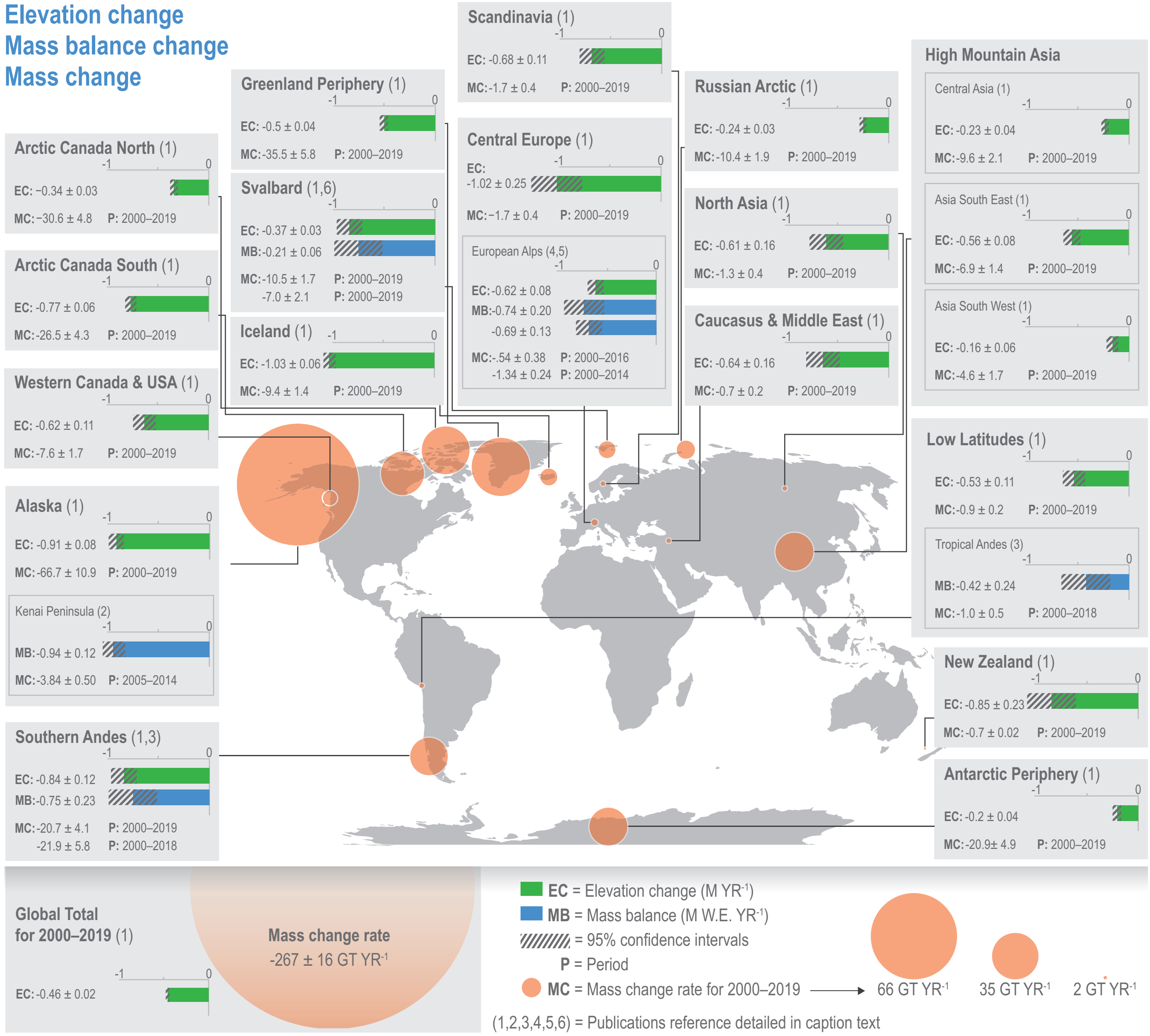


Figure 4.5 | Global and regional estimates of changes in glacier characteristics (elevation, m yr⁻¹; mass Gt yr⁻¹, mass balance, m.w.e. yr⁻¹) and 95% confidence intervals of the estimates. Results are taken from the post-SROCC publications, which are labelled in the chart titles as 1 – (Hugonnet et al., 2021); 2 – (Yang et al., 2020); 3 – (Dussaillant et al., 2019); 4 – (Davaze et al., 2020); 5 – (Sommer et al., 2020); 6 – (Schuler et al., 2020).

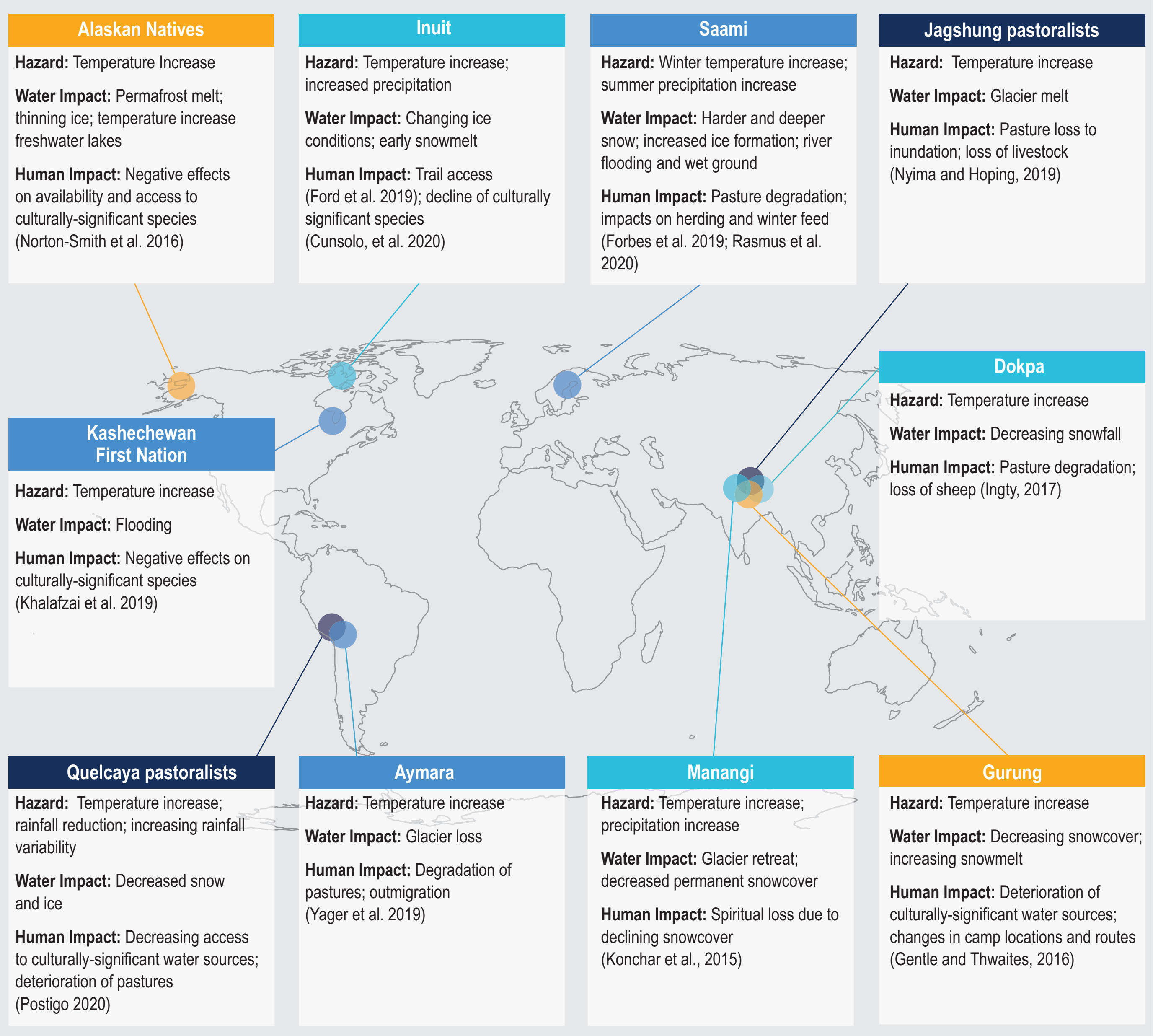
(glaciers, snow, permafrost) are melting or thawing since the end of the 20th and beginning of the 21st century. Widespread cryospheric changes are affecting humans and ecosystems in mid-to-high latitudes and the high-mountain regions (*high confidence*). These changes are already impacting irrigation, hydropower, water supply, cultural and other services provided by the cryosphere, and populations depending on ice, snow and permafrost.

4.2.3 Observed Changes in Streamflow

AR5 (Jiménez Cisneros et al., 2014) concluded with *medium evidence* and *high agreement* that trends in annual streamflow have generally followed observed changes in regional precipitation and temperature since the 1950s. AR6 WGI (Eyring et al., 2021; Gulev et al., 2021) (12.4.5) conclude with *medium confidence* that anthropogenic climate change has altered local and regional streamflow in various parts of the world, but with no clear signal in the global mean.

Between the 1950s and 2010s, stream flows showed decreasing trends in parts of western and central Africa, eastern Asia, southern Europe, western North America and eastern Australia, and increasing

Map of selected observed impacts on cultural water uses of Indigenous Peoples of the cryosphere



Alaskan Natives

Hazard: Temperature Increase

Water Impact: Permafrost melt; thinning ice; temperature increase freshwater lakes

Human Impact: Negative effects on availability and access to culturally-significant species (Norton-Smith et al. 2016)

Inuit

Hazard: Temperature increase; increased precipitation

Water Impact: Changing ice conditions; early snowmelt

Human Impact: Trail access (Ford et al. 2019); decline of culturally significant species (Cunsolo, et al. 2020)

Saami

Hazard: Winter temperature increase; summer precipitation increase

Water Impact: Harder and deeper snow; increased ice formation; river flooding and wet ground

Human Impact: Pasture degradation; impacts on herding and winter feed (Forbes et al. 2019; Rasmus et al. 2020)

Jagshung pastoralists

Hazard: Temperature increase

Water Impact: Glacier melt

Human Impact: Pasture loss to inundation; loss of livestock (Nyima and Hoping, 2019)

Kashechewan First Nation

Hazard: Temperature increase

Water Impact: Flooding

Human Impact: Negative effects on culturally-significant species (Khalafzai et al. 2019)

Dokpa

Hazard: Temperature increase

Water Impact: Decreasing snowfall

Human Impact: Pasture degradation; loss of sheep (Ingty, 2017)

Quelcaya pastoralists

Hazard: Temperature increase; rainfall reduction; increasing rainfall variability

Water Impact: Decreased snow and ice

Human Impact: Decreasing access to culturally-significant water sources; deterioration of pastures (Postigo 2020)

Aymara

Hazard: Temperature increase

Water Impact: Glacier loss

Human Impact: Degradation of pastures; outmigration (Yager et al. 2019)

Manangi

Hazard: Temperature increase; precipitation increase

Water Impact: Glacier retreat; decreased permanent snowcover

Human Impact: Spiritual loss due to declining snowcover (Konchar et al., 2015)

Gurung

Hazard: Temperature increase

Water Impact: Decreasing snowcover; increasing snowmelt

Human Impact: Deterioration of culturally-significant water sources; changes in camp locations and routes (Gentle and Thwaites, 2016)

Figure 4.6 | Map of selected observed impacts on cultural water uses of Indigenous Peoples of the cryosphere. Map location is approximate; text boxes provide names of the Indigenous Peoples whose cultural water uses have been impacted by climate change; changed climate variable; impact on water; and specific climate impact on cultural water use (Section 4.3.7).

trends in northern Asia, northern Europe, and northern and eastern North America (Dai, 2016; Gudmundsson et al., 2017; Gudmundsson et al., 2019; Li et al., 2020b; Masseroni et al., 2020). Significant spatial heterogeneity is also found in streamflow changes at the regional scale. Significant declines occurred at 11% of stations and significant increases at 4% of stations, with most decreases occurring in southern Canada (Bonsal et al., 2019). An increasing trend (1950–2010) is found in the northern region, mainly due to climate warming. Mixed trends are found in other regions.

The spatial differences in annual mean streamflow trends around the world are influenced by climatic factors, particularly changes in precipitation and evaporation (Zang and Liu, 2013; Greve et al., 2014; Hannaford, 2015; Ficklin et al., 2018), as well as by anthropogenic forcing (Gudmundsson et al., 2016; 2017; 2021).. Other factors (e.g., land use change and CO_2 effects on vegetation) dominate in some areas, especially dryland regions (Berghuijs et al., 2017b). Human activities can reduce runoff through water withdrawal and land use changes (Zaherpour et al., 2018; Sun et al., 2019a; Vicente-Serrano et al., 2019), and human regulation of streamflows via impounding reservoirs can also play a major role (Hodgkins et al., 2019).

Streamflow trends are attributed to varying combinations of climate change and direct human influence through water and land use in different basins worldwide, with conclusions on the relative contribution of climatic and anthropogenic factors sometimes depending on the methodology (Dey and Mishra, 2017). Precipitation explains over 80% of the changes in discharge of large rivers from 1950 to 2010 in northern Asia and northern Europe, where the impact of human activities is relatively limited (Li et al., 2020b). In northwest Europe, precipitation and evaporation changes explain many observed trends in streamflow (Vicente-Serrano et al., 2019). In several polar areas in northern Europe (e.g., Finland), North America (e.g., British Columbia in Canada) and Siberia, many studies reported increased winter streamflow primarily due to climate warming, for instance, more rainfall instead of snowfall and more glacier runoff in the winter period (e.g., Bonsal et al., 2020) (Section 4.2.2). A similar phenomenon of the earlier snowmelt runoff is also found in North America during 1960–2014 (Dudley et al., 2017). Thus, climate drivers largely explain changes in the average and maximum runoff of predominantly snow-fed rivers (Yang et al., 2015a; Bring et al., 2016; Tananaev et al., 2016; Frolova et al., 2017b; Ficklin et al., 2018; Magritsky et al., 2018; Rets et al., 2018).

In contrast, in southwestern Europe, land cover changes and increased water demands by irrigation are the main drivers of streamflow reduction (Vicente-Serrano et al., 2019) (Section 4.3.1). In addition, the human intervention also contributed to the increase of the winter streamflow due to the release of water in the winter season for hydropower generation in large rivers in the northern regions (Rawlins et al., 2021). In some regions, the impact of human activities on runoff and streamflow outplays the climate factors, for example, in some typical catchments with area near to or less than 15000 km^2 in China (Zhai and Tao, 2017).

Shi et al. (2019) found that in 40 major basins worldwide, both climatic and direct human impact contribute to observed flow changes to varying degrees. Climate change or variability is the main contributor to changes in basin-scale trends for 75% of rivers, while direct human effects on streamflow dominate for 25%. However, this does not consider attribution of the climate drivers to anthropogenic forcing. Using time series of low, mean and high river flows from 7250 observatories around the world (1971–2010) and global hydrological models (GHMs) driven by Earth System Model (ESM) simulations with and without anthropogenic forcing of climate change, Gudmundsson et al. (2021) also found direct human influence to have a relatively small impact on global patterns of streamflow trends. Gudmundsson et al. (2021) further identified anthropogenic climate change as a causal driver of the global pattern of recent trends in mean and extreme river flow (Figure 4.7). Overall, the sign of observed trends and simulations accounting for human influence on the climate system was found to be consistent for decreased mean flows in western and eastern North America, southern Europe, northeast South America and the Indian sub-continent, and increased flows in northern Europe. Similar conclusions were drawn for low and high flows, except for the Indian sub-continent. However, in some regions, the observed trend was opposite to that simulated with anthropogenic climate forcing. Thus, human water and land use alone did not explain the observed pattern of trends.

Although there are different observational and simulated runoff and streamflow data sets (e.g., Global Runoff Data Centre, GRDC), it is still challenging to obtain and update long-term river discharge records in several regions, particularly Africa, South and East Asia (Dai, 2016). When observed data are scarce, hydrological models are used to detect trends in runoff and streamflow. However, simulations of streamflow can differ between models depending on their structures and parametrisations, contributing to uncertainties for trend detection, especially when considering human intervention (e.g., Caillouet et al., 2017; Hattermann et al., 2017; Smith et al., 2019b; Telteu et al., 2021).

In summary, both climate change and human activities influence the magnitude and direction of change in runoff and streamflow. There are no clear trends of changing streamflow on the global level. However, trends emerge on a regional level (a general increasing trend in the northern higher latitude region and mixed trend in the rest of the word) (*high confidence*). Climatic factors contribute to these trends in most basins (*high confidence*). They are more important than direct human influence in a larger share of major global basins (*medium confidence*), although direct human influence dominates in some (*medium confidence*). Overall, anthropogenic climate change is attributed as a driver to the global pattern of change in streamflow (*medium confidence*).

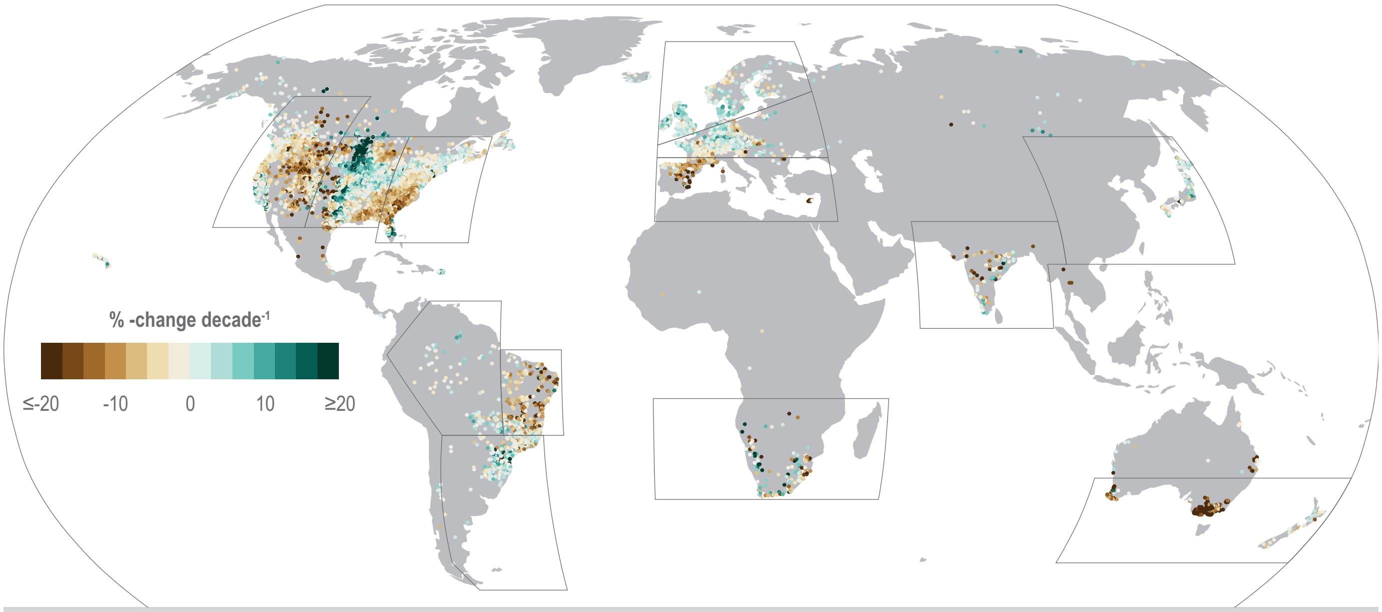
4.2.4 Observed Changes in Floods

AR6 WGI Chapter 11 (Seneviratne et al., 2021) assessed with *high confidence* the increase in the extreme precipitation and associated increase in the frequency and magnitude of river floods. However, there is *low confidence* in changes in the river flooding regionally, which is strongly dependent upon complex catchment characteristics and land use patterns. SROCC (Hock et al., 2019b) summarised with *high confidence* that changes in the cryosphere have led to changes in frequency, magnitude and location of rain-on-snow floods, snowmelt floods and glacier-related floods.

There is *high confidence* that the frequency and magnitude of river floods have changed in the past several decades in some regions mentioned below (and in WGI 11.5.2; SM4.1) with impacts across human and natural systems (Section 4.3). A global flood database based on *in situ* measurement and satellite remote-sensing during 1985–2015 show that floods have increased 4-fold and 2.5-fold in the tropics and northern mid-latitudes, respectively (Najibi and Devineni, 2018). Estimates of flood exposure using satellite-derived inundation area and high-resolution population data showed a 20–24% increase during 2000–2018 (Tellman et al., 2021). Analyses of *in situ* streamflow measurement showed both increases and decreases in the frequency of river floods for 1960–2010 in Europe (Berghuijs et al., 2017a; Blöschl et al., 2019a) and the USA (Berghuijs et al., 2017a), an overall increase in China, Brazil and Australia (Berghuijs et al., 2017a) but decrease in some areas in the Mediterranean (Tramblay et al., 2019) and southern Australia (Ishak et al., 2013; Do et al., 2017). Warming in the last 40–60 years has led to a 1–10-d earlier per decade spring flood occurrence depending on the location (the most frequent being 2–4 d per decade) (*high confidence*) (Yang L. et al., 2015; Blöschl et al., 2017; Dudley et al., 2017; Solander et al., 2017; Rokaya et al., 2018; Kireeva et al., 2020).

Observed changes in river flows and attribution to externally forced climate change

(a) Percentage changes in flow in individual rivers 1971–2010



(b) Observed streamflow trend

Simulated streamflow trend with human water and land use

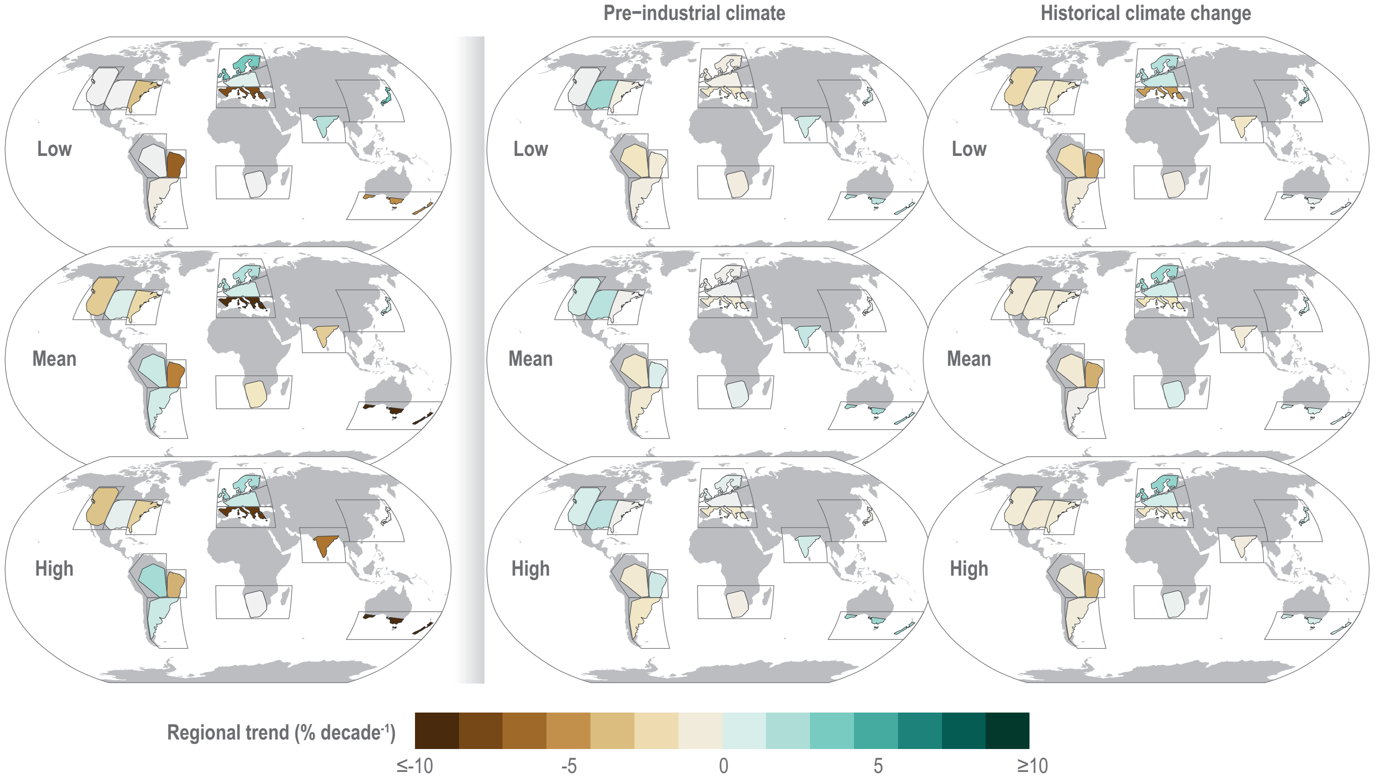


Figure 4.7 | Observed changes in river flows and attribution to externally forced climate change.

(a) Percentage changes in flow in individual rivers 1971 to 2010. Black box outlines show climatic regions with at least 80 gauging stations with almost complete daily observations over 1971–2010, using the SREX (Seneviratne et al., 2012) regions.

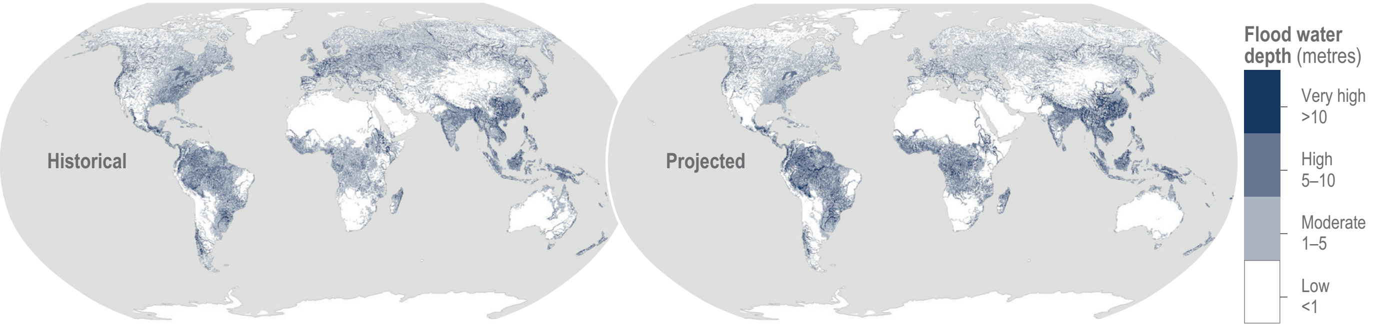
(b) Left column: observed regional median trends from 1971 to 2010 in SREX regions with at least 80 gauging stations with almost complete daily observations over that period. Middle column: trends simulated by eight global hydrological models driven by four CMIP5 Earth System Models, with human water and land use from 1971 to 2020 and the pre-industrial control climate state. Right column: same as the middle column but with ESM-simulated climates from 1971 to 2010 with both anthropogenic forcings (greenhouse gases, aerosols and land use) and natural external forcings (solar variability and volcanic eruptions). Top row: low flows (annual 10th percentile). Middle row: mean flows. Bottom row: high flows (annual 90th percentile). Reproduced from Gudmundsson et al. (2021).

Table 4.3 | Selected major heavy-precipitation events from 2014 to 2021 that led to flooding and their impacts. Studies were selected for presentation based on the availability of scientific literature with impacts information and do not necessarily represent the most severe events. Impactful events are included even if not found to have a component attributable to climate change. This is not a systematic assessment of event attributions studies and their physical science conclusions. 'Sign of influence' indicates whether anthropogenic climate change was found to have made the event *more or less likely*, and 'mechanism/magnitude of influence' quantifies the change in likelihood and the processes or quantities involved.

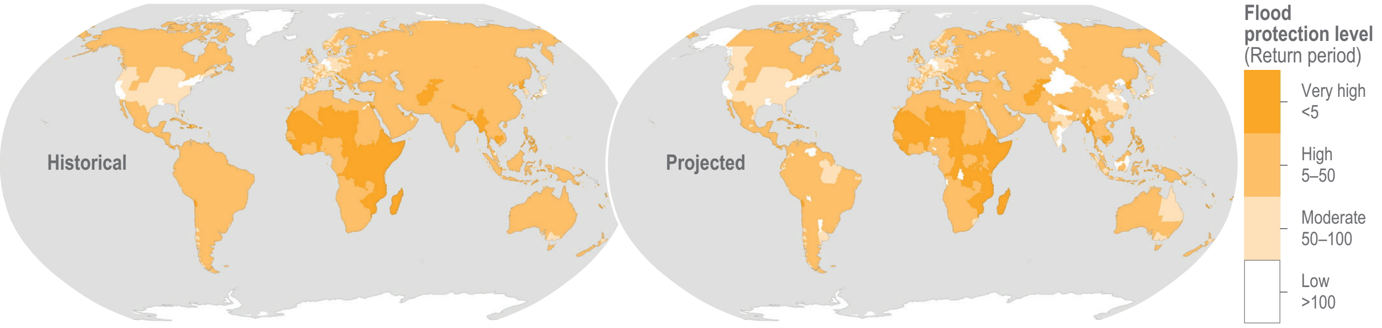
Year	Country/region	Impact	Anthropogenic climate change influence on the likelihood of an event		Reference
			Sign of influence	Mechanism/magnitude of influence	
2021	Germany, Belgium, Luxembourg and neighbouring countries	At least 222 fatalities, substantial damage to transport and communications infrastructure and houses, severe disruption to businesses and livelihoods.,	Increase	One-day rainfall intensity increased by 3–19%, the likelihood of event increased by a factor between 1.2 and 9.	Kreienkamp et al. (2021)
2019	Canada (Ottawa)	Thousands of people evacuated, extended states of emergency, and about $200 million in insured losses	Increase	Spring maximum 30-d rainfall accumulation in 2019 was three times as likely with anthropogenic forcing.	Kirchmeier-Young et al. (2021)
	Southern China	Over 6 million people across several southern China provinces were affected by heavy rains, floods and landslides. These extremes caused at least 91 deaths, collapsed over 19,000 houses, damaged around 83,000 houses and affected 419,400 ha of crops (China Ministry of Emergency Management 2020). The direct economic loss was estimated to be more than 20 billion RMB (equivalent to 3 billion USD)	Decrease	Anthropogenic forcings have reduced the likelihood of heavy precipitation in southern China like the 2019 March–July event by about 60%.	Li et al. (2021b)
2018	USA (Mid-Atlantic)	One fatality, $12 million damages	Increase	1.1 to 2.3 times more likely	Winter et al. (2020)
	Central western China	Persistent heavy rain led to floods, landslides and house collapse affecting 2.9 million people. The direct economic loss of over USD 1.3 billion.	Decrease	~47% reduction in the probability	Zhang et al. (2020b)
	Northwestern China	Extreme flooding in the Upper Yellow River basin affected about 1.4 million people and led to 30 deaths and disappearances.	Decrease	34% reduction in the probability	Ji et al. (2020)
	Japan	237 fatalities, more than 6000 buildings destroyed by floods and landslides	Increase	7% increase in total precipitation	Kawase et al. (2020)
	Australia (Tasmania)	$100 million in insurance claims	Unknown	Unknown	Tozer et al. (2020)
2017	Peru	Widespread flooding and landslides affected 1.7 million people, 177 fatalities, estimated total damage of $3.1 billion	Increase	At least 1.5 times more likely	Christidis et al. (2019)
	Uruguay and Brazil	Direct economic loss in Brazil of USD 102 million, displacement of more than 3500 people in Uruguay	Increase	At least double, with a most likely increase of about fivefold	de Abreu et al. (2019)
	North-East Bangladesh	Flash flood affected ~850,000 households, ~220,000 ha of nearly harvestable Boro rice damaged. Crop failure contributed to a record 30% rice price hike compared to the previous year.	Increase	Doubled the likelihood of the 2017 pre-monsoon extreme 6-d rainfall event	Rimi et al. (2019)
	China	7.8 million people affected 34 fatalities, about 0.8 million people displaced, 605,000 hectares of crops affected, 116,000 hectares without harvest. 32,000 houses collapsed, 41,000 were severely damaged. Direct economic loss 24.12 billion Chinese Yuan (~ USD 3.6 billion)	Increase	Doubled the probability from 0.6% to 1.2%	Sun et al. (2019b)
2016	South China	Widespread severe flooding, waterlogging, and landslides in the Yangtze–Huai region.	Increase	1.5-fold (0.6 to 4.7) increase in the probability	Sun and Miao (2018)
	China (Wuhan)	237 fatalities, 93 people missing, at least USD 22 billion in damage	Increase	Approximately 60% of the risk	Zhou et al. (2018a)
	China (Yangtze River)	Direct economic loss of about USD 10 billion	Increase	Increased probability by 38% (± 21%)	Yuan et al. (2018)
	Australia	Flooding and wild weather impacted some agriculture and power generation.	None	Minimal	Hope et al. (2018)
2015	India (Chennai)	City declared a disaster area. Damages estimated as $3 billion.	None	None	van Oldenborgh et al. (2017a)
2014	Indonesia (Jakarta)	26 reported deaths, thousands of buildings flooded, much infrastructure damaged. Losses up to USD 384 million	Unclear	2-d rain event approximately 2.4 times more likely compared to 1900, but cause not established	Siswanto et al. (2015)

Risk of historical (1961–2005) and projected (2051–2070) river flooding

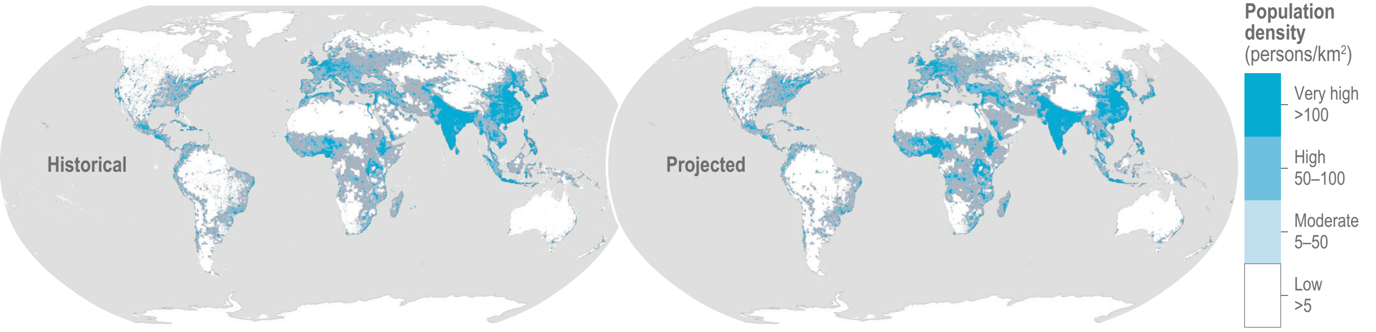
(a) Flood water (hazard)



(b) Flood protection standard (vulnerability)



(c) Population distribution (exposure)



(d) Population exposed to river flooding (risk)

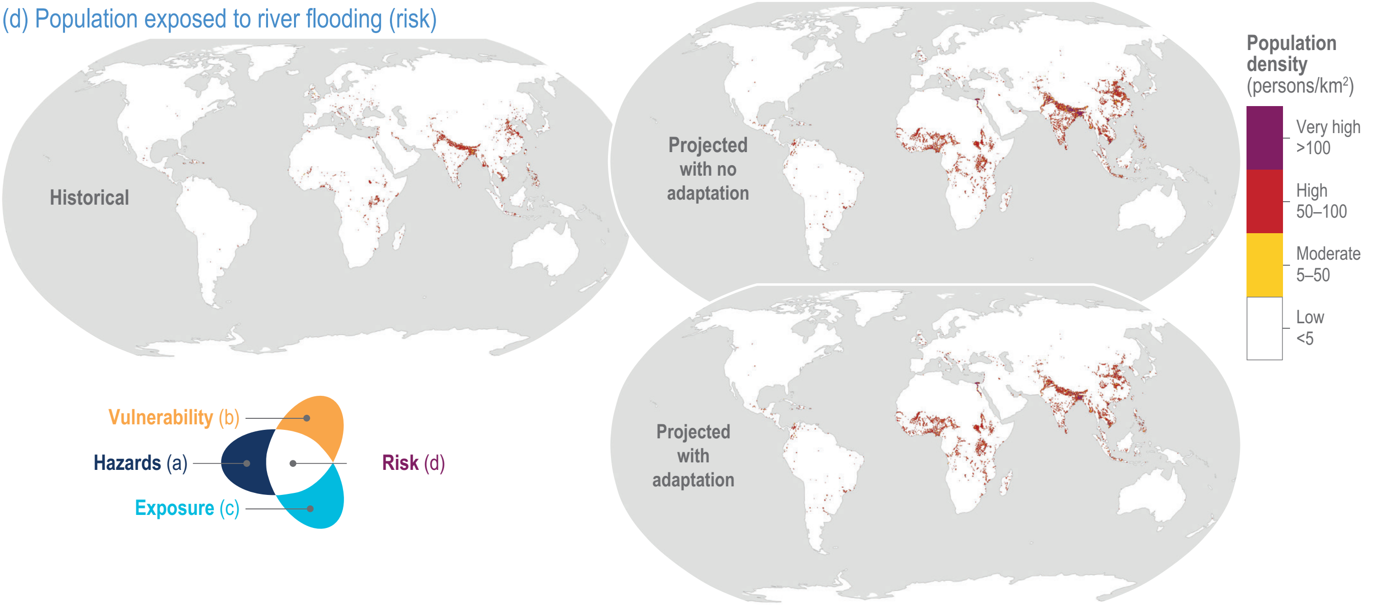


Figure 4.8 |

(a) Modelled mean global fluvial flood water depth (Tanoue et al., 2016; Tanoue et al., 2021) based on a land surface model and a river and inundation model driven by reanalysis climate forcing of five CMIP5 GCMs (metres). The annual maximum daily river water was allocated along elevations, and inundation depth was calculated for each year and averaged for the target period.

(b) Local flood protection standard (return period) at sub-country scale (Scussolini et al., 2016) based on published reports and documents, websites and personal communications with experts. Note that the vulnerability of this map reflects local flood protection such as complex infrastructure and does not fully reflect the other source of vulnerabilities, including exposure.

(c) Population distribution per 30 arc second grid cell (Klein Goldewijk et al., 2010; Klein Goldewijk et al., 2011).

(d) Population exposed to flood (number of people where inundation occurs) per 30 arc-second grid cell. Population under inundation depth > 0 m (a) was counted when the return period of annual maximum daily river water exceeds the flood protection standard (c) calculated by the authors. All values are averages for the period 1958–2010 for the past and 2050–2070 for the future.

Between 1970 to 2019, 44% of all disasters and 31% of all economic losses were flood related (WMO, 2021). Observed flood risks changes in recent decades are often caused by human factors such as increased urbanisation and population growth rather than climate change alone (Tramblay et al., 2019). There is *medium confidence* that flood vulnerability varies among various regions and countries (Jongman et al., 2012; Scussolini et al., 2016; Tanoue et al., 2016) (Figure 4.8), reflecting differences in GDP, severity and characteristics of hazard and political and social conditions (Rufat et al., 2015). Flood vulnerability has decreased with economic development in many regions, while increased exposure has elevated risk in some places (Mechler, 2016; Tanoue et al., 2016). Global annual mean expected damage considering the current flood protection standard is estimated to be USD 54 million under the climate of 1976–2005 and unevenly distributed (Alfieri et al., 2017). Similar estimation using different models shows an increase of flood exposure in the past (USD 31 million for 1971–1990 and USD 45 million for 1991–2010 without population change as fixed in 2010) (Tanoue et al., 2016) (Section 4.7.5).

The link between rainfall and flooding is complex. While observed increases in extreme precipitation have increased the frequency and magnitude of pluvial floods and river floods in some regions, floods could decrease in some regions due to other factors. These factors could include soil wetness condition, cryospheric change, land cover change and river system management, adaptation measures or water usage within the river basin (WGI FAQ8.2). For example, in the USA and Europe, a study indicated that major (e.g., 25–100-year return period) floods did not show significant long-term trends (Hodgkins et al., 2019). Nevertheless, anthropogenic climate change increased the likelihood of a number of major heavy precipitation events and floods that resulted in disastrous impacts in southern and eastern Asia, Europe, North America and South America (Table 4.3) (*high confidence*). Davenport et al. (2021) demonstrated that anthropogenic changes in precipitation extremes had contributed one third of the cost of flood damages (from 1988 to 2017) in the USA. Anthropogenic climate change has altered 64% (eight out of 22 events increased, eight decreased) of floods events with significant losses and damages during 2010–2013 (Hirabayashi et al., 2021a). Gudmundsson et al. (2021) attributed observed change in extreme river flow trends to anthropogenic climate change (Section 4.2.3). Although there is growing evidence on the effects of anthropogenic climate change on each event, given the relatively poor regional coverage and high model uncertainty, there is *low confidence* in the attribution of human-induced climate change to flood change on the global scale.

In snow-dominated regions, 1~10 d earlier spring floods per decade due to warmer temperature are reported for the last decades (*high confidence*), such as in Europe (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., 2017a; Frolova et al., 2017b; Kireeva et al., 2020), Canada (Yang L. et al., 2015; Burn et al., 2016; Rokaya et al., 2018) and the USA (Mallakpour and Villarini, 2015; Solander et al., 2017).

There is a knowledge gap in how ice-related floods, including glacier-related and ice-jam floods, respond to ongoing climate change. Despite the increase in the number of glacial lake studies (Wang and Zhou, 2017; Harrison et al., 2018; Begam and Sen, 2019; Bolch et al., 2019), changes in the frequency of occurrence of glacier-related floods associated with climate change remain unclear (*medium confidence*). Studies show that the compound occurrence of high surges and high river discharge has increased in some regions (WGI Chapter 11), but few studies quantify changes and impacts. Increases in precipitation from tropical cyclones (WGI Chapter 11) and associated high tide are expected to exacerbate coastal flooding. However, more studies are required to quantify their impacts. In addition, limitations in the duration of data hinder the assessment of trends in low-likelihood high-impact flooding (WGI BOX 11.2).

In summary, the frequency and magnitude of river floods have changed in the past several decades with high regional variations (*high confidence*). Anthropogenic climate change has increased the likelihood of extreme precipitation events and the associated increase in the frequency and magnitude of river floods (*high confidence*). There is *high confidence* that the warming in the last 40–60 years has led to a maximum of 10 days earlier spring floods per decade, shifts in timing and magnitude of ice-jam floods and changes in frequency and magnitude of snowmelt floods.

4.2.5 Observed Changes in Droughts

There are different types of droughts, and they are interconnected in terms of processes (Douville et al., 2021). *Meteorological droughts* (periods of persistent low precipitation) propagate over time into deficits in soil moisture, streamflow and water storage, leading to a reduction in water supply (*hydrological drought*). Increased atmospheric evaporative demand increases plant water stress, leading to *agricultural and ecological drought.*

Hydrological drought can result in shortages of drinking water and cause substantial economic damages. Agricultural drought threatens food production through crop damage and yield decreases (e.g., Section 4.3.1) (*high confidence*) and consequent economic impacts (Table 4.4). For example, drought in India in 2014 was reported to have led to an estimated USD 30 billion in losses (Ward and Makhija, 2018). Ecological drought increases the risks of wildfire (Table 4.4). Cascading effects of droughts can include health issues triggered by a lack of sanitation (Section 4.3.3); can cause human displacements and loss of social ties, sense of place and cultural identity; and migration to unsafe settlements (*medium confidence*) (Serdeczny et al., 2017) (Section 4.3.7). Between 1970 and 2019, only 7% of all disaster events were drought-related, yet they contributed disproportionately to 34% of disaster-related death, mostly in Africa (WMO, 2021). Nevertheless, IK, TK and LK have increased drought resilience among crop and livestock farmers, for example, in South Africa (Muyambo

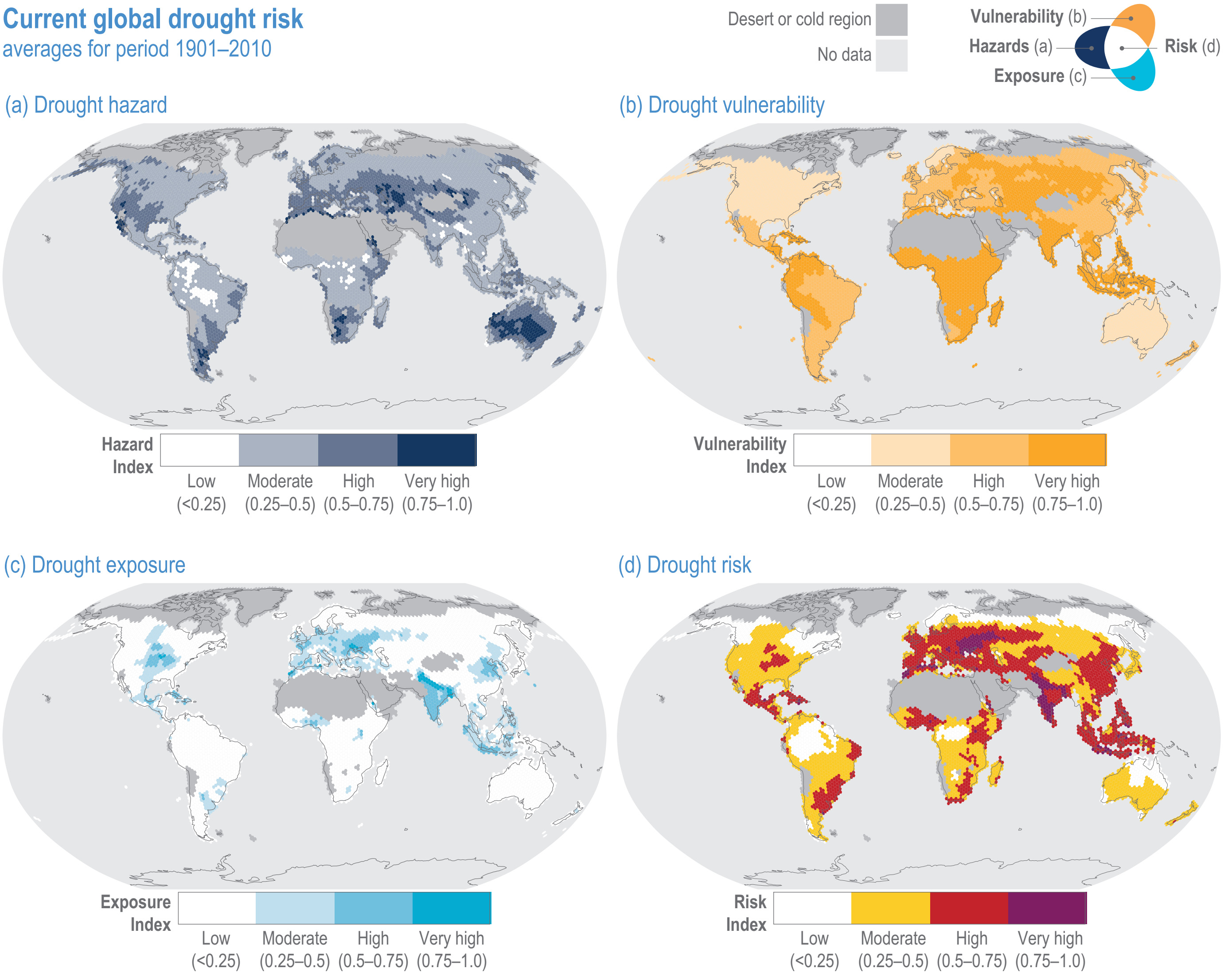


Figure 4.9 | Current global drought risk and its components.

(a) Drought hazard computed for the events between 1901 and 2010 by the probability of exceedance the median of global severe precipitation deficits, using precipitation data from the Global Precipitation Climatology Centre (GPCC) for 1901–2010.

(b) Drought vulnerability is derived from an arithmetic composite model combining social, economic and infrastructural factors proposed by the United Nations International Strategy for Disaster Risk Reduction (UNISDR, 2004).

(c) Drought exposure computed at the sub-national level with the non-compensatory Data Envelopment Analysis (DEA) model (Cook et al., 2014).

(d) Drought risk based on the above components of hazard, vulnerability and exposure, scored on a scale of 0 (lowest risk) to 1 (highest risk) with the lowest and highest hazard, exposure and vulnerability (Carrão et al., 2016).

et al., 2017), Uganda (Mfitumukiza et al., 2020) and India (Patel et al., 2020) (Section 4.8.4).

When hazard, vulnerability and exposure are considered together, drought risk is lower for sparsely populated regions, such as tundra and tropical forests, and higher for populated areas and intensive crop and livestock farming regions, such as southern and central Asia, southeastern South America, central Europe and the southeastern USA (Figure 4.9). Dynamics in exposure and vulnerability are rarely addressed (Jurgilevich et al., 2017; Hagenlocher et al., 2019). Quantifying economic vulnerability to drought in terms of damages as a percentage of exposed GDP, Formetta and Feyen (2019) show a disproportionate burden of drought impact on low-income countries, but with a clear decrease in global economic drought vulnerability between 1980–1989 and 2007–2016, including a convergence between lower-income and higher-income countries due to stronger vulnerability reduction in less-developed countries. Nevertheless, during 2007–2016, economic vulnerability to drought was twice as high in lower-income countries compared to higher-income countries (Formetta and Feyen, 2019).

AR6 WGI (Douville et al., 2021; Seneviratne et al., 2021) found that increasing agricultural and ecological droughts trends are more evident than increasing trends in meteorological drought in several regions due to increased evaporative demand. Therefore, WGI concluded with *high confidence* that the increased frequency and the severity of agricultural/ecological droughts over the last decades in the Mediterranean and western North America can be attributed to anthropogenic warming.

In addition, there is *high confidence* in anthropogenic influence on increased meteorological drought in southwestern Australia and *medium confidence* that recent drying and severe droughts in southern Africa and southwestern South America can be attributed to human influence. Increased agricultural/ecological and (or) meteorological and (or) hydrological drought is also seen with either *medium confidence* or *high confidence* in the trend but with *low confidence* on attribution to anthropogenic climate change in western, northeastern and central Africa; central, eastern and southern Asia; eastern Australia; southern and northeastern South America and the South American monsoon region; and western and central Europe. Finally, decreased drought in one or more categories is seen with *medium confidence* in western and eastern Siberia; northern and central Australia; southeastern South America; central North America and northern Europe, but with *low confidence* in attribution to anthropogenic influence, except in northern Europe, where anthropogenic influence on decreased meteorological drought is assessed with *medium confidence*.

Major drought events worldwide have had substantial societal and ecological impacts, including reduced crop yields, shortages of drinking water, wildfires causing deaths of people and very large numbers of animals, impacting the habitats of threatened species, and widespread economic losses (Table 4.4, Cross-Chapter Box DISASTER in Chapter 4). In addition, anthropogenic climate change was found to have increased the likelihood or severity of most such events examined in event attribution studies.

Although long-term drought trends are clearer for agricultural or ecological drought compared to meteorological droughts (Douville et al., 2021; Seneviratne et al., 2021), most attribution studies for individual extreme events focus on meteorological (precipitation) drought and sometimes also consider temperature anomalies. A complete examination of drought relevant to societal impacts often requires consideration of hydrological and agricultural drought, so extreme event attribution conclusions relating to precipitation alone may not fully capture the processes leading to societal effects. There is, therefore, a critical knowledge gap in the attribution of changes in drought indicators more closely related to societal impacts such as soil moisture and the availability of fresh water supplies.

In summary, droughts can have substantial societal impacts (*virtually certain*), and agricultural and ecological drought conditions in particular have become more frequent and severe in many parts of the world but less frequent and severe in some others (*high confidence*). Drought-induced economic losses relative to GDP are approximately twice as high in lower-income countries compared to higher-income countries, although the gap has narrowed since the 1980s, and at the global scale there is a decreasing trend of economic vulnerability to drought (*medium confidence*). Nevertheless, anthropogenic climate change has contributed to the increased likelihood or severity of drought events in many parts of the world, causing reduced agricultural yields, drinking water shortages for millions of people, increased wildfire risk, loss of lives of humans and other species and loss of billions of dollars of economic damages (*medium confidence*).

4.2.6 Observed Changes in Groundwater

AR5 concluded that the extent to which groundwater abstractions are affected by climate change is not well known due to the lack of long-term observational data (Jiménez Cisneros et al., 2014). AR6 (Douville et al., 2021) confirmed that, despite considerable progress since AR5, limitations in the spatio-temporal coverage of groundwater monitoring networks, abstraction data and numerical representations of groundwater recharge processes continue to constrain understanding of climate change impacts on groundwater.

Globally, groundwater use has societal and economic benefits, providing a critical buffer against precipitation variability. Groundwater irrigation has ensured food security, livelihood support and poverty alleviation, for example, in India (Sekhri, 2014), Bangladesh (Salem et al., 2018) and sub-Saharan Africa (Taylor et al., 2013a; Cuthbert et al., 2019b). Groundwater is a safe drinking water source during natural hazard-induced disasters (Richts and Vrba, 2016). However, groundwater over-exploitation leads to the attenuation of societal benefits, including reduced agricultural production (Asoka and Mishra, 2020; Jain et al., 2021), decrease in adaptive capacity of communities (Blakeslee et al., 2020) and water quality deterioration (Mas-Pla and Menció, 2019). Loss of traditional water systems based on groundwater, such as *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), also leads to loss of cultural values for local communities.

Even though global groundwater abstraction (789 ± 30 km3 yr−1) is just about 6% of the annual recharge (~13,466 km^3) (Hanasaki et al.,

Table 4.4 | Selected major drought events from 2013 to 2020 and their societal impact. Studies were selected for presentation based on the availability scientific literature impacts information and do not necessarily represent the most severe events.Impactful events are included even if not found to have a component attributable to climate change. This is not a systematic assessment of event attributions studies and their physical science conclusions. 'Sign of influence' indicates whether anthropogenic climate change was found to have made the event more or less likely, and 'mechanism/magnitude of influence' quantifies the change in likelihood and the processes or quantities involved.

Year	Country/region	Impact	Influence of anthropogenic climate change on the likelihood of an event		Reference
			Sign of influence	*Mechanism/magnitude of influence*	
2019/2020	Australia	Wildfires burning ~97,000 km^2 across southern and eastern Australia; 34 human fatalities; 5900 buildings destroyed; millions of people affected by hazardous air quality; between 0.5 and 1.5 billion wild animals and tens of thousands of livestock killed; at least 30% of habitat affected for seventy taxa, including 21 already listed as threatened with extinction, over USD 110 billion financial loss	Increase	Extreme high temperatures causing drying of fuel. The likelihood of extreme heat at least doubled due to the long-term warming trend, and the likelihood of Fire Weather Index as severe or worse as observed in 2019/2020 by at least 30%, despite no attributable increase in meteorological (precipitation) drought.	van Oldenborgh et al. (2020); Ward et al. (2020); Haque et al. (2021)
2019	Western Cape, South Africa	Water supply was reduced to 20% of capacity in January 2018. Agricultural yields in 2019 declined by 25%.	Increase	Anthropogenic greenhouse forcing at least doubled the likelihood of drought levels seen in 2015–2019, offsetting anthropogenic aerosol forcing.	Kam et al. (2021)
	Yunnan, southwestern China	Water scarcity affected nearly 7 million residents and resulted in crop failure over at least 1.35×10^4 km^2 cropland. More than 94% of the total area in the province was drought-stricken, and around 2 million people faced drinking water shortages, with a direct economic loss of about 6.56 billion RMB.	Increase	Anthropogenic influence increased the risk of 2019 March–June hot and dry extremes over Yunnan province in southwestern China by 123–157% and 13–23%, respectively.	Wang et al. (2021b)
	Southwestern China	Over 640,100 hectares of crops with rice, corn and potatoes were extensively damaged. Over 100 rivers and 180 reservoirs dried out. Over 824,000 people and 566,000 head of livestock experienced a severe lack of drinking water, with a direct economic loss of 2.81 billion Chinese yuan (USD 400 million).	Increase	Anthropogenic forcing has likely increased the likelihood of the May–June 2019 severe low-precipitation event in southwestern China by approximately 1.4 to 6 times.	Lu et al. (2021)
	South China	A lightning-caused forest fire in Muli County killed 31 firefighters and burned about 30 ha of forest.	Increase	Anthropogenic global warming increased the weather-related risk of extreme wildfire by 7.2 times. In addition, the El Niño event increased risk by 3.6 times.	Du et al. (2021)
	Middle and lower reaches of the Yangtze River, China	Reduced agriculture productivity and increased load on power system supplies and transportations, and on human health	Decrease	Anthropogenic forcing reduced the probability of rainfall amount in the extended rainy winter of 2018/2019 by ~19%, but exerted no influence on the excessive rainy days.	Hu et al. (2021)
2018	South China	Shrinking reservoirs, water shortages. Area and yield for early rice reduced by 350 thousand hectares and 1.28 million tons relative to 2017	Increase	Likelihood increased by 17 times in the HadGEM3-A model. However, the event did not occur without human influence in the CAM5 model.	Zhang et al. (2020)
	China (Beijing)	A record 145 consecutive dry days (CDD), severe drought, increased risk of wildfires	Increase	The likelihood of the record 145 CDD was increased by between 1.29 and 2.09 times by anthropogenic climate change and between 1.43 and 4.59 times by combining the La Niña event and a weak Arctic polar vortex.	Du et al. (2021)
2017	USA (Northern Great Plains)	"billion-dollar disaster"; widespread wildfires (one of Montana's worst wildfire seasons on record) compromised water resources, destruction of property, livestock sell-offs, reduced agricultural production, agricultural losses of USD 2.5 billion	Increase	1.5 times more likely due to increased ET (minimal anthropogenic impact on precipitation)	Hoell et al. (2019)
	East Africa	Extensive drought across Tanzania, Ethiopia, Kenya and Somalia contributed to extreme food insecurity approaching near-famine conditions.	Increase	Likelihood doubled	Funk et al. (2019)
2016	Southern Africa	Millions of people were affected by famine, disease and water shortages. In addition, a 9-million-tonne cereal deficit resulted in 26 million people in need of humanitarian assistance.	Increase	Anthropogenic climate change *likely* increased the intensity of the 2015/2016 El Niño, and a drought of this severity would have been very unlikely (probability ~9%) in the pre-industrial climate.	Funk et al. (2018)

Year	Country/ region	Impact	Influence of anthropogenic climate change on the likelihood of an event		Reference
			Sign of in-fluence	*Mechanism/magnitude of influence*	
2016	Brazil	Três Marias, Sobradinho, and Itaparica reservoirs reached 5% of volume capacity. Ceará registered 39 (of 153) reservoirs empty. Another 42 reached inactive volume; 96 (of 184) Ceará municipalities experienced water supply interruption.	Not found	Not found	Martins et al. (2018)
2016	Thailand	Severe drought affected 41 Thai provinces, had devastating effects on major crops, such as rice and sugar cane, and incurred a total loss in the agricultural production of about half a billion USD.	Increase	The record temperature of April 2016 in Thailand would not have occurred without the influence of both anthropogenic forcings and El Niño. Anthropogenic forcing has contributed to drier Aprils, but El Niño was the dominant cause of low rainfall.	Christidis et al. (2018)
2015	Washington state, USA	USD 335 million loss for the agricultural industry	Increase	Snowpack drought resulted from exceedingly high temperatures despite normal precipitation	Fosu et al. (2016)
2014	São Paulo, Brazil	In January 2015, the largest water supply system used for Sao Paulo, Cantareira, sank to a water volume of just 5% of capacity, and the number of people supplied fell from 8.8 million people to 5.3 million people, with other systems taking over supplies for the remainder.	No impact	Anthropogenic climate change is not found to be a major influence on the hazard, whereas increasing population and water consumption increased vulnerability.	Otto et al. (2015)
2014	Southern Levant, Syria	While the extent to which the 2007/2008 drought in the Levant region destabilised the Syrian government was not clear, 'there is no questioning the enormous toll this extreme event took on the region's population. The movement of refugees from both the drought and war-affected regions into Jordan and Lebanon ensured that the anomalously low precipitation in the winter of 2013/2014 amplified impacts on already complex water and food provisions.'	Increase	The persistent drought in the 2014 rainy season was unprecedented for the critical January–February period in the observational record, and was made ~45% more likely by anthropogenic climate change.	Bergaoui et al. (2015)
2013–2014	Mediterranean coastal Middle East, northward through Turkey and eastward through Kazakhstan, Uzbekistan and Kyrgyzstan	The eastern (main) basin of the Aral Sea dried up for the first time in modern history.	Unclear	High western Pacific sea surface temperatures (SSTs) linked to drought in the Middle East and central-southwest Asia, and the SSTs in that region showed a strong warming trend.	Barlow and Hoell (2015)
2014	East Africa	Some isolated food security crises	Increase	Anthropogenic warming contributed to the 2014 East African drought by increasing East African and west Pacific temperatures, and increasing the gradient between standardised western and central Pacific SST, causing reduced rainfall, ET and soil moisture.	Funk et al. (2018)

2018), a few hotspots of groundwater depletion have emerged at local to regional scales since the end of 20th century to the beginning of the 21st century due to intensive groundwater use for irrigation. The variability in groundwater storage is a function of human abstraction and natural recharge, which is in turn controlled by local geology (Green, 2016). In humid regions, precipitation influences recharge, and linear associations between precipitation and recharge are often observed (Kotchoni et al., 2019); for example, over humid locations in sub-Saharan Africa (Cuthbert et al., 2019b).

A global review (Bierkens and Wada, 2019) of groundwater storage changes highlights that estimates of depletion rates at the global scale are variable. These estimates range from approximately 113 to 510 km^3 yr^{-1} and variation in estimates is due to methods and spatio-temporal scales considered (*high confidence*). Global hydrological models (Herbert and Döll, 2019) show that human-induced groundwater depletion at rates exceeding 20 mm yr^{-1} (2001–2010) is occurring in the major aquifers systems such as the High Plains and California Central Valley aquifers (USA), Arabian aquifer (Middle East), North-Western Sahara Aquifer System (North Africa), Indo-Gangetic Basin (India) and North China Plain (China) (*high confidence*). Groundwater depletion at lower rates (<10 mm yr^{-1}) is taking place in the Amazon Basin (Brazil) and Mekong River Basin (South East Asia), primarily due to climate variability and change (*high confidence*). A global-scale analysis

(Shamsudduha and Taylor, 2020) of GRACE satellite measurements (2002–2016) for the 37 world's large aquifer systems reveals that trends in groundwater storage are mostly nonlinear and declines are not secular (*high confidence*). There are strong statistical associations between changes in groundwater storage and extreme annual precipitation from 1901 to 2016 in the Great Artesian Basin (Australia) and the California Central Valley aquifer (USA). Groundwater recharge of high magnitudes can be generated from intensive precipitation events. On the other hand, recharge can become more episodic, mostly in arid to semiarid locations (*robust evidence, medium agreement*). For example, in central Tanzania, seven rainfall events between 1955 and 2010 generated 60% of total recharge (Taylor et al., 2013b). Similarly, in southern India (Asoka et al., 2018) and the southwestern USA (Thomas et al., 2016), focused recharge via losses from ephemeral river channels, overland flows, and floodwaters is documented (Cuthbert et al., 2019b).

In cold regions, where snowmelt dominates the local hydrological processes, Irannezhad et al. (2016) and Vincent et al. (2019) show high recharge to aquifers from glacial meltwater, while Nygren et al. (2020) report a decrease in groundwater recharge due to a shift in main recharge period from spring (snowmelt) to winter (rainfall). In Finland, a sustained reduction (almost 100 mm in 100 years) of long-term snow accumulation combined with early snowmelt has reduced spring recharge (Irannezhad et al., 2016) (*medium confidence*).

Data from ground-based long-term records in the Indo-Gangetic Basin reveals that sustainable groundwater supplies are constrained more by extensive contamination (e.g., arsenic, salinity) than depletion (MacDonald et al., 2016). Many low-lying coastal aquifers are contaminated with increased salinity due to land use change, rising sea levels, reduced stream flows and increased storm surge inundation (Lall et al., 2020). Nearly 26 million people are currently exposed to very high (>1500 $\mu S\ cm^{-1}$) salinity in shallow groundwater in coastal Bangladesh (Shamsudduha and Taylor, 2020).

Groundwater-dependent ecosystems (GDEs), such as terrestrial wetlands, stream ecosystems and estuarine and marine ecosystems (Kløve et al., 2014), support wetlands and biodiversity, provide water supply and baseflows to rivers, offer recreational services and help control floods (Rohde et al., 2017). Globally, 10–23% of the watersheds have reached the environmental flow limits due to groundwater pumping (de Graaf et al., 2019). A recent study of 4.2 million wells across the USA shows that induced groundwater recharge in nearly two thirds of these wells could reduce stream discharges, thereby threatening GDEs (Jasechko et al., 2021). Work (2020) found reduced spring flow due to increased groundwater abstraction in 26 out of 56 springs studied in Florida (USA). GDEs in semiarid and arid regions tend to have much longer groundwater response times and may be more resilient to climate change than those in humid areas where groundwater occurrence is mostly at shallow levels (Cuthbert et al., 2019a; Opie et al., 2020). However, groundwater depletion impacts on the full range of ecosystem services remain understudied (Bierkens and Wada, 2019).

A better understanding of and incorporating subsurface storage dynamics into ESMs will improve climate–groundwater interactions under global warming (Condon et al., 2020). Long-term groundwater-level monitoring data are of critical importance (Famiglietti, 2014) for understanding the sensitivity of recharge processes to climate variability and, more critically, calibration and validation of hydrological models (Goderniaux et al., 2015). GRACE satellite-derived groundwater storage estimates provide important insights at a regional scale (Rodell et al., 2018) but overlook more localised depletion or short-term storage gains. Low- and middle-income countries such as central Asia and sub-Saharan Africa lack such monitoring networks, which is a significant knowledge gap.

In summary, groundwater storage has declined in many parts of the world, most notably since the beginning of the 21st century, due to the intensification of groundwater-fed irrigation (*high confidence*). Groundwater in aquifers across the tropics appears to be more resilient to climate change as enhanced recharge is observed to occur mostly episodically from intense precipitation and flooding events (*robust evidence, medium agreement*). In higher altitudes, warmer climates have altered groundwater regimes and may have led to reduced spring recharge due to reduced duration and snowmelt discharges (*medium confidence*).

4.2.7 Observed Changes in Water Quality

AR5 (Jiménez Cisneros et al., 2014) concluded with *medium evidence* and *high agreement* that climate change affected water quality, posing additional risks to drinking water quality and human health (Field et al., 2014b), particularly due to increased eutrophication at higher temperatures or release of contaminants due to extreme floods (Jiménez Cisneros et al., 2014). In addition, SROCC (Hock et al., 2019b; Meredith et al., 2019) assessed that glacier decline and permafrost degradation impacts water quality through increases in legacy contaminants (*medium evidence, high agreement*).

Warming temperatures and extreme weather events can potentially impact water quality (Khan et al., 2015). Water quality can be compromised through algal blooms that affect the taste and odour of recreational and drinking water and can harbour toxins and pathogens (Khan et al., 2015). Warming directly affects thermal water regimes, promoting harmful algal blooms (Li et al., 2018; Noori et al., 2018) (Section 4.3.5). Additionally, permafrost degradation leads to an increased flux of contaminants (MacMillan et al., 2015; Roberts et al., 2017; Mu et al., 2019). The increased meltwater from glaciers (Zhang et al., 2019) releases deposited contaminants and reduces water quality downstream (Zhang et al., 2017; Hock et al., 2019b).

Floods intensify the mixing of floodwater with wastewater and the redistribution of pollutants (Andrade et al., 2018). In addition, contaminated floodwaters pose an immediate health risk through waterborne diseases (Huang et al., 2016b; Paterson et al., 2018; Setty et al., 2018). Wildfires, along with heavy rainfalls and floods, can also affect turbidity, which increases drinking water treatment challenges and has been linked to increases in gastrointestinal illness (de Roos et al., 2017). Droughts reduce river dilution capacities and groundwater levels (Wen et al., 2017) increasing the risk of groundwater contamination (Kløve et al., 2014). More generally, contaminated water diminishes its aesthetic value, compromising recreational activities, reducing tourism and property values and creating challenges for management and drinking water treatment (Eves and Wilkinson, 2014; Khan et al., 2015; Walters et al., 2015).

Between 2000 and 2010, ~10% of the global population faced adverse water quality issues (van Vliet et al., 2021). Adverse drinking water quality has been associated with extreme weather events in countries located in Asia, Africa and South and North America (Jagai et al., 2015; Levy et al., 2016; Huynh and Stringer, 2018; Leal Filho et al., 2018; Abedin et al., 2019) (*medium evidence, high agreement*). Dilution factors in 635 of 1049 US streams fell extremely low during drought conditions. Additionally, the safety threshold for endocrine-disrupting compound concentration exceeded in roughly a third of streams studied (Rice and Westerhoff, 2017). Natural acid rock drainage, which can potentially release toxic substances, has experienced intensification in an alpine catchment of the Central Pyrenees due to climate change and severe droughts in the last decade. River length affected by natural acid drainage increased from 5 km in 1945 to 35 km in 2018 (Zarroca et al., 2021). Threefold increases in contaminants and fivefold increases in nutrients have been observed in water sources after wildfires (Khan et al., 2015). Due to permafrost thawing, the concentration of major ions, especially SO_4^{2-} in two high Arctic lakes, has rapidly increased up to 500% and 340% during 2006–2016 and 2008–2016, respectively (Roberts et al., 2017). The exports of dissolved organic carbon (DOC), particulate organic carbon and mercury in six Arctic rivers were reported to increase with significant deepening of active layers caused by climate warming during 1999–2015 (Mu et al., 2019). Sustained warming in Lake Tanganyika in Zambia during the last ~150 years reduced lake mixing, which has depressed algal production, shrunk the oxygenated benthic habitat by 38% and further reduced fish and mollusc yield (Cohen et al., 2016). From 1994 to 2010, coastal benthos at King George Island in Antarctica have observed a remarkable shift primarily linked to ongoing climate warming and the increased sediment runoff triggered by glacier retreats (Sahade et al., 2015). The recovery time of macroinvertebrates from floods was found longer in cases of pre-existing pollution problems (Smith et al., 2019a).

In summary, although climate-induced water quality degradation due to increases in water and surface temperatures or melting of the cryosphere has been observed (*medium confidence*), evidence of global-scale changes in water quality is *limited* because many studies are isolated and have limited regional coverage.

4.2.8 Observed Changes in Soil Erosion and Sediment Load

AR5 established potential impacts of climate change on soil erosion and sediment loads in mountain regions with glacier melt (*low to medium evidence*) (Jiménez Cisneros et al., 2014). SRCCL (Olsson et al., 2020) reported with *high confidence* that rainfall changes attributed to human-induced climate change have already intensified drivers of land degradation. Nonetheless, attributing land degradation to climate change alone is challenging because of the role of land management practices (*medium evidence, high agreement*).

Climate change impacts soil erosion and sedimentation rates both directly from increasing rainfall or snowmelt intensity (Vanmaercke et al., 2014; Polyakov et al., 2017; Diodato et al., 2018; Golosov et al., 2018; Li et al., 2020a; Li et al., 2020b) and indirectly from increasing wildfires (Gould et al., 2016; Langhans et al., 2016; DeLong et al., 2018), permafrost thawing (Schiefer et al., 2018; Lafrenière and Lamoureux, 2019; Ward Jones et al., 2019) and vegetation cover changes (Micheletti et al., 2015; Potemkina and Potemkin, 2015; Carrivick and Heckmann, 2017; Beel et al., 2018). In addition, accelerated soil erosion and sedimentation have severe societal impacts through land degradation, reduced soil productivity and water quality (Section 4.2.7), increased eutrophication and disturbance to aquatic ecosystems (Section 4.3.5), sedimentation of waterways and damage to infrastructure (Graves et al., 2015; Issaka and Ashraf, 2017; Schellenberg et al., 2017; Hewett et al., 2018; Panagos et al., 2018; Sartori et al., 2019) (*medium confidence*).

In the largest river basin of the Colombian Andes, regional climate change and land use activities (ploughing, grazing and deforestation) caused a 34% erosion rate increase over 10 years, with the anthropogenic soil erosion rate exceeding the climate-driven erosion rate (Restrepo and Escobar, 2018). Sedimentation increases due to soil erosion in mountainous regions burned by wildfires, as a result of warming and altered precipitation, is documented with *high confidence* in the USA (Gould et al., 2016; DeLong et al., 2018), Australia (Nyman et al., 2015; Langhans et al., 2016), China (Cui et al., 2014) and Greece (Karamesouti et al., 2016) and can potentially damage downstream aquatic ecosystems (Section 4.3.5) and water quality (Section 4.2.7) (Cui et al., 2014; Murphy et al., 2015; Langhans et al., 2016) (*medium confidence*). In Australia, for instance, sediment yields from post-fire debris flows (113–294 t ha^{-1}) are 2–3 orders of magnitude higher than annual background erosion rates from undisturbed forests (Nyman et al., 2015). The positive trend in sediment yield in small ponds in the semiarid southwestern USA over the last 90 years was not entirely related to the rainfall or runoff trends, but was a result of complex interaction between long-term changes in vegetation, soil and channel networks (Polyakov et al., 2017).

Regional climate changes (precipitation decrease) and human activities (landscape engineering, terracing, large-scale vegetation restoration, soil conservation) over the Loess Plateau (China) caused a distinct stepwise reduction in sediment loads from the upper-middle reach of the Yellow River, with 30% of the change related to climate change (Tian et al., 2019). Substantial increases in sediment flux were identified on the Tibetan Plateau (Li et al., 2020a; Li et al., 2021a), for example, the sediment load from the Tuotuohe headwater increased by 135% from 1985–1997 to 1998–2016, mainly due to climate change (Li et al., 2020a). In 1986–2015, the sedimentation rate in dry valley bottoms of the Southern Russian Plain was two-2–5 times lower than in 1963–1986 due to the warming-induced surface runoff reduction during spring snowmelt (Golosov et al., 2018). Declining erosion trends are primarily associated with soil conservation management in northern Germany (Steinhoff-Knopp and Burkhard, 2018) and reforestation in southwestern China (Zhou et al., 2020).

The climate change impact on erosion and sediment load varies significantly over the world (Li et al., 2020b) (*high confidence*). There was a statistically significant correlation between sediment yield and air temperature for the non-Mediterranean region of western and central

Europe (Vanmaercke et al., 2014) and northern Africa (Achite and Ouillon, 2016). Still, such correlation is yet to be found for the other European rivers (Vanmaercke et al., 2015). Increased sediment and particulate organic carbon fluxes in the Arctic regions are caused by permafrost warming (Schiefer et al., 2018; Lafrenière and Lamoureux, 2019; Ward Jones et al., 2019). Potemkina and Potemkin (2015) demonstrate that regional warming and permafrost degradation have contributed to an increased forested area over the last 40–70 years, reducing soil erosion in eastern Siberia. The sediment dynamics of small rivers in the eastern Italian Alps, depending on extreme floods, is sensitive to climate change (Rainato et al., 2017). In the northeastern Italian Alps, precipitation change during 1986–2010 affected soil wetness conditions, influencing sediment load (Diodato et al., 2018). Regional warming in northern Africa (Algeria) dramatically changed river streamflow and increased sediment load over four decades (84% more every decade compared to the previous) (Achite and Ouillon, 2016).

A long-term global soil erosion monitoring network based on the unified methodological approach is needed to correctly evaluate erosion rates, detect their changes and attribute them to climate or other drivers.

In summary, in the areas with high human activity, factors other than climate have a more significant impact on soil erosion and sediment flux (*high confidence*). On the other hand, in natural conditions, for example, in high latitudes and high mountains, the influence of climate change on the acceleration of the erosion rate is observed (*limited evidence, medium agreement*).

4.3 Observed Sectoral Impacts of Current Hydrological Changes

The intensification of the hydrological cycle due to anthropogenic climate change has multifaceted and severe impacts for cultural, economic, social and political pathways. In this section, we assess burgeoning evidence since AR5 which shows that environmental quality, economic development and social well-being have been affected by climate-induced hydrological changes since many aspects of the economy, environment and society are dependent upon water resources. We advance previous IPCC reports by assessing evidence on the impacts of climate change-induced water insecurity for energy production (Section 4.3.2), urbanisation (Section 4.3.4), conflicts (Section 4.3.6), human mobility (Section 4.3.7) and cultural usage of water (Section 4.3.8).

Integrating qualitative and quantitative data, we show that it is evident that societies heightened exposure to water-induced disasters—such as floods and droughts—and other hydrological changes have increased vulnerability across most sectors and regions, with few exceptions. Through the assessment of literature relying on IK, we are also able to present evidence on how observed changes impact particularly Indigenous Peoples, local communities and marginalised groups, such as women, people without social protections and minorities.

Importantly, we note that climate change-induced hydrological changes are, for most sectors, one of the several factors, often coupled with urbanisation, population growth and heightened economic disparities, that have increased societal vulnerability and required communities across the globe to alter their productive and cultural practices.

4.3.1 Observed Impacts on Agriculture

AR5 concluded with *high confidence* that agricultural production was negatively affected by climate change, with droughts singled out as a major driver of food insecurity. In contrast, evidence of floods on food production was *limited* (Porter et al., 2014).

Globally, 23% of croplands are irrigated, providing 34% of global calorie production. Of these lands, 68% experience blue water scarcity at the least one month yr^{-1} and 37% up to five months yr^{-1}. Such agricultural water scarcity is experienced in mostly drought-prone areas in low-income countries (Rosa et al., 2020a). Approximately three quarters of the global harvested areas (~454 million hectares) experienced drought-induced yield losses between 1983 and 2009, and the cumulative production losses corresponded to USD 166 billion (Kim et al., 2019). Globally, droughts affected both harvested areas and yields, with a reported cereal production loss of 9–10% due to weather extremes between 1964 and 2007. Yield losses were greater by about 7% during recent droughts (1985–2007) due to greater damage—reducing harvested area—compared to losses from earlier droughts (1964–1984), with 8–11% greater losses in high-income countries than in low-income ones (Lesk et al., 2016). Globally, between 1961 and 2006, it has been estimated that 25% yield loss occurred, with yield loss probability increasing by 22% for maize, 9% for rice and 22% for soybean under drought conditions (Leng and Hall, 2019). Mean climate and climate extremes are responsible for 20–49% of yield anomalies variance, with 18–45% of this variance attributable to droughts and heatwaves (Vogel et al., 2019). Drought has been singled out as a major driver of yield reductions globally (*high confidence*) (Lesk et al., 2016; Meng et al., 2016; Zipper et al., 2016; Anderson et al., 2019; Leng and Hall, 2019).

Yields of major crops in semiarid regions, including the Mediterranean, sub-Saharan Africa, South Asia and Australia, are negatively affected by precipitation declines in the absence of irrigation (Iizumi et al., 2018; Ray et al., 2019), but this trend is less evident in wetter regions (Iizumi et al., 2018). Precipitation and temperature changes reduced global mean yields of maize, wheat and soybeans by 4.1, 1.8 and 4.5%, respectively (Iizumi et al., 2018). Of the global rice yield variability of ~32%, precipitation variability accounted for a larger share in drier South Asia than in wetter East and Southeast Asia (Ray et al., 2015). Between 1910 and 2014 agro-climatic conditions became more conducive to maize and soybean yield growth in the American Midwest due to increases in summer precipitation and cooling due to irrigation (Iizumi and Ramankutty, 2016; Mueller et al., 2016) (Box 4.3). In Australia, between 1990 and 2015, the negative effects of reduced precipitation and rising temperature led to yield losses, but yield losses were partly avoided because of elevated CO_2 atmospheric concentration and technological advancements (Hochman et al., 2017a). Overall, temperature-only effects are stronger in wetter regions like Europe and East and Southeast Asia, and precipitation-only effects are stronger in drier regions (Iizumi et al., 2018; Ray et al., 2019) (*medium evidence, high agreement*). In Asia, the gap between rain-fed and irrigated maize yield widened from 5% in the 1980s to 10% in the 2000s (Meng et al., 2016). In North America, yields of maize and soybeans have increased (1958–2007), yet meteorological drought has been associated with 13% of overall yield variability. However, yield variability was not a concern where irrigation is prevalent (Zipper et al., 2016). However, when water scarcity has reduced irrigation, yields have been negatively impacted (Elias et al., 2016). In Europe, yields have been affected negatively by droughts (Beillouin et al., 2020), with losses tripling between 1964 and 2015 (Brás et al., 2021). In West Africa, between 2000 and 2009, drought, among other altered climate conditions, led to millet and sorghum yield reductions between 10 and 20% and 5 and 15%, respectively (Sultan et al., 2019). Between 2006 and 2016, droughts contributed to food insecurity and malnutrition in northern, eastern and southern Africa, Asia and the Pacific. In 36% of these nations—mainly in Africa—where severe droughts occurred, undernourishment increased (Phalkey et al., 2015; Cooper et al., 2019). An attribution study showed that anthropogenic emissions increased the chances of October–December droughts over the region by 1.4–4.3 times and resulted in below-average harvests in Zambia and South Africa (Nangombe et al., 2020). Root crops, a staple in many tropics and subtropical countries, and vegetables are particularly prone to drought, leading to smaller fruits or crop failure (Daryanto et al., 2017; Bisbis et al., 2018). Livestock production has also been affected by changing seasonality, increasing frequency of drought, rising temperatures and vector-borne diseases and parasites through changes in the overall availability, as well as reduced nutritional value, of forage and feed crops (Varadan and Kumar, 2014; Naqvi et al., 2015; Zougmoré et al., 2016; Henry et al., 2018; Godde et al., 2019) (*medium confidence*).

Floods have led to harvest failure and crop and fungal contamination (Liu et al., 2013; Uyttendaele et al., 2015). Globally, between 1980 and 2018, excess soil moisture has reduced rice, maize, soybean and wheat yields between 7 and 12% (Borgomeo et al., 2020). Changes in groundwater storage and availability, which are affected by the intensity of irrigated agriculture, also negatively impacted crop yields and cropping patterns (Section 4.2.6, Box 4.3, 4.7.2). Moreover, extreme precipitation can lead to increased surface flooding, waterlogging, soil erosion and susceptibility to salinisation (*high confidence*). For example, in Bangladesh, in March and April 2017, floods affected 220,000 ha of a nearly harvest-ready summer paddy crop and resulted in almost a 30% year-on-year increase in paddy prices. An attribution study of those pre-monsoon extreme rainfall events in Bangladesh concluded that anthropogenic climate change doubled the likelihood of the extreme rainfall event (Rimi et al., 2019). Moreover, floods, extreme weather events and cyclones have led to animal escapes and infrastructure damage in aquaculture (Beveridge et al., 2018; Islam and Hoq, 2018; Naskar et al., 2018; Lebel et al., 2020) (see Section 5.9.1).

Worldwide, the magnitudes of climate-induced water-related hazards and their impact on agriculture are differentiated across populations and genders (Sections 4.3.6; 4.8.3). Evidence shows that hydroclimatic factors pose high food insecurity risks to subsistence farmers, whose first and only source of livelihood is agriculture, and who are situated at low latitudes where the climate is hotter and drier (Shrestha and Nepal, 2016; Sujakhu et al., 2016). Historically, they have been the most vulnerable to observed climate-induced hydrological changes (Savo et al., 2016). 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 farmers will undertake (Caretta and Börjeson, 2015; Savo et al., 2016; Sujakhu et al., 2016; Su et al., 2017) (Section 4.8.4) (*high confidence)*.

In summary, ongoing climate change in temperate climates has some positive impacts on agricultural production. In subtropical/tropical climates, climate-induced hazards such as floods and droughts negatively impact agricultural production (*high confidence*). People living in deprivation and Indigenous Peoples have been disproportionally affected. They often rely on rain-fed agriculture in marginal areas with high exposure and high vulnerability to water-related stress and low adaptive capacity (*high confidence)*.

4.3.2 Observed Impacts on Energy and Industrial Water Use

AR5 (Jiménez Cisneros et al., 2014) concluded with *medium evidence* and *high agreement* that hydropower negatively impacts freshwater ecosystems. SROCC (IPCC, 2019a) concluded with *medium confidence* that climate change has led to both increases and decreases in annual/seasonal water inputs to hydropower plants.

Water is a crucial input for hydroelectric and thermoelectric energy production, which together account for 94.7% of the world's current electricity generation (Petroleum, 2020). Climate change impacts hydropower production through changes in precipitation, evaporation, volume and timing of runoff; and impacts cooling of thermoelectric power plants through reduced streamflow and increased water temperatures (Yalew et al., 2020). In addition, extreme weather events, like tropical cyclones, landslides and floods, damage energy infrastructure (MCTI, 2020; Yalew et al., 2020), while high temperature and humidity increase the energy requirement for cooling (Maia-Silva et al., 2020).

With 1308 GW installed capacity in 2019, hydropower became the world's largest single source of renewable energy (IHA, 2020) (also see Figure 6.12, WGIII). While hydropower reduces emissions relative to fossil fuel-based energy production, hydropower reservoirs are being increasingly associated with GHG emissions caused by submergence and later re-emergence of vegetation under reservoirs due to water level fluctuations (Räsänen et al., 2018; Song et al., 2018; Maavara et al., 2020). A recent global study concluded that reservoirs might emit more carbon than they bury, especially in the tropics (Keller et al., 2021) (*medium confidence*).

In Ghana, between 1970 and 1990, rainfall variability accounted for 21% of interannual variations in hydropower generation (Boadi and Owusu, 2019). In Brazil's São Francisco River, following drought events in 2016 and 2017, hydropower plants operated with an average capacity factor of only 23% and 17%, respectively (de Jong et al., 2018). In Switzerland, increased glacier melt contributed to 3–4% of hydropower production since 1980 (Schaefli et al., 2019) (Section 4.2.2). In the USA, hydropower generation dropped by nearly 27% for every standard deviation increase in water scarcity. Equivalent social costs of loss in hydropower generation between 2001 and 2012 were approximately USD 330,000 (at 2015 value) per month for every power plant that experienced water scarcity (Eyer and Wichman, 2018). Globally, for the period 1981–2010, the utilisation rate of hydropower was reduced by 5.2% during drought years compared to long-term average values (van Vliet et al., 2016a). Thus, there is a growing body of evidence of negative impacts of extreme events on hydropower production (*high confidence*).

Impacts of water scarcity on thermoelectric plants are more unequivocal than hydropower plants. For example, a scenario-based simulation study showed that 32% of the world's coal-fired power plants (CFPPs) plants are currently experiencing water scarcity for at least five months or more in a year (Rosa et al., 2020c). In the UK, almost 50% of freshwater thermal capacity is lost on extreme high-temperature days, causing losses in the range of average GBP 29–66 million yr^{-1}. For ~20% of particularly vulnerable power plants, these losses could increase to GBP 66–95 million yr^{-1} annualised over 30 years (Byers et al., 2020). Globally, for the period 1981–2010, the utilisation rate of thermoelectric power was reduced by 3.8% during drought years compared to long-term average values (van Vliet et al., 2016a), and none of the studies reported increases in thermoelectric power production as a consequence of climate change (*high confidence*).

In the energy sector, a large number of studies document the impact of extreme climate events (e.g., droughts or extreme temperature days) on production of hydropower and thermoelectric power, yet there are limited studies that measure trends in energy production due to long-term climate change. This remains a knowledge gap.

Mining in regions already vulnerable to climate change-induced water scarcity is under threat, leading some countries like El Salvador to ban metal mining completely (Odell et al., 2018). Likewise, food and agro-processing companies are aware of water-related threats to their operations, with 77% of 35 publicly traded companies evaluated in 2019 explicitly citing water as a risk factor in their annual reports, up from 59% in 2017 (CDP, 2018; CERES, 2019). Changes in water availability affect the mining, electrical, metal and agro-processing sectors (UNIDO, 2017; Odell et al., 2018; Frost and Hua, 2019), but these impacts are less understood due to the lack of studies.

In summary, there is *high confidence* that climate change has had negative impacts on hydro and thermal power production globally due to droughts, changes in the seasonality of river flows, and increasing ambient water temperatures.

4.3.3 Observed Impacts on Water, Sanitation and Hygiene (WaSH)

AR5 showed that local changes in temperature and rainfall had altered the distribution of some water-related diseases (*medium confidence*), and extreme weather events disrupt water supplies, impacting morbidity, mortality and mental health (*very high confidence*) (Field et al., 2014b). In addition, melting and thawing of snow, ice and permafrost (Section 4.2.2) have also adversely impacted water quality, security and health (*high confidence*) (IPCC, 2019a) (Section 4.2.7).

Literature since AR5 confirms that temperature, precipitation and extreme weather events are linked to increased incidence and outbreaks of water-related and neglected tropical diseases (Colón-González et al., 2016; Levy et al., 2016; Azage et al., 2017; Harp et al., 2021) (*high confidence*). For example, the rainy season in Senegal has been associated with an 84% increase in relative risk of childhood diarrhoea, and an additional wet day per week was associated with up to 2% increases in diarrhoeal disease in Mozambique (Thiam et al., 2017; Horn et al., 2018). In Ecuador, increases of 1.5 cases of diarrhoea per 1000 were associated with heavy rainfall after dry periods, while a decrease of one case per 1000 was associated with heavy rain after wet periods (Carlton et al., 2014). Floods have been associated with 22% increases in relative risk of diarrhoea in China (Liu et al., 2018c). In addition, higher levels of faecal contamination of drinking water and hands (i.e., lack of WaSH) has been statistically significantly associated with increased child diarrhoea (Goddard et al., 2020).

In 2020, 2 billion people lacked access to uncontaminated water, while 771 million lacked basic sanitation services, primarily in sub-Saharan Africa and rural areas (WHO and UNICEF, 2021). Even in high-income countries, poor-quality drinking water can be a health issue (Murphy et al., 2014). For example, in a sampled population in Canada, reported exposure to exposure routes for waterborne illness included 7% from private wells and 71.8% from municipal water (David et al., 2014). Drinking water treatment can be compromised by degraded source water quality and extreme weather events, including droughts, storms, ice storms and wildfires that overwhelm or cause infrastructure damage (Sherpa et al., 2014; Khan et al., 2015; Howard et al., 2016; White et al., 2017) (*high confidence*). Adverse health effects are exacerbated due to the absence of adequate WaSH, particularly in poorer households (Khan et al., 2015; Kostyla et al., 2015; Cissé et al., 2016), WaSH infrastructure failure (Khan et al., 2015; Wanda et al., 2017) or inadequate WaSH facilities in emergency shelters (Alam and Rahman, 2014). For example, WaSH coverage decreased from 65% to 51% due to damage from floods and earthquakes in Malawi (Wanda et al., 2017). Loss of electricity also impacts WaSH service delivery (Cashman, 2014), and infrastructure damage caused by climate hazards may reverse progress on universal access to WaSH (Kohlitz et al., 2017) (*limited evidence, high agreement*). In addition, wastewater outflows have been associated with a 13% increased relative risk of gastrointestinal illness through contaminated drinking water sources (Jagai et al., 2015) (*limited evidence, high agreement*). Harmful algal blooms represent an emerging health risk, but lack of monitoring and reporting prevent risk exposure assessments (Carmichael and Boyer, 2016; Nichols et al., 2018) (*limited evidence, high agreement*). Chemical contaminants (e.g., nitrates, arsenic) have been linked to non-communicable diseases, including neurological disorders, liver and kidney damage, and cancers (Jones Rena et al., 2016), and to some water-related diseases (e.g., schistosomiasis) (*low evidence, medium agreement*).

Water insecurity and inadequate WaSH have been associated with increased disease risk (*high confidence*), stress and adverse mental health (*limited evidence, medium agreement*), food insecurity and adverse nutritional outcomes, and poor cognitive and birth outcomes (*limited evidence, medium agreement*) (Workman and Ureksoy, 2017; Sclar et al., 2018; Boateng et al., 2020; Rosinger and Young, 2020; Wutich et al., 2020). Climate-induced water scarcity and supply disruptions disproportionately impact women and girls. The necessity of water collection takes away time from income-generating activities, child care and education (Yadav and Lal, 2018; Schuster et al., 2020) (*medium evidence, medium agreement*). Consumption of larger volumes of water is essential for healthy women during pregnancy, lactation and caregiving, which increases the amount of water that has to be fetched. Fetching of water is associated with increased risk of sexual abuse, demand for sexual favours at controlled water collection points, physical injuries (e.g., musculoskeletal or from animal attacks), domestic violence for not completing daily water-related domestic tasks (*limited evidence, high agreement*), and poorer maternal and child health (Mercer and Hanrahan, 2017; Pommells et al., 2018; Anwar et al., 2019; Collins et al., 2019a; Geere and Hunter, 2020; Venkataramanan et al., 2020) (*medium evidence, high agreement*). Menstrual hygiene management is a public health issue but poorly linked to climate change, despite relationships between lack of adequate WaSH, poor menstrual hygiene, and urinary tract infections (Ellis et al., 2016; Pouramin et al., 2020). Water insecurity also affects emotional, spiritual and cultural relationships that are often critical to Indigenous health (Wilson et al., 2019) (*limited evidence, high agreement*).

There are gaps in data on climate-driven water-related disease burden for both infectious and non-communicable diseases. Increased demands for water and WaSH services for infectious diseases, such as HIV/AIDS and COVID-19 (Box 4.4) exacerbate existing vulnerabilities and inequities (Stanley et al., 2017; Armitage and Nellums, 2020a; Rodriguez-Lonebear et al., 2020). Additionally, limited research has been undertaken to quantify the effects of climate-compromised WaSH on health and well-being.

In summary, WaSH-related household water insecurity and disease incidence are products of geography, politics, social and environmental determinants, vulnerability and climate change (Bardosh et al., 2017; Stoler et al., 2021).

4.3.4 Observed Impacts on Urban and Peri-Urban Sectors

All previous IPCC reports have focused on future water-related risks to urban areas due to climate change rather than documented observed impacts.

Climate extremes have profound implications for urban and peri-urban water management, particularly in an increasingly urbanised world (*high confidence*). Over half (54%) of the global population currently lives in cities (WWAP, 2019), and global urbanisation rates continue to increase across all SSPs (Jiang and O'Neill, 2017). Using observed station data for 217 urban areas worldwide, Mishra et al. (2015) noted that 17% of cities experienced statistically significant increases (p value < 0.05) in the frequency of daily precipitation extremes from 1973 to 2012 and hypothesised that such observed climate changes in urban areas were largely due to large-scale changes rather than local land cover changes.

Since AR5, factors such as rapid population growth, urbanisation, ageing infrastructure and changes in water use have also magnified climate risks, such as drought and flooding, and contributed to urban and peri-urban water insecurity (*medium agreement, medium evidence*) (Section 4.1.2). For example, despite an increase in flooding events from 1.1 flood events yr^{-1} (1986–2005) to five flood events yr^{-1} (2006–2016) in Ouagadougou (Burkina Faso), analyses of rainfall indices showed few have significant trends at a 5% level over the period 1961–2015 and that the generalised extreme value distribution fit the time series of annual maximum daily rainfall (Tazen et al., 2019). On the other hand, long-term annual variations of maximum hourly precipitation in Shanghai (China) increased significantly during 1916–2014, especially from 1981.

Advances in the attribution of extreme weather events have made it possible to determine the causal relationship between droughts, floods and climate change for some cities, particularly those with long hydro-meteorological records (Bader et al., 2018; Otto et al., 2020). Attribution analysis shows that urbanisation contributed to the increase in both frequencies of local and abrupt heavy rainfall events in the city, at a rate of 1.5 and 1.8 10 yr^{-1}, respectively (Liang and Ding, 2017). A multi-method attribution showed that the likelihood of prolonged rainfall deficit in Cape Town (South Africa) during 2015–2017 was made more likely by a factor of 3.3 (1.4–6.4) due to anthropogenic climate change (Otto et al., 2018). These results show that climate change has impacted the return time of extreme droughts in the Western Cape, exceeding the capacity of the existing water supply system to cope (Otto et al., 2018) (Box 9.4; 9.8.2). In Baton Rouge (USA), a rapid attribution study showed that the probability of an event such as the intense precipitation and flash flooding of August 2016 has increased by at least a factor of 1.4 due to radiative forcing (USA) (van der Wiel et al., 2017). In Houston (USA), a study found that the combination of urbanisation and climate change nearly doubled peak discharge (84%) during Hurricane Harvey (August 2017), suggesting that land use change magnified the effects of climate change on catchment response to extreme precipitation events (Sebastian et al., 2019) (14.4.3.1; Box 14.5 The Economic Consequences of Climate Change in North America, Cross-Chapter Box DISASTER in Chapter 4). According to a multi-method approach, the 2014/2015 drought event in Sao Paulo (Brazil) was more likely to have been driven by water use changes and population growth than climate change (Otto et al., 2015) (Cross-Chapter Box DISASTER in Chapter 4).

The science of weather event attribution requires high-quality observational data and climate models that are currently available only in highly developed countries (Otto et al., 2020). In addition, further research is necessary to determine the impacts of climate change on water-related extremes in the urban areas of developing countries (Bai et al., 2018). For example, a combination of observational analysis and global coupled climate models showed that the 2015 flooding event in Chennai (India) could not be attributed to anthropogenic climate change, with the effects of that being relatively small in the region due to the impact of GHG increases being largely counteracted by those of aerosols (van Oldenborgh et al., 2017a) (Section 4.2.5). Further research is also required to determine the impacts of climate change on water-related extremes in informal settlements where vulnerability to water insecurity is high due to poverty, overcrowding, poor-quality housing and lack of basic infrastructure (Scovronick et al., 2015; Grasham et al., 2019; Williams et al., 2019; Satterthwaite et al., 2020).

Cross-Chapter Box DISASTER | Disasters as the Public Face of Climate Change

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Introduction

Some extreme weather events are increasing in frequency and (or) severity as a result of climate change (Seneviratne et al., 2021) (*high confidence*). These include extreme rainfall events (Roxy et al., 2017; Myhre et al., 2019; Tabari, 2020); extreme and prolonged heat leading to catastrophic fires (Bowman et al., 2017; Krikken et al., 2019; van Oldenborgh et al., 2020); and more frequent and stronger cyclones/hurricanes and resulting extreme rainfall (Griego et al., 2020). These extreme events, coupled with high vulnerability and exposure in many parts of the world, turn into disasters and affect millions of people every year. New advances enable the detection and attribution of these extreme events to climate change (Otto et al., 2016; Seneviratne et al., 2021), with the most recent study saying that heavy rains leading to devastating floods in western Europe that captured the world's attention in July 2021 were made more likely due to climate change (Kreienkamp et al., 2021). Most WGII chapters (this volume) report various extreme event-induced disasters and their societal impacts. This cross-chapter box brings together authors from WGI and WGII to emphasise that disasters following extreme events have become the most visible and public face of climate change (Solecki and Rosenzweig, 2014). These disasters reflect immediate societal and political implications of rising risks (*high confidence*), but also provide windows of opportunity to raise awareness about climate change and to implement disaster-reduction policies and strategies (*high confidence*) (Albright, 2020; Boudet et al., 2020).

Here, we document eight catastrophic climate-related disasters that took place between 2017 and 2021. These disasters resulted in the loss of lives and livelihoods and had adverse impacts on biodiversity, health, infrastructure and the economy. These disasters provided important rallying points for discussions around climate change, equity and vulnerability in some cases. These disasters also offer valuable lessons about the role of effective climate change adaptation in managing disaster risks and the importance of Loss and Damage mechanisms in global negotiation processes (Jongman et al., 2014; Mechler et al., 2014; Cutter and Gall, 2015).

Case 1. Compounded events and impacts on human systems: Cyclones Idai and Kenneth in Mozambique in 2019

While individual events alone can lead to major disasters, when several events occur in close spatial and temporal proximity, impacts get compounded, with catastrophic results (Zscheischler et al., 2018; Zscheischler et al., 2020). In March 2019, Cyclone Idai (category 2) was the deadliest storm on record to strike the African continent, with the coastal city of Beira in Mozambique being particularly hard hit with at least 602 deaths (CRED, 2019; Zehra et al., 2019; Phiri et al., 2020). Nationally, Idai caused massive housing, water supply, drainage and sanitation destruction, but its impact extended to South Africa through disruption of the regional electricity grid (Yalew et al., 2020). In April 2019, amidst heightened vulnerabilities in the aftermath of cyclone Idai, cyclone Kenneth (category 4) hit the country, affecting 254,750 people and destroying more than 45,000 homes (Kahn et al., 2019). These circumstances caused the rapid spread of cholera, which triggered a massive vaccination programme to control the epidemic (Kahn et al., 2019; Lequechane et al., 2020). While there were no specific detection and attribution studies for Idai and Kenneth, overall, there is *high confidence* that the rainfall associated with tropical cyclones is more intense because of global warming. However, there remain significant uncertainties about the impact of climate change on the numbers and strength of tropical cyclones per se (Walsh et al., 2019; Zhang G. et al., 2020).

Case 2. COVID-19 as the compounding risk factor: Cyclone Amphan in India and Bangladesh, 2020

Cyclone Amphan hit coastal West Bengal and Bangladesh on 20 May 2020. It was the first supercyclone to form in the Bay of Bengal since 1999 and one of the fiercest to hit West Bengal, India, in the last 100 years. The cyclone intensified from a cyclonic storm (category 1) to a supercyclone (category 5) in less than 36 hours (Balasubramanian and Chalamalla, 2020). Several hours before and on 20 May, extreme rain events resulted in heavy cumulative rainfall, flash flooding and landslides in several adjoining districts (Mishra and Vanganuru, 2020). As per the initial estimates, about 1600 km^2 area in the mangrove forests of *Sundarbans* were damaged, and over 100 lives were lost. Earlier cyclones in the region have shown that impacts of these events are gendered (Roy, 2019). The cyclone damage was somewhat lessened due to the delta's mangroves (Sen, 2020). The estimated damage was USD 13.5 billion. Cyclone Amphan was the largest source of displacement in 2020, with 2.4 million displacements in India alone, of which 800,000 were pre-emptive evacuations by authorities

Cross-Chapter Box DISASTER (continued)

(IDMC, 2020). Because it happened amidst the COVID-19 crisis, evacuation plans were constrained due to social distancing norms (Baidya et al., 2020). Social media played an important role in disseminating pre-cyclone warnings and information on post-cyclone relief work (Crayton et al., 2020; Poddar et al., 2020).

Case 3. Further exacerbating inequities in human systems: Hurricane Harvey, USA, 2017

Hurricane Harvey, a category 4 hurricane, made landfall on Texas and Louisiana in August 2017, causing catastrophic flooding and 80 deaths and inflicting $125 billion (2017 USD) in damage, of which $67 billion (2017 USD) was attributable to climate change (Frame et al., 2020). Several studies estimated the return period of the rainfall associated with this event and assessed that human-induced climate change increased the likelihood by a factor of approximately three using a combination of observations and climate models (Risser and Wehner, 2017; van Oldenborgh et al., 2017b). The impacts of Hurricane Harvey were exacerbated by extensive residential development in flood-prone locations. A study showed that urbanisation increased the probability of such extreme flood events several folds (Zhang W. et al., 2018) through the alteration of ground cover and disruption and redirection of water flow. Water quality in cities also deteriorated (Horney et al., 2018; Landsman et al., 2019), and 85% of flooded land subsided at a rate of 5 mm yr^{-1} following the event (Miller and Shirzaei, 2019). Notably, the impacts of Harvey were unequally distributed along racial and social categories in the greater Houston area. Neighbourhoods with larger Black, Hispanic and disabled populations were the worst affected by the flooding following the storm and rainfall (Chakraborty et al., 2018; Chakraborty et al., 2019; Collins et al., 2019b). In addition, racial and ethnic disparities were shown to impact post-disaster needs, ranging from household damage to mental health and recovery (Collins et al., 2019b; Flores et al., 2020; Griego et al., 2020).

Case 4. Impacts worsened due to sociocultural and political conditions: The "Coastal Niño" in Peru, 2017

The Coastal Niño event of 2017 led to extreme rainfall in Peru, which was made more likely by at least 1.5 times as compared to pre-industrial times due to anthropogenic climate change and Coastal Niño (Christidis et al., 2019) and comparable to the El Niño events of 1982–1983 and 1997–1998 (Poveda et al., 2020). This event showed evidence of larger anomalies in flood exposure (Muis et al., 2018; Christidis et al., 2019; Rodríguez-Morata et al., 2019) and sediment transport (Morera et al., 2017). In Peru, this Niño event led to USD 6 to 9 billion of monetary losses, more than a million inhabitants were affected, 6614 km of roads were damaged, 326 bridges were destroyed, 41,632 homes were damaged or became uninhabitable and 2150 schools and 726 health posts were damaged (French and Mechler, 2017; French et al., 2020), leaving half of the country in a state of emergency (Christidis et al., 2019). Furthermore, institutional and systemic sociocultural and political conditions at multiple levels significantly worsened disaster risk management which hampered response and recovery (French et al., 2020). Citizens and zero-order responders proved to be more effective and quicker than national disaster risk management response (Briones et al., 2019).

Case 5. Triggering institutional response for future preparedness: Mega-fires of Chile, 2017

The mega-fire that occurred in Chile in January 2017 had the highest severity recorded on the planet (CONAF, 2017), burning in three weeks an area close to 350,000 hectares in south-central Chile. These events have been associated with the prolonged ongoing drought that has persisted for more than one decade and with the increase in heat waves (González et al., 2018; Miranda et al., 2020). This extreme drought and the total burned area of the last decades have been attributed to anthropogenic climate change in at least 25% and 20% of their severity, respectively (Boisier et al., 2016). The mega-fire of summer 2017 resulted in 11 deaths, more than 1500 houses burned and the destruction of the small town of Santa Olga. The smoke from these fires exposed 9.5 million people to air pollution, causing an estimated 76 premature deaths (Bowman et al., 2017; González et al., 2020). The direct costs incurred by the State exceeded USD 360 million (González et al., 2020). The 2017 mega-fires led to a series of institutional responses such as management plans that include preventive forestry techniques, regulatory plans containing rural–urban interface areas, an emergency forest fire plan, and promotion of native species (González et al., 2020).

Case 6. Loss of human lives and biodiversity: Bushfires in Australia, 2019/2020

In the summer of 2019/2020, bushfires in Australia killed 417 people due to smoke and killed between 0.5 and 1.5 billion wild animals and tens of thousands of livestock (van Oldenborgh et al., 2020). These fires also destroyed approximately 5900 buildings and burnt 97,000 km^2 of

Cross-Chapter Box DISASTER (continued)

vegetation, which provided habitat for 832 species of native vertebrate fauna. Seventy taxa had more than 30% of their habitat impacted, including 21 already identified as threatened with extinction (Ward et al., 2020). In addition, millions of people experienced levels of smoke 20 times higher than the government-identified safe level. The year 2019 had been Australia's warmest and driest year on record. In the summer of 2019/2020, the seasonal mean and mean maximum temperatures were the hottest by almost 1°C above the previous record. Eight of the 10 hottest days on record for national mean temperatures occurred in December 2019. While the prevailing weather conditions were strongly influenced by the Indian Ocean Dipole pressure pattern, with a contribution from weakly positive ENSO conditions in the Pacific, the fact that Australia is approximately 1°C warmer than the early 20th century demonstrates links to anthropogenic climate change. Eight climate models using event attribution methodologies (comparison of simulations with present-day and pre-industrial forcings) indicates that anthropogenic climate change made the heat conditions of December 2019 more than twice as likely (van Oldenborgh et al., 2020).

Case 7. Improved preparedness reduced mortality: Heatwave in Europe, 2019

In 2019, Europe experienced several record-breaking heatwaves. In June, the first one featured record heat for that time in early summer, with temperatures of 6°C–10°C above normal over most of France and Germany, northern Spain, northern Italy, Switzerland, Austria and the Czech Republic (Climate, 2019). The second heatwave also resulted in all-time records for Belgium, Germany, Luxembourg, the Netherlands and the UK in July. Attribution studies (Vautard et al., 2020) demonstrated that these would have had extremely small odds in the absence of human-induced climate change or would have been 1.5°C–3°C colder without human-induced climate change. This study concluded that state-of-the-art climate models underestimate the trends in local heat extremes compared to the observed trend. Since the 2003 heatwave, which resulted in tens of thousands of deaths across Europe, many European countries have adopted heatwave plans, including early warning systems. Therefore, mortality in 2019 was substantially lower than it might have been. Unfortunately, mortality is not registered systematically across Europe, and therefore, comprehensive analyses are missing. But even based on the countries that provide the numbers, more specifically France, Belgium and the Netherlands, the European heatwave of 2019 resulted in over 2500 deaths (CRED, 2019). Despite their deadliness and the fact that climate change increases the frequency, intensity and duration of heatwaves globally (Perkins-Kirkpatrick and Lewis, 2020), heatwaves are not consistently reported in many countries (Harrington and Otto, 2020), rendering it currently impossible to estimate climate change impacts on lives and livelihoods comprehensively.

Case 8. Loss of human lives and property: Floods in Europe in 2021

From 12 to 15 July 2021, extreme rainfall in Germany, Belgium, Luxembourg and neighbouring countries led to severe flooding. The severe flooding was caused by very heavy rainfall over a period of 1–2 d, wet conditions prior to the event and local hydrological factors. The observed rainfall amounts in the Ahr/Erft region and the Belgian part of the Meuse catchment substantially exceeded previous records for observed rainfall. An attribution study (Kreienkamp et al., 2021) focused on the heavy rainfall rather than river discharge and water levels, because sufficient hydrological data was not available, partly because hydrological monitoring systems were destroyed by the event. Considering a larger region of western Europe between the northern side of the Alps and the Netherlands, in any given location, one such event can be expected every 400 years on average in the current climate. The floods resulted in least 222 fatalities and substantial damage to houses, roads, communication infrastructure, motorways, railway lines and bridges.

Table Cross-Chapter Box DISASTER.1 | Summarising impacts, losses and damages, displacement and climate change detection and attribution of these seven disaster case studies.

Name of the disaster event	Impacts, losses and damages; and displacement	Climate change detection and attribution
Cyclones Idai and Kenneth, March and April 2019, Mozambique, Africa	254,750 affected people, and more than 45,000 houses were destroyed. Sparked cholera outbreaks that resulted in 6600 cases and over 200 deaths. More than 500,000 people were displaced in 2019. As of 31 December 2019, more than 132,000 people were internally displaced in Mozambique (IDMC, 2020).	There are no detection and attribution studies on Idai and Kenneth, but it is known that rainfall associated with tropical cyclones are now more intense because of global warming, but there remain significant uncertainties concerning changes in the number and strength of the cyclones themselves (Walsh et al., 2019; Zhang G. et al., 2020).
Cyclone Amphan, May 2020, West Bengal, India and Bangladesh	About 1600 km^2 area in the mangrove forests of Sundarbans were damaged. The city of Kolkata lost a substantial portion of its green cover due to Amphan. The estimated damage was USD 13.5 billion. Cyclone Amphan was the largest source of displacement in 2020, with 2.4 million displacements in India and a similar number in Bangladesh. Out of these 2.4 million, roughly 800,000 were pre-emptive evacuations or organised by the authorities (IDMC, 2020).	The combined decline of both aerosols (due to COVID-19-related lockdowns) and clouds may have contributed to the increased sea surface temperature, further compounding the climate change-related warming of the oceans (Vinoj and Swain, 2020). However, there are no attribution studies on tropical cyclones in the Indian Ocean.

Cross-Chapter Box DISASTER (continued)

Name of the disaster event	Impacts, losses and damages; and displacement	Climate change detection and attribution
Hurricane Harvey, 2017, USA	Catastrophic flooding and many deaths inflicted $125 billion (2017 USD). In addition, economic costs due to the rainfall are estimated at $90 billion, of which $67 billion are attributed to climate change (Frame et al., 2020).	Several attribution studies found that the rainfall associated with Harvey has increased by a factor of three, while intensity in rainfall and wind speed also increased due to human-induced climate change (Emanuel, 2017; Risser and Wehner, 2017; Patricola and Wehner, 2018; van Oldenborgh et al., 2020).
Coastal Niño 2017, Peru	USD 6–9 billion monetary losses with 114 deaths, 414 injuries and 1.08 million inhabitants affected. In addition, 6614 km of improved roads were damaged, 326 bridges destroyed, 41,632 homes destroyed or uninhabitable, and 242,433 homes, 2150 schools and 726 health centres damaged.	Clear anthropogenic climate change fingerprint detected. For example, while the anomalously warm ocean favoured extreme rainfall of March 2017 in Peru, the human influence was estimated to make such events at least 1.5 times more likely (Christidis et al., 2019).
Mega-fires in Chile, January 2017	The mega-fire that occurred in Chile in January 2017 burned in three weeks an area close to 3500 km^2 in south-central Chile. As a result, thousands of people were displaced.	There is no attribution study on the fires in Chile (yet). Still, there is an increasing number of attribution studies on wildfires worldwide, finding that because climate change has increased the likelihood of extreme heat, which is part of the fire weather, the likelihood of wildfire weather conditions has increased too (Krikken et al., 2019; van Oldenborgh et al., 2020).
Australian bushfires of 2019/2020	Killed 417 people due to smoke, and between 0.5 and 1.5 billion wild animals and tens of thousands of livestock. Destroyed ~5900 buildings and burnt 97,000 km^2 of vegetation that provided habitat for 832 species of native vertebrate fauna.	Anthropogenic climate change made the extreme heat condition of December 2019 more than twice as likely (van Oldenborgh et al., 2020).
Heatwaves of Europe, 2019	Record heat in several European countries, and deadliest global disaster of 2019, with over 2500 deaths (CRED, 2019)	There have been many attribution studies on heatwaves in Europe, finding that human-induced climate change is increasing the frequency and intensity of heatwaves. In the case of 2019, the observed heat would have been extremely unlikely without climate change. The studies also find that climate models underestimate the increase in heat waves in Europe compared to observed trends (Vautard et al., 2020).
Floods in western Europe (Germany, Belgium), July 2021	Severe flooding resulting in at least 222 fatalities and substantial damage to houses, roads, communication infrastructure, motorways, railway lines and bridges. Some communities were cut off for days due to road closures, inhibiting emergency responses, including evacuation.	Climate change was found to have increased the intensity of the maximum 1-d rainfall event in the summer season in this large region by about 3–19% compared to a global climate 1.2°C cooler than at the present day. The increase was similar for the 2-d event. The likelihood of such an event today was found to have increased by a factor between 1.2 and 9 for both the 1-d and 2-d events in the large region (Kreienkamp et al., 2021).

Disaster risk reduction needs to be a central component of adaptation and mitigation for meeting Sustainable Development Goals and for a climate-resilient future

Disasters resulting from extreme events are increasingly experienced by a large section of human population (Hoegh-Guldberg et al., 2018). Disasters expose inequalities in natural and managed systems and human systems as they disproportionately affect poor and marginalised communities like ethnic minorities, people of colour, Indigenous Peoples, women and children. Therefore, disaster risk reduction is fundamental for climate justice and climate resilient development (UNISDR, 2015). Far from being disconnected policy objectives, disaster risk reduction and climate change mitigation/adaptation are two sides of the same coin as recognised explicitly by the Paris Agreement and Sendai Framework of 2015. There can be no sustainable development without disaster risk reduction, as explicitly recognised by the SDGs of 2015. Furthermore, disaster events can increase awareness among citizens and provide a platform for all important stakeholders, including climate activists, to come together, and give a clarion call for the urgency of climate action.

In summary, disasters are a stark illustration of the potential for extreme weather events to impact people and other species. With the frequency, severity and (or) likelihood of several types of extreme weather increasing, disasters can increasingly be regarded as ‘the public face of climate change’ (*high confidence*). Detection and attribution studies make the climate change fingerprint of several types of disasters increasingly clear (*high confidence*). Moreover, existing vulnerabilities and exposures play an important role in turning extreme events into disasters, further exacerbating existing racial, gender and social inequalities (*high confidence*). Therefore, disaster risk reduction needs to be central to adaptation and mitigation efforts to meet the SDGs and the Paris Agreement for a climate-resilient future.

In summary, water-related hazards such as drought and flooding have been exacerbated by climate change in some cities (*high confidence*). Further research is necessary to determine the extent and nature of water-related climate change impacts in the urban areas of developing countries (*high confidence*).

4.3.5 Observed Impacts on Freshwater Ecosystems

The loss and degradation of freshwater ecosystems have been widely documented, and SRCCL assessed with *medium confidence* the loss of wetlands since the 1970s (Olsson et al., 2020).

The links between air and water temperatures and ecological processes in freshwater ecosystems are well recognised. Increasing temperatures affect wetlands by influencing biophysical processes, affecting feeding and breeding habits and species' distribution ranges, including their ability to compete with others. Increased temperatures can also cause deoxygenation in the lower depths of the water columns and throughout the entire water column if heating destabilises the water column. Under extreme heat, often associated with minimal rainfall or water flows, the drying of shallower areas and the migration or death of individual organisms can occur (Dell et al., 2014; Miller et al., 2014; Scheffers et al., 2016; Szekeres et al., 2016; Myers et al., 2017; FAO, 2018a) (*high confidence*). A global systematic review of studies since 2005 shows that climate change is a critical direct driver of freshwater ecosystems impacts through increasing temperatures or declining rainfall, for example, by causing physiological stress or death (thermal stress, dehydration or desiccation), limiting food supplies, or resulting in migration of animals to other feeding or breeding areas, and possibly increased competition with animals already present in those migrating locations {Diaz et al. 2019; Dziba et al. 2018}. Other drivers include land use changes, water pollution, extraction of water, drainage and conversion, and invasive species, which to varying extents interact synergistically with climate change or are exacerbated due to climate change (Finlayson et al., 2017; Ramsar Convention, 2018).

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), with high levels of the overall percentage of threatened species recorded in Madagascar and Indian Ocean islands (43%); in Europe (36%); in the tropical Andes (35%); and New Zealand (41%) (Ramsar Convention, 2018). Where long-term data are available, only 13% of the wetlands recorded in and around the year 1700 remained by 2000. However, these data may overestimate the rate of loss (Davidson, 2014) (*limited evidence, medium agreement*). Many wetland-dependent species have seen a long-term decline, with the Living Planet Index showing that 81% of populations of freshwater species are in decline and others being threatened by extinction (Davidson and Finlayson, 2018; Darrah et al., 2019; Diaz et al., 2019) (*high confidence*).

Temperature changes lead to changes in the distribution patterns of freshwater species. Poleward and up-elevation range shifts due to warming temperatures tend to ultimately lead to reduced range sizes. Freshwater species in the tropics are particularly vulnerable (Jezkova and Wiens, 2016; Sheldon, 2019). Systematic shifts towards higher elevation and upstream were found for 32 stream fish species in France (Comte and Grenouillet, 2013). In North America, for the bull trout (*Salvelinus confluentus*) a reduction in the number of occupied sites was documented in a watershed in Montana (Eby et al., 2014). Other impacts include disruption of seasonal movements of migratory waterbirds that regularly visit freshwater ecosystems, with adverse impacts on their feeding and breeding (Finlayson et al., 2006; Bussière et al., 2015). Keystone species, such as the beaver (*Caster Canadensis*) in North America, have been moving into new areas as the vegetation structure has changed in response to higher temperatures enabling shrubs to establish in the Arctic and alpine tundra ecosystems (Jung et al., 2016). Increased occurrence and intensity of algal blooms have occurred due to the interactive effects of thermal extremes and low dissolved oxygen concentrations in water (Griffith and Gobler, 2020) (Section 4.2.7). A global review found that almost 90% of all studies reviewed documented a decline in salmonid populations in North America and Europe, and identified knowledge gaps elsewhere (Myers et al., 2017). Another review (Pecl et al., 2017) found declines in Atlantic salmon in Finland and poleward shift in coastal fish species, while another review (Scheffers et al., 2016) noted hybridisation between freshwater species like invasive rainbow trout (*Oncorhynchus mykiss*) and native cutthroat trout (*O. clarkia*).

Lakes have been warming, as shown by an increasing trend of summer surface water temperatures between 1985 and 2009 of 0.34°C per decade (O'Reilly et al., 2015). However, responses of individual lakes to warming were very dependent on local characteristics (O'Reilly et al., 2015), with warming enhancing the impacts of eutrophication in some instances (Sepulveda-Jauregui et al., 2018). For example, temperature increases led to lower oxygen concentrations in eutrophic coastal wetlands due to phytoplankton and microbial respiration (Jenny et al., 2016) and stimulated algal blooms (Michalak, 2016) and affected the community structure of fish and other biotas (Mantyka-Pringle et al., 2014; Poesch et al., 2016).

Rising temperatures have a strong impact in the arctic zone, where the southern limit of permafrost is moving north and leading to changes in the landscape (Arp et al., 2016; Minayeva et al., 2018). Thawing of the permafrost leads to increased erosion and runoff and changes in the geomorphology and vegetation of arctic peatlands (Nilsson et al., 2015; Sun et al., 2018b). Permafrost thawing has led to the expansion of lakes in the Tibetan Plateau (Li et al., 2014). As northern high-latitude peatlands store a large amount of carbon, permafrost thawing can increase methane and carbon dioxide emissions (Schuur et al., 2015; Moomaw et al., 2018). This represents a major gap in our understanding of the rates of change and their consequences for freshwater ecosystems.

The extent of past degradation due to multiple drivers is important, as climate change is expected to interact synergistically and cumulatively with these (Finlayson et al., 2006), exacerbate existing problems for wetland managers and potentially increase emissions from carbon-rich wetland soils (Finlayson et al., 2017; Moomaw et al., 2018). Freshwater ecosystems are also under extreme pressure from changes in land use and water pollution, with climate change exacerbating these, such as the further decline of snow cover (DeBeer et al., 2016) and increased consumptive use of fresh water, and leading to the decline, and possibly extinction, of many freshwater-dependent populations (*high confidence*). Thus, differentiating between the impacts of multiple drivers is needed, especially given the synergistic and cumulative nature of such impacts, which remains a knowledge gap.

In summary, climate change is one of the key drivers of the loss and degradation of freshwater ecosystems and the unprecedented decline and extinction of many freshwater-dependent populations. The predominant key drivers are changes in land use and water pollution (*high confidence*).

4.3.6 Observed Impacts on Water-Related Conflicts

According to AR5, violent conflict increases vulnerability to climate change (Field et al., 2014a) (*medium evidence, high agreement*). Furthermore, the IPCC SRCCL (Hurlbert et al., 2019) concluded with *medium confidence* that climatic stressors can exacerbate the negative impacts of conflict.

Since AR5, only a 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). Some studies associate conflicts with local abundance of water (Salehyan and Hendrix, 2014; Selby and Hoffmann, 2014; de Juan, 2015), mainly because of political mobilisation around abundant waters and the need for developing new rules of allocation among competing users. Others provide evidence that the increase in water availability in some areas compared with a decrease in other surrounding areas can affect the risk of a conflict in a region (de Juan, 2015) (*low to medium confidence*). However, the large majority acknowledges reduction of water availability due to climate change as having the potential to exacerbate tensions (de Stefano et al., 2017; Waha et al., 2017), especially in regions and within groups dependent on agriculture for food production (von Uexkull et al., 2016; Koubi, 2019) (*high confidence*). Particularly representative is the case of Syria, where drought aggravated existing water and agricultural insecurity (Kelley et al., 2015). However, whether drought caused civil unrest in Syria remains highly debated (Gleick, 2014; Kelley et al., 2017; Selby et al., 2017; Ash and Obradovich, 2019). Additionally, there is no consensus on the causal association between observed climate changes and conflict (Hsiang Solomon et al., 2013; Burke et al., 2015; Selby, 2019). However, evidence suggests that changes in rainfall patterns amplify existing tensions (Abel et al., 2019); examples include Syria, Iraq (Abbas et al., 2016; von Lossow, 2016) and Yemen (Mohamed et al., 2017) (*medium confidence*). There is also *medium evidence* that in some regions of Africa (e.g., Kenya, Democratic Republic of the Congo), there are links between observed water stress and individual attitude for participating in violence, particularly for the least resilient individuals (von Uexkull et al., 2020) (*medium confidence*). A reverse association from conflict to climate impacts has also been observed (Buhaug, 2016). For example, conflict-affected societies cannot address climate-change impacts due to other associated vulnerabilities such as poverty, food insecurity and political instability.

For transboundary waters, the probability of inter-state conflict can both increase and decrease (Dinar et al., 2019) depending on climatic variables (e.g., less precipitation) and other socioeconomic and political factors, such as low levels of economic development and political marginalisation (Koubi, 2019). Climate change concerns also play a role in stimulating cooperative efforts, as in the case of the Ganges-Brahmaputra-Meghna River Basin (Mirumachi, 2015; Link et al., 2016) (*medium confidence*). More generally, there is some evidence that when hydrological conditions change in transboundary river basins, formal agreements (e.g., water treaties or river basin organisations) can enhance cooperation (de Stefano et al., 2017; Dinar et al., 2019) (*medium evidence, high agreement*). Still, more cooperation does not necessarily reduce the risk of conflict, especially when water variability increases beyond a certain threshold (*low evidence, medium agreement*) (Dinar et al., 2015; Dinar et al., 2019).

In summary, there is no consensus on the causal association between observed climate change and conflicts. Still, evidence exists that those tensions can be amplified depending on climatic variables and other concomitant socioeconomic and political factors.

4.3.7 Observed Impacts on Human Mobility and Migration

AR5 (Adger and Pulhin, 2014) found links between climate change and migration in general (*medium evidence, high agreement*), but provided no assessment of climate-induced hydrological changes and migration specifically. Likewise, SRCCL (Mirzabaev et al., 2019; Olsson et al., 2020) and SROCC (Hock et al., 2019b) 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 (see Cross-Chapter Box MIGRATE in Chapter 7). This chapter confirms this evidence, focusing on climate-induced hydrological changes.

Climate-induced hydrological changes can, through slow-onset (e.g., drought) or rapid-onset (e.g., flood) events, influence human mobility and migration through effects on the economy and livelihoods (Adger et al., 2018). There is *medium confidence* that climate-induced hydrological changes have affected bilateral migration (Backhaus et al., 2015; Cattaneo and Peri, 2016; Falco et al., 2019). However, there is *medium evidence* and *low agreement* on the effects on the movements of refugees globally (Missirian and Schlenker, 2017; Owain and Maslin, 2018; Abel et al., 2019; Schutte et al., 2021).

There is *robust evidence* that floods and droughts have, mainly through adverse impacts on agriculture (Mastrorillo et al., 2016; Nawrotzki and Bakhtsiyarava, 2017; Bergmann et al., 2021; Zouabi, 2021) (Section 4.6.2), both increased and decreased the risk of temporary or permanent migration (Obokata et al., 2014; Afifi et al., 2016; Thiede et al., 2016; Murray-Tortarolo and Salgado, 2021; Wesselbaum, 2021). However, migration effects depend on the nature of the hydrological change, for example, whether it is a slow-onset or rapid-onset event (Kaczan and Orgill-Meyer, 2020), the perception of change (Koubi et al., 2016; de Longueville et al., 2020) or the socioeconomic situation of the affected communities (Ocello et al., 2015; Afifi et al., 2016; Thiede et al., 2016) (*robust evidence; medium agreement*).

The Internal Displacement Monitoring Centre (IDMC) estimates that an average of 12 million new displacements happen each year due to droughts and floods alone. By the end of 2020, there were 7 million people displaced due to natural disasters, including drought and floods (IDMC, 2020). Furthermore, household water insecurity has also been singled out as a driver of migration, given its physical, mental health and socioeconomic effects (Stoler et al., 2021) (*medium confidence*).

More research is needed to understand better the contexts in which climate-induced hydrological changes affect the likelihood of migration or alter existing patterns (Obokata et al., 2014; Gray and Wise, 2016; Cattaneo et al., 2019).

In summary, climate-induced hydrological changes can increase and decrease the likelihood of migration (*robust evidence, medium agreement*). The outcome is determined mainly by the socioeconomic, political and environmental context (*medium confidence*).

4.3.8 Observed Impacts on the Cultural Water Uses of Indigenous Peoples, Local Communities and Traditional Peoples

AR5 concluded with *high confidence* that the livelihoods and cultural practices of the diverse Indigenous Peoples of the Arctic have been impacted by climate change (Larsen et al., 2014). SROCC found with *high confidence* that cryospheric and associated hydrological changes have affected culturally significant terrestrial and freshwater species and ecosystems in high-mountain and polar regions, thus impacting residents' livelihoods and cultural identity, including Indigenous Peoples (Hock et al., 2019b; IPCC, 2019a; Meredith et al., 2019). SROCC also concluded that IKLK are vital in determining community responses to environmental risk. The report further noted that IKLK helps increase adaptive capacity and reduces long-term vulnerability, but did not assess climate-related impacts on cultural water uses on low-lying islands (Oppenheimer et al., 2019).

Freshwater (including ice and snow) has diverse meanings and symbolic representations, as well as associated practices, management and reciprocal responsibilities for many Indigenous Peoples, local communities and traditional peoples (Cave and McKay, 2016; Craft, 2018; Hansen and Antsanen, 2018; Ngata, 2018; Chiblow 2019; Wilson et al., 2019; Moggridge and Thompson, 2021). Climate-driven hydrological changes are affecting culturally significant terrestrial and freshwater species and ecosystems, particularly for Indigenous Peoples, local communities and traditional peoples in the Arctic, high mountain areas, and small islands (*high confidence*). These climate impacts on cultural water uses are influencing travel, hunting, herding, fishing and gathering practices, which have negative implications for livelihoods, cultural traditions, economies and self-determination (Table 4.5).

Some of these losses may be classified as non-economic losses and damages, such as loss of culture and traditions (Thomas and Benjamin, 2018b; McNamara et al., 2021). The vulnerability of these cultural uses to climate change is exacerbated by historical and ongoing processes of colonialism and capitalism, which dispossessed Indigenous Peoples and disrupted culturally significant multi-species relationships (Whyte, 2017; Whyte, 2018; Wilson et al., 2019; Whyte, 2020; Rice et al., 2021) (14.4.7.3; 9.13.2.4). Despite these significant structural barriers, there is *medium confidence* that some Indigenous Peoples, local communities and traditional peoples are adapting to the risks of climate-driven hydrological changes to cultural water uses and practices (Section 4.6.9).

There is *high confidence* that the prospect of loss (anticipatory grief) due to climate-related hydrological change, such as inundation or relocation, affects Indigenous Peoples, local communities and traditional peoples. These communities are especially susceptible to detrimental mental health impacts because of the implications of climate change for their cultural, land-based practices (du Bray et al., 2017). For example, fears of cultural loss in Tuvalu (Gibson et al., 2019) are resulting in worry, anxiety and sadness among local people, with similar responses reported in Fiji and other Pacific islands (du Bray et al., 2017; Yates et al., 2021) (Box 15.1).

There is *high confidence* that glacier retreat and increasing glacier runoff variability are negatively affecting cultural beliefs and practices in high-mountain areas. For example, the loss of glaciers threatens the ethnic identity of the Indigenous Manangi community of the Annapurna Conservation Area of Nepal (Konchar et al., 2015; Mukherji et al., 2019). Likewise, ice loss in the Cordillera Blanca in the Peruvian Andes has challenged traditional approaches of interacting with the glaciers (Motschmann et al., 2020) (Section 4.2.2). There is *high confidence* that cryospheric changes in high-mountain areas also impact traditional pastoral practices by altering seasonal conditions, pasture quality and water availability. For example, pasture quality in India (Ingty, 2017); Tibet Autonomous Region, People's Republic of China (Nyima and Hopping, 2019); and Bolivia (Yager et al., 2019) has been negatively impacted by climate-related hydrological changes, leading some Indigenous herders to diversify livestock, while herders in Nepal (Popular and Rik, 2016) and Peru (Postigo, 2020) have altered their routes in response to local water scarcity. Local communities in high-mountain areas understand these hydrological changes through cultural and spiritual frameworks (*medium evidence, high agreement*). For instance, in the Peruvian Andes and the Hindu Kush Himalaya, changing ice is attributed to a lack of spiritual devotion (Drenkhan et al., 2015; Konchar et al., 2015; Scoville-Simonds, 2018). Communities in the Peruvian Andes also interpret climate impacts in the broader context of socioeconomic and political injustice and inequality (Drenkhan et al., 2015; Paerregaard, 2018).

In polar areas, there is *high confidence* that the appearance of land previously covered by ice, changes in snow cover, and thawing permafrost are contributing to changing seasonal activities. These include changes in accessibility, abundance and distribution of culturally important plant and animal species. These changes are harming the livelihoods and cultural identity of Indigenous Peoples, local communities and traditional peoples. In northern Fennoscandia, for example, reindeer herders reported experiences of deteriorated foraging conditions due to changes in the winter climate (Forbes et al., 2019; Rasmus et al., 2020). In addition, Inuit and First Nations communities in Canada (Ford et al., 2019; Khalafzai et al., 2019) and Alaskan Natives and Native American communities in the USA (Norton-Smith et al., 2016) identified disruption to access routes to traditional hunting grounds and climate-related stresses to culturally important species.

Further research is needed to provide culturally informed integrated assessments of climate change impacts on Indigenous Peoples', local communities' and traditional uses of water in the context of multiple

Table 4.5 | Selected observed impacts on cultural water uses of Indigenous Peoples (also see Figure 4.6).

Region	Indigenous Peoples	Climate hazard	Water-related impact	Situated knowledge	Reference
Asia	Manangi	Increased temperatures; increased precipitation	Glacier retreat; decreased permanent snow cover	Manangi villagers reported a deep sense of spiritual loss associated with the decline of mountain snows and the receding glacier, which some attributed to a lack of spiritual devotion.	Konchar et al. (2015); Mukherji et al. (2019)
Asia	Gurung	Increased temperatures	Decreasing snow; increased snowmelt	Indigenous Gurung herders reported water scarcity in traditional water sources such as streams and wells along traditional livestock migration routes. As a result of these changes, they have altered their routes and camp locations.	Popular and Rik (2016)
Asia	Dokpa	Increased temperatures	Decreasing snowfall	Dokpa herders reported that pasture conditions have deteriorated due to shallower snowpack, shorter winters and erratic rainfall, which has impacted sheep populations. As a result of these changes, Dokpa herders are replacing traditionally important sheep with yaks, which are more tolerant to poor-quality pasturage.	Ingty (2017)
Asia	Jagshung pastoralists	Increased temperatures	Glacier melt	Due to the expansion of the majority of large lakes on the Tibetan Plateau, herders in Jagshung Village have lost large areas of pastures to inundation. As a result, the quality of nearby feed has also deteriorated, which has led to reduced livestock populations and productivity.	Nyima and Hopping (2019)
Central and South America	Aymara	Increased temperatures	Glacier loss	Decreasing rain and snow have led to degraded and dry peatland pastures (*bofedales*). This reduction of pasture contributes to out-migration, over-grazing and the loss of ancestral practices and community commitment to pasture management (Table 12.5).	Yager et al. (2019)
Central and South America	Quelcaya pastoralists	Increased temperatures; reduced rainfall; increasing precipitation variability	Decreased snow and ice	Pastoralists reported water scarcity in traditional water sources along migration routes. As a result, women pastoralists had to herd livestock farther to find water. Pastoralists also reported the deterioration of pasture due to decreasing water availability (Table 12.5).	Postigo (2020)
Europe	Saami	Increased winter temperature; Increased summer precipitation	Harder and deeper snow cover; increased ice formation; flooding rivers and wet ground	Changes in the quality of winter pastures (especially decreased access to forage and the amount of forage) have increased the number of working hours and altered reindeer herding practices. Rainy summers increase the difficulty of gathering and moving reindeer to round-up sites and limit hay production for supplementary winter feed (13.8.1.2).	Forbes et al. (2019); Rasmus et al. (2020)
North America	Kashechewan First Nation	Increased temperatures	Flooding	The timing and extent of spring flooding have changed, which, combined with inadequate infrastructure, have increased the frequency and risk of flooding for the Kashechewan community. Earlier snowmelt has also affected the migration patterns of migratory birds and reduced the duration of traditional hunting and harvesting camps for culturally important species (14.4.6.7, 14.4.7.1).	Khalafzai et al. (2019)
North America	Inuit	Increased temperatures (an average of 2.18°C from 1985 to 2016)	Changing ice conditions	Trail access models showed that overall land and water trail access in the Inuit Nunangat had been minimally affected by temperature increase between 1985 and 2016. However, these findings illustrate that although Inuit are developing new trails and alternative forms of transport, these changes could negatively impact cultural identity and well-being (14.4.6.7, 14.4.7.1).	Ford et al. (2019)
North America	Inuit	Increased temperatures; increased precipitation	Early snowmelt	Inuit in Labrador, Canada, are grieving the rapid decline of culturally significant caribou, which is partly due to rising temperatures in the circumpolar north and the associated changes to caribou habitat and migration. In addition, the decline of this species is negatively affecting their sense of cultural identity because of the importance of hunting and cultural continuity (14.4.6.7, 14.4.7.1).	Cunsolo et al. (2020)
North America	Alaskan Natives	Increasing temperatures	Increasing temperature of freshwater lakes; permafrost melt; thinning ice	In Alaska, permafrost melting and the shorter ice season make it more difficult for hunters to access traditional hunting grounds. Increased temperatures are changing the habitats and migration patterns of culturally important freshwater species. Declining fish health and populations threaten requirements of treaty rights and tribal shares of harvestable fish populations 14.4.6.7, 14.4.7.1.	Albert et al. (2018); Norton-Smith et al. (2016)

Region	Indigenous Peoples	Climate hazard	Water-related impact	Situated knowledge	Reference
Small islands	iTaukei	Sea level rise	Flooding, inundation and salt-water intrusion	The village of Vunidogola was relocated in response to inundation, storm surges and flooding, which villagers found emotionally and spiritually distressing. Although the village was relocated as a single unit and on customary lands, the shift away from the coast has impacted spiritual relationships, as the ocean is an integral part of village culture (15.6.5).	Charan et al. (2017); Piggott-McKellar et al. (2019a)
Small islands	iTaukei	Sea level rise	Coastal erosion; inundation	Villagers of Viti Levu reported their grief at the potential loss of their traditions and livelihoods. In addition, they are concerned as to how climate change is affecting their cosmology and cultural traditions and understand possible relocation as another source of cultural loss (15.6.5).	du Bray et al. (2017); McNamara et al. (2021)
Small islands	Funafuti	Sea level rise	Coastal erosion; inundation	In addition to climate impacts and stresses affecting Tuvalu, the potential for further environmental hardships in the future exacerbated worry and distress for local people, who are anxious about future cultural loss arising from sea level rise (15.6.5).	Gibson et al. (2019); Yates et al. (2021); McNamara et al. (2021)

stresses, disparities and inequities (Yates et al., 2021). In the Arctic, for example, increased rates of development and resource extraction, including hydropower dams, mining, fisheries and sport hunting, all threaten water quality, habitat condition and the ecosystem services provided by Arctic freshwaters (Mustonen and Mustonen, 2016; Knopp et al., 2020).

In summary, the cultural water uses of Indigenous Peoples, local communities and traditional peoples are being impacted by climate change (*high confidence*), with implications for cultural practices and food and income security, particularly in the Arctic, high-mountain areas and small low-lying islands.

4.4 Projected Changes in the Hydrological Cycle Due to Climate Change

The terrestrial hydrological cycle is projected to intensify through a higher exchange of water between the land surface and the atmosphere. A rise of near-surface atmospheric water capacity is projected because of greater warming leading to changes in the atmospheric circulation patterns, the intensification of the convection processes, and the increased temperature of the underlying surface. Continuation of projected warming and other physical mechanisms will further accelerate the melting of snow cover and glaciers and thawing of permafrost (*high confidence*).

Methodologically, the projected changes in the hydrological cycle due to climate change are assessed directly from climate models or hydrological system models driven by the climate models' projections (SM4.1). The latter is simulated by the CMIP-based multi-model experiments carried out under the scenarios of future climate forcing and socioeconomic changes (e.g., RCPs, SSPs scenarios) or the pre-assigned global warming levels over the 21st century. Since AR5, there has been an improvement of the physical basis of the climate change impact projections owing to the advances in modelling clouds, precipitation, surface fluxes, vegetation, snow, floodplains, groundwater and other processes relevant to the water cycle (Douville et al., 2021) (SM4.1).

The subsections highlight the projected responses of these hydrological systems/processes to multiple drivers, high variability and the uncertainty of the projections, depending on regions, seasons, temporal and spatial scales, and the influence of the non-climatic factors.

4.4.1 Projected Changes in Precipitation, Evapotranspiration and Soil Moisture

4.4.1.1 Projected Changes in Precipitation

WGI (Douville et al., 2021) concludes with *high confidence* that without large-scale reduction in GHG emissions, global warming is projected to cause substantial changes in the water cycle at both global and regional scales. However, WGI also noted large uncertainties in many aspects of regional water cycle projections by climate models. Water cycle variability and extremes are projected to increase faster than average changes in most regions of the world and under all emission scenarios (*high confidence*). The concept of 'wetter regions get wetter, drier regions get drier' from AR5 (Collins et al., 2013) is assessed by AR6 WGI (Douville et al., 2021) as too simplistic. WGI (Seneviratne et al., 2021) further concludes that heavy precipitation will generally become more frequent and more intense with additional global warming.

In the CMIP6 multi-model ensemble, as in previous generations of ensembles, the projected changes in annual mean precipitation vary substantially across the world. Importantly, in most land regions, the future changes are subject to high uncertainty even in the sign of the projected change (*high confidence*). Figure 4.10 illustrates this using the 5th, 50th and 95th percentile changes across the ensemble at individual grid points. For any given location, the range of projected changes generally increases with global warming (*high confidence*).

For example, in parts of the Indian sub-continent, the projected changes in mean precipitation at 1.5°C global warming range from a 10–20% decrease to a 40–50% increase. The multi-model median change is close to zero. Most other regions show a smaller range of changes (except for very dry regions where a small absolute change in precipitation appears as a larger percentage change). Nevertheless, across most global land regions, both increases and decreases in precipitation are projected across the ensemble. At 1.5°C global warming, a complete consensus

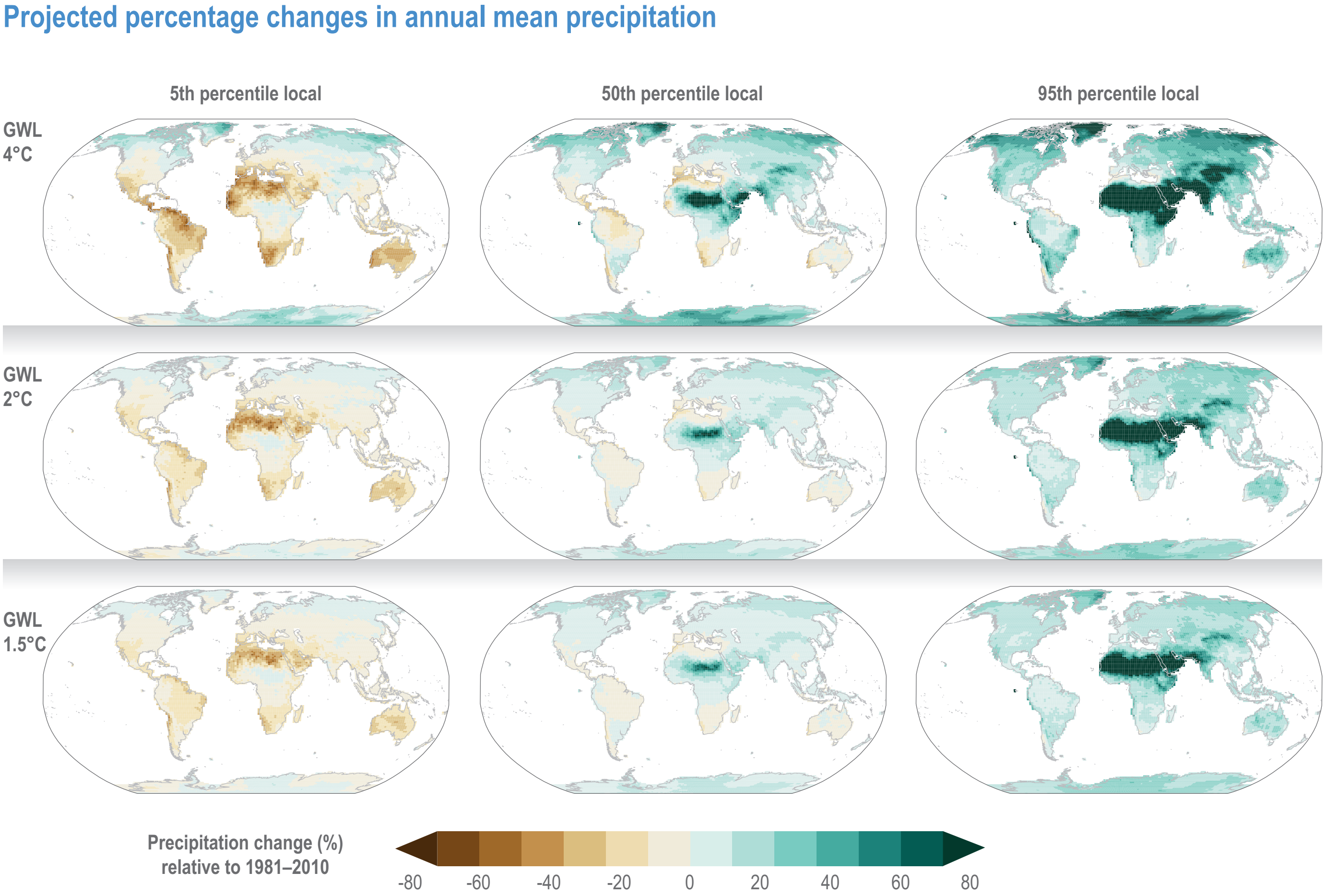


Figure 4.10 | Projected percentage changes in annual mean precipitation at global warming levels (GWLs) of 4°C (top), 2°C (middle) and 1.5°C (bottom) for the CMIP6 multi-model ensemble of GCMs driven by the SSP5-8.5 scenario. For any given GWL, similar ranges of changes are seen with other scenarios that reach that GWL, and the difference between scenarios is smaller than the ensemble uncertainty (Seneviratne et al., 2021). The distribution of outcomes is shown at local scales with the 5th, 50th and 95th percentile precipitation changes in individual grid boxes. Note that these are uncertainties at the individual point and are not spatially coherent, that is, they do not represent plausible global patterns of change. Results for 1.5°C, 2°C and 4°C global warming are defined as 20-year means relative to 1850–1900 and use 40, 40 and 31 ensemble members, respectively, due to some members not reaching 4°C global warming.

on increased precipitation is seen only in the central and eastern Sahel, south-central Asia, parts of Greenland and Antarctica, and the far northern regions of North America and Asia, with projected increases in the latter ranging up to 20–30%. No land regions see a complete consensus on decreased precipitation, but South America, southern Africa and the Mediterranean region show a stronger consensus towards reduced precipitation.

The geographical patterns of local agreement/disagreement in projected precipitation change remain broadly similar with increased global warming, but the range of uncertainty generally increases (*high confidence*). For example, in northeastern Amazonia, the driest projections increase from a 10% decrease at 1.5°C global warming to a 40% decrease at 4°C global warming. In comparison, the wettest projections remain at up to a 10% increase. In the far north of North America and Asia, the higher end of projected increases in precipitation extends to approximately 40–60%. A few regions are projected to see a shift in the consensus on the sign of the change. These include parts of the Indian sub-continent where at 4°C global warming, the projected changes shift to a consensus on increased precipitation ranging between a few percent to over 70%.

Notably, the multi-model median change in precipitation is relatively small in many regions—less than 10% over most of the global land surface at 1.5°C global warming. In contrast, in many locations, the 5th to 95th percentile range can include changes that are much larger changes than the median and also changes that are relatively large but opposite in sign. At 4°C global warming, the median projected changes are larger, ranging from a 20% decrease to a 40% increase (excluding very dry areas, where percentage changes can be much larger due to very small baseline values), but nevertheless often remain a poor indicator of the range of changes across the ensemble. Therefore, use of the median or mean projected changes for future adaptation decisions could substantially underestimate the risk of large changes in precipitation. It could mean that the risk of the opposite sign of changes is not accounted for. Indeed, for mean precipitation, different multi-model ensembles can show different levels of significance of the central estimate of change (Uhe et al., 2021: Figure 4.11a). Consequently, information on the range of possible outcomes can be valued by users for effectively informing risk assessments (Lowe et al., 2018).

There is a stronger consensus on changes in heavy precipitation than mean precipitation within individual ensembles such as CMIP6

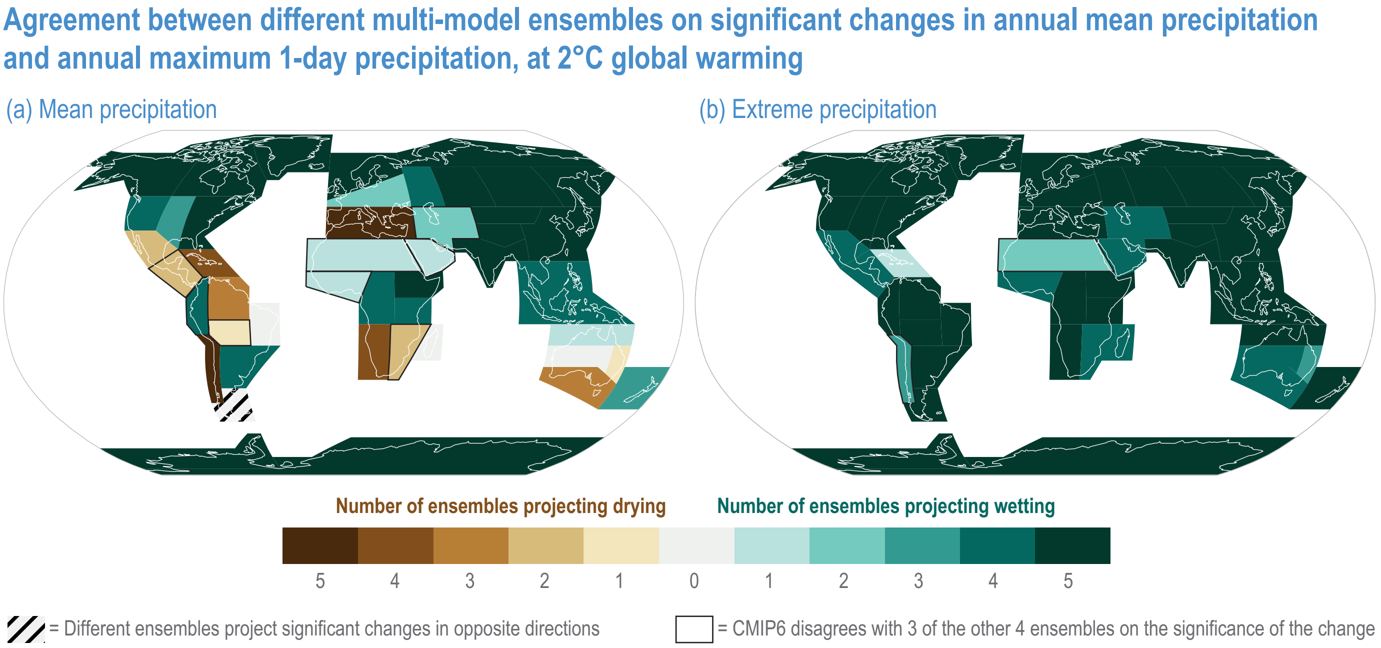


Figure 4.11 | Agreement between different multi-model ensembles on significant changes in (a) annual mean precipitation and (b) annual maximum 1-d precipitation (Rx1day) at 2°C global warming (Uhe et al., 2021). Using central estimates from five ensembles of climate models (CMIP5, CMIP6, HAPPI, HELIX and UKCP18) using different models and different experimental designs for the ensembles, the maps show the number of ensembles for which the central estimate shows a significant drying or wetting change at 2°C global warming relative to pre-industrial levels. The different ensembles reach 2°C global warming at different times. The projected changes are aggregated over the new climatic regions defined for IPCC AR6 (Iturbide et al., 2020). Hatched regions show where different ensembles project significant changes in opposite directions, i.e., there is no agreement on either drying or wetting. Regions with thick outlines are where CMIP6 disagrees with three of the other four ensembles on the significance of the change, highlighting where over-relying on CMIP6 alone may not fully represent the level of confidence in the projections.

(Figure 4.12) and especially between the means of the different ensembles (Figure 4.11b). At 4°C global warming, the 50th percentile projection is for increased annual maximum 1-d precipitation over virtually all global land, with the median increase being over 20% for a majority of the land. The 95th percentile increase is 20–40% over most mid-latitude areas and at least 40-–70% over the tropics and subtropics, exceeding 80% over western Amazonia, central Africa and most of the Indian sub-continent. The 5th percentile also shows an increase over most global land; in other words, decreased heavy precipitation has less than a 5% probability in these regions (Figure 4.12a), although decreases remain possible but of low probability in some regions, particularly northern South America and northern and western Africa. At the 50th and 95th percentiles, similar global patterns of change are projected at 2°C and 1.5°C global warming, with smaller local magnitudes (Figure 4.12e,f,h,i). At the 5th percentile, decreased Rx1day is seen over much larger land areas (Figure 4.12d,g), which may be a result of internal climate variability being relatively larger than the long-term trend at lower GWLs. In CMIP5, precipitation extremes are projected to be *more likely* to increase than to decrease on average over both the humid and arid regions of the world, but with larger uncertainty in arid areas (Donat et al., 2019).

In the 50th percentile projections at 4°C global warming, dry spells are projected to become up to 40 d longer in South America and southern Africa and up to 20 d shorter in large parts of Asia (Figure 4.13a,b,c). In most regions, the projected changes in dry spell lengths are highly uncertain. In southern Africa, the increase in dry spell length ranges from 10 d to over 40 d. In northeast Asia, dry spells are projected to become shorter by up to 20–30 d. In much of South America, dry spells could increase by over 40 d or decrease by over 10 d. Similar global patterns with smaller magnitudes of change are projected for 2°C and 1.5°C global warming in all three percentiles (Figure 4.13d,e,f,g,h,i).

Taken together, these projections of more intense precipitation and changes in the length of dry spells give a clear picture of increasingly volatile precipitation regimes, with many regions seeing both longer dry spells and heavier events when precipitation does occur (*high confidence*).

The critical knowledge gap for precipitation projections is the ability to make precise projections. With such large uncertainties in many regions, climate model projections can inform risk assessments, but cannot provide confident predictions of specific outcomes.

In summary, the annual mean precipitation range is projected to increase or decrease by up to 40% or more at 4°C global warming over many land areas. The ranges of projected precipitation changes are smaller at lower levels of global warming (*high confidence*). Either an increase or decrease is possible in most regions, but there is an agreement among models on the increase in the far north (*high confidence*). There is a stronger model consensus on heavy precipitation increasing with global warming over most land areas (*high confidence*). There are widely varying projections of change in dry spell length (*high confidence*), but in regions with increasing projected dry spells, the potential increase is larger at higher levels of global warming (*high confidence*).

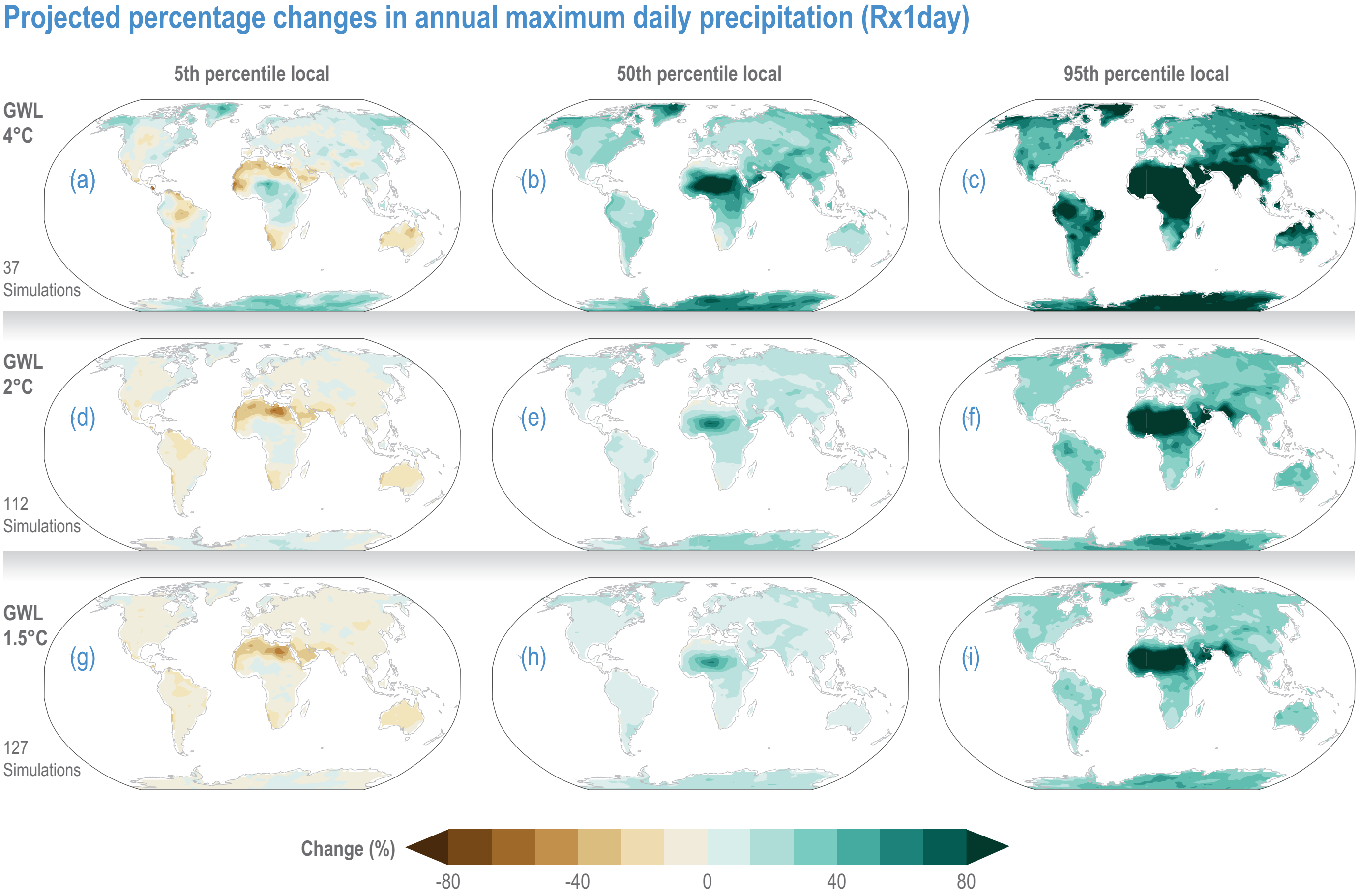


Figure 4.12 | Projected percentage changes in annual maximum daily precipitation (Rx1day) averaged over 20 years centred at the time of first passing (a–c) 4°C, (d–f) 2°C and (g–i) 1.5°C global warming levels (GWLs) relative to 1851–1900. Results are based on simulations from the CMIP6 multi-model ensemble under the SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios. Uncertainties in the projections are quantified with the (a, d, g) 5th, (b, e, h) 50th and (c, f, i) 95th percentile local values from the ensemble at each GWL. Note that these are uncertainties at the individual point and are not spatially coherent, that is, they do not represent plausible global patterns of change. The 50th percentile maps (b, e, h) present the same data over land as Figure 11.16 of Seneviratne et al. (2021). The numbers on the left indicate the number of simulations included at each warming level, including multiple realisations from some models with varying initial conditions, depending on data availability. Results for the 1.5°C GWL include 37 unique models. Fewer models and realisations are available for the 2°C and 4°C GWLs, as fewer scenarios and/or models reach those warming levels. For individual models, the global patterns of changes are very similar across scenarios, and any differences between scenarios are smaller than the ensemble uncertainty for an individual scenario. The CMIP6 projections of changes in mean and extreme precipitation are discussed in more detail by WGI (Doblas-Reyes et al., 2021; Seneviratne et al., 2021).

4.4.1.2 Projected Changes in Evapotranspiration

AR5 (Collins et al., 2013) found that the CMIP5 model projections of ET increases or decreases followed the same pattern over land as precipitation projections, with additional impacts of reduced transpiration due to plant stomatal closure in response to rising CO_2 concentrations. AR6 WGI (Douville et al., 2021) assessed that it is *very likely* that ET will increase over land, with regional exceptions in drying areas.

In most CMIP5 and CMIP6 models, projected ET changes are driven not just by meteorological conditions and soil moisture but also by plant physiological responses to elevated CO_2, which themselves influence meteorology and soil moisture through surface fluxes (Halladay and Good, 2017; Lemordant and Gentine, 2019). Elevated CO_2 causes stomatal closure which decreases ET, but also increases leaf area index (LAI) which in turn increases ET, but these do not necessarily compensate (Skinner et al., 2017). Higher LAI increases transpiration, depleting soil moisture but increasing shading, thus reducing soil evaporation (Skinner et al., 2017), but LAI may not increase in areas where it is already high (Lemordant et al., 2018). Projected ET decreases from physiological effects alone are widespread but greatest in tropical forests (Swann et al., 2016; Kooperman et al., 2018).

Future changes in regional ET are therefore highly uncertain. The CMIP6 multi-model ensemble projects changes in ET varying both in magnitude and sign across the ensemble members (Figure 4.14). At 4°C global warming, the ensemble median projection shows increased ET of approximately 25% in mid/high latitudes but decreases of up to 10% across most of tropical South America, southern Africa and Australia. These CMIP6 ensemble projections resemble ET changes projected by the CMIP5 ensemble, except over central Africa and Southeast Asia (Berg and Sheffield, 2019). However, the ensemble ranges are wide and include both increases and decreases in projected ET in many locations, with mid-latitude ET increases being up to approximately 50% and ET decreases in southern Africa being up to approximately 30%. Projected changes

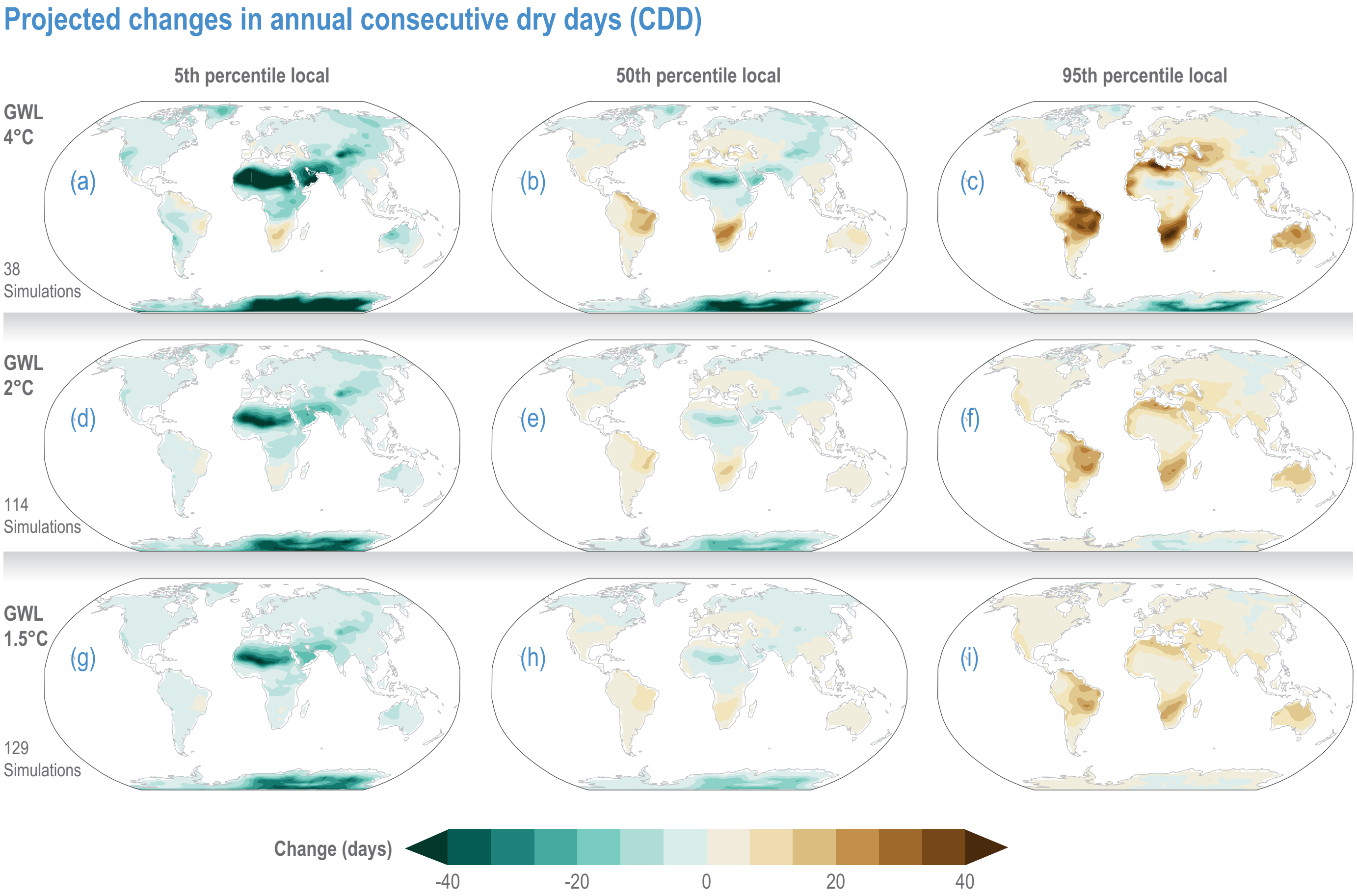


Figure 4.13 | As Figure 4.12 for projected changes in annual consecutive dry days (CDD), the highest number of days yr^{-1} with precipitation < 1 mm. The 50th percentile maps (b, e, h) present the same data as Figure 11.19a,b,c of Seneviratne et al. (2021).

are proportionally smaller at lower levels of global warming, while patterns of change remain similar.

The relative importance of the physiological and radiative effects of CO_2 on future ET is a crucial knowledge gap, partly because many ESM land surface schemes still use representations of this process based on older experimental studies. Furthermore, large-scale experimental studies using free-air CO_2 enrichment (FACE) techniques to constrain the models have not yet been performed in certain critical ecosystems, such as tropical forests. Finally, uncertainties in equilibrium climate sensitivity (ECS) imply uncertainties in the CO_2 concentration accompanying any given level of warming (Betts and McNeall, 2018).

In summary, the sign of projected ET change depends on region, but there is *medium confidence* that ET will increase in the global mean and mid/high latitudes and decrease in northern South America and southern Africa. In addition, the impacts of rising CO_2 concentrations on plant stomata and leaf area play a role in model projections of ET change (*high confidence*), but there is *low confidence* in their overall contribution to global ET change.

4.4.1.3 Projected Changes in Soil Moisture

AR5 (Collins et al., 2013) mainly focused on surface (upper 10 cm) soil moisture, summarising 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 global warming increases. AR6 WGI (Douville et al., 2021) draw broadly similar conclusions based on new ESMs, noting that compared to CMIP5, the CMIP6 models project more consistent drying in the Amazon basin, Siberia, westernmost North Africa and southwestern Australia. WGI (Douville et al., 2021) also note that soil moisture in the upper 10 cm shows more widespread drying than in the total soil column.

The CMIP6 multi-model ensemble of ESMs show varying levels of consensus on projected changes in surface soil moisture with global warming (Figure 4.15). As in CMIP5 (Cheng et al., 2017), uncertainties are substantial, often associated with uncertainties in projected regional precipitation changes (Section 4.4.1.1), and in most regions, both increases and decreases are projected across the ensemble. In the far north of North America and Asia, projected changes in soil moisture at 4°C global warming range from a 20–30% decrease to an increase of 30–40%. In northern mid-latitudes, projections range from a 10–20% decrease to an increase of 20–30%, except for eastern North

Projected percentage changes in annual mean evapotranspiration (ET)

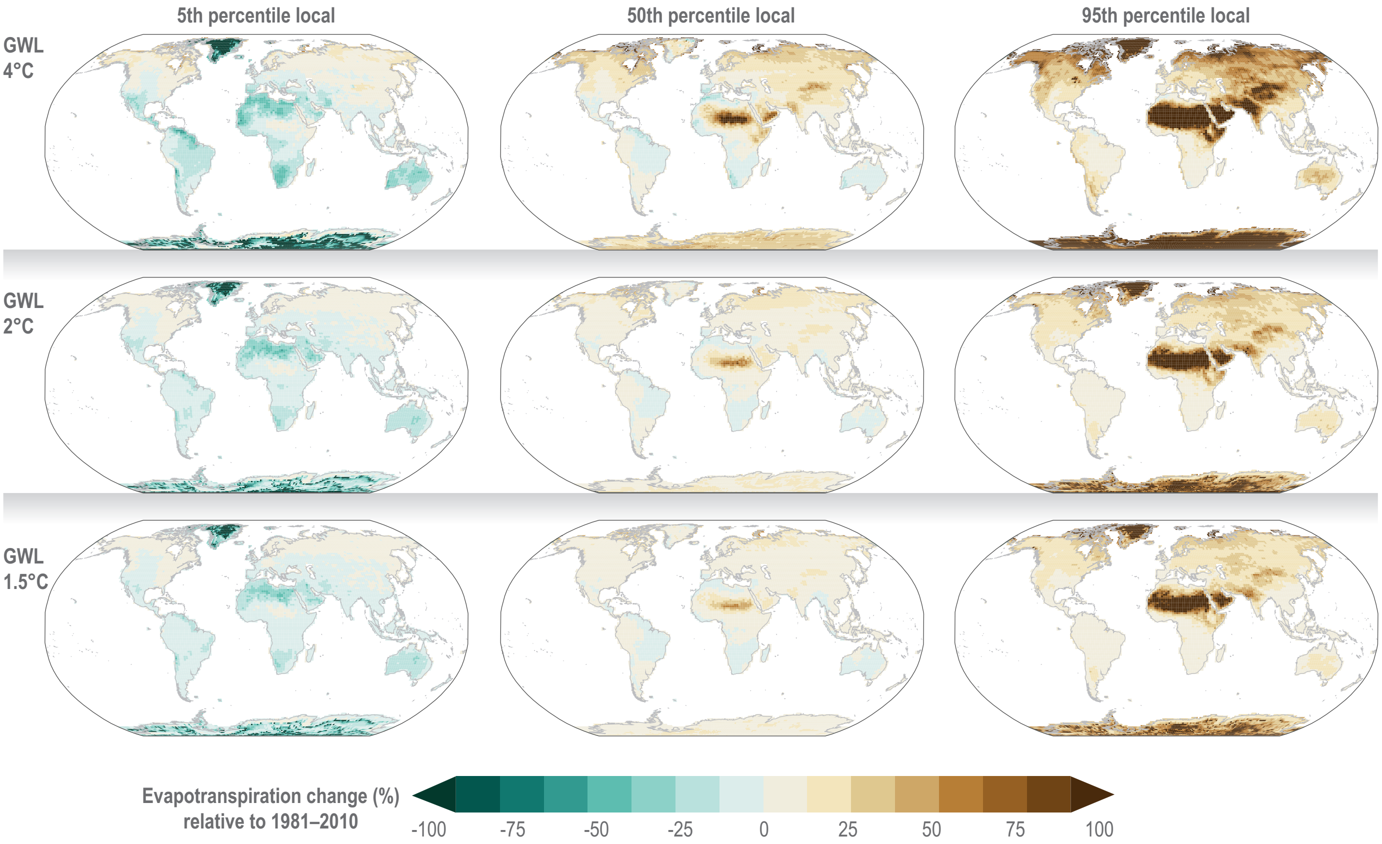


Figure 4.14 | Projected percentage changes in annual mean ET at global warming levels (GWLs) of 4°C (top), 2°C (middle) and 1.5°C (bottom) for the CMIP6 multi-model ensemble of GCMs driven by SSP5-8.5 concentrations. The distribution of outcomes is shown at local scales with the 5th, 50th and 95th percentile ET changes in individual grid boxes. Note that these are uncertainties at the individual point and are not spatially coherent, that is, they do not represent plausible global patterns of change. Results for 1.5°C, 2°C and 4°C global warming are defined as 20-year means relative to 1850–1900 and use 40, 40 and 31 ensemble members, respectively, due to some members not reaching 4°C global warming.

America, where the projected changes (both increases and decreases) are less than 10%, and western Europe and the Mediterranean where there is a stronger consensus towards decreased soil moisture of up to 25%. South America, southern Africa and Asia also show a stronger consensus towards decreased soil moisture of up to 40% or more in some regions.

Most CMIP6 models simulate direct CO_2 effects on plant transpiration, which has been shown to be a strong influence on projected future changes in soil moisture (Milly and Dunne, 2016). Approaches that neglect this process project greater decreases in soil moisture availability than the climate models (Roderick et al., 2015; Swann et al., 2016). Therefore, although several studies project increased global aridity and dryland expansion (Feng and Fu, 2013; Sherwood and Fu, 2014; Huang et al., 2016a), these may overestimate future drying (Berg et al., 2017). Nevertheless, land surface models, including vegetation responses to $CO_{2,}$ still project reduced soil moisture in many regions (Grillakis, 2019).

A critical knowledge gap concerns the relative importance of climate and CO_2 physiological effects on soil moisture, in relation to uncertainties in climate sensitivity. For a given level of global warming, the relative importance of climate effects and the direct effects of CO_2 on transpiration depend on the CO_2 concentration accompanying that level of warming (Betts and McNeall, 2018). Some CMIP6 models have very high climate sensitivities (Meehl et al., 2020), which are assessed as being of low probability on the basis of other lines of evidence (Sherwood et al., 2020). This means that the CO_2 concentration accompanying specific global warming levels may be too low and lead to overly large projections of soil moisture decrease in those models.

In summary, projected soil moisture changes increase with levels of global warming (*high confidence*), although there remains substantial disagreement on specific regional changes. In the CMIP6 multi-model ensemble at 4°C global warming, decreased soil moisture of up to 40% is projected in Amazonia, southern Africa and western Europe in all models (*high confidence*). In all other regions, there is no consensus on the sign of projected soil moisture changes, and projected changes at 4°C global warming include decreases of up to 30% and increases of up to 40%. Projected changes are smaller at lower levels of global warming, with similar geographical patterns of change.

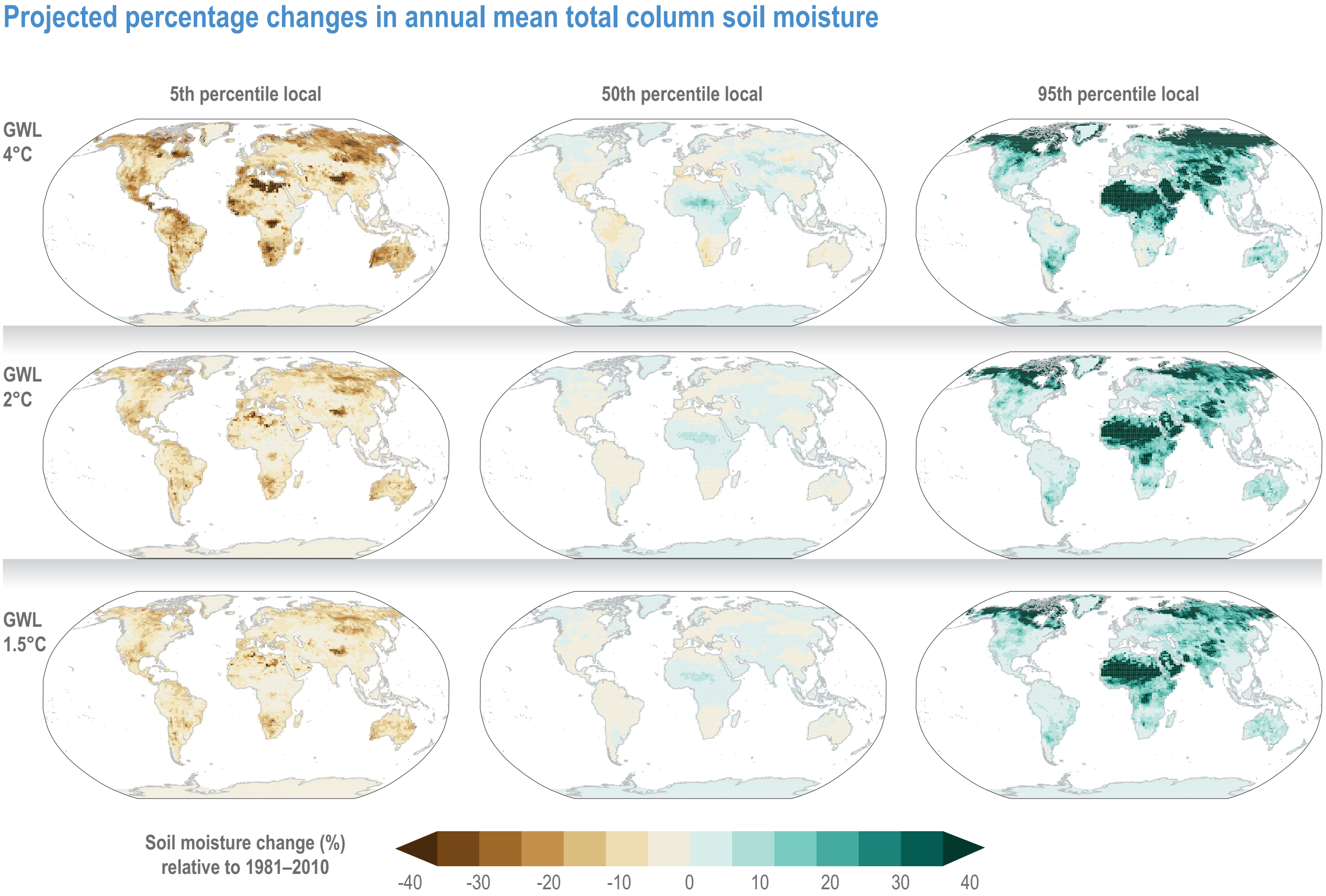


Figure 4.15 | Projected percentage changes in annual mean total column soil moisture relative to 1981–2010 at global warming levels (GWLs) of 4°C (top), 2°C (middle) and 1.5°C (bottom) for the CMIP6 multi-model ensemble of GCMs driven by SSP5-8.5 concentrations. The distribution of outcomes is shown at local scales with the 5th, 50th and 95th percentile soil moisture changes in individual grid boxes. Note that these are uncertainties at individual points and are not spatially coherent, that is, they do not represent plausible global patterns of change. Results for 1.5°C, 2°C and 4°C global warming are defined as 20-year means relative to 1850–1900 and use 34, 34 and 26 ensemble members, respectively, due to some members not reaching 4°C global warming. Fewer models are shown here than in Figure 4.10 on precipitation and Figure 4.14 on ET because some do not provide soil moisture output.

4.4.2 Projected Changes in the Cryosphere (Snow, Glaciers and Permafrost)

AR5 noted that global glacier mass loss is *very likely* to increase further during the 21st century (Jiménez Cisneros et al., 2014). According to the SROCC (Hock et al., 2019b), it is *very likely* that glaciers will continue to lose mass throughout the 21st century: from 18% (by 2100, relative to 2015) for RCP2.6 to 36% for RCP8.5. AR5 (Collins et al., 2013) and SROCC (Meredith et al., 2019) reported with *high confidence* that permafrost would continue to thaw in the 21st century, but the projections are uncertain. Constraining warming to 1.5°C would prevent the thawing of a permafrost area of 1.5 to 2.5 million km^2 compared to thawing under 2°C (*medium confidence*) (IPCC, 2018b). AR5 (Collins et al., 2013) and SROCC (Meredith et al., 2019) concluded that Northern Hemisphere snow extent and mass would likely reduce by the end of the 21st century, both in plain and mountain regions. AR6 assessed with *medium confidence* that under RCP2.6 and RCP8.5 from 2015 to 2100, glaciers are expected to lose 18% and 36% of their early 21st-century mass, respectively (AR6 WGI, (Fox-Kemper et al., 2021)).

Global glacier mass loss since 2015 and 2100 was projected to be 18 ± 13% by 2100 with 0.9 – 2.3°C global warming and 36 ± 20% with 3.2 – 5.4°C global warming (Marzeion et al., 2020), which corresponds with previous findings (Radić et al., 2014; Hock et al., 2019a; Shannon et al., 2019). The regional glacier loss rate projections are unevenly distributed worldwide and considerably vary between scenarios (Huss and Hock, 2018; Hock et al., 2019a). In most regions, 'peak water' has already been reached or is expected to be reached before mid-century (with an earlier 'peak water' for RCP2.6 scenario compared with RCP8.5) (Huss and Hock, 2018; Pritchard, 2019; Marzeion et al., 2020; Rounce et al., 2020). 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 seasons (Farinotti et al., 2016; Huss and Fischer, 2016; Hanzer et al., 2018; Brunner et al., 2019).

Such changes in runoff could potentially lead to water shortages for over 200 million people in the high mountains of Asia (Pritchard, 2019; Shahgedanova et al., 2020). There is *medium confidence* that under a 4°C warming scenario, 40% of current irrigated demand in sub-basins relying primarily on snowmelt runoff would need to be supplemented from other water sources (Qin et al., 2020). Basins where such alternate sources are not available will face agricultural water scarcity (Section 4.5.1). Globally, 1.5 billion people are projected to critically depend on runoff from the mountains by the mid-21st century under the RCP6.0 scenario (Viviroli et al., 2020). Furthermore, there is *medium confidence* that projected changes in snow and glacier melt runoff will affect water inputs to hydropower, leading to a decline in hydroelectricity production in mountain basins, for example, in India (Ali et al., 2018), Switzerland (Schaefli et al., 2019) and the USA (Lee et al., 2016) (Section 4.5.2) (IPCC AR6 WGI, 2021) (Sections 9.5.1.3 and 8.4.1.7.1).

Projections of snow cover metrics [IPCC AR6 WGI, 2021 (Section 9.5.3.3)] suggest a further decrease in snow water equivalent (SWE) and snow cover extent (SCE), though the inter-model spread is considerable (Lute et al., 2015; Thackeray et al., 2016; Kong and Wang, 2017; Henderson et al., 2018) (*high confidence*). The projected CMIP6 SCE and SWE changes share the broad features of the CMIP5 projections: SCE is expected to decrease in the Northern Hemisphere by approximately 20%, relative to the 1995–2014 mean value, around 2060 and stabilise afterwards under the RCP2.6 scenario, while the RCP8.5 scenario leads to snow cover losses up to 60% by 2100 (Mudryk et al., 2020). Regionally, the SWE loss will probably lead to more frequent snow droughts; for example, the frequency of consecutive snow droughts is projected to increase to 80–100% of years at 4°C warming in western Canada (Shrestha et al., 2021) and 42% of years under the RCP8.5 scenario in the western USA (Marshall et al., 2019) by 2100. Thus, by the mid- to late 21st century, for more than 2/3 of snow-dominated areas in the western USA, the ability to predict seasonal droughts and prepare robust water management plans will decline (Livneh and Badger, 2020) (Section 4.4.5).

There is a *high agreement* between the CMIP6 projections and the previous findings that permafrost will undergo increasing thaw and degradation during the 21st century worldwide (Fox-Kemper et al., 2021) . The CMIP6 models project that the annual mean frozen volume in the top 2 m of the soil could decrease by 10–40% for every degree increase of global temperature (Burke et al., 2020; Yokohata et al., 2020b). The CMIP5-based equilibrium sensitivity of permafrost extent to stabilised global mean warming is established to be about 4.0×10^6 km^2 °C^{-1} (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) at the level of 1.5°C temperature rise (Kong and Wang, 2017).

The observational knowledge gaps (Section 4.2.2) impede efforts to calibrate and evaluate models that simulate the past and future evolution of the cryosphere and its social impacts.

In summary, in most basins fed by glaciers, runoff is projected to increase initially in the 21st century and then decline (*medium confidence*). Projections suggest a further decrease in seasonal snow cover extent and mass in mid to high latitudes and high mountains (*high confidence*), though the projection spread is considerable. Permafrost will continue to thaw throughout the 21st century (*high confidence*). There is *medium confidence* that future changes in cryospheric components will negatively affect irrigated agriculture and hydropower production in regions dependent on snowmelt runoff.

4.4.3 Projected Changes in Streamflow

AR5 (Jiménez Cisneros et al., 2014) concluded that increases in the mean annual runoff are projected in high latitudes and the wet tropics and decreases in dry tropical regions, but with very considerable uncertainty. Both the patterns of change and uncertainties were found to be primarily driven by projected changes in precipitation. SR1.5 (Hoegh-Guldberg et al., 2018) concluded with *medium confidence* that areas with either positive or negative changes in mean annual runoff/streamflow are projected to be smaller for 1.5°C than for 2°C of global warming. AR6 WGI (Douville et al., 2021) conclude with *medium confidence* that global runoff will increase with global warming but with significant regional and seasonal variations. WGI further concluded with *high confidence* that runoff will increase in the high northern latitudes and decrease in the Mediterranean and southern Africa. However, there was *medium confidence* that runoff will increase in central and eastern African regions and decrease in Central America and parts of southern South America. The magnitude of the change is projected to increase with emissions. There is *medium confidence* that the seasonality of runoff and streamflow will increase with global warming in the subtropics. In snow-dominated regions, there is *high confidence* that peak flows associated with spring snowmelt will occur earlier in the year and *medium confidence* that snowmelt-induced runoff will decrease with reduced snow, except in glacier-fed basins where runoff may increase in the near term.

Changes in runoff and streamflow are projected over most of the ice-free land surface with all recent climate and hydrological model ensembles (Figure 4.16). Changes in streamflow could increase the number of people facing water scarcity or insecurity (*high confidence*) (Schewe et al., 2014; Gosling and Arnell, 2016; McMillan et al., 2016). Projections of future runoff at basin scales show considerable uncertainty in many regions, including differences in signs in many regions (Figure 4.16). This uncertainty is driven by uncertainties in regional precipitation patterns and hydrological models (Koirala et al., 2014; Asadieh et al., 2016), including vegetation responses to CO_2 and its effects on ET (Betts et al., 2015). This uncertainty in future water availability contributes to the policy challenges for adaptation, for example, for managing risks of water scarcity (Greve et al., 2018; Box 4.1). In many regions, some models project large changes in runoff/streamflow but with low consistency between models on the sign of the change (Figure 4.16). In streamflow projections driven by 11 CMIP5 models with the RCP8.5 scenario, strong model consistency (agreement by at least 10 models) is only seen over 21% of global land (Koirala et al., 2014). Consensus on the sign of projected change is smaller with the RCP4.5 scenario.

Considering a wider set of projections, the consensus on increased flows becomes stronger at higher GWLs in (for example) the Yukon, Mackenzie, Kemijoki, Amur, Hwang Ho, Yangtze, Mekong, Ganges-Brahmaputra, Nile, Zaire and Parana basins (Figure 4.16). The consensus on decreased flows becomes stronger for higher GWLs in (for example) the Colorado, Tagus, Helmand, Tigris-Euphrates and Amazon. However, in both cases, some models have projected changes of the opposite sign to the consensus. Moreover, the distribution of projected outcomes becomes notably broader at higher GWLs in (for example) the Mississippi, Yangtze and Amazon. Therefore, even with a strong global climate change signal,

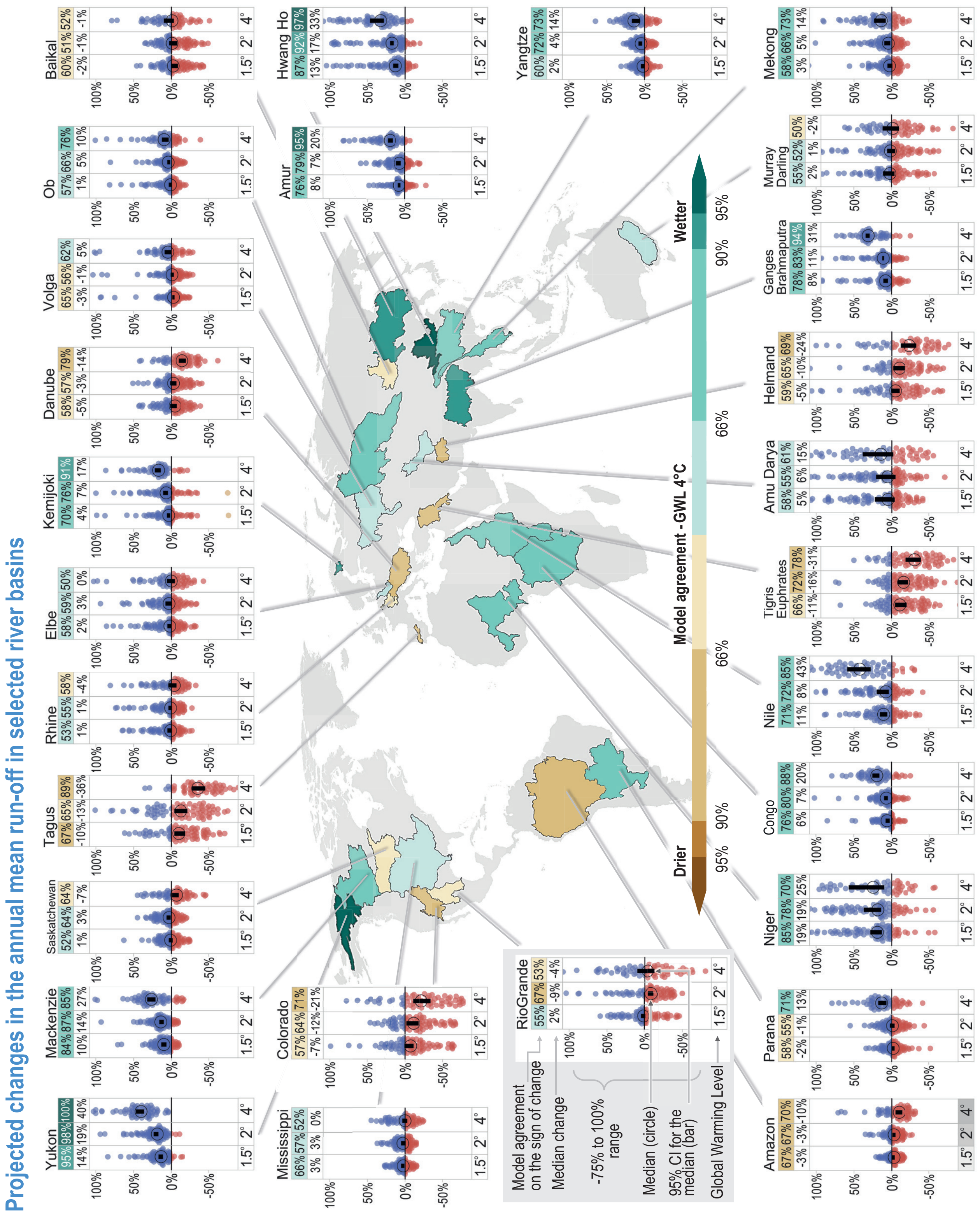


Figure 4.16 | Projected changes in the annual mean runoff in selected river basins at global warming levels (GWLs) of 1.5°C, 2°C and 4°C in a combined ensemble. For each named basin, the sinaplot dots show individual model outcomes for percentage increased flows (blue) and decreased flows (red) at each GWL. Black circles show the ensemble median, and black bars show the 95% confidence range in the median. See inset with the Rio Grande sinaplot for additional guidance on interpretation. In the map, the colours in the basins show the percentage model agreement on the sign of the projected change in streamflow at the 4°C GWL. The combined ensemble is comprised of four multi-model ensembles: the CMIP5 multi-model ensemble of GCMs driven with RCP8.5; the CMIP6 multi-model ensemble of GCMs driven with SSP5-8.5; varying combinations of hydrological models with five GCMs in the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP); and the JULES land ecosystems and hydrology model driven by GCMs from the HELIX study (Betts et al., 2018; Koutroulis et al., 2019). In CMIP5 and CMIP6, the projected runoff changes are directly from the GCM land surface schemes without bias correction. In ISIMIP and HELIX, bias-corrected climate model outputs were used to drive the hydrology models. A comparison of the projected changes at the 4°C GWL for the four individual ensembles is shown in Figure Cross-Chapter Box CLIMATE.1 in Chapter 1.

uncertainties in changes in mean runoff/streamflow can remain large or even increase. Nevertheless, since projected changes typically increase with global warming, limiting warming to 1.5°C or 2°C substantially reduces the potential for either large increases or decreases in mean streamflow compared to 3°C or 4°C (Warszawski et al., 2014; Falkner, 2016; Gosling et al., 2017; Figure 4.16) (*high confidence*).

In CMIP5, strong model consistency on changes in high and low streamflows is seen with similar global patterns to the mean flows, but over smaller areas (Koirala et al., 2014). By the end of the 21st century, with RCP8.5, increases in mean, high and low flows are projected for the Lena, and mean and low flows for the MacKenzie (Gelfan et al., 2017; Pechlivanidis et al., 2017; Döll et al., 2018). Increased mean and high flows are projected in the Ganges, high flow in the Rhine and Mississippi, while decreasing mean and low flows are projected in the Rhine (Krysanova et al., 2017; Pechlivanidis et al., 2017; Vetter et al., 2017). Decreases in mean, high and low flows are projected for the Tagus (Krysanova et al. 2017; Vetter et al. 2017). Low flows are projected to decrease in the Mediterranean region and increase in the Alps and northern Europe (Marx et al., 2018). A general shift in the runoff distribution towards more extreme low runoff is projected in Mexico, western USA, western Europe, southeastern China and the West Siberian Plain, and more extreme high runoff is projected in Alaska, northern Canada and large parts of Asia (Zhai et al., 2020).

While projected changes in high and low flows are similar to those in mean flows in many regions, this is not the case everywhere. When a single hydrological model and a sample of climate models are selected to explore uncertainties systematically, approximately 56% of the global population is projected to be affected by increased extreme high flows at 1.5°C warming, rising to 61% at 2°C warming (Zhai et al., 2020). Those affected by extreme low flows decrease is projected to remain close to 45% at both 1.5°C and 2°C warming. However, these results are based on the median of the ensemble projections, so they are subject to high uncertainty. At 1.5°C global warming, 15% of the population is projected to be affected concurrently by decreased extreme low flows and increased extreme high flows, increasing to 20% at 2°C warming. In 25 combinations of five CMIP5 climate models and five global hydrological models under the RCP8.5 scenario reaching approximately 4°C GWL at the end of the century, 10% of the global land area is projected to face simultaneously increasing high extreme streamflow and decreasing low extreme streamflow. These regions include the British Isles and the shores of the North Sea, large parts of the Tibetan Plateau, South Asia and western Oceania, and smaller regions of Africa and North and South America, affecting over 2.1 billion people with 2015 population distributions (Asadieh and Krakauer, 2017). With 11 CMIP5 models driving a single hydrological model, simultaneous increases in high flows and decreases in low flows are projected over 7% of global land (Koirala et al., 2014).

By the end of the 21st century, global changes in streamflow extremes are projected to be approximately twice as large with RCP8.5 (over 4°C GWL) than with RCP2.6 (approximately 2°C GWL) (Asadieh and Krakauer, 2017).

Glacier retreat and associated runoff changes represent a major global sustainability concern (Section 4.4.2). By 2100, using an ensemble of 14 CMIP5 climate models driven by the RCP4.5 scenario, one third of the 56 large-scale glacierised catchments are projected to experience a mean annual runoff decline by over 10%, with the most significant reductions in central Asia and the Andes (Huss and Hock, 2018). Thus, communities dependent on glacier runoff are particularly vulnerable (Jiménez Cisneros et al., 2014).

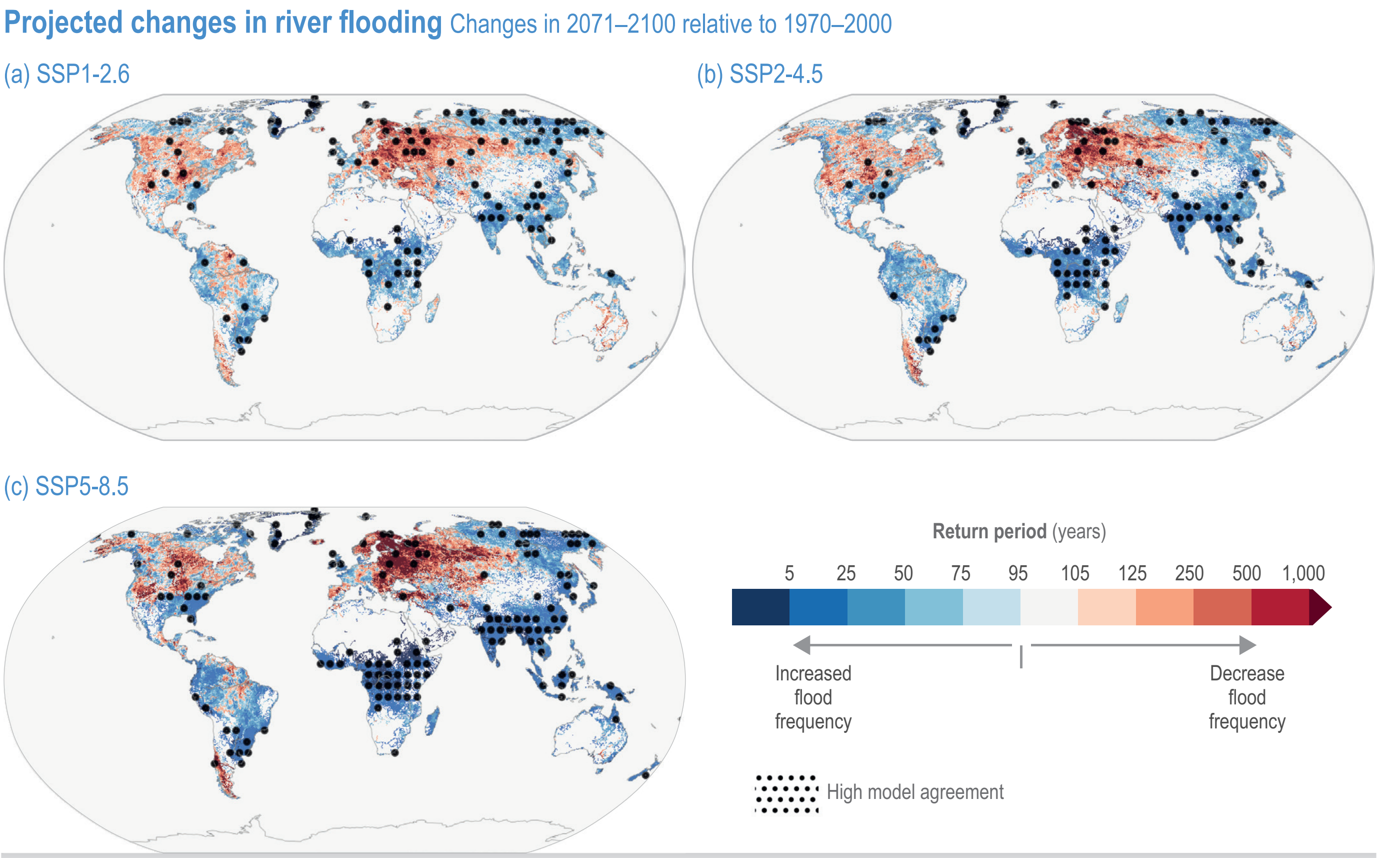
Societal impacts of change in runoff spread throughout several socioeconomic sectors, such as agriculture, health and energy production, affecting overall water security (Wang et al., 2021a). Decreases in runoff may lead to water scarcity and result in increased multi-sectoral effects in sub-Saharan Africa (Serdeczny et al., 2017), western Africa, the Middle East, Mexico, Northeastern Brazil, central Argentina, Mediterranean Africa and Europe (Gosling and Arnell, 2016; Greve et al., 2018), and southeastern Australia (Barnett et al., 2015).

In summary, mean and extreme streamflow changes are projected over most of the ice-free land surface (*high confidence*). The magnitude of streamflow change is projected to increase with global warming in most regions (*high confidence*), but there is often high uncertainty on the sign of change. There is *high confidence* that mean streamflows will increase in the northern high latitudes and decrease in the Mediterranean and southern Africa. Annual mean runoff in one third of assessed glacierised catchments is projected to decline by at least 10% by 2100 under RCP4.5, with the most significant reductions in central Asia and the Andes (*medium confidence*). Elsewhere, projections include both increased and decreased flows. Substantial fractions of ensemble projections disagree with the multi-model mean (*high confidence*), with implications for long-term planning for water management. With 1.5 and 2°C global warming, approximately 15 and 20% of the current global population, respectively, would experience both an increase in high streamflows and a decrease in low streamflows (*medium confidence*). At 4°C global at the end of the century, 10% of the global land area is projected to simultaneously experience an increase in high extreme streamflow and decrease in low extreme streamflow.

4.4.4 Projected Changes in Floods

SR1.5 (Hoegh-Guldberg et al., 2018) concluded with *medium confidence* that global warming of 2°C would lead to an expansion of the area affected by flood hazards, compared to conditions at 1.5°C global warming. Both AR5 (Jiménez Cisneros et al., 2014) and SROCC (Hock et al., 2019b) concluded that spring snowmelt floods would be earlier (*high confidence*), and hazards from floods involving meltwater will gradually diminish, particularly at low elevation (*medium confidence*). SROCC (Hock et al., 2019b) and AR6 WGI Chapter 9 stated that given *limited evidence* and the complexity of the process, the changes of glacier-related floods under climate change are not clear. AR6 WGI Chapters 8 and 11 summarised that there is *medium confidence* for a general increase in flooding due to warming, but there are significant regional and seasonal variations.

There is *high confidence* that the frequency and magnitude of river floods are projected to change at a global scale. For example, the frequency of river floods is projected to increase in many regions, including Asia, central Africa, western Europe, Central and South



Projected changes in river flooding Changes in 2071–2100 relative to 1970–2000

(d) Global and regional potential exposure of the population

Figure 4.17 | Multi-model median return period (years) in the 2080s for the 20th-century 100-year river flood, based on a global river and inundation model, CaMa-Flood, driven by runoff output of nine CMIP6 Models in the SSP1-2.6 (a), SSP2-4.5 (b) and SSP5-8.5 (c) scenario respectively. All changes are estimated in 2071–2100 relative to 1970-–2000. A dot indicates regions with high model consistency (more than seven models out of nine show the same direction of change).

(d) Global or regional potential exposure (% to the total population affected by flooding) under different global warming levels with a constant population scenario and climate of CMIP5-HELIX (circle, Alfieri et al., 2017) and CMIP6 (triangle, Hirabayashi et al., 2021b), and with the population scenario of SSP5 and climate of CMIP6 (bar chart, Hirabayashi et al., 2021b). Inundation is calculated when the magnitude of flood exceeds current flood protection (Scussolini et al., 2016). Note that number of GCMs used to calculate global warming level (GWL) 4.0 is less than that for other GWLs, as the global mean temperature change of some GCMs did not exceed 4°C.

America and eastern North America, and decrease in northern North America, southern South America, the Mediterranean and eastern Europe in 2050 and beyond (Koirala et al., 2014; Arnell et al., 2016) (Figure 4.17). There is *low agreement* in projections in changes to snowmelt flood magnitude. A negative trend in snowmelt flood magnitude, together with an increase in rain-fed winter floods, is projected with *medium confidence*, for example, in mid-latitude and low-altitude basins of Scandinavia (Arheimer and Lindström, 2015; Vormoor et al., 2016) and throughout Europe as a whole (Kundzewicz et al., 2017), and northeastern North America (Arnell and Lloyd-Hughes,

Table 4.6 | Projected economic impact by river flooding in billion USD in different emission scenarios or for different global warming levels (GWLs). The percentage of the total GDP of the region is given in brackets.

Description	The economic impact in billion USD (% of GDP)	Reference
No adaptation with current flood protection, no economic development (fixed at the level of 2010), USD at 2010 purchasing power parity (PPP), mean of 7 GCMs with the RCP8.5 scenario	– Current (1976–2005): 75 (0.11%) – GWL 1.5°C: 145 (0.22%) – (Asia 92, Australasia 8, Europe 29, Africa 7, North America 3, Central and South America 5) – GWL 2°C: 172 (0.26%) – (Asia 114, Australasia 7, Europe 32, Africa 9, North America 4, Central and South America 7) – GWL 3°C: 249 (0.37%) – (Asia 176, Australasia 9, Europe 38, Africa 11, North America 4, Central and South America 11) – GWL 4°C: 343 (0.51%) – (Asia 241, Australasia 19, Europe 55, Africa 9, North America 6, Central and South America 14)	Alfieri et al. (2017), with regional aggregation and currency conversion
No adaptation with current flood protection, USD at 2010 PPP, mean of five CMIP5 GCMs and 10 hydrological models	– Current (1976–2005): 142 (0.21%) – GWL 1.5°C, SSP3: 370 (0.55%), SSP5: 485 (0.72%) – GWL 2°C, SSP3: 597 (0.89%), SSP5: 888 (1.32%) – GWL 3°C, SSP3: 1024 (1.52%), SSP5: 1616 (2.40%)	Dottori et al. (2018) with currency conversion
No adaptation and no flood protection, mean value in 2030 (2010–2030) and 2080 (2010–2080), USD at 2010 PPP, mean of five CMIP5 GCMs	– Current (1960–1999): 1,032 (1.6%) – RCP2.6, SSP1: 2030: 2366 (1.44%), 2080: 7429 (1.43%) – RCP6.0, SSP3: 2030: 1987 (1.44%), 2080: 3353(1.14%) – RCP8.5, SSP5: 2030: 2304 (1.37%), 2080: 3684(1.77%)	Winsemius et al. (2016)
Partial adaptation (protected against 100-year floods in high-income countries, against 5-year floods for all others), mean value in 2030 (2010–2030) and 2080 (2010–2080), USD at 2010 PPP, mean of five CMIP5 GCMs	– Current (1960–1999): 163 (0.25%) – RCP2.6, SSP1: 2030: 558 (0.34%), 2080: 851 (0.48%) – RCP6.0, SSP3: 2030: 418 (0.29%), 2080: 413(0.32%) – RCP8.5, SSP5: 2030: 418 (0.33%), 2080: 441 (0.57%)	Winsemius et al. (2016)
A model calibrated to fit reported damages, future vulnerability scenarios considering autonomous adaptation, USD at 2005 PPP, mean of 11 CMIP5 GCMs,	– Current (1991–2005): 14 (0.044%) – RCP2.6, SSP1: 2081–2100, 121 (0.037%) – RCP6.0, SSP2: 2081–2100, 133 (0.042%) – RCP8.5, SSP3: 2081–2100, 130 (0.063%)	Kinoshita et al. (2018)
No adaptation and current flood protection, USD at 2005 PPP, mean of five CMIP5 GCMs	– Current (1961–2005): 102 (0.39%) – RCP2.6, SSP1: 2020–2100, 2333 (0.99%) – RCP4.5, SSP2: 2020–2100, 2221 (0.99%) – RCP6.0, SSP3: 2020–2100, 1328 (0.80%) – RCP8.5, SSP5: 2020–2100, 4007 (1.21%)	Tanoue et al. (2021)
Optimised adaptation, USD at 2005 PPP, mean of five CMIP5 GCMs	– Current (1961–2005): 102 (0.39%) – RCP2.6, SSP1: 2020–2100, 1621 (0.69%) – RCP4.5, SSP2: 2020–2100, 1567 (0.70%) – RCP6.0, SSP3: 2020–2100, 872 (0.52%) – RCP8.5, SSP5: 2020–2100, 2558 (0.77%)	Tanoue et al. (2021)

2014). With *medium confidence*, a positive trend is projected in high-latitude basins, for example, for large Arctic rivers such as Lena and Mackenzie (Eisner et al., 2017; Gelfan et al., 2017; Pechlivanidis et al., 2017) and high-altitude upstreams, such as the Ganges, Brahmaputra, Salween, Mekong and the upper Indus Basin (Lutz et al., 2014) and alpine catchments (Hall et al., 2014). Moderate decreasing trends or insignificant changes are projected for snowmelt floods in the Fraser River Basin of British Columbia (Shrestha et al., 2017).

There is *high confidence* that climate change and projected socioeconomic development would increase exposure in inundation areas (Figure 4.17), resulting in a large increase in direct flood damages as several times more in all warming levels (Table 4.6). Alfieri et al. (2017) estimated a 120 and 400% increase in population affected by river flooding for 2°C and 4°C warming, respectively, and a 170% increase in damage for 2°C warming without socioeconomic impact development (Section 4.7.5). Dottori et al. (2018) estimated the same but with a 134% increase in fatalities with population increase under the SSP3 scenario. The highest numbers of people affected by river flooding are projected for countries in southern, eastern and southeastern Asia, with tens of millions of people per year per country projected to be affected (Figure 4.17; Alfieri et al., 2017; Hirabayashi et al., 2021b). Kinoshita et al. (2018) showed that climate change contributes a 2.8–28.8% increase in global fatality for the period 2071–2100 compared to 1991–2005, but socioeconomic change (~131.3% increase) and associated vulnerability change (~72.1% reduction) have a greater impact of the projected flood-related fatality rate than climate change alone. Winsemius et al. (2016) discussed that projected flood damage could be reduced to 1/20th in absolute value with adequate adaptation strategies. Direct flood damages are projected to increase by 4–5 times at 4°C compared to 1.5°C, highly depending on scenarios and assumptions (Table 4.6; Box 4.7).

In all climate scenarios projected, earlier snowmelt leads to earlier spring floods (*high confidence*), for example, in northern and eastern Europe (Gobiet et al., 2014; Hall et al., 2014; Etter et al., 2017; Lobanova et al., 2018), northern North America (Vano et al., 2015; Musselman et al., 2018; Islam et al., 2019b), large Arctic rivers (Gelfan et al., 2017; Pechlivanidis et al., 2017) and high-altitude Asian basins (Lutz et al., 2014; Winsemius et al., 2016). There is *high confidence* that snowmelt floods will occur 25–30 d earlier in the year by the end of the 21st century with RCP8.5, but there is only *low agreement* in the projected magnitude of snowmelt flood (Arheimer and Lindström, 2015; Vormoor et al., 2016; Islam et al., 2019b).

Challenges to projecting flood risk are large because of the complexity of the projecting snowmelt, high-intensity rainfall and soil wetness in large river basins. Even though increases in the number and area of glacier lakes may cause increases in glacier-related floods (Section 4.2.2), knowledge of the frequency or magnitude of glacier-related projected floods is limited. Some local studies indicate that the severity of ice-jam flooding is projected to decrease (Rokaya et al., 2019; Das et al., 2020), but a model study in Canada projected increases in damage of ice-jam floods (Turcotte et al., 2020). While most flood risk projections do not consider the impact of urban expansion, Güneralp et al. (2015) estimate that urban areas exposed to flooding will increase by a factor of 2.7 due to urban growth by 2030 (Section 4.5.4). Given the significant differences in assumption in flood protection, exposure or vulnerability scenario among studies, uncertainties in the global estimation of flood losses and damages are large are large (Table 4.6, 4.7.5).

Floods and their societal impacts, especially the enhancement of hazards and increase in vulnerability, depend on complex political, economic and cultural processes (Carey et al., 2017; Caretta et al., 2021). Thus, assessments that analyse long-term flood impacts need to account for the interplay of water and society relations. Unfortunately, such studies remain scarce (Pande and Sivapalan, 2017; Ferdous et al., 2018; Caretta et al., 2021). In particular, projected socioeconomic, cultural and political impacts on the vulnerable group are understudied, as is their resourcefulness through LK, adaptive capacity and community-led adaptation (Sections 4.6.9; 4.8.4; Cross-Chapter Box INDIG in Chapter 18).

In summary, there is *high confidence* that the magnitude and frequency of floods are projected to increase in many regions, including Asia, central Africa, western Europe, Central and South America and eastern North America, and decrease in northern North America, southern South America, the Mediterranean and eastern Europe. Projected increases in flooding pose increasing risks, with a 1.2–1.8 and 4–5 times increase in global GDP loss at 2°C and 4°C compared to 1.5°C warming, respectively (*medium confidence*). Without adaptation, projected increases in flooding are 1.4 to 2.5 and 2.5 to 3.9 times in global GDP loss at 2°C and 3°C compared to 1.5°C warming, respectively (*medium confidence*). However, regional differences in risks are large because of the strong influence of socioeconomic conditions and significant uncertainty in flood hazard projection. In small river basins and urban areas, there is *medium confidence* that projected increases in heavy rainfall would contribute to increases in rain-generated local flooding. However, the snowmelt floods are projected to decrease (*medium confidence*) and occur 25–30 d earlier in the year by the end of the 21st century with RCP8.5 (*high confidence*).

4.4.5 Projected Changes in Droughts

AR6 WGI (Douville et al., 2021) concluded that the total land area subject to increasing drought frequency and severity would expand (*high confidence*), and in the Mediterranean, southwestern South America and western North America, future aridification will far exceed the magnitude of change seen in the last millennium (*high confidence*). WGI (Seneviratne et al., 2021) also find many consistencies among projections of climate change effects on different forms of drought (meteorological, agricultural/ecological and hydrological drought, 4.2.5), but also significant differences in some regions, particularly in the levels of confidence in projected changes.

Many studies focus on precipitation-based drought indices (Carrão et al., 2018), but higher evaporative demands and changes in snow cover are additional drivers of hydrological, agricultural and ecological drought (*medium confidence*) in many regions of the world (Koirala et al., 2014; Prudhomme et al., 2014; Touma et al., 2015; Wanders et al., 2015; Zhao and Dai, 2015; Naumann et al., 2018; Cook et al., 2020a). Furthermore, these droughts (hydrological, agricultural and ecological) are often modulated by prevailing soil and hydro-morphological characteristics. Therefore, the choice of drought definition can affect the magnitude and even the sign of the projected drought change.

In a study with multiple climate models, global water models and scenarios, the choice of drought definition was the dominant source of uncertainty in the sign of projected change in drought frequency in over 17% of global land by 2070–2099, including several major wheat- and maize-growing areas where agricultural (soil moisture) drought is of high importance (Satoh et al., 2021). Cook et al. (2020a) noted that in the CMIP6 projections, soil moisture and runoff drying are more robust, spatially extensive and severe than precipitation, resulting in the frequency of agricultural drought increasing over wider areas than for meteorological drought. At 1.5°C global warming, the likelihood of extreme agricultural (soil moisture) drought is projected to at least double (100% increase) over large areas of northern South America, the Mediterranean, western China and high latitudes in North America and Eurasia (Figure 4.18, left column). The likelihood is projected to increase by 150–200% in these regions at 2°C global warming, with an expansion of the affected areas, and increase by over 200% at 4°C global warming. Agricultural drought likelihood also increases by 100–250% at 4°C global warming in southwestern North America, southwest Africa, southern Asia and Australia. The likelihood of extreme drought is projected to decrease in central North America, the Sahel, the Horn of Africa, the eastern Indian sub-continent and parts of western and eastern Asia. Using eight global hydrological models driven by a subset of four of the CMIP5 climate models, Lange et al. (2020) projected a 370% (30–790%) increase of the global population annually exposed to agricultural (soil moisture) droughts in response to 2°C global warming. Therefore, it is essential to consider the drought type when applying drought projections to impact and risk in decision-making, especially for informing adaptation. For example, if responses are explicitly tailored to agricultural (soil moisture) drought changes, projected changes in a meteorological (precipitation) drought metric may not provide accurate information.

Compared to CMIP5, the CMIP6 ensemble projects more consistent drying in the Amazon basin (Parsons, 2020), more extensive declines in total soil moisture in Siberia (Cook et al., 2020a) and stronger declines in westernmost North Africa and southwestern Australia. Projected declines in soil moisture in these geographies would cause a significant risk of agricultural drought. Also, importantly, projected changes in drought in

Projected changes in the likelihood of an extreme single-year agricultural (soil moisture) drought event

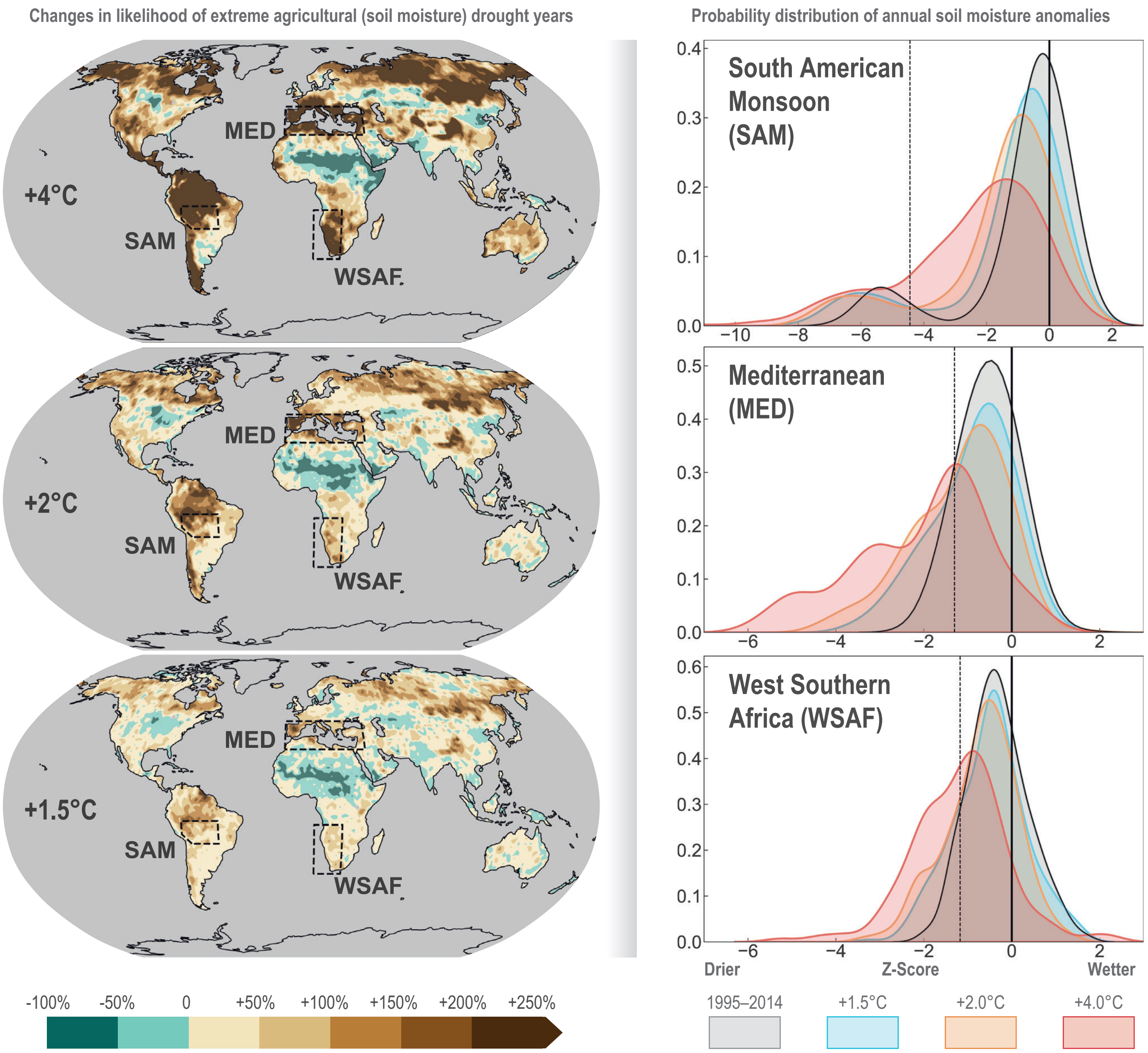


Figure 4.18 | Projected changes in the likelihood of an extreme single-year agricultural (soil moisture) drought event, with extreme drought defined as the driest 10% of years from 1995 to 2014, using total soil moisture projections pooled from the CMIP6 ensemble following Cook et al. (2020a). All ensemble members are treated as equally likely potential outcomes, and likelihoods are calculated using the whole ensemble. Left: Percentage change in the likelihood of extreme drought at GWLs of 4°C (top), 2°C (middle) and 1.5°C (bottom), with 'extreme drought' defined locally as the 10th percentile in individual grid boxes. Right: probability distribution functions of regional mean soil moisture anomalies for the climatic regions Mediterranean (MED), South American Monsoon (SAM) and West Southern Africa (WSAF) (Iturbide et al., 2020), at 1.5°C, 2°C and 4°C GWLs. The solid vertical line shows the baseline, that is, the 50th percentile in 1995–2014. The dashed vertical line shows the 10th percentile for 1995–2014, defining 'extreme drought' at the regional scale. Projections used the SSP5-8.5 scenario to maximise the number of ensemble members at higher GWLs, but global patterns of change are very similar for all scenarios (Cook et al., 2020a), and for any given GWL, similar results can be expected with other scenarios (Seneviratne et al., 2021).

many regions depend on the season and may not be evident in annual mean changes. For example, in northwestern Asia, hydrological (runoff) drought frequency is projected to decrease by 50–100% in autumn and winter but increase by up to 250% in spring and summer (Cook et al., 2020a). In contrast, meteorological (precipitation) drought frequency is projected to increase by up to 350% throughout the year.

Drought projections are subject to uncertainties due to limits of predictability and understanding of the relevant biophysical processes. Uncertainties in regional climate changes are significant in many regions (see Figure 4.10, Figure 4.13, Figure 4.15), and in climate model ensembles, the range of regional outcomes generally increases with global warming. This widening of the range of outcomes can contribute to the increased likelihood of extreme droughts across the ensemble as a whole (Figure 4.18, right column). The response of transpiration to elevated CO_2 is also a significant uncertainty. The inclusion of CO_2 physiological effects leads to smaller projected increases in agricultural, ecological or hydrological drought (Milly and Dunne, 2016; Yang et al.,

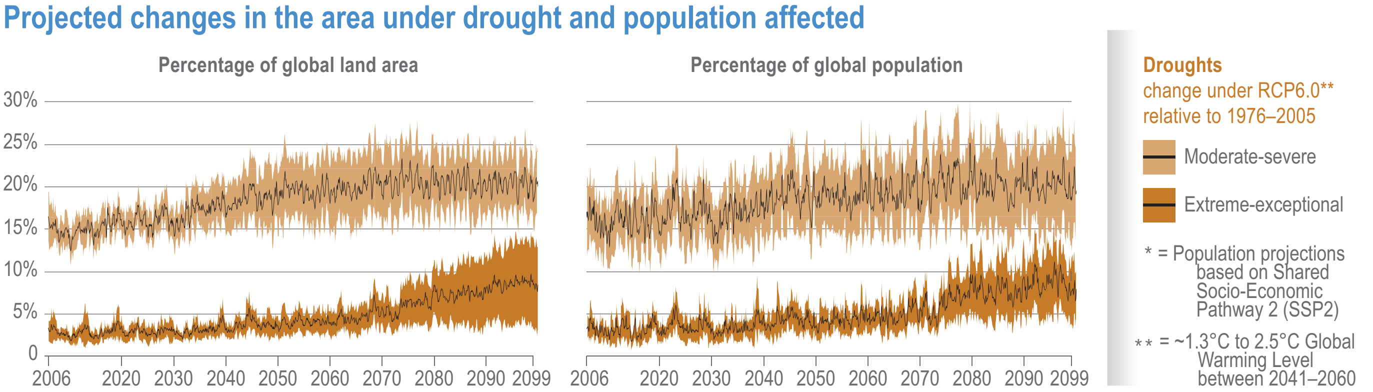


Figure 4.19 | Projected changes in the area under drought and population affected, defined with changes in the Terrestrial Water Storage–Drought Severity Index (TWS-DSI) projected with seven terrestrial hydrology models driven by four CMIP5 climate models using RCP6.0.

(a) Fractional global land area under moderate-to-severe drought (top), defined as $-0.8 \leq \text{TWS-DSI} < -1.6$, and extreme-to-exceptional drought (bottom), defined as $\text{TWS-DSI} < -1.6$.

(b) Fraction of global population exposed to moderate-to-severe (top) and extreme-to-exceptional (bottom) drought, using the SSP2 population projection. Dark lines show the ensemble means; shaded areas indicate uncertainty as ± 1 standard deviation. Reproduced from Pokhrel et al. (2021).

2020). 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). Most CMIP6 climate models include CO$_2$ physiological effects, but many hydrological models used for impacts studies do not.

Terrestrial water storage (TWS) is the sum of continental water stored in canopies, snow and ice, rivers, lakes and reservoirs, wetlands, soil and groundwater (Pokhrel et al., 2021). TWS drought can therefore be considered to be a combination of agricultural, ecological and hydrological drought. The proportion of the global population exposed to TWS drought is projected to increase with ongoing climate change (Figure 4.19). By the late 21st century, under RCP6.0, the global land area in extreme-to-exceptional TWS drought is projected to increase from 3% to 7% (Pokhrel et al., 2021), with increasing uncertainty over time. Combined with a medium population growth scenario (SSP2), this leads to the global population in this level of drought increasing from 3% to 8%, again with increasing uncertainty over time. Hydrological droughts can also be driven by direct human impact via water abstraction (Javadinejad et al., 2019).

Critical knowledge gaps include uncertainties in regional drought due to regional climate change uncertainties, challenges in constraining plant physiological responses to atmospheric CO$_2$, and the uncertainties in modelling the role of different population projections in projecting regional drought risk.

In summary, the likelihood of drought is projected to increase in many regions over the 21st century (*high confidence*) even with strong climate change mitigation, and more severely in the absence of this. Different forms of drought broadly show similar patterns of projected change in many regions (*high confidence*), but the frequency of agricultural drought is projected to increase over wider areas than for meteorological drought (*medium confidence*). Clarity on the definition of drought is therefore important for informing decision-making. With the RCP6.0 and SSP2 scenarios, the global population exposed to extreme-to-exceptional terrestrial water storage drought is projected to increase from 3% to 8% over the 21st century.

4.4.6 Projected Changes in Groundwater

AR5 concluded that the range of projected future changes in groundwater storage was large, from statistically significant declines to increases due to several uncertainties in existing models (Jiménez Cisneros et al., 2014). AR6 (Douville et al., 2021) concluded with *high confidence* that projected increases in precipitation alone cannot ensure an increase in groundwater storage under a warming climate unless unsustainable trends in groundwater extraction are also reversed.

Projected impacts of climate change on groundwater systems are commonly simulated using models at local to global scales (Bierkens and Wada, 2019). The relations between climate change and groundwater are more complex than those embedded in current numerical models (Cuthbert et al., 2019b). For instance, groundwater systems register effects of drought with several years of lag effect, and aquifer response times to changes in hydraulic forcing also vary across aquifers (Cuthbert et al., 2019a). For instance, long groundwater response times can buffer drought impacts and lengthen recovery times to sustained drought events (Van Lanen et al., 2013; Opie et al., 2020).

Global total and non-renewable groundwater withdrawals are projected to increase from 952 km^3 year^{-1} (2010) to 1621 km^3 year^{-1} (2099) and from 304 km^3 year^{-1} (2010) to 597 km^3 year^{-1} (2099), respectively (Bierkens and Wada, 2019). At the same time, groundwater depletion is projected to increase from approximately 204 (± 30) km^3 year^{-1} in 2000 to 427 (± 56) km^3 year^{-1} by 2099 (Wada, 2016). Much of the projected depletion is a function of increased future abstraction of groundwater for irrigation and increased ET (Condon et al., 2020) in a warmer climate. For example, the projected doubling of average water use by 2050 in Tunisia is attributed partly (3.8–16.4%) to climate change and mainly to socioeconomic policies (Guermazi et al., 2019). Similarly, groundwater depletion in the Bengal Basin and North China Plain is more due to irrigation development than climate change per se (Leng et al., 2015; Kirby et al., 2016).

A recent synthesis of modelling studies conducted in various climates showed that out of 33 studies, 21 reported a decrease in the projected groundwater recharge or storage, eight reported an increase and the rest showed no substantial change (Amanambu et al., 2020). A global-scale multi-model ensemble study projected decreasing recharge in southern Chile, Brazil, central continental USA, the Mediterranean and East China, but consistent and increasing recharge for northern Europe and East Africa (Reinecke et al., 2021). In continental Spain, a modelling study (Pulido-Velazquez et al., 2018) projected significant reductions in groundwater recharge in the central and southeast region but a small and localised increase in east and northeastern areas. In subarctic Alaska, increased contribution of glacier melts to streamflow and aquifer recharge under a warming climate is projected (Liljedahl et al., 2017). In contrast, over the Iranian and Anatolia Plateaus, groundwater recharge is projected to reduce by ~77% in the spring season (March–May) due to a decrease in snowfall (Wu et al., 2020). Overall, several recent studies of climate change impacts on groundwater in different parts of the world have concluded that projected groundwater recharge could either increase or decrease, and results are often uncertain (*high confidence*) (Meixner et al., 2016; Zaveri et al., 2016; Hartmann et al., 2017; Mehran et al., 2017; Tillman et al., 2017; Kahsay et al., 2018; Herbert and Döll, 2019).

Wu et al. (2020) reported a projected increase in future groundwater storage in the semiarid regions of northwest India, North China Plain, the Guarani Aquifer in South America and Canning Basin in Australia due to significant increases in projected precipitation, but the models do not consider local hydrogeological characteristics. However, the projected irrigation expansion could negate this positive gain in groundwater storage (Sishodia et al., 2018; Wu et al., 2020). In drylands (e.g., playas in the southwestern USA), where focused groundwater recharge processes dominate, greater recharge is projected to occur from the increased number of significant runoff-generating extreme precipitation events in the future (McKenna and Sala, 2018). Overall, an emerging body of studies have projected amplification of episodic recharge in the tropics and semiarid regions due to extreme precipitation under global warming (*medium confidence*).

Climate change is also projected to impact groundwater-dependent ecosystems and groundwater quality negatively (*medium confidence*). Projected increase in precipitation intensity and storms can contaminate groundwater by mobilising contaminants such as chemical fertilisers, pesticides and antibiotics and leaching of human waste from pit latrines into groundwater (Amanambu et al., 2020; Lall et al., 2020). By 2050, environmentally critical streamflow is projected to be affected in 42–79% of the world's watersheds. The majority of these watersheds currently experience intensive groundwater use, and changes in critical streamflow are projected to negatively impact aquatic ecosystems (de Graaf et al., 2019). Using a global synthesis of 9404 data points from 32 countries across six continents, McDonough et al. (2020) report increases in DOC concentrations in groundwater following projected changes in precipitation and temperature. For example, hotspots of high DOC concentration (increases of up to 45%) are associated mainly with increased temperatures in the wettest quarter of the year in the southeastern USA under RCP8.5 scenarios.

The projected rise in sea levels can lead to saline intrusion into aquifers in low-lying areas and small islands and threaten coastal ecosystems and livelihood resilience; for example, in already vulnerable countries like Bangladesh and vulnerable ecosystems like the mangrove forest of Sundarbans (Befus et al., 2020; Dasgupta et al., 2020; Shamsudduha et al., 2020). However, hydrogeological properties, aquifer settings and impacts of over-abstraction are more important determinants of salinisation of coastal aquifers than slowly rising sea levels (Michael et al., 2013; Taylor et al., 2013a). The projected contribution of global groundwater depletion to sea level rise is expected to increase from 0.57 (± 0.09) mm year^{-1} in 2000 to 0.82 (± 0.13) mm year^{-1} by 2050, driven by a growing trend in groundwater extraction (Wada, 2016). However, several uncertainties around model parametrisation remain (Wada et al., 2017).

There are several knowledge gaps in our understanding of the global-scale sensitivity of groundwater systems to climate change and resulting feedbacks (Maxwell and Condon, 2016; Cuthbert et al., 2019a). There are process uncertainties in groundwater recharge simulation due to the potential impact of atmospheric CO_2 on vegetation and resulting changes in ET (Reinecke et al., 2021). There are uncertainties in impact models due to poor representation of recharge pathways (diffuse compared to focused) and inability to adequately capture feedbacks among climate, land use and groundwater systems (Meixner et al., 2016). Finally, there are gaps in long-term observational data, especially in less-developed countries (Amanambu et al., 2020), making it challenging to evaluate the performance of impact models (Gleeson et al., 2020).

In summary, groundwater abstraction is projected to deplete the long-term, non-renewable storage as withdrawals are projected to increase significantly in all major aquifers worldwide (*medium evidence, high agreement*). In the tropics and semiarid regions, growing precipitation intensification under global warming may enhance the resilience of groundwater through increased episodic recharge (*medium confidence*). However, in the semiarid areas, over-abstraction continues to be a threat to groundwater storage and can nullify the benefits of increased future recharge.

4.4.7 Projected Changes in Water Quality

AR5 concluded that climate change was projected to reduce water quality (Jiménez Cisneros et al., 2014). SR1.5 assessed with *low confidence* differences in projected impacts under 1.5°C compared with 2°C of warming (Hoegh-Guldberg et al., 2018). In addition, SROCC reported water quality degradation due to the release of legacy contaminants in glaciers and permafrost (*medium confidence*) (Hock et al., 2019b). The AR6 WGI Report does not explicitly mention water quality issues.

Water insecurity due to water quality degradation is projected to increase under climate change due to warming, enhanced floods and sea level rise (Arnell and Lloyd-Hughes, 2014; Dyer et al., 2014; Whitehead et al., 2015) (*medium confidence*). Drought-driven diminishing river and lake levels (Jeppesen et al., 2015) and continued water abstraction for irrigation (Aragüés et al., 2015) may contribute to the salinisation of soil and water. In addition, warming is projected to disrupt the historical sequestration of contaminants in permafrost in the Arctic and mountain regions (Bond and Carr, 2018).

Quantitative projections on climate-induced water quality degradation are sparse. Aminomethylphosphonic acid and glyphosate are projected to exceed drinking water quality standards in dry years in a high-emissions scenario in the Meuse River in Europe by 2050 (Sjerps et al., 2017). From 2020 to 2050, based on scenarios RCP2.6, RCP4.5 and RCP8.5, the incidences of total nitrogen pollution are projected as 97.3, 97.1 and 94.6%, respectively, in drought–flood abrupt alternation months compared to 69.3, 69.7 and 67.5% in normal months in the Luanhe River basin in China (Bi et al., 2019). From 2012 to 2050, freshwater river area is expected to decrease from 40.8% to 17.1–19.7% under different sea level rise scenarios in the southwest coastal zone of Bangladesh (Dasgupta et al., 2013). Under the warming scenario of +4.8°C increase by the end of the century, the average nutrient abundance is projected to triple in a shallow lake in the northwest of England (Richardson et al., 2019).

While there is some understanding of the potential effect of glacier and permafrost degradation on water quality, projections are lacking. Research is limited mainly in Europe and North America, and quantifying the future water quality changes is still incipient.

In summary, climate change is projected to increase water pollution incidences, salinisation and eutrophication due to increasing drought and flood events, sea level rise and water temperature rise, respectively, in some local rivers and lakes, but there is a dearth of exact quantification at a global scale (*medium confidence*).

4.4.8 Projected Changes in Soil Erosion and Sediment Load

AR5 stated that soil erosion and sediment load are projected to change (*low confidence*) due to warming and increased rainfall intensity (Jiménez Cisneros et al., 2014). SRCCL concluded that future climate change will increase, with *medium confidence*, the potential for water-driven soil erosion in many dryland areas, causing soil organic carbon decline (Mirzabaev et al., 2019). SR1.5 (Hoegh-Guldberg et al., 2018) concluded that because of the complex interactions among climate change, land cover, soil management, etc., the differences between mean annual sediment load under 1.5°C and 2°C of warming are unclear.

Globally, climate change is estimated to be responsible for 30–66% increase of soil erosion by 2070, while socioeconomic developments impacting land use may lead to ± 10% change of soil erosion (Borrelli et al., 2020). At a regional scale, different effects of the climate change impact on soil losses are found owing to the ensemble experiments with climate models coupled with regional/local models of soil erosion and sediment yield. In the 21st century, the soil erosion rates are projected to increase for the European countries (Czech Republic (Svoboda et al., 2016), Belgium (Mullan et al., 2019), Spain (Eekhout et al., 2018; Eekhout and de Vente, 2019a; Eekhout and De Vente, 2019b), Germany (Gericke et al., 2019)) by 10–80% depending on the emission scenario and time period of the projection, as well as for the USA (Garbrecht and Zhang, 2015) and Australia (Yang et al., 2015b; Zhu et al., 2020). Only a few studies demonstrated decreasing trend in soil erosion, for example, up to 9% with RCP8.5 scenario in Greece (Vantas et al., 2020). Sediment yield is projected to both increase (5–16% with the SRES A1, B1, B2 scenarios in Vietnam and Laos (Giang et al., 2017), 11% with the RCP8.5 scenario and 8% with the SRES A2 scenario in the USA (Yasarer et al., 2017 and Wagena et al., 2018, respectively), 19–37% with the RCP4.5, RCP8.5 scenarios in Burkina Faso (Op de Hipt et al., 2018)) and decrease (30% with the SRES A1B scenario in the southwest USA (Francipane et al., 2015), 8–11% with the SRES A1B scenario in Spain (Rodríguez-Blanco et al., 2016), 11–52% with the RCP4.5, RCP8.5 scenarios in Ethiopia (Gadissa et al., 2018), 13–62% with the RCP2.6, RCP8.5 scenarios in Canada (Loiselle et al., 2020)) over the different regions of the world in the 21st century.

Post-fire sedimentation is projected to increase for nearly nine tenths of watersheds by >10% and for more than one third of watersheds by >100% by the 2041 to 2050 decade in the western USA with the SRES A1B scenario (Sankey et al., 2017).

In summary, soil losses mainly depend on the combined effects of climate and land use changes. Herewith, recent studies demonstrate increasing impact of the projected climate change (increase of precipitation, thawing permafrost) on soil erosion (*medium confidence*).

4.5 Projected Sectoral Water-Related Risks

Observed sectoral water-related impacts have been documented across world regions. Climate change is projected to further exacerbate many of these risks, especially at warming levels above 1.5°C (Figure 4.20). For some sectors and regions, climate change may also hold the potential for beneficial outcomes, though feedback and cascading effects as well as risks of climate extremes are not always well understood and often underestimated in impact projections. Risks manifest as a consequence of the interplay of human and natural vulnerability, sector-specific exposure as well as the climate hazard as a driver of climate change. Challenges to water security are driven by factors across these components of risk, where climate change is but one facet of driving water insecurity in the face of global change. While the focus of this chapter is on climate change and its effects on water security, for many sectors and regions the dynamics of socioeconomic conditions is a core driver. They play an essential role in understanding and alleviating water security risks. The following sections outline sectoral risks for both, risks driven by water-related impacts, such as drought, flood or changes in water availability, as well as risks with effects on water uses, mainly focusing on changing water demand as a consequence of climate change. It therefore does not cover all climate change-driven risks to the respective sectors, but is limited to those that stand in relation to water. The focus within this chapter is on global to regional processes (additional regional to local information in Table SM4.4; Figure 4.20 as well as across regional chapters of this report).

4.5.1 Projected Risks to Agriculture

AR5 concluded that overall irrigation water demand would increase by 2080, while the vulnerability of rain-fed agriculture will further increase (Jiménez Cisneros et al., 2014). SR1.5 concluded that both the food and the water sectors would be negatively impacted by global warming with higher risks at 2°C than at 1.5°C, and these risks could coincide spatially and temporally, thus increasing hazards, exposures and vulnerabilities across populations and regions (*medium confidence*). SR1.5 further reinforced AR5 conclusions in terms of projected crop yield reductions, especially for wheat and rice (*high confidence*), loss of livestock and increased risks for small-scale fisheries and aquaculture (*medium confidence*) (Hoegh-Guldberg et al., 2018), conclusions which are further corroborated by SRCCL (Mbow et al., 2019).

Climate change impacts agriculture through various pathways (5.4 – Crop-based Systems), with projected yield losses of up to 32% by 2100 (RCP8.5) due to the combined effects of temperature and precipitation. Limiting warming could significantly reduce potential impacts (up 12% yield reduction by 2100 under RCP4.5) (Ren et al., 2018a). Though overall changes differ across models, regions and seasons, differences in impacts between 1.5°C and 2°C can also be identified (Ren et al., 2018a; Ruane et al., 2018; Schleussner et al., 2018). Globally, 11% (± 5%) of croplands are estimated to be vulnerable to projected climate-driven water scarcity by 2050 (Fitton et al., 2019).

Overall drought-driven yield loss is estimated to increase by 9–12% (wheat), 5.6–6.3% (maize), 18.1–19.4% (rice) and 15.1–16.1% (soybean) by 2071–2100, relative to 1961–2016 (RCP8.5) (Leng and Hall, 2019). In addition, temperature-driven increases in water vapour deficit could have additional negative effects, further exacerbating drought-induced plant mortality and thus impacting yields (Grossiord et al., 2020) (see also Cross-Chapter Box 1 in Chapter 5 of WGI report). Currently, global agricultural models do not fully differentiate crop responses to elevated CO_2 under temperature and hydrological extremes (Deryng et al., 2016) and largely underestimate the effects of climate extremes (Schewe et al., 2019).

Flood-related risks to agricultural production are projected to increase over Europe, with a mean increase of expected annual output losses of approximately €11 million (at 1.5°C GWL); €12 million (at 2°C GWL) and €15 million (at 3°C GWL) relative to the 2010 baseline (Koks et al., 2019). In parts of Asia, where flooding impacts on agriculture are already significant, projections indicate an increase in damage to area under paddy by up to 50% in Nepal, 16% in the Philippines, 55% in Indonesia, 23% in Cambodia and Vietnam and 13% in Thailand (2075–2099 compared with 1979–2003; RCP8.5) (Shrestha et al., 2019a).

Global crop water consumption of green water resources (soil moisture) is projected to increase by about 8.5% by 2099 relative to 1971–2000 as a result of climate drivers (RCP6.0), with additional smaller contributions by land use change (Huang et al., 2019) (Sections 4.4.1.3, 4.4.8). In India, a substantial increase in green and blue water consumption is projected for wheat and maize, with a slight reduction of blue water consumption for paddy fields (Mali et al., 2021). Temperate drylands, especially higher latitude regions, may become more suitable for rain-fed agriculture (Bradford et al., 2017). Locally and regionally, however, some of those areas with currently larger areas under rain-fed production, for example, in Europe, may become less suitable for rain-fed agriculture (Table 1 to 4.5.1) (Bradford et al., 2017; Shahsavari et al., 2019).

While global crop models and estimates of yield impacts often focus on major staple crops relevant for global food security, crops of high economic value are projected to become increasingly water dependent. For example, climate-driven yield increases for tea are projected for various tea-producing regions if no water limitations and full irrigation is assumed, but decreases in yields are projected under continued present-day irrigation assumptions (Beringer et al., 2020). Water-related impacts on global cotton production are highly dependent on the CO_2-fertilisation effect, with increases projected for higher CO_2 concentration if no water limitations are implemented. However, substantial decreases in cotton production are projected if lower or no fertilisation effects are accounted for due to increasing water limitations (Jans et al., 2018). Reductions in economically valuable crops will probably increase the vulnerability of population groups, especially small-holder farmers with limited response options (Morel et al., 2019).

To stabilise yields against variations in moisture availability, irrigation is the often the most common adaptation response (Section 4.6.2, Box 4.3). Projections indicate a potentially substantial increase in irrigation water requirements (Boretti and Rosa, 2019). Increasing agricultural water demand is driven by various factors, including population growth, increased irrigated agriculture, cropland expansion and higher demand for bio-energy crops for mitigation (Chaturvedi et al., 2015; Grafton et al., 2015; Turner et al., 2019; 4.7.6). Depending on underlying assumptions and the constraints on water resources implemented in the global agricultural models, irrigation water requirements are projected to increase two- to three-fold by the end of the century (Hejazi et al., 2014; Bonsch et al., 2015; Chaturvedi et al., 2015; Huang et al., 2019). While the combined effects of population and land use change as well as irrigation expansion account for the significant part of the projected increases in irrigation water demand by the end of the century, around 14% of the increase is directly attributed to climate change (RCP6.0) (Huang et al., 2019).

With various degrees of water stress being experienced under current conditions and further changes in regional water availability projected, as well as continuing groundwater depletion as a consequence of over-abstraction for irrigation purposes (Sections 4.2.6 and 4.4.6), limitations to major irrigation expansion will occur in some regions, including South and Central Asia, the Middle East and parts of North and Central America (Grafton et al., 2015; Turner et al., 2019). Constraining projections of available irrigation water through consideration of environmental flow requirements further reduces the potential for irrigation capacity and expansion (Bonsch et al., 2015). Changes in land use and production patterns, for example, expansion of rain-fed production and increasing inter-regional trade, would be required to meet growing food demand while preserving environmental flow requirements, though this may increase local food security-related vulnerabilities (Cross-Chapter Box INTERREG in Chapter 16) (Pastor et al., 2014). 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).

Over 50% of the global lowlands equipped for irrigation will depend heavily on runoff contributions from the mountain cryosphere by 2041–2050 (SSP2–RCP6.0) and are projected to make unsustainable use of blue water resources (Viviroli et al., 2020). Projected changes in snowmelt patterns indicate that for all regions dependent on snowmelt for irrigation during warm seasons, alternative water sources will have to be found for up to 20% (at 2°C GWL) and up to 40% (at 4°C GWL) of seasonal irrigation water use, relative to current water use patterns (1986–2015) (Qin et al., 2020). Regional studies further corroborate these global findings (Biemans et al., 2019; Malek et al., 2020). Basins where such alternate sources are not available will face agricultural water scarcity.

Elevated CO_2 concentrations play an important role in determining future yields in general and have the potential to beneficially affect plant water use efficiency (Deryng et al., 2016; Ren et al., 2018a; Nechifor and Winning, 2019). The elevated CO_2 effects are projected to be most prominent for rain-fed C3 crops (Levis et al., 2018). Combined results from field experiments and global crop models show that CO_2 fertilisation could reduce consumptive water use by 4–17% (Deryng et al., 2016). To account for uncertainties, global agricultural models provide output with and without account for CO_2 fertilisation effects, though recent progress on reducing model uncertainty indicates that non-CO_2 model runs may no longer be needed for adequate projections of yield impacts (Toreti et al., 2019).

Due to the complex interactions among determinants for livestock production, the future signal of water-related risks to this sector is unclear. Globally, 10% (± 5%) of pasture areas are projected to be vulnerable to climate-induced water scarcity by 2050 (Fitton et al., 2019). Water use efficiency gains through elevated CO_2 concentrations have the potential to increase forage quantities, though effects of nutritional values are ambiguous (Augustine et al., 2018; Derner et al., 2018; Rolla et al., 2019). In addition, spatial shifts in temperature/humidity regimes may shift suitable regions for livestock production, opening up new suitable areas for some regions or encouraging shifts in specific breeds better adapted to future climatic regimes (Rolla et al., 2019) (5.5 – Livestock Systems and 5.10 Mixed Systems).

Projections of climate impacts on freshwater aquaculture are limited (5.9.3.1 – Projected Impacts; Inland freshwater and brackish aquaculture). In particular, in tropical regions, reductions in water availability, deteriorating water quality, and increasing water temperatures pose risks to terrestrial aquaculture, including temperature-related diseases and endocrine disruption (Kibria et al., 2017, Section 4.4.7). On the other hand, freshwater aquaculture in temperate and arctic polar regions may benefit from temperature increases with an extension of the fish-growing season (Kibria et al., 2017).

Global crop models, which provide the basis for most projections of agricultural risk, continue to have limitations in resolving water availability. For example they do not fully resolve the effects of elevated CO_2 for changing water use efficiency (Durand et al., 2018), potentially overestimating drought impacts on maize yield (Fodor et al., 2017) and may underestimate limitations to further expansion of irrigation (Elliott et al., 2014; Frieler et al., 2017b; Winter et al., 2017; Jägermeyr and Frieler, 2018; Kimball et al., 2019; Yokohata et al., 2020a).

In summary, agricultural water use is projected to increase globally due to cropland expansion and intensification and climate change-induced changes in water requirements (*high confidence*). Parts of temperate drylands may experience increases in suitability for rain-fed production based on mean climate conditions; however, risks to rain-fed agriculture increase globally because of increasing variability in precipitation regimes and changes in water availability (*high confidence*). Water-related impacts on economically valuable crops will increase regional economic risks (*medium evidence, high agreement*). Regions reliant on snowmelt for irrigation purposes will be affected by substantial reductions in water availability (*high confidence*).

4.5.2 Projected Risks to Energy and Industrial Water Use

AR5 concluded with *high confidence* that climate-induced changes, including changes in water flows, will affect energy production, and the actual impact will depend on the technological processes and location of energy production facilities (Arent et al., 2014). SR1.5 concluded with *high confidence* that climate change is projected to affect the hydropower production of northern European countries positively. However, Mediterranean countries like Greece, Spain and Portugal are projected to experience approximately a 10% reduction in hydropower potential under a 2°C warming level, which could be reduced by half if global warming could be limited to 1.5°C (Hoegh-Guldberg et al., 2018). In addition, SROCC concluded with *high confidence* that an altered amount and seasonality of water supply from snow and glacier melt is projected to affect hydropower production negatively (IPCC, 2019a).

Since AR5, a large number of studies have modelled future changes in hydropower production due to climate-induced changes in volume and seasonality of streamflow and changes in sediment load due to accelerated melting of cryosphere at both global (van Vliet et al., 2016b; Turner et al., 2017) and regional scales (Tarroja et al., 2016; Ali et al., 2018; de Jong et al., 2018; Tobin et al., 2018; Arango-Aramburo et al., 2019; Carvajal et al., 2019; Arias et al., 2020; Meng et al., 2021).

For hydropower production at a global scale, Turner et al. (2017) projected an uncertainty in the direction of change in global hydropower production to the tune of +5% to −5% by the 2080s, under a high-emissions scenario. On the other hand, van Vliet et al. (2016b) projected an increase in global hydropower production between +2.4% to +6.3% under RCP4.5 and RCP8.5, respectively, by the 2080s, as compared to a baseline period of 1971–2000, but with significant regional variations (*high confidence*). For example, regions like central Africa, India, central Asia and northern high-latitude areas are projected to see more than 20% increases in gross hydropower potential (*high confidence*). On the other hand, southern Europe, northern Africa, southern USA and parts of South America, southern Africa and southern Australia are projected to experience more than 20% decreases in gross hydropower potential. The Mediterranean region is projected to see almost a 40% reduction in hydropower production (*high confidence*) (Turner et al., 2017). On the other hand, northern Europe and India are projected to add to their hydropower production capacity due to climate change by mid-century (*high confidence*) (van Vliet et al., 2016b; Turner et al., 2017; Emodi et al., 2019).

In hydropower plants located in the Zambezi basin, electricity output is projected to decline by 10–20% by 2070 compared to baseline (1948–2008) under a drying climate; only marginal increases are projected under a wetting climate (Spalding-Fecher et al., 2017). In the

Mekong Basin, the total hydropower generation is projected to decline by 3.0% and 29.3% under 1.5°C and 2°C, respectively (Meng et al., 2021). In this context, 1.5°C will come up in 2036 under RCP2.6 and in 2033, under RCP6.0; and 2°C will come up in 2056 under RCP6.0 (Frieler et al., 2017a). In India, hydropower production is projected to increase by up to 25% by the end of the 21st century due to increased temperature and precipitation under the RCP8.5 scenario. However, hydropower production is projected to decline in plants located in snow-dominated rivers due to earlier snowmelt (Ali et al., 2018). In Colombia, hydropower production is projected to decrease by ~10% under the RCP4.5 dry scenario by 2050 (Arango-Aramburo et al., 2019). In a sub-basin of the Amazon River (one of the hydropower hotspots in Brazil), dry-season hydropower potential is projected to decline by –7.4 to –5.4% from historical baseline conditions under RCP4.5 (Arias et al., 2020). In the São Francisco basin of Brazil, hydropower production is projected to reduce by –15% to –20% by 2100 under the IPCC A1B scenario (de Jong et al., 2018), which will affect the Brazilian energy mix in the future. In Ecuador, under various policy pathways and dry and wet scenarios under RCP4.5, hydropower production is projected to increase by +7% to +21% or decline by –25% to –44% by 2050 (Carvajal et al., 2019). In Europe, different impacts are projected across different sub-regions (WGII, Chapter 13, Table 13.7- Projected climate change risks for energy supply in Europe by 2100). In northern Europe, up to 20% of hydropower potential increases are projected under 3°C warming; increases of up to 15% and 10% are projected under 2°C and 1.5°C warming levels. In Mediterranean parts of Europe, hydropower potential reductions of up to –40% are projected under 3°C warming; while reductions below –10% and –5% are projected under 2°C and 1.5°C warming levels, respectively (van Vliet et al., 2016b; Tobin et al., 2018). Hydropower plants in Switzerland are projected to lose ~1.0 TWh of hydroelectricity production per year by 2070–2090 due to net glacier mass loss in the earlier part of the century (Schaefli et al., 2019). In the Italian Alps, under the warmest scenario of RCP8.4, up to 4% decreases in hydropower production are projected (Bombelli et al., 2019). The magnitude of change differs significantly among models. In California, USA, the average annual hydropower generation is expected to decline by 3.1% under RCP4.5 by 2040–2050, compared to the baseline 2000–2010 (Tarroja et al., 2016). In the Skagit River basin in the USA, hydropower generation is projected to increase by 19% in the winter/spring and decline by 29% in summer by the 2080s (Lee et al., 2016).

Apart from climate impacts on hydropower production, climate-induced flood loads and reservoir water level change may lead to dam failure under RCP2.6 and RCP4.5 scenarios (Fluixá-Sanmartín et al., 2018; Fluixá-Sanmartín et al., 2019) (*medium confidence*). For example, the incidence of 100-year floods in the Skagit River basin in the USA and peak winter sediments are projected to increase by 49% and 335%, respectively, by 2080, necessitating fundamental changes in hydropower plant operation. Nevertheless, some risks, such as floods, will remain unmitigated even with changes in hydropower operation rules (Lee et al., 2016). Overall, impacts of future extreme events on energy infrastructure have been less studied than impacts of gradual changes (Cronin et al., 2018). Furthermore, future hydropower development may also impact areas of high freshwater megafauna in South America, South and East Asia and in the Balkan region, and sub-catchments with a high share of threatened freshwater species are particularly vulnerable (Zarfl et al., 2019). Therefore, future hydropower dams will need to be sited carefully (Dorber et al., 2020).

There is *high confidence* that changes in future cooling water availability are projected to affect thermoelectric production capacity negatively at global (van Vliet et al., 2016b; Zhou et al., 2018b) and regional scales (Bartos and Chester, 2015; Behrens et al., 2017; Ganguli et al., 2017; Zhou et al., 2018b; Emodi et al., 2019). Global mean water temperature is projected to increase by +1°C for RCP2.6 and +2.7°C for RCP8.5 (van Vliet et al., 2016b). Correspondingly, global cooling water sufficiency is projected to decline by –7.9% to –11.4% by 2040–2069 and –11.3% to –18.6% by 2070–2090 (Zhou et al., 2018b), thereby impacting thermoelectric power production.

In Asia, under a 2°C global warming scenario, coal power plants' annual usable capacity factor in Mongolia, Southeast Asia and parts of China and India are projected to decrease due to water constraints (Wang et al., 2019b). In the EU, an assessment of 1326 thermal electric plants in 818 basins projected that the number of basins with water stress would increase from 47 in 2014 to 54 in 2030 (Behrens et al., 2017) with consequent impacts on cooling water supplies. In the western USA, by 2050, vulnerable power plants are projected to lose 1.1–3.0% of average summer generation capacity, which could rise to 7.2 to 8.8% loss under a 10-year drought condition (Bartos and Chester, 2015). Further, 27% of thermoelectric production in the USA may be at severe risk of low-capacity utilisation due to water stress by 2030 (Ganguli et al., 2017). Thermoelectric plant capacity on the hottest summer day in the USA and EU is projected to fall by 2% under a 2°C global warming and by 3.1% under a 4°C global warming, requiring overbuilding of electricity infrastructure by 1–7% given the current energy mix portfolio (Coffel and Mankin, 2020). A systematic review showed consistent decreases in mid to end of the century in thermal power production capacity due to insufficiency of cooling water in southern, western and eastern Europe (*high confidence*); North America and Oceania (*high confidence*), central, southern and western Asia (*high confidence*) and western and southern Africa (*medium confidence*) (Emodi et al., 2019). Overall, apart from emissions benefits, moving away from thermal power generation to other renewable energy will also lower the chances of climate-induced curtailment of energy production (*high confidence*).

Global freshwater demand for the energy sector is projected to increase under all 2°C scenarios due to the rapid increase in electricity demand in developing countries (Fricko et al., 2016). Despite the water shortage and climate change impacts, industry and energy sectors' share in global water demand has been projected to rise to 24% by 2050 (UN Water, 2020), which will increase the competition among various water-use sectors (Boretti and Rosa, 2019). Furthermore, mining activities, which are highly dependent on sufficient water availability, are also at risk due to climate change (Aleke and Nhamo, 2016). Given that some of the intensely mined regions, such as the Atacama Desert in Chile, are already water-scarce, even small changes in rainfall could destabilise water-intensive mining operations and affect the production and processing activities at mines (Odell et al., 2018). Overall, there is a lack of literature on the impact of climate change on future mining activities and other water-intensive industries.

In summary, globally, hydropower and thermoelectric power capacities are projected to increase and decrease, respectively, due to changes in river runoff and increases in ambient water temperatures (*high confidence*). In the future, freshwater demand for energy and industrial sectors is projected to rise significantly at the global level, triggering competition for water across sectors. Although climate change also poses risks to mining and other water-intensive industries, quantifying these risks is difficult due to limited studies.

4.5.3 Projected Risks to Water, Sanitation and Hygiene (WaSH)

Climate-related extreme events impact WaSH services and local water security. While not WaSH-specific, AR5 showed that more people would experience water scarcity and floods (*high confidence*) and identified WaSH failure due to climate change as an emergent risk (*medium confidence*) leading to higher diarrhoea risk (Field et al., 2014b). In addition, both SR1.5 (IPCC, 2018a) and SRCCL (IPCC, 2019b) projected the risk from droughts, heavy precipitation, water scarcity, wildfire damage and permafrost degradation to be higher at 2°C warming than 1.5°C (*medium confidence*), and all these could potentially impact water quality and WaSH services.

Waterborne diseases result from complex causal relationships between climatic, environmental and socioeconomic factors that are not fully understood or modelled (Boholm and Prutzer, 2017) (*high confidence*). WaSH-related health risks are related to extreme events, harmful algal blooms and WaSH practices (Chapter 7 WGII 7.3.2). In addition, changes in thermotolerance and chlorine resistance of certain viruses have been observed in laboratory experiments simulating different temperatures and sunlight conditions (Carratalà et al., 2020), increasing potential health risks even where traditional water treatment exists (Jiménez Cisneros et al., 2014) (*low confidence*). Studies show that degraded water quality increases the willingness to pay for clean water regardless of national economic status. However, payment for clean, potable water, particularly in low- and middle-income countries, can represent a significant percentage of people's income, limiting economic well-being and the possibility for re-investment in other livelihoods or activities (Constantine et al., 2017; van Houtven et al., 2017; Price et al., 2019).

Collectively, drinking water treatment, sanitation and hygiene interrupt disease transmission pathways, particularly for water-related diseases. However, WaSH systems themselves are vulnerable to extreme events (Section 4.3.3). For example, sewage overflows resulting from heavy rainfall events are expected to increase waterborne disease outbreaks (Khan et al., 2015). High diarrhoeal disease burdens mean that small changes in climate-associated risk are projected to have significant impacts on disease burdens (Levy et al., 2018). For example, up to 2.2 million more cases of *E. coli* by 2100 in Bangladesh under a 2.1°C GWL are projected (Philipsborn et al., 2016), while up to an 11-fold and 25-fold increase by 2050 and 2080, respectively, under a 2–4°C GWL, in disability-adjusted life years, associated with cryptosporidiosis and giardiasis in Canada is projected (Smith et al., 2015). In addition, an additional 48,000 deaths of children under 15 years of age globally from diarrhoea by 2030 are also projected (WHO, 2014). Notably, high levels of treatment compliance and boiling water before consumption offset the projected impact of climate change on giardiasis in Canada in the 2050 scenario, but could not wholly offset the projected impact in 2080 (Smith et al., 2015). Climate change impacts on WaSH-attributable disease burden are also projected to delay China's progress towards disease reduction by almost 9% under RCP8.5 (Hodges et al., 2014). Disruptions in the drinking water supply can lead to increased household water storage, potentially increasing vector larvae breeding habitats (see Section 3.6.3). In combination with the projected expansion of vector ranges given climate change (Liu-Helmersson et al., 2019), there is the potential for increased risk of vector-borne disease during periods of water shortage or natural disasters (Section 4.3.3). Moreover, energy requirements for water and wastewater treatment are indirectly responsible for GHG emissions, while the breakdown of excreta contributes directly to emissions (Box 4.5, Section 4.7.6). These contributions need to be better articulated and accounted for as part of the WaSH and climate change dialogue (Dickin et al., 2020).

In summary, climate change is expected to compromise WaSH services, compounding existing vulnerabilities and increasing water-related health risks (*medium evidence, high agreement*). Therefore, additional research is required on disease-, country-, and population-specific risks due to future climate change impacts (Baylis, 2017; Bhandari et al., 2020; Harper et al., 2020).

4.5.4 Projected Risks to Urban and Peri-Urban Sectors

AR5 reported with *medium confidence* that climate change would impact residential water demand, supply and 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 in coastal areas due to higher ambient and water temperatures (*medium evidence, high agreement*), 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 with *medium confidence* that constraining warming to 1.5°C instead of 2°C might mitigate risks for water availability, but socioeconomic drivers could affect water availability more than variations in warming levels, while the risks differ across regions (Hoegh-Guldberg et al., 2018).

In nearly a third of the world's largest cities, water demand may exceed surface water availability by 2050, based on RCP6.0 projections and the WaterGAP3 modelling framework (Flörke et al., 2018). Under all SSPs, the global volume of domestic water withdrawal is projected to reach 700–1500 $km^3 yr^{-1}$ by 2050, indicating an increase of 50 to 250%, compared to the 2010 water use intensity (400–450 $km^3 yr^{-1}$) (Wada et al., 2016). Increasing water demand by cities is already spurring competition between cities and agricultural users for water, which is expected to continue (Garrick et al., 2019) (Section 4.5.1). By 2030, South and Southeast Asia are expected to have almost three quarters of the urban land under high-frequency flood risk (10.4.6). South Asia, South America and mid-latitudinal Africa are projected have the largest urban extents exposed to floods and droughts (Güneralp et al., 2015). An analysis of 571 European cities from the Urban Audit database (using RCP8.5 projections without assessing urban heat island effects) found drought conditions are expected to intensify (compared to the historical period 1951–2000) in southern European cities, particularly in Portugal and Spain (Guerreiro et al., 2018; Section CCP4.3.3). Changes in river flooding are projected to affect cities in northwestern European cities and the UK between 2051 and 2100 (Guerreiro et al., 2018) (Sections 6.2.3.2, CCP2.2.1, CCP2.2.3).

Globally, climate change is projected to exacerbate existing challenges for urban water services. These challenges include population growth, the rapid pace of urbanisation and inadequate investment, particularly in less developed economies with limited governance capacity (*high confidence*) (Ceola et al., 2016; van Leeuwen et al., 2016; Reckien et al., 2017; Tapia et al., 2017; Veldkamp et al., 2017). More specifically, in Arusha (Tanzania), a combination of urban growth modelling, satellite imagery and groundwater modelling projected that rapid urbanisation would reduce groundwater recharge by 23–44% of 2015 levels by 2050 (under business as usual and an RCP8.5 scenario), causing groundwater levels to drop up to 75 m (Olarinoye et al., 2020). Flood risk modelling showed a median increase in flood risk of 183% in 2030 based on baseline conditions in Jakarta (Indonesia) with flood risks increasing by up to 45% due to land use changes alone (Budiyono et al., 2016). A probabilistic analysis of surface water flood risk in London (UK) using the UKCP09 Weather Generator (with 10th and 90th percentile uncertainty bounds) found that the annual damage is expected to increase from the baseline by 101% and 128% under 2030 and 2050 high-emission scenarios, respectively (Jenkins et al., 2018).

Modified streamflow is projected to affect the amount and variability of inflow to urban storage reservoirs (*high confidence*), which may exacerbate existing challenges to urban reservoir capacity, such as sedimentation and poor water quality (Goharian et al., 2016; Howard et al., 2016; Yasarer and Sturm, 2016). For example, in Melbourne (Australia), a combination of stochastic hydro-climatological modelling, rainfall-runoff modelling and climate model data projects a mean precipitation shift over catchments by –2% at 1.5°C and –3.3% at 2°C, relative to 1961–1990. Considering an annual water demand of 0.75 of the mean yearly inflow, the median water supply shortage risk was calculated to be 0.6% and 2.9% at 1.5°C and 2°C warming levels, respectively. At the higher demand level of 0.85 of the mean annual inflow, the median water shortage risk is higher, between 9.6% and 20.4% at 1.5°C and 2°C warming, respectively, without supply augmentation desalination (Henley et al., 2019).

As climate change poses a substantial challenge to urban water management, further refinement of urban climate models, downscaling and correction methods (e.g., Gooré Bi et al., 2017; Jaramillo and Nazemi, 2018) is needed. Additionally, given that 90% of urban growth will occur in less developed regions, where urbanisation is largely unplanned (UN-Habitat, 2019), further research is needed to quantify the water-related risks of climate change and urbanisation on informal settlements (Grasham et al., 2019; Satterthwaite et al., 2020, 4.5.3).

In summary, rapid population growth, urbanisation, ageing infrastructure and changes in water use are responsible for increasing the vulnerability of urban and peri-urban areas to extreme rainfall and drought, particularly in less developed economies with limited governance capacity (*high confidence*). In addition, modified stream flows due to climate change (Section 4.4.3) are projected to affect the amount and variability of inflows to storage reservoirs that serve urban areas and may exacerbate challenges to reservoir capacity, such as sedimentation and poor water quality (*high confidence*).

4.5.5 Projected Risks to Freshwater Ecosystems

AR5 concluded that climate change is projected to be an important stressor on freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios of RCP6.0 and RCP8.5 (*high confidence*), even though direct human impacts will continue to be the dominant threat (Settele et al., 2014). Rising water temperatures are also projected to cause shifts in freshwater species distribution and worsen water quality problems (*high confidence*), especially in those systems that already experience high anthropogenic loading of nutrients (Settele et al., 2014).

Changes in precipitation and temperatures are projected to affect freshwater ecosystems and their species through, for example, direct physiological responses from higher temperatures or drier conditions or a loss of habitat for feeding or breeding (Settele et al., 2014; Knouft and Ficklin, 2017; Blöschl et al., 2019b). In addition, 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 destabilisation of food webs. A review of the impact of climate change on biodiversity and functioning of freshwater ecosystems found that under all scenarios, except the one with the lowest GHG emission scenario, freshwater biodiversity is expected to decrease proportionally to the degree of warming and precipitation alteration (Settele et al., 2014) (*medium evidence*, *high agreement*).

These are several examples of such projected changes. Due to higher water temperatures, changes in macroinvertebrates and fish are projected under all future warming scenarios (Mantyka-Pringle et al., 2014). Decreased abundance of many fish species, such as salmonids, under higher temperatures, is also projected, although the effects between species are variable (Myers et al., 2017). Poleward and shifts of freshwater species are projected as they try to stay within preferred cooler environmental conditions (Pecl et al., 2017). Other anticipated changes include physiological adjustments with impacts on morphology with some species shrinking in body size because large surface-to-volume ratios are generally favoured under warmer conditions (Scheffers et al., 2016) and changes in species communities and food webs as a consequence of increases in metabolic rates in response to increased temperatures with the flow-on effects for many ecosystem processes (Woodward et al., 2010). Changes in the seasonality of flow regimes and variability (Blöschl et al., 2019b) 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 (Sabo et al., 2010) and changes in nutrient loadings and water quality (Woodward et al., 2010). The impacts on freshwater systems in drylands are projected to be more severe (Jaeger et al., 2014; Gudmundsson et al., 2016). Changes to snow and glacier melting, including the complete melting of some glaciers (Leadley et al., 2014; Kraaijenbrink et al., 2017), are projected to reduce water availability and cause declines in biodiversity in high altitudes through local extirpations and species extinctions in regions of high endemism. Lake nutrient dynamics are expected to change, for example, at 2°C warming, and net increase in CH_4 emissions by 101–183% in hypereutrophic lakes and 47–56% in oligotrophic lakes in Europe are projected (Sepulveda-Jauregui et al., 2018). Similarly, under the high-GHG emission scenario, lake stratification is projected to begin 22.0 ± 7.0 d earlier and end 11.3 ± 4.7 d later by the end of this century (Woolway et al., 2021). While overall future trends on climate change on freshwater species and habitats are largely negative, evidence indicates that different species are projected to respond at different rates, with interactions between species expected to be disrupted and which may result in novel biological communities and rapid change in ecological processes and functions (Pecl et al., 2017).

These impacts are expected to be most noticeable where significant air temperature increases are projected, leading to local or regional population extinctions for cold-water species because of range shrinking, especially under the RCP4.5, 6.0 and 8.5 scenarios (Comte and Olden, 2017). The consequences for freshwater species are projected to be severe with local extinctions as the freshwater ecosystems dry. In the Americas, under all scenarios that have been examined, the risk of extinction of freshwater species is projected to increase above that already occurring levels due to biodiversity loss caused by pollution, habitat modification, over-exploitation and invasive species (IPBES, 2019). Freshwater ecosystems are also at risk of abrupt and irreversible change, especially those in the higher latitudes and altitudes with significant changes in species distributions, including those induced by melting permafrost systems (Moomaw et al., 2018; IPBES, 2019).

While changes in the species distribution across freshwater ecosystems are projected, the extent of change and the ability of individual species or populations to adapt are not widely known. Species that cannot move to more amenable habitats may become extinct, whereas those who migrate may relocate. An unknown outcome could be establishing novel ecosystems with new assemblages of species, including invasive alien species, in response to changes in the environment with the prospect of irreversible changes in freshwater ecosystems (Moomaw et al., 2018).

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

4.5.6 Projected Risks to Water-Related Conflicts

AR5 concluded with *medium confidence* that climate change can indirectly increase the risks of violent conflicts, though the link to hydrological changes were not spelled out (Jiménez Cisneros et al., 2014). Furthermore, according to IPCC SR1.5 (Hoegh-Guldberg et al., 2018), if the world warms by 2°C–4°C by 2050, rates of human conflict could increase, but again, the role of hydrological change in this was not explicit (*medium confidence*).

The impact of climate change on shared water resources might increase tensions among states, particularly in the absence of strong institutional capacity (Petersen-Perlman et al., 2017; Dinar et al., 2019). On the other hand, although the mere existence of formal agreements does not necessarily reduce the risks of conflicts, robust treaties and institutions can promote cooperative events, even under hydrological stress (Link et al., 2016). Yet, since both conflictive and cooperative events are possible under conditions of climatic variability, whether conflict arises or increases depends on several contextual socioeconomic and political factors, including the adaptive capacity of the riparian states (Koubi, 2019), the existence of power asymmetries (Dinar et al., 2019) and pre-existing social tensions (*medium confidence*).

At the intra-state level, analysis suggests that additional climate change will increase the probability of conflict risks, with 13% increase probability at the 2°C GWL and 26% probability at the 4°C GWL scenario (Mach et al., 2019). However, to date, other factors are considered more influential drivers of conflict, including lack of natural resource use regulations (Linke et al., 2018b), societal exclusion (von Uexkull et al., 2016; van Weezel, 2019), poor infrastructures and a history of violent conflict (Detges, 2016) (*high confidence*). In addition, *medium-high evidence* exists that climate change imposes additional pressures on regions that are already fragile and conflict-prone (Matthew, 2014; Earle et al., 2015) (*medium agreement*).

Recent research indicates that climatic change can multiply tensions in regions dependent on agriculture when coupled with other socioeconomic and political factors (Koubi, 2019), including a low level of human development (Ide et al., 2020) and deterioration of individual living conditions (Vestby, 2019). On the other side, intergroup cohesion (De Juan and Hänze, 2020) and policies that improve societal development and good governance reduce the risk of conflict associated with the challenges to adaptation to climate change (Hegre et al., 2016; Witmer et al., 2017) (*medium confidence*) at both the intra-state and inter-state level.

Increased risk of conflict between different sectors (agriculture, industry, domestic) and needs (urban, rural) is projected to arise in several river basins due to climate change and socioeconomic developments, including urbanisation (Flörke et al., 2018). Future climatic conditions and population growth are expected to exert additional pressures on managing already stressed basins such as the Nile, the Indus, Colorado, the Feni, the Irrawaddy, the Orange and the Okavango (Farinosi et al., 2018). In addition, recent scenario analysis in global transboundary basins supports the finding that there is more potential for conflict in areas already under water stress, such as central Asia and the northern parts of Africa (Munia et al., 2020) (*medium confidence*).

In summary, the impact of climate change on water resources might increase tensions, particularly in the absence of strong institutional capacity. However, whether conflict arises or increases depends on several contextual socioeconomic and political factors. Evidence exists that climate change imposes additional pressures on regions already under water stress or fragile and conflict-prone (*medium confidence*).

4.5.7 Projected Risks to Human Mobility and Migration

SR1.5 found with *medium confidence* that migration is expected to increase with further warming, but that there are major knowledge gaps preventing more detailed assessments (Hoegh-Guldberg et al., 2018). However, as in AR5, there was no specific focus on hydrological changes-induced migration.

In general, the projected population growth in at-risk areas, especially in low-income countries, is expected to increase future migration and displacement (McLeman et al., 2016; Rigaud et al., 2018). For example, a study looking at potential flood exposure found that low-income countries, particularly in Africa, are at higher risk for flood-induced displacement (Kakinuma et al., 2020). One model, focusing on slow-onset climate impacts, such as water stress, crop failure and sea level rise, projected between 31–72 million people (RCP2.6, SSP4) and 90–143 million people (RCP8.5, SSP4) internally displaced by 2050 in sub-Saharan Africa, South Asia and Latin America (Rigaud et al., 2018). Another estimate, incorporating temperature increase and precipitation, projects that asylum applications to the EU could increase by between 0.098 million (RCP4.5) and 0.66 million (RCP8.5) yr^{-1}, as a consequence of temperature increases in agricultural areas of low-income countries (Missirian and Schlenker, 2017) (*limited evidence; medium agreement*).

More detailed local and regional models are needed, incorporating migrant destinations (Abel et al., 2019) and immobility (Zickgraf, 2018).

In summary, research that projects future migration changes due to climate-induced hydrological changes is *limited* and shows significant uncertainties about the number of migrants and their destinations (*limited evidence; medium agreement*).

4.5.8 Projected Risks to the Cultural Water Uses of Indigenous Peoples, Local Communities and Traditional Peoples

AR5 found that climate change will threaten cultural practices and values, although the risks vary across societies and over time (*medium evidence, high agreement*). Furthermore, AR5 concluded that significant changes in the natural resource base on which many cultures depend would directly affect the cultural core, worldviews, cosmologies and symbols of indigenous cultures (Adger and Pulhin, 2014). SR1.5 concluded with *high confidence* that limiting global warming to 1.5°C, rather than 2°C, will strongly benefit terrestrial and wetland ecosystems and their services, including the cultural services provided by these ecosystems (Hoegh-Guldberg et al., 2018). SROCC found with *high confidence* that cultural assets are projected to be negatively affected by future cryospheric and associated hydrological changes (Hock et al., 2019b).

There is *high confidence* that the cultural water uses of Indigenous Peoples, local communities and traditional peoples are at risk of climate change-related hydrological change (Table 4.7). Climate-driven variations in streamflow, saltwater intrusion and projected increases in water temperature will exacerbate declines of culturally important species and lead to variations or depletion of culturally important places and subsistence practices. For example, in New Zealand, the increasing risk of flood events may impact culturally important fish species for Māori (Carter, 2019), while habitat changes may shift the distribution of culturally significant plants (Bond et al., 2019). In Australia, Yuibera and Koinmerburra Traditional Owners fear the saltwater inundation of culturally significant sites and waterholes (Lyons et al., 2019), while the flooding of culturally significant wetlands will negatively affect the Lumbee Tribe (USA) (Emanuel, 2018). Moreover, changes in the carrying capacity of ice, snow quality and formation will probably increase the physical risks to Saami practising reindeer herding (Jaakkola et al., 2018).

Further research is necessary to assess the extent and nature of climate-driven risks to cultural water uses in the context of broader socioeconomic, cultural and political challenges facing diverse Indigenous Peoples and local and traditional communities. In addition, given the significance of IKLK to adaptive capacity and community-led adaptation, the potential risks of climate-related hydrological changes to diverse cultural water uses warrant closer study (Sections 4.6.9, 4.8.4, Cross-Chapter Box INDIG in Chapter 18).

In sum, there is *high confidence* that climate-driven hydrological changes to cultural water uses and culturally significant ecosystems and species are projected to pose risks to the physical well-being of Indigenous Peoples, local communities and traditional peoples.

4.6 Key Risks and Adaptation Responses in Various Water Use Sectors

Anthropogenic climate change has impacted every aspect of the water cycle (Section 4.2), and risks are projected to intensify with every degree of global warming (Section 4.4), with impacts already visible in all sectors of the economy and ecosystems (Section 4.3) and projected to intensify further (Section 4.5). In response to climate- and non-climate-induced water insecurity, people and governments worldwide are undertaking various adaptation responses across all sectors. In addition, there are several projected studies for future adaptation responses. We draw upon a list of 359 case studies of observed adaptation and 45 articles on projected future adaptation. Further information on selection and inclusion criteria is available in SM4.2. In this section, we document those adaptation responses (current and future) in different water use sectors. In the next (Sections 4.7.1, 4.7.2, 4.7.3), benefits of current adaptation and effectiveness of future adaptation are discussed.

4.6.1 Key Risks Related to Water

The preceding sections have outlined the various pathways along which climate affects water resources and water-using sectors. In synthesis, fundamental changes in observed climate are already visible in water-related outcomes (*high confidence*), including ~500 million people experiencing historically unfamiliar precipitation regimes (Section 4.2.1.1); cryospheric changes impacting various societal and ecosystem components (Section 4.2.2); increasing vulnerability to flood impacts, driven by both by climate and socioeconomic factors

Table 4.7 | Selected projected risks to Indigenous Peoples' uses of water.

Region	Indigenous People	Climate hazard	Water-related risk	Situated knowledge	Reference
Asia	Ifugao	Increased temperatures; increasing rainfall (wet season); decreasing rainfall (dry season)	Flooding (wet season); water deficit (dry season)	Increases in future wet season rainfall pose increase risks of excess surface water runoff and potential for soil erosion, which may cause the collapse of Ifugao rice terraces. Reductions in future dry season rainfall and warmer temperatures indicate significant water deficits during the growing season of local *tinawon* rice.	Soriano and Herath (2020)
Australasia	Yuibera and Koinmerburra Traditional Owner groups	Sea-level rise	Flooding	Culturally important coastal waterholes, wetlands and sites are at risk of saltwater inundation due to rising sea levels. If inundated, Traditional Owners may not be able to maintain cultural connections to these important sites (11.4.1).	Lyons (2019 }
Australasia	Māori	Increased precipitation	Flooding	Increasing flood events may negatively impact spawning and fishing sites of the culturally important īnaka (whitebait; *Galaxias maculates*) in the Waikōuaiti River (11.4.2).	Carter (2019)
Australasia	Māori	Increased temperature; precipitation variability	Ecosystem change	Changes in temperature and precipitation are projected to shift the range of wetland plants (Kūmarahou and Kuta) in New Zealand, which may decrease access to these culturally significant species, which are used for medicinal and weaving purposes. The changing distribution of these plants may lead to a loss of Indigenous knowledge and affect inter-tribal reciprocity and gifting practices (11.4.2).	Bond et al. (2019)
Central and South America	Warao	Sea level rise	Flooding	The partial or total inundation of the Orinoco Delta will result in the loss of freshwater wetlands and species, which will produce rapid shifts in the culturally significant lands and resources of the Warao. Among the affected species is the Mauritia palm, on which Warao culture and livelihoods are based.	Vegas-Vilarrúbia et al. (2015)
Europe	Saami	Increased temperatures; changes in precipitation	Winter thaw	Reindeer herding is culturally important for Saami and provides a means to maintain traditions, language and cultural identity, thus constituting an essential part of Saami physical and mental well-being. More frequent ice formation on soil and snow, which will reduce the availability and quality of winter forage for reindeer, will negatively impact reindeer herding and thus Saami identity and well-being (13.8.1.2).	Jaakkola et al. (2018); (Markkula et al. (2019)
North America	Lumbee Tribe	Increased temperatures; increased rainfall variability	Flooding	Climate-related degradation and flooding of wetlands and streams in the Lumbee River watershed will negatively affect cultural practices of fishing and harvesting that rely on access to and resources obtained from the area.	Emanuel (2018)

(Section 4.2.4); and as climate change-driven increases in drought impacts (Section 4.2.5).

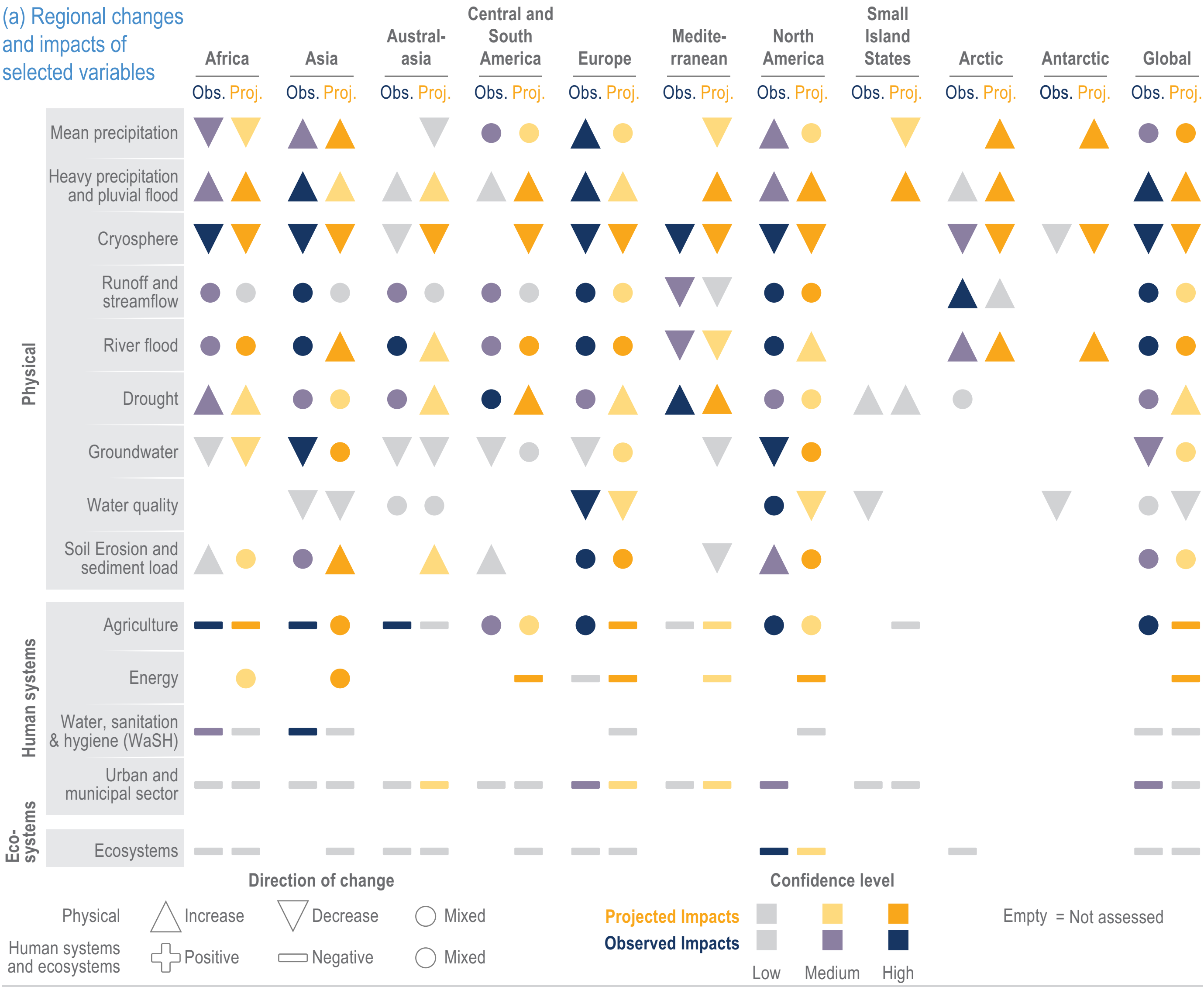
Further increases in risks are projected to manifest at different levels of warming. Climate change is impacting all components of the hydrological cycle, but the water use sectors are also facing the consequences of climate change, given the central role of water for all aspects of human and environmental systems (Section 4.1, Box 4.1). Therefore, risks to water security are also identified as a representative key risk (RKR) (WGII, Chapter 16, Section 16.5.2.3.7).

Approximately 4 billion people globally face physical water scarcity for at least one month yr^{-1} which is driven by both climatic and non-climatic factors (Mekonnen and Hoekstra, 2016). Increases in physical water scarcity are projected, with estimates between 800 million and 3 billion for 2°C global warming and up to approximately 4 billion for 4°C global warming (Gosling and Arnell, 2016). Projected increases in hydrological extremes pose increasing risks to societal systems globally (*high confidence*), with a potential doubling of flood risk between 1.5°C and 3°C of warming (Dottori et al., 2018) and an estimated 120–400% increase in population at risk of river flooding at 2°C and 4°C, respectively (Alfieri et al., 2017). Also projected are increasing risks of fatalities and socioeconomic impacts (Section 4.4.4). Similarly, a near doubling of drought duration (Naumann et al., 2018) and an increasing share of the population affected by various types, durations and severity levels of drought are projected (*high confidence*) (Section 4.4.5). Increasing return periods of high-end hydrological extremes pose significant challenges to adaptation, requiring integrated approaches to risk management, which take the various economic and non-economic, as well as direct and indirect losses and damages into account (Jongman, 2018).

Increasing sectoral risks are reported across regions and sectors with rising temperatures and associated hydrometeorological changes (Cross-Chapter Box INTEREG in Chapter 16). Risks to agricultural yields due to combined effects of water and temperature changes, for example, could be three times higher at 3°C compared to 2°C (Ren et al., 2018b), with additional risks as a consequence of increasing climate extremes (Leng and Hall, 2019). In addition, climate-driven water scarcity and increasing crop water demands, including for irrigation, pose additional challenges for agricultural production

Regional synthesis of assessed changes in water and consequent impacts

(a) Regional changes and impacts of selected variables



(b) Physical changes, impacts on ecosystems, and impacts on human systems

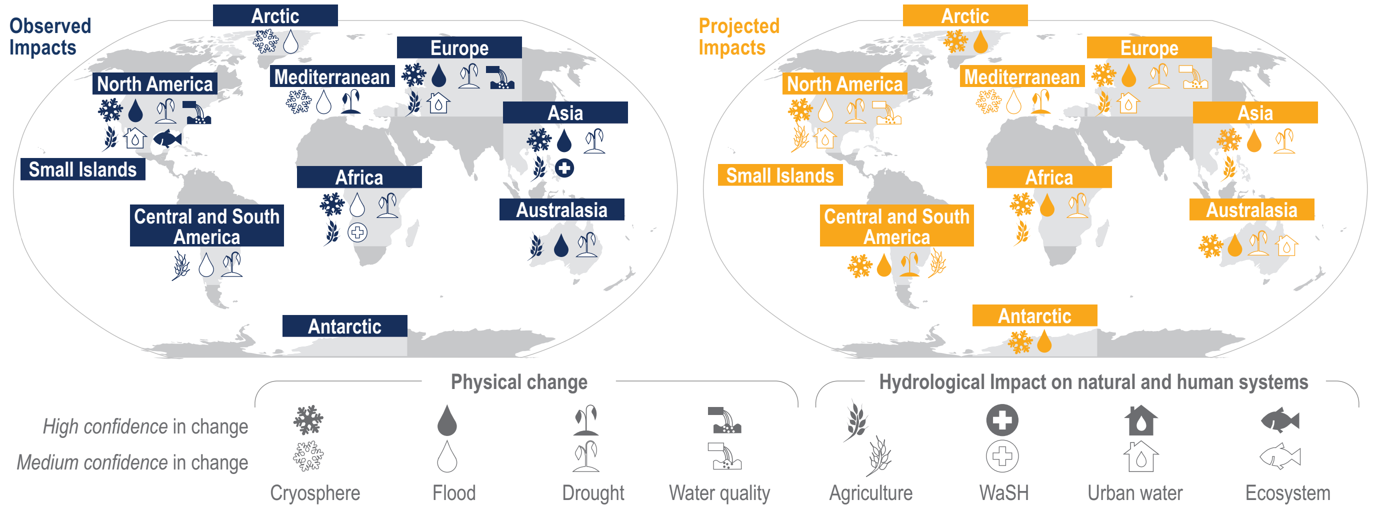


Figure 4.20 | Regional synthesis of changes in water and consequent impacts assessed in this chapter.

(a) Regional changes and impacts of selected variables. Confidence levels higher than medium are shown.

(b) Assessment result of all variables. For each region, physical changes, impacts on ecosystems and impacts on human systems are shown. For physical changes, upward/downward triangles refer to an increase/decrease, respectively, in the amount or frequency of the measured variable, and the level of confidence refers to confidence that the change has occurred. For impacts on ecosystems and human systems, plus or minus marks depict whether an observed impact of hydrological change is positive (beneficial) or negative (adverse), respectively, to the given system, and the level of confidence refers to confidence in attributing an impact on that system to a climate-induced hydrological change. The hydrological impact may be different to the overall change in the system; for example, over much of the world, crop yields have increased overall, largely for non-climatic reasons, but in some areas, hydrological impacts of climate change are countering this. Circles indicate that within that region, both increase and decrease of physical changes are found, but are not necessarily equal; the same holds for cells showing 'both' assessed impacts. Cells assigned 'n.a.' indicates variables not assessed due to limited evidences. Decrease (increase) in water quality refers to adverse (positive) change in quality. Agriculture refers to impacts on crop production. Note: Energy refers to impacts on hydro and thermoelectric power generation. Ecosystems refers to impacts on freshwater ecosystem.

in many regions (*high confidence*). Regional water-related risks to agricultural production are diverse and vary strongly across regions and crops (Section 4.5.1). As there are limitations to how well global agricultural models can represent available water resources (Elliott et al., 2014; Jägermeyr et al., 2017), water limitations to agricultural production may well be underestimated. For example, the potential for irrigation, commonly assumed to play an important role in ensuring food security, could be more limited than models assume (Box 4.3).

With higher levels of warming, risks to water-dependent energy production increase substantially across regions (van Vliet et al., 2017). While there are increasing potentials of ~2–6% for hydropower production by 2080 (*medium confidence*), risks to thermoelectric power production increase for most regions (*high confidence*), for example, with potentially near doubling of the risk to European electricity production from 1.5°C to 3°C (Tobin et al., 2018). Shifting to a higher share of renewable sources less dependent on water resources for energy production could substantially reduce the vulnerability of this sector (Section 4.5.2).

Increasing hydrological extremes also have consequences for the maintenance and further improvement of the provision of WaSH services (*medium confidence*). Risks related to the lack or failure of WaSH services under climate change include increased incidence and outbreaks of water-related diseases, physical injuries, stress, exacerbation of the underlying disease, and risk of violence, which is often gendered (Section 4.5.3). Although globally, 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), climate projections suggest up to 2.2 million more cases of *E. coli* by 2100 (2.1°C increase) in Bangladesh (Philipsborn et al., 2016), up to an 11-fold and 25-fold increase by 2050 and 2080, respectively (2°C–4°C increase), in disability-adjusted life years associated with cryptosporidiosis and giardiasis in Canada (Smith et al., 2015), and an additional 48,000 deaths of children under 15 years of age globally from diarrhoea by 2030 (WHO, 2014).

Increasing water demand in conjunctions with changing precipitation patterns will pose risks to urban water security by mid-century, with water demand in nearly a third of the world's largest cities potentially exceeding surface water availability by 2050 (RCP6.0) (Flörke et al., 2018) and the global volume of domestic water withdrawal projected to increase by 50–250% (Wada et al., 2016) (Section 4.5.4). Globally, climate change will exacerbate existing challenges for urban water services, driven by further population growth, the rapid pace of urbanisation and inadequate investment, particularly in less developed economies with limited governance capacity (*high confidence*).

Risks to freshwater ecosystems increase with progressing climate change, with freshwater biodiversity decreasing proportionally with increasing warming if 1.5°C is exceeded (*medium evidence, high agreement*). Risks include range shift, a decline in species population, extirpation and extinction (Section 4.5.5).

The potential for climate change to influence conflict is highly contextual and depends on various socioeconomic and political factors. However, water-specific conflicts between sectors and users may be exacerbated for some regions of the world (*high confidence*) (Section 4.5.7).

Human migration takes many forms and can be considered a consequence and impact of climate change and an adaptation response (Section 4.5.8). Projections indicate a potentially substantial increase in internal and international displacement due to water-related climate risks (Missirian and Schlenker, 2017; Rigaud et al., 2018). In the context of water-related adaptation, short-term migration as an income diversification approach is commonly documented. However, permanent relocation and fundamental changes to livelihoods are more transformational and yet can be associated with tangible and intangible losses (Mechler et al., 2019). In the context of climate-induced hydrological change, increased vulnerability among migrants and the risk of trapped populations poses significant additional risks. However, quantifications that disentangle different climate drivers and show specific risks emanating from hydrological change are unavailable (Rigaud et al., 2018).

Hydrological change, especially increasing extreme events, pose risks to the cultural uses of water of Indigenous Peoples, local communities and traditional peoples (*high confidence*), with implications for the physical well-being of these groups (*high confidence*). Increasing risks are documented across groups and regions; however, partly due to the unquantifiable nature of these risks, the lack of research funding for the social dimensions of climate change, particularly in the Global South, and the systemic underrepresentation of marginalised groups in scientific research, quantitative projections are limited (Section 4.5.8).

Adaptation is already playing an integral part in reducing climate impacts and preparing for increasing climate risk, and it will grow in importance evermore with increasing risks at higher levels of warming. The remaining subsections describe these adaptation responses.

4.6.2 Adaptation in the Agricultural Sector

AR5 reported a range of available hard and soft adaptation options for water-related adaptation in the agricultural sector. However, the evidence on the effectiveness of these adaptation responses, now and

Box 4.2 | Observed Risks, Projected Impacts and Adaptation Responses to Water Security in Small Island States

AR5 and SR1.5 recognised the exceptional vulnerability of islands, especially concerning water security and potential limits to adaptation that may be reached due to freshwater resources (Klein et al., 2014; Hoegh-Guldberg et al., 2018; Roy et al., 2018).

Small islands are already regularly experiencing droughts and freshwater shortages (*high confidence*) (Holding et al., 2016; Pearce et al., 2018; Gheuens et al., 2019; MacDonald et al., 2020). Freshwater supply systems vary from household or small community systems such as rainwater harvesting systems and private wells to large public water supply systems using surface, groundwater and, in some cases, desalinated water (Alsumaiei and Bailey, 2018b; Falkland and White, 2020). In many cases, communities rely on more than one water source, including a strong reliance on rainwater and groundwater (Elliott et al., 2017; MacDonald et al., 2020). Groundwater resources in freshwater lenses (FWLs) are essential in providing access to freshwater resources, especially during droughts when the collected rainwater is insufficient (Barkey and Bailey, 2017; Bailey et al., 2018), leading to greater risks of water-borne diseases, with significant effects on nutrition (Elliott et al., 2017; Savage et al., 2020), and improper sanitation poses additional risks to the limited groundwater resources (MacDonald et al., 2017). Drought events have also severely affected FWL recharge (Barkey and Bailey, 2017), with extraction rates further threatening available groundwater volumes (Post et al., 2018). In conjunction with sea level rise, this poses serious risks to groundwater salinisation (Alsumaiei and Bailey, 2018b; Storlazzi et al., 2018; Deng and Bailey, 2019). In addition, FWLs are threatened by climate change due to changes in rainfall patterns, extended droughts and wash-over events caused by storm surges and sea level rise (*high confidence*) (see Chapter 15) (Chui and Terry, 2015; Alsumaiei and Bailey, 2018a; Alsumaiei and Bailey, 2018b; Post et al., 2018; Storlazzi et al., 2018; Deng and Bailey, 2019). After small-scale wash over events, the FWLs have been shown to recover to pre-wash over salinity levels within a month (Oberle et al., 2017).

Due to wash-over events exacerbated by sea level rise and lens thinning due to pumping, recovery time for FWLs is projected to take substantially longer (Oberle et al., 2017; Alsumaiei and Bailey, 2018a; Storlazzi et al., 2018). Projections indicate that atolls may be unable to provide domestic freshwater resources due to the lack of potable groundwater by 2030 (RCP8.5+ ice-sheet collapse), 2040 (RCP8.5) or the 2060s (RCP4.5) (Storlazzi et al., 2018). Projections of future freshwater availability in small islands further underline these substantial risks to island water security (Karnauskas et al., 2016; Karnauskas et al., 2018). Population growth, changes in rainfall patterns and agricultural demand are projected to increase water stress in small islands (Gohar et al., 2019; Townsend et al., 2020). While some islands are projected to experience an increase in rainfall patterns, this may refer to shorter intense rainfall events, thereby increasing the risk of flooding during the wet season, while not decreasing their risk of droughts during dry periods (Aladenola et al., 2016; Gheuens et al., 2019). In addition, projected shifts in the timing of the rainfall season might pose an additional risk for water supply systems (Townsend et al., 2020).

Observed adaptation during drought events includes community water sharing (Bailey et al., 2018; Pearce et al., 2018) as well as using alternative water resources such as water purchased from private companies (Aladenola et al., 2016), desalination units (Cashman and Yawson, 2019; MacDonald et al., 2020) or accessing deeper or new groundwater resources (Pearce et al., 2018). Rainwater harvesting to adapt the water supply system in the Kingston Basin in Jamaica was able to significantly alleviate water stress, for example. Still, it would not fill the total supply gap caused by climate change (Townsend et al., 2020). Likewise, groundwater sustainability with increasing climate change in Barbados cannot be ensured without aquifer protection, leading to higher optimised food prices if no additional adaptation measures are implemented (Gohar et al., 2019). The potential of using multiple water sources is rarely assessed in future water supply projections in small islands (Elliott et al., 2017). In the Republic of Marshall Islands, more than half of all interviewed households have already had to migrate once due to a water shortage (MacDonald et al., 2020). In Cariacou, Grenada, increases in migration rates have been observed following drought events (Cashman and Yawson, 2019). with long-term cross border and internal migration shown to be having significant impacts on well-being, community-cohesion, livelihoods and people-land relationships (Yates et al., 2021).

In sum, small islands are already regularly experiencing droughts and freshwater shortages (*high confidence*). For atoll islands, freshwater availability may be severely limited as early as 2030 (*low confidence*). The effects of temperature increase, changing rainfall patterns, sea level rise and population pressure combined with limited options available for water-related adaptation leave small islands partially water-insecure currently, with increasing risks in the near-term and at warming above 1.5°C (*high confidence*).

in the future, was not assessed (Noble et al., 2014; Porter et al., 2014). Assessing the feasibility of different irrigation measures as adaptation, SR1.5 (de Coninck et al., 2018) found mixed evidence, depending on the applied methodology.

There is *high confidence* that water-related adaptation is occurring in the agricultural sector (Acevedo et al., 2020; Ricciardi et al., 2020), and water-related adaptation in the agricultural sector makes up the majority of documented local, regional and global evidence of implemented adaptation (*high confidence*) (Section 4.7.1, Figure 4.23 and Figure 4.24, Table 4.8). However, while there is increasing evidence of adaptation and its benefits across multiple dimensions, the link between adaptation benefits and climate risk reduction is unclear due to methodological challenges (*medium confidence*) (Section 4.7.1). On the other hand, while it is methodologically possible to measure the effectiveness of future adaptation in reducing climate risks, the main limitation here is that not all possible ranges of future adaptations can be modelled given the limitations of climate and impact models (*high confidence*) (Section 4.7.2). Furthermore, findings on current adaptation are constrained by what is documented in peer-reviewed articles. At the same time, there may be a range of options implemented on the ground by local governments or as a part of corporate social responsibility that is not published in peer-reviewed publications.

Water and soil conservation measures (e.g., reduced tillage, contour ridges or mulching) are frequently documented as adaptation responses to reduce water-related climate impacts (Kimaro et al., 2016; Traore et al., 2017). This measure features in all continents' top four adaptation responses except Australasia (Figure 4.27). Especially for rain-fed farming, which currently is the norm in most of Africa, large parts of Central and South America and Europe, water and soil conservation measures and various components of conservation agriculture are some of the most frequently used adaptation responses (Jat et al., 2019). This measure is deemed to have economic benefits and benefits for vulnerable communities who adopt this measure (*high confidence*) and benefits in terms of water saving and positive ecological and sociocultural benefits (*medium confidence*). However, this measure can be sometimes maladaptive (*low evidence, medium agreement*) and can have mitigation co-benefits (*low evidence, high agreement*) (Figure 4.29). Furthermore, water- and soil management-related measures show high potential efficacy in reducing impacts in a 1.5°C world, with declining effectiveness at higher levels of warming (Figure 4.28 and Figure 4.29)

Changes in cropping patterns, the timing of sowing and harvesting, crop diversification towards cash crops and the adoption of improved crop cultivars that can better withstand hazards like floods and drought are among the most used adaptation responses by farmers. This is among the top two measures in Asia and Africa (Figure 4.27). Extra income allows households to re-invest in improved agricultural techniques and improved cultivars (Taboada et al., 2017; Khanal et al., 2018b). Beneficial outcomes are documented in terms of increases in incomes and yields and water-related outcomes (*medium confidence*, from *robust evidence, but medium agreement*), but benefits to vulnerable communities are not always apparent on the whole (Figure FAQ4.4.1). Changes in cropping patterns and systems are also among those adaptation options assessed for their potential to reduce future climate impacts, though effectiveness is shown to be limited (Brouziyne et al., 2018; Paymard et al., 2018). Assessments of the future effectiveness of crop rotation systems for adaptation show a continued reduction in required irrigation water use, though studies of effectiveness beyond 2°C global mean temperature increase are not available (Kothari et al., 2019; Yang et al., 2019b) (Figure 4.28 and Figure 4.29).

Conservation agriculture and climate-smart agriculture (includes improved cultivars and agronomic practices) have proven to increase soil carbon, yields and technical efficiency (Penot et al., 2018; Salat and Swallow, 2018; Ho and Shimada, 2019; Makate and Makate, 2019; Okunlola et al., 2019). Some water-related measures in conservation agriculture include allowing for shading and soil moisture retention, with the co-benefit of reducing pest attacks (Thierfelder et al., 2015; Raghavendra and Suresh, 2018; Islam et al., 2019a). Especially for traditional food grains in small-holder agriculture, improved practices such as modern varieties or integrated nutrient management can play an important role in making production more resilient to climate stress (Handschuch and Wollni, 2016). This measure is also among the top four most frequent adaptation measures in all continents except Australia and North America (Figure 4.27). In addition, this measure is shown to have positive economic benefits (*high confidence*) and also benefits on other parameters (*medium confidence*) (Figure FAQ4.4.1). Such approaches are also among those most frequently assessed for their effectiveness in addressing future climate change, but show limited effectiveness across warming levels (Figure 4.28 and Figure 4.29).

The use of non-conventional water sources, that is, desalinated and treated waste water, is emerging as an important component of increasing water availability for agriculture (DeNicola et al., 2015; Martínez-Alvarez et al., 2018b; Morote et al., 2019). While desalination has a high potential in alleviating agricultural water stress in arid coastal regions, proper management and water quality standards for desalinated irrigation water are essential to ensure continued or increased crop productivity. In addition to the energy intensity (Section 4.7.6), risks of desalinated water include lower mineral content, higher salinity, crop toxicity and soil sodicity (Martínez-Alvarez et al., 2018b). Similarly, waste-water reuse can be an important contribution to buffer against the increasing variability of water resources. However, waste-water guidelines that ensure the adequate treatment to reduce adverse health and environmental outcomes due to pathogens or other chemical and organic contaminants will be essential (Angelakis and Snyder, 2015; Dickin et al., 2016) (Box 4.5; 4.6.4).

IKLK are crucial determinants of adaptation in agriculture for many communities globally. Indigenous Peoples have intimate knowledge about their surrounding environment and are attentive observers of climate changes. As a result, they are often best placed to enact successful adaptation measures, including shifting to different crops, changing cropping times or returning to traditional varieties (Mugambiwa, 2018; Kamara et al., 2019; Nelson et al., 2019) (Section 4.8.4).

Migration and livelihood diversification is often an adaptation response to water-related hazards and involves securing income sources away from agriculture, including off-farm employment and temporary or permanent migration, and these are particularly important in Asia and Africa (Figure 4.27). Income and remittances are sometimes re-invested, for instance, for crop diversification (Rodriguez-Solorzano, 2014; Musah-Surugu et al., 2018; Mashizha, 2019). While there is extensive documentation on the benefits of migration, the quality of studies is such that links between migration and subsequent benefits are not clear, making our conclusion of benefits from this measure as having *medium confidence*. On the other hand, there is more rigorous evidence on the maladaptive nature of migration as an adaptation measure (Figure FAQ4.4.1). However, adverse climatic conditions, especially droughts, have been found to reduce international migration, as resources are unavailable to consider this option (Nawrotzki and Bakhtsiyarava, 2017), resulting in limits to adaptation (Ayeb-Karlsson et al., 2016; Brottem and Brooks, 2018; Ferdous et al., 2019). In addition, it is difficult to model this option in future climate adaptation models.

Policies, institutions and capacity building are important adaptation measures in agriculture and often have beneficial outcomes, but the quality of studies precludes a high degree of certainty about those impacts (Figure FAQ4.4.1). Access to credits, subsidies or insurance builds an important portfolio of reducing reliance on agricultural income alone (Rahut and Ali, 2017; Wossen et al., 2018). Training and capacity building are essential tools to ensure effective adaptation in agriculture, increasing food security (Chesterman et al., 2019; Makate and Makate, 2019). Through better understanding, the implementation of available responses reduces exposure to climate impacts. In addition, public regulations, including water policies and allocations and incentive instruments, and availability of appropriate finance play an essential role in shaping and enabling (Sections 4.8.5, 4.8.6, 4.8.7), but also limiting (Section 4.8.2), water-related adaptation for agriculture (see also Chapter 17).

Water-stressed regions already rely on importing agricultural resources, thus importing water embedded in these commodities (D'Odorico et al., 2014). Virtual water trade will continue to play a role in reducing water-related food insecurity (Cross-Chapter Box INTERREG in Chapter 16) (Pastor et al., 2014; Graham et al., 2020b).

While an increasing body of literature documents water-related adaptation in the agricultural sector, both in reducing current climate impacts and addressing future climate risk, knowledge gaps remain about assessing the effectiveness of such measures to reduce impacts and risks. Additional considerations on co-benefits of trade-offs for overall sustainable development are not always sufficiently considered in the available literature.

In sum, water-related adaptation in the agricultural sector is widely documented, with irrigation, agricultural water management, crop diversification and improved agronomic practices among the most common adaptation measures adopted (*high confidence*). However, the projected future effectiveness of available water-related adaptation for agriculture decreases with increasing warming (*medium evidence, high agreement*).

4.6.3 Adaptation in Energy and Industrial Sectors

While AR5 (Arent et al., 2014) had looked at demand and supply changes in the energy sector due to climate change, none of the AR5 chapters had assessed adaptations in the energy sector per se. A modelling study by van Vliet et al. (2016b) demonstrated that increasing the efficiency of hydropower plants by up to 10% could offset the impacts of decreased water availability in most regions by mid-century, under both RCP2.6 and RCP8.5 scenarios (*medium confidence*). Changing hydropower operation protocol and plant design can be effective adaptation measures, yet may be insufficient to mitigate all future risks related to increased floods and sediment loads (Lee et al., 2016).

van Vliet et al. (2016b) projected that even a 20% increase in efficiency of thermoelectric power plants might not be enough to offset the risks of water stress by mid-century (*medium confidence*). Therefore, thermoelectric power plants will need additional adaptation measures such as changes in cooling water sources and alternative cooling technologies (van Vliet et al., 2016c). In China, many CFPPs in water-scarce North China have adopted air cooling technologies (Zhang et al., 2016a). In Europe, wet/dry cooling towers (Byers et al., 2016) and seawater cooling (Behrens et al., 2017) have been the preferred options. Overall, freshwater withdrawals for adapted cooling systems under all scenarios are projected to decline by –3% to –63% by 2100 compared to the base year of 2000 (Fricko et al., 2016) (*medium confidence*).

Diversifying energy portfolios to reduce water-related impacts on the energy sector is another effective adaptation strategy with high mitigation co-benefits. A modelling study from Europe shows that for a 3°C scenario, an energy mix with an 80% share of renewable energy can potentially reduce the overall negative impacts on the energy sector by a factor of 1.5 times or more (Tobin et al., 2018). In addition, hydropower can also play a role in compensating for the intermittency of other renewable energies (François et al., 2014). For example, integrating hydro, solar and wind power in energy generation strategies in the Grand Ethiopian Renaissance Dam can potentially deliver multiple benefits, including decarbonisation, compliance with environmental flow norms and reduce potential conflicts among Nile riparian countries (Sterl et al., 2021). Furthermore, reducing the share of thermoelectric power with solar and wind energy (Tobin et al., 2018; Arango-Aramburo et al., 2019; Emodi et al., 2019) can be synergistic from both climate and water perspectives, as solar and wind energy have lower water footprints (*high confidence*).

Indigenous Peoples, mountain communities and marginalised minorities often bear the brunt of environmental and social disruptions due to hydropower. As a consequence, hydropower operators face resistance prior to and during construction. Benefit-sharing mechanisms help redistribute some of the gains from hydropower generation to the communities in the immediate vicinity of the project. For instance, sharing of hydropower revenues and profits to fund local infrastructure and pay dividends to local people has been practiced in Nepal and in some countries of the Mekong basin to enhance the social acceptability of hydropower projects (Balasubramanya et al., 2014; Shrestha et al., 2016) (*low confidence*).

Most water-intensive industries are increasingly facing water stress, making the reuse of water an attractive adaptation strategy (see Box 4.5). For example, Singapore, where the share of industrial water use is projected to grow from 55% in 2016 to 70% in 2060, is increasing its NEWater (highly treated wastewater) supply share from 30% to 55% to meet the growing demand of industrial and cooling

Box 4.3 | Irrigation as an Adaptation Response

Irrigation has consistently been used as a crop protection and yield enhancement strategy and has become even more critical in a warming world (Siebert et al., 2014). Approximately 40% of global yields come from irrigated agriculture, with a doubling of irrigated areas over the last 50 years and now constituting around 20% of the total harvested area (FAO, 2018b; Meier et al., 2018; Rosa et al., 2020b). Thus, irrigation is one of the most frequently applied adaptation responses in agriculture and features centrally in projections of adaptation at all scales. Expansions of irrigated areas over the coming century are projected, leading to shifts from rain-fed to irrigated agriculture in response to climate change (Malek and Verburg, 2018; Huang et al., 2019; Nechifor and Winning, 2019). However, there are regional limitations to this expansion due to renewable water resource limitations, including water quality issues (Zaveri et al., 2016; Turner et al., 2019). Depending on the specific spatial, temporal and technological characteristics of irrigation expansion, up to 35% of current rain-fed production could sustainably shift to irrigation with limited negative environmental effects (Rosa et al., 2020b).

Irrigation increases resilience and productivity relative to rain-fed production by reducing drought and heat stress on crop yields and by lowering ET demand by cooling canopy temperatures (Siebert et al., 2014; Tack et al., 2017; Li and Troy, 2018; Zaveri and B. Lobell, 2019; Agnolucci et al., 2020; Rosa et al., 2020b). Large-scale irrigation also affects local and regional climates (Cook et al., 2020b). While cooling effects, including reduction of the extreme heat due to irrigation, have been observed (Qian et al., 2020; Thiery et al., 2020), increases in humid heat extremes because of irrigation with potentially detrimental health outcomes have also been reported (Krakauer et al., 2020; Mishra et al., 2020). For the heavily irrigated North China Plain, a night-time temperature increase overcompensated daytime cooling effects, leading to an overall warming effect (Chen and Jeong, 2018). In addition, modification of rainfall patterns has been linked to irrigation (Alter et al., 2015; Kang and Eltahir, 2019; Mathur and AchutaRao, 2020). For example, increases in extreme rainfall in central India in recent decades has been linked to the intensification of irrigated paddy cultivation in northwest India (Devanand et al., 2019).

Different irrigation techniques are associated with significant differences in irrigation water productivity (Deligios et al., 2019), and replacing inefficient systems can reduce average non-beneficial water consumption by up to 76% while maintaining stable crop yields (Jägermeyr et al., 2015). Several adjustments can improve water use efficiency, including extending irrigation intervals, shortening the time of watering crops or reducing the size of the plot being irrigated (Caretta and Börjeson, 2015; da Cunha et al., 2015; Dumenu and Obeng, 2016). Deficit irrigation is an important mechanism for improving water productivity (Zheng et al., 2018) and increasing regional crop production under drying conditions (Malek and Verburg, 2018). Access to irrigation can also play a role in alleviating poverty, contributing to reducing vulnerability and risks (Balasubramanya and Stifel, 2020). However, the diversity of irrigation-related techniques and the consequent differences in effect and water-use intensity is often underreported (Vanschoenwinkel and Van Passel, 2018).

The use of water-saving technologies like laser levelling, micro-irrigation, efficient pumps and water distribution systems (Kumar et al., 2016); increasing irrigation efficiency (Wang et al., 2019a) through improved agronomic practices (Kakumanu et al., 2018) and economic instruments like water trading in developed countries like Australia (Kirby et al., 2014) are known to reduce water application rates and increase yields, and 'save' water at the plot level, but may exacerbate basin-scale water scarcity (van der Kooij et al., 2013; Zhou et al., 2021).

Asia accounts for 69–73% of the world's irrigated area. However, irrigation currently plays a relatively minor role in most of Africa, except in the contiguous irrigated area along the Nile basin and North Africa and South Africa (Meier et al., 2018). In India, long-term data (1956–1999) on the irrigated area shows that farmers adjust their irrigation investments and crop choices in response to medium-run rainfall variability (Taraz, 2017). da Cunha et al. (2015) report that farmers' income tends to be higher on irrigated lands in Brazil. In Bangladesh, farmers invest a part of their increased incomes in improving irrigation access (Delaporte and Maurel, 2018). The severity of drought increases the likelihood of farmers adopting supplementary irrigation in Bangladesh (Alauddin and Sarker, 2014). In Vietnam, irrigation improvement had the highest positive impact on crop yield among all farm-level adaptive practices (Ho and Shimada, 2019). In South Africa, access to irrigation was one of the most important predictors of whether or not farmers would adopt a whole suite of other adaptation responses (Samuel and Sylvia, 2019).

Irrigation is also associated with adverse environmental and socioeconomic outcomes, including groundwater over-abstraction, aquifer salinisation (Foster et al., 2018; Pulido-Bosch et al., 2018; Quan et al., 2019; Blakeslee et al., 2020) and land degradation (Singh et al., 2018). Further, while irrigation expansion is one of the most commonly proposed adaptation responses, there are limitations to further increases in water use, as many regions are already facing water limitations under current climatic conditions *(high confidence)* (Rockström et al., 2014; Steffen et al., 2015; Kummu et al., 2016).

Projections of the future effectiveness of irrigation indicate a varying degree of effectiveness depending on the region and specific type and combination of approaches used. At the same time, overall residual impacts increase at higher levels of warming (Section 4.7.1.2). Uncertainties in regional climate projections and limitations in the ability of agricultural models to fully represent water resources are important limitations in our understanding of the potential of further irrigation expansion (Section 4.5.1) (Greve et al., 2018).

Box 4.3 (continued)

In light of the volume of irrigated agriculture globally, and the projected increase in water requirements for food production, increasing water productivity and thus improving the ratio of water used per unit of agricultural output is necessary globally to meet agricultural water demand (Section 4.5.1) (Jägermeyr et al., 2015; Jägermeyr et al., 2017). For example, assuming a doubling of global maize production by 2050 increased water productivity could reduce total water consumption compared to the baseline productivity by 20–60% (Zheng et al., 2018). Under economic optimisation 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). Shifting currently rain-fed production areas to irrigation will be an important element in ensuring food security with increasing temperatures, though investment in storage capacities to buffer seasonal water shortage will be essential to ensure negative environmental impacts are minimised (Rosa et al., 2020b).

activities (PUB, 2016). In addition, the mining industry has also adopted water adaptations measures, such as water recycling and reuse; using brackish or saline sources; and working with regional water utilities to reduce water extraction and improve water use efficiency (Northey et al., 2017; Odell et al., 2018).

In summary, energy and industrial sector companies have undertaken several adaptation measures to reduce water stress, with varying effectiveness levels. However, residual risks will remain, especially at higher levels of warming (*medium confidence*).

4.6.4 Adaptation in the Water, Sanitation and Hygiene Sector

AR5 pointed to adaptive water management techniques (*limited evidence, high agreement*) (Field et al., 2014b), while SR1.5 documented the need for reducing vulnerabilities and promoting sustainable development and disaster risk reduction synergies (*high confidence*) (IPCC, 2018a). WaSH has also been identified as a low-regrets adaptation measure (Cutter et al., 2012).

Access to appropriate, reliable WaSH protects against water-related diseases, particularly after climate hazards such as heavy rainfalls and floods (Carlton et al., 2014; Jones et al., 2020). WaSH interventions have been demonstrated to reduce diarrhoea risk by 25–75% depending on the specific intervention (Wolf et al., 2018) (*high confidence*). Conversely, inadequate WaSH is associated with an estimated annual loss of 50 million daily adjusted life years (Prüss-Ustün et al., 2019), of which 89% of deaths are due to diarrhoea, and 8% of deaths from acute respiratory infections (Chapter 7 WGII 7.3.2), making universal access to WaSH (i.e., achievement of SDG 6.1, 6.2) a critical adaptation strategy (*high confidence*). However, not all WaSH solutions are suited to all climate conditions (Sherpa et al., 2014; Howard et al., 2016), so health outcome improvements are not always sustained under changing climate impacts (Dey et al., 2019) (*medium evidence, high agreement*). As such, WaSH infrastructure also needs to be climate-resilient (Smith et al., 2015; Shah et al., 2020). In addition to new WaSH infrastructure design and implementation, expansion and replacement of existing infrastructure offer opportunities to implement climate-resilient designs and reduce greenhouse emissions (Boholm and Prutzer, 2017; Dickin et al., 2020) (*medium evidence, high agreement*).

Effective adaptation strategies include protecting source water and managing both water supply and demand. Source water protection (Shaffril et al., 2020) has proven effective in reducing contamination. Improved integrated (urban) water resources management (Kirshen et al., 2018; Tosun and Leopold, 2019) and governance (Chu, 2017; Miller et al., 2020) and enhanced ecosystem management (Adhikari et al., 2018b) lead to policies and regulations that reduce water insecurity and, when developed appropriately, reduce inequities (*medium confidence*). Supply (source) augmentation, including dams, storage and rainwater/fog harvesting, can increase the supply or reliability of water for drinking, sanitation and hygiene (DeNicola et al., 2015; Pearson et al., 2015; Majuru et al., 2016; Poudel and Duex, 2017; Lucier and Qadir, 2018; Goodrich et al., 2019) (*high confidence*). For example, rainwater harvesting in an Inuit community increased water for hygiene by 17%, reduced water retrieval efforts by 40% and improved psychological and financial health (Mercer and Hanrahan, 2017). However, climate change impacts will affect amounts of rainwater available. A recent study concluded that domestic water demand met through rainwater harvesting generally improves under climate change scenarios for select communities in Canada and Uganda, with the exception of drier summers in some areas of Canada (Schuster-Wallace et al., 2021). Further, it is important to recognise that many of these interventions require financial investments that make them inaccessible to the poorest (Eakin et al., 2016). Demand for water can be decreased through reductions in water loss from the system (e.g., pipe leakage) (Orlove et al., 2019) and water conservation measures (Duran-Encalada et al., 2017) (*medium confidence*).

During periods of water insecurity, people often implement maladaptive strategies (Magnan et al., 2016), that is, strategies that can increase the risk of adverse health impacts, increase exposure to violence or cause malnutrition (Kher et al., 2015; Pommells et al., 2018; Collins et al., 2019a; Schuster et al., 2020) (*medium evidence, high agreement*). Examples include walking further, using less safe water sources, prioritising drinking and cooking over personal/household hygiene, or reducing food/water intake. Conversely, some rebalancing of gender roles can occur when women and girls cannot source sufficient water, with men building additional water supply or storage infrastructure or fetching water (Singh and Singh, 2015; Magesa and Pauline, 2016; Shrestha et al., 2019b). Some adaptation strategies create unintended health threats such as increased odds

(1.55) of mosquito larvae in water storage pots (Ferdousi et al., 2015), which could have even more significant impacts in the future given projected range expansion for vectors as a result of climate change (Liu-Helmersson et al., 2019). Other unintended consequences include pathogen contamination (Gwenzi et al., 2015) and time or financial trade-offs (Schuster et al., 2020) (*medium evidence, high agreement*). Wastewater reuse for irrigation may have adverse health impacts if wastewater is not treated (Dickin et al., 2016). Conversely, especially where women are responsible for domestic and productive water management, adaptive agricultural water strategies, such as water-efficient irrigation or low-water crops, mean that less water from finite water supplies are used for agriculture, leaving more water locally available for domestic purposes (see section 4.6.2). These co-benefits across sectors become important community water stress adaptations (Chinwendu et al., 2017), with water savings from one use leading to more water available for other uses. This can reduce domestic water burdens and, therefore, gender inequities (Section 4.8.3) (*limited evidence, high agreement*). Further analyses of co-benefits, particularly employing a gender lens, are required to improve adaptation strategies (McIver et al., 2016).

In summary, ensuring access to climate-resilient WaSH infrastructure and practices represents a key adaptation strategy that can protect beneficiaries against water-related diseases induced by climate change (*high confidence*). Better management of water resources, supply augmentation and demand management are important adaptation strategies (*high confidence*). Reliable, safe drinking water reduces adverse physical and psychological impacts of climate-related water stress and extreme events (*robust evidence, medium agreement*). WaSH infrastructure expansion and replacement provide opportunities to redesign and increase resilience in rural and urban contexts (*limited evidence, high agreement*).

4.6.5 Adaptation in Urban and Peri-Urban Sectors

AR5 reported that although case studies of the potential effectiveness of adaptation measures in cities are growing, not all considered how adaptation would be implemented in practice (Jiménez Cisneros et al., 2014). Furthermore, AR5 concluded that more attention had been given to adaptations that help ensure sufficient water supplies than

Box 4.4 | COVID-19 Amplifies Challenges for WaSH Adaptation

While COVID-19 is an airborne disease (see Cross-Chapter Box COVID in Chapter 7), public health responses to the COVID-19 pandemic and the associated socioeconomic and environmental impacts of these measures intersect with WaSH (Armitage and Nellums, 2020a). Notably, COVID-19 and climate change act as compound risks in the context of water-induced disasters, exacerbating existing threats to sustainable development (Neal, 2020; Pelling et al. 2021).

The principal WaSH response to COVID-19 relates to hand hygiene, an infection control intervention that requires access to sufficient, clean and affordable water beyond cooking, hydration and general sanitation needs, as outlined in SDG6 (Armitage and Nellums, 2020a). However, despite significant progress, more than 800 million people in central and southern Asia, and 760 million in sub-Saharan Africa, lack basic hand-washing facilities in the home (UNICEF, 2020). Notably, one in four healthcare facilities in select low- and middle-income countries lacks basic water access, and one in six lacks hand-washing facilities (WHO, 2019) (Section 4.3.3). Moreover, household water insecurity also impacts marginalised and minority groups in the Global North (Deitz and Meehan, 2019; Rodriguez-Lonebear et al., 2020; Stoler et al., 2021).

Compound disasters have arisen due to either the co-occurrence of drought, storms or floods and COVID-19. COVID-19 acts as a stress multiplier for women and girls in charge of water collection and minorities and disabled people who are not engaged in water management (Phillips et al., 2020; Rodriguez-Lonebear et al., 2020). Across the world, existing inequalities deepened due to lockdowns, which further limited access to clean water and education for women and girls, and reinstated gendered responsibilities of child, elderly and sick care, which had been previously externalised (Cousins, 2020; Neal, 2020; Zavaleta-Cortijo et al., 2020). Accordingly, COVID-19 has further steepened the path to reach SDGs 2, 3, 4, 5 and 11 (Lambert et al., 2020; Mukherjee et al., 2020; Neal, 2020; Pramanik et al., 2021). In addition, the pandemic exacerbated food insecurity in drought-affected eastern and southern Africa (Phillips et al., 2020; Mishra et al., 2021). As the twin risk of COVID-19 and hurricanes on the US Gulf Coast (Pei et al., 2020; Shultz et al., 2020) and cyclone Amphan in Bangladesh (Pramanik et al., 2021) showed, increased hand washing, additional WaSH and evacuation and shelter infrastructures proved essential for preventing further spread of COVID-19 (Baidya et al., 2020; Ebrahim et al., 2020; Guo et al., 2020; Mukherjee et al., 2020; Pei et al., 2020; Shultz et al., 2020; Pramanik et al., 2021). Moreover, while immediate steps can be taken during disaster response to minimise climate-attributable loss of life, climate adaptation requires long-term strategies that intersect with pandemic preparedness (Phillips et al., 2020).

Public health responses to COVID-19 geared towards infection control and caring for the sick can trigger increased water demand where population numbers and density are high (Mukherjee et al., 2020; Sivakumar, 2021). As COVID-19 has highlighted the importance of WaSH (Section 4.3.3), this pandemic could also result in long-term positive outcomes in community resilience, improved infection control and health protection while addressing longer-term environmental challenges of climate change (Phillips et al., 2020).

to increasing the capacity of sewage and drainage systems to adapt to heavier rainfall or sea level rise (Revi et al., 2014).

Since AR5 knowledge on urban adaptation has advanced, even though there is still limited documentation of water adaptation in urban contexts as compared to other adaptation responses (Figure 4.23.) The majority of case studies on urban adaptation are also from developed countries, most commonly in Europe and Australasia (Figure 4.24). Water-related urban and peri-urban climate change adaptation can involve 'hard' engineering structures (grey), managed or restored biophysical systems (green and blue) or hybrid approaches that combine these strategies (Ngoran and Xue, 2015; Palmer et al., 2015) (Figure 4.21, also see Figure 4.22 for types of urban adaptation options).

In most regions, hybrid adaptation approaches are underway. For example, sustainable urban drainage systems (SUDS) are a common adaptation measure that can reduce flooding and improve stormwater quality while reducing the urban heat island effect (e.g., Chan et al., 2019; Loiola et al., 2019; Song et al., 2019; Huang et al., 2020; Lin et al., 2020) (Box 4.6; 12.5.5.3.2; 12.7.1). Municipal, catchment and local community plans to minimise water-related climate risks are another form of adaptation (Stults and Larsen, 2018). Plans involve supply augmentation (Chu, 2017; Bekele et al., 2018), as well as floodplain management, land use planning, stakeholder coordination and water demand management (Andrew and Sauquet, 2017; Flyen et al., 2018; Robb et al., 2019; Tosun and Leopold, 2019), with some US cities including strategies to address social inequalities that climate change may exacerbate (Chu and Cannon, 2021).

Such adaptation measures are concentrated in more developed countries (Olazabal et al., 2019). For example, about 80% of European cities with more than 500,000 inhabitants have either mitigation and/or adaptation plans (Reckien et al., 2018). In contrast, a survey of cities with more than one million inhabitants found 92% of Asian cities, 89% of African cities and 87% of Latin American cities did not report adaptation initiatives (Araos et al., 2016) (12.5.8.1). Autonomous adaptation measures (e.g., elevating housing and drainage maintenance) are pursued to reduce flood risk in urban Senegal (Schaer, 2015), Kenya (Thorn et al., 2015), Brazil (Mansur et al., 2018) and Guyana (Mycoo, 2014) (Box 4.7; 9.8.5.1; 12.5.5.3; FAQ12.2).

Further studies are required to ascertain the effectiveness of adaptation measures implemented since AR5, particularly for the growing populations of informal and peri-urban settlements. For example, in urban Africa, such informal settlements are sites of political contestation as residents resist municipal relocation strategies for flood alleviation (Douglas, 2018). In addition, the growing complexity of challenges facing urban water management, such as climate change, urbanisation and environmental degradation, warrants a transformative shift away from prevailing siloed approaches of water supply, sanitation and drainage to more integrated systems that enhance adaptive capacity (Ma et al., 2015; Franco-Torres et al., 2020).

In summary, although water-related adaptation is underway in the urban, peri-urban and municipal sectors of some nations, governance, technical and economic barriers remain in implementing locally informed strategies, particularly in developing countries (*high confidence*).

4.6.6 Adaptation for Communities Dependent on Freshwater Ecosystems

AR5 concluded that some adaptation responses in the urban and agricultural sectors could negatively impact freshwater ecosystems (*medium confidence*) (Settele et al., 2014).

Adaptation measures to cope with changes in ecosystems, including freshwater ecosystems, such as ecosystem-based adaptation (EbA) interventions have gained wide recognition at the global policy level (Reid, 2016; Barkdull and Harris, 2019; Piggott-McKellar et al., 2019b). These have been implemented in many locations around the world, yet, challenges remain, including improving the evidence base of their effectiveness, scaling up of these interventions, mainstreaming across sectors and receiving more adaptation finance (*medium confidence*).

A systematic review of 132 academic papers and 32 articles from non-peer-reviewed literature (Doswald et al., 2014) provided a comprehensive global overview of EbA, which showed that EbA interventions were used in various ecosystems, including inland wetlands (linked to 30 publications). An investigation of EbA effectiveness by Reid et al. (2019), where nine case studies covering South Asia, Africa and South America were associated with freshwater systems, concluded that EbA enabled the enhancement of the adaptive capacity or resilience to climate change, particularly for the more vulnerable groups in the community. 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 the use of urban wetlands (Barkdull and Harris, 2019). EbA is a subset of NbS that is rooted in climate change adaptation and covers both mitigation and adaptation (Pauleit et al., 2017) (Section 4.6.5, Box 4.6). Although adaptation measures for freshwater ecosystems have been implemented in many places (Shaw et al., 2014; Lukasiewicz et al., 2016; Karim and Thiel, 2017; Milman and Jagannathan, 2017; FAO, 2018a; Piggott-McKellar et al., 2019b), the evidence base for the effectiveness of these measures to cope with changes in freshwater ecosystems needs improvement. These measures also require further financial support, mainstreaming across sectors and the scaling up of individual measures (*medium confidence*).

In summary, adaptation measures to cope with changes in freshwater ecosystems have been implemented in many locations around the world. However, challenges remain, including improving the evidence base of their effectiveness, scaling up these interventions, mainstreaming across sectors and receiving more adaptation finance (*medium confidence*).

4.6.7 Adaptation Responses for Water-Related Conflicts

AR5 concluded with *high confidence* that challenges for adaptation actions (though not water) are particularly high in regions affected by conflicts (Field et al., 2014a). Although climate–conflict linkages are disputed (Section 4.3.6), the potential for synergies between conflict risk reduction and adaptation to climate change exists (Mach et al., 2019). For example, discourses around climate–conflict inter-linkages can present

Strategies for Urban Water Adaptation

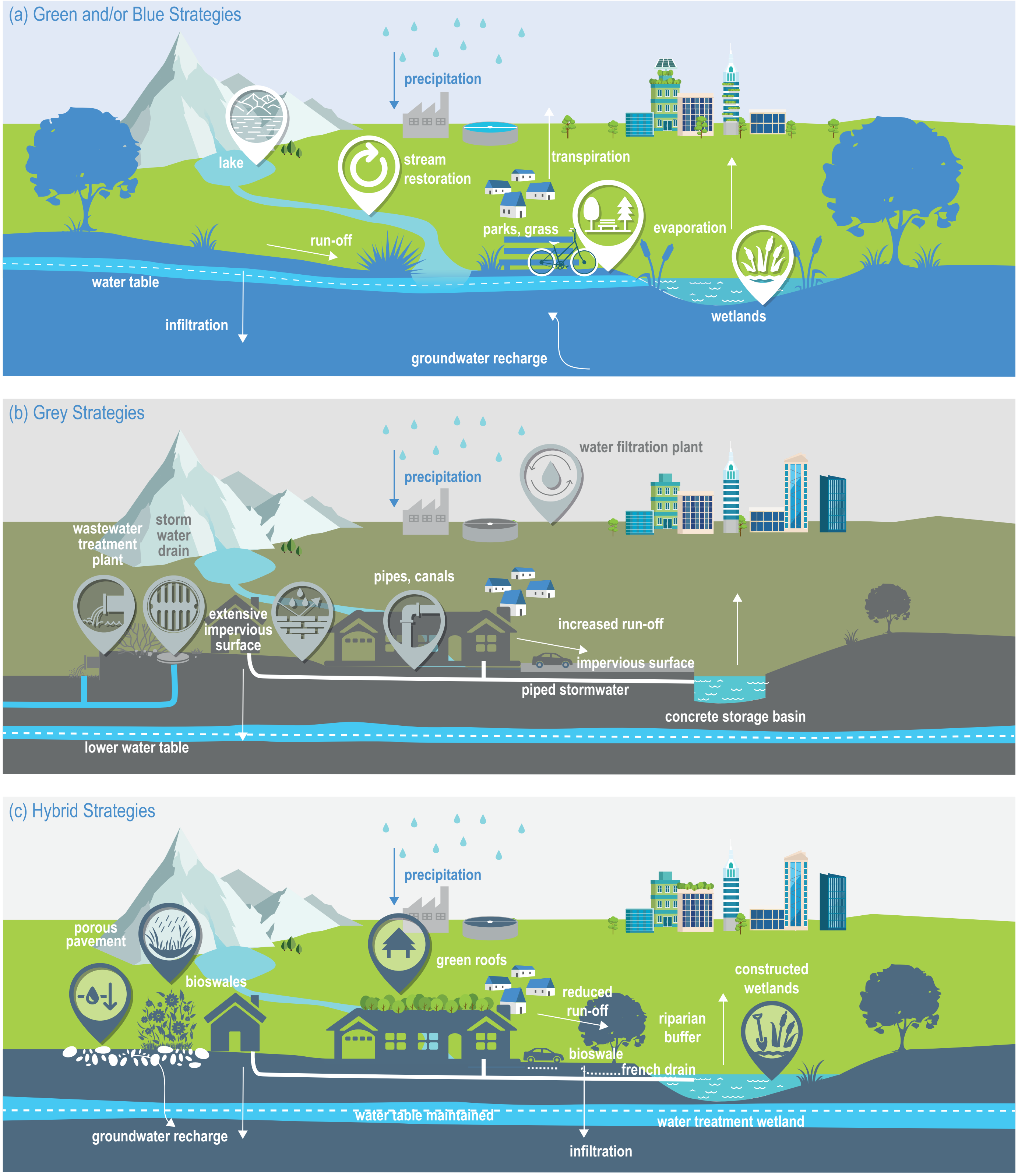


Figure 4.21 | Strategies for urban water adaptation.

(a) Green and blue strategies of urban water adaptation prioritise ecosystem restoration, such as wetlands restoration.

(b) Grey water strategies are hard engineering approaches to urban water adaptation, including infrastructure such as pipes and canals, with extensive areas of impervious surfaces.

(c) Hybrid approaches combine green, blue and grey adaptation strategies, such that ecosystem functions are complemented by engineered infrastructure, such as constructed wetlands, green roofs and riparian buffers. Green and blue and hybrid approaches are variously classified in terms of a circular economy, water sensitive urban design, nature-based solutions (NbS), integrated urban water management, and ecological infrastructure. Adapted from Depietri and McPhearson (2017).

Box 4.5 | Reduce, Remove, Reuse and Recycle (4Rs): Wastewater Reuse and Desalination as an Adaptation Response

Circular economies can increase the available sustainable adaptation space by moving away from a linear mode of production of 'extract-produce-use-discard' to a '4Rs' closed loop to reduce pollution at the source, remove contaminants from wastewater, reuse treated wastewater and recover valuable by-products (UN Water, 2017; see WGIII 11.3.3).

It is estimated that 380 billion m^3 of wastewater is produced annually worldwide, which equals about 15% of agricultural water withdrawals. The recovery of nitrogen, phosphorus and potassium from wastewater can offset 13.4% of the global agriculture demand for these nutrients (Jiménez and Asano, 2008; Fernández-Arévalo et al., 2017). Recycling human waste worldwide could satisfy an estimated 22% of the global demand for phosphorus (UN Water, 2017). It has been estimated that some 36 million ha worldwide (some 12% of all irrigated land) reuse urban wastewater, mainly for irrigation. However, only around 15% is adequately treated (Thebo et al., 2017), thus the need to invest in sustainable, low-cost wastewater treatment to protect public health. The irrigation potential of this volume of wastewater stands at 42 million ha. Wastewater production is expected to increase globally to 574 billion m^3 by 2050, a 51% increase compared to 2015, mainly due to a growing urban population (Qadir et al., 2020). Water reuse with treated wastewater for potable and non-potable purposes can be practised in a manner that is protective of public health and the environment (WHO, 2006; WHO, 2017). For example, when implemented with sufficient treatment standards, the use of recycled water for the irrigation of crops is protective of public health (Blaine et al., 2013; Paltiel et al., 2016), as was determined by an appointed panel of experts in the state of California (Cooper et al., 2012). However, there are several barriers to the adoption of wastewater reuse; these include technical barriers and public health aspects related to microbiological and pharmaceuticals risks (Jiménez and Asano, 2008; Jaramillo and Restrepo, 2017; Saurí and Arahuetes, 2019). These are currently being addressed by strengthening regulatory standards, with, for example, 11 out of 22 Arab States adopting legislation permitting the use of treated wastewater (WHO, 2006; US EPA, 2017; WHO, 2017; EC, 2020). Benefits of wastewater reuse usually outweigh the costs (Stacklin, 2012; Hernández-Sancho et al., 2015; UN Water, 2017).

Desalination is particularly important in arid and semiarid climates, coastal cities and small island states (Box 4.2). There were 16,000 operational desalination plants globally in 2017, with a daily desalinated water production of 95 million m^3 d^{-1} (IDA, 2020). In 2012, desalinated water was equivalent to 0.6% of the global water supply, and 75.2 TWh of energy per year was used to generate desalinated water; in other words, about 0.4% of the worldwide electricity consumption (IRENA, 2012). Unfortunately, only 1% of total desalinated water uses renewable sources (IRENA, 2012; Amy et al., 2017; Balaban, 2017; Martínez-Alvarez et al., 2018a; Jones et al., 2019) (Section 4.7.6). Desalination has already helped to meet urban and peri-urban water supply, particularly during annual or seasonal drought events, with half of the world's desalination capacity in the Arab region (UN Environment, 2019; UN Water, 2021). In addition, seawater desalination could help address water scarcity in 146 (50%) large cities (including 12 (63.2%) megacities) (He et al., 2021). Desalination is also being adopted for irrigation. For example, in the island of Gran Canary (Spain), 30% of the agricultural surface area is irrigated with desalinated water to irrigate high-value crops (Burn et al., 2015; Martínez-Alvarez et al., 2018a; Monterrey-Viña et al., 2020). The expected growth of desalination, if not coupled with renewable energy (RE), causes a projected 180% increase in carbon emissions by 2040 (GCWDA, 2015; Pistocchi et al., 2020). There have been advances in large-scale and on-farm renewable desalination (Abdelkareem et al., 2018). Using renewable energy to decarbonise desalination has meant that the projected global average levelled cost of water could decrease from €2.4 m^{-3} (2015) to approximately €1.05 m^{-3} by 2050, considering unsubsidised fossil fuel costs (Caldera and Breyer, 2020). Desalination will be maladaptive if fossil fuel is used (Tubi and Williams, 2021).

In summary, a resilient circular economy is central to deliver access to water and sanitation, with, wastewater treatment, desalination and water reuse as viable adaptation options compatible with the Paris Agreement, while safeguarding ecological flows according to the SDG6 targets for climate resilient development (*medium evidence, high agreement*).

opportunities for peace building and cooperation (Matthew, 2014; Abrahams, 2020). Indeed, adaptation efforts are needed in the context of conflict, where the pre-existing vulnerability undermines the capacity to manage climatic stresses. In addition, adaptive capacity depends on contextual factors such as power relations and historical, ethnic tensions (Petersen-Perlman et al., 2017; Eriksen et al., 2021), which need to be adequately considered in the design of adaptation strategies.

Some adaptation options, such as water conservation, storage and infrastructure, voluntary migration, planned relocation due to flood risk/sea level rise, and international water treaties, can reduce vulnerability to climate change and conflicts. However, on the other hand, these adaptation options sometimes may have unintended consequences by increasing existing tensions (Milman and Arsano, 2014); displacing climate hazards to more vulnerable and marginalised groups (Milman and Arsano, 2014; Mach et al., 2019), for example, pastoralists (Zografos et al., 2014); and favouring some over others, such as industry over agriculture (Iglesias and Garrote, 2015)¸ upstream countries over downstream countries (Veldkamp et al., 2017), and men over women (Chandra et al., 2017). Such unintended consequences may happen when adaptation measures intended to reduce vulnerability produce maladaptive outcomes by rebounding or shifting vulnerability to

Box 4.6 | Nature-based Solutions for Water-Related Adaptation

In the context of climate change-induced water insecurity, nature-based solutions (NbS) are an adaptation response that relies on natural processes to enhance water availability and water quality and mitigate risks associated with water-related disasters while contributing to biodiversity (IUCN, 2020).

Until recently, NbS have been considered mainly for mitigation (Kapos et al., 2020; Seddon et al., 2020). Yet, NbS increase the low-cost adaptation options that expand the adaptation space due to their multiple co-benefits (Cross-Chapter Box NATURAL in Chapter 2). Furthermore, a meta-review of 928 NbS measures globally shows that NbS largely addresses water-related hazards like heavy precipitation (37%) and drought (28%) (Kapos et al., 2020).

Natural infrastructure (green and blue) uses natural or semi-natural systems, for example, wetlands, healthy freshwater ecosystems, etc., to supply clean water, regulate flooding, enhance water quality and control erosion (6.3.3.1 to 6.3.3.6.). Grey infrastructure can damage biophysical and hydrological processes, seal soils and bury streams. Compared with grey physical infrastructure, natural infrastructure is often more flexible, cost-effective and can provide multiple societal and environmental benefits simultaneously (McVittie et al., 2018; UN Water, 2018; IPBES, 2019). There is increasing evidence and assessment methods on the role of NbS for climate change adaptation and disaster risk reduction at different scales (Chausson et al., 2020; Seddon et al., 2020; Cassin and Matthews, 2021) (Section 4.6.5).

At the landscape scale, there is evidence that impacts from fluvial and coastal floods can be mitigated through water-based NbS like detention/retention basins, river restoration and wetlands (Thorslund et al., 2017; Debele et al., 2019; Huang et al., 2020). Several examples show the effectiveness of floodplain restoration, natural flood management and making room for the river measures (see FAQ2.5, Hartmann et al., 2019; Mansourian et al., 2019; Wilkinson et al., 2019) (*medium evidence, high agreement*). Likewise, the use of managed aquifer recharge (MAR) in both urban and rural settings will be crucial for groundwater-related adaptation (Zhang et al., 2020a).

At the urban and peri-urban scale, the use and effectiveness of NbS is a crucial feature to build resilience in cities for urban stormwater management and heat mitigation (Depietri and McPhearson, 2017; Carter et al., 2018; Huang et al., 2020; Babí Almenar et al., 2021) (*high confidence*). NbS have been used for stormwater management by combining water purification and retention functions (Prudencio and Null, 2018; Oral et al., 2020). NbS have also been used to mitigate impacts from high-impact extreme precipitation events by integrating large-scale NbS investment plans into urban planning in cities like New York and Copenhagen, highlighting the importance of blended finance and investment (including insurance) to mainstream NbS investments (Liu and Jensen, 2017; Rosenzweig et al., 2019; Lopez-Gunn et al., 2021). According to the CDP database, one in three cities use NbS to address climate hazards, and this trend is growing (Kapos et al., 2020).

NbS are cost-effective and can complement or replace grey solutions (Cross-Chapter Box FEASIB in Chapter 18, 3.2.3) (Chausson et al., 2020). Moreover, estimates of NbS are increasingly based on integrated economic valuations that incorporate co-design with stakeholders to incorporate LK (Pagano et al., 2019; Giordano et al., 2020; Hérivaux and Le Coent, 2021; Palomo et al., 2021) (*medium evidence, high agreement*). Yet, the performance of NbS themselves may be limited at higher GWLs (Calliari et al., 2019; Morecroft et al., 2019).

More knowledge is needed on the long-term benefits of NbS, particularly to hydro-meteorological hazards (Debele et al., 2019). There is still *low evidence* for slow-onset events, including the applicability of NbS to manage highly vulnerable ecosystems and in agriculture (Sonneveld, 2018),

In summary, there is growing evidence on NbS effectiveness as an adaptation measure and its critical role for transformative adaptation to address climate change water-related hazards and water security (*medium evidence, high agreement*). Moreover, several NbS– —for example, natural (blue and green) and grey infrastructure—can help address water-related hazards such as coastal hazards, heavy precipitation, drought, erosion and low water quality (*high confidence*).

other actors (Juhola et al., 2016). For example, in the Mekong River basin, the construction of dams and water reservoirs contributes to the adaptation efforts of the upstream Southeast Asia countries while increasing current/future vulnerability to floods and droughts in downstream countries and can emerge as a cause of conflict (Earle et al., 2015; Ngô et al., 2016).

Furthermore, adaptation in the context of water-related conflicts is also constrained by economic, institutional and political factors, competition for development (Anguelovski et al., 2014) and gender considerations (Sultana, 2014; Chandra et al., 2017), which need to be taken into account when designing adaptation plans/measures.

4.6.8 Adaptations Through Human Mobility and Migration

AR5 noted that whether migration is adaptive or maladaptive depends on the context and the individuals involved; however, it did not focus specifically on hydrological change-induced migration (Noble et al., 2014). Migration is often regarded as a transformational adaptation strategy in response to climate-induced hydrological changes (Gemenne and Blocher, 2017) but rarely as the primary or only adaptation measure (Wiederkehr et al., 2018; de Longueville et al., 2020; Cross-Chapter Box MIGRATE in Chapter 7). Migration is among one of the top five adaptation responses documented in Asia and Africa (Figure 4.27) and confers several benefits to migrants, yet maladaptations are also documented (Figure 4.29). This strategy is not available to everyone. Vulnerable populations exposed to hydrological changes may become trapped due to a lack of economic and social capital required for migration (Adams, 2016; Zickgraf, 2018) (*medium confidence*).

Spontaneous migration, undertaken without outside assistance, has shown the potential to improve the resilience of migrants and communities (Call et al., 2017; Jha et al., 2018a), but may also lead to increased vulnerability and insecurity in some instances (Adger et al., 2018; Linke et al., 2018a; Singh and Basu, 2020). Migration is not a viable strategy for everyone, but age, gender and socioeconomic status play a significant role in encouraging or inhibiting the chances of successful migration (Maharjan et al., 2020; Bergmann et al., 2021; Erwin et al., 2021). Migration has increased vulnerability among women and female-headed households (Patel and Giri, 2019), but has also triggered gender-positive processes such as increased female school enrolment (Gioli et al., 2014) (*medium confidence*). Remittances, that is, transfers of money from migrants to beneficiaries in sending areas, may reduce vulnerability and increase adaptive capacity to climate-induced hydrological changes (Ng'ang'a et al., 2016; Jha et al., 2018b) (*medium confidence*). Managed retreat refers to the planned and assisted moving of people and assets away from risk areas, such as government- or community-led resettlement (Hino et al., 2017; Maldonado and Peterson, 2018; Tadgell et al., 2018; Arnall, 2019). Such initiatives may reduce exposure to risk (Lei et al., 2017). However, they often fail to include affected populations in the process and may lead to greater impoverishment and increased vulnerability (Wilmsen and Webber, 2015) (*medium confidence*).

More research on how to ensure migration becomes a successful adaptation strategy is needed (McLeman et al., 2016). In addition, impacts on women, youth and marginalised groups (McLeman et al., 2016; Miletto, 2017) and immobility issues need more attention (Zickgraf, 2018).

In summary, measures that facilitate successful migration and inclusive resettlement may facilitate adaptation to climate-induced hydrological changes (*medium confidence*).

4.6.9 Adaptation of the Cultural Water Uses of Indigenous Peoples, Local Communities and Traditional Peoples

AR5 reported that religious and sacred values inform actions taken to adapt to climate change (Noble et al., 2014). Neither AR5 nor SR1.5 reviewed adaptation of indigenous, local and traditional uses of water. SROCC highlighted the context-specific adaptation strategies of vulnerable communities in coastal, polar and high-mountain areas, reporting that adaptive capacity and adaptation limits are not only physical, technical, institutional and financial, but also culturally informed (Hock et al., 2019b; Meredith et al., 2019; Oppenheimer et al., 2019).

There is *high confidence* that some Indigenous Peoples, local communities and traditional peoples could adapt, and are adapting to climate-driven hydrological changes and their impacts on culturally significant sites, species, ecosystems and practices in polar, high-mountain and coastal areas, where sufficient funding, decision-making power and resourcing exist (e.g., Golden et al., 2015; Bunce et al., 2016; Anderson et al., 2018). However, there is also *high confidence* that there are significant structural barriers and limits to their adaptation, and that the outcomes of some adaptation strategies can be uneven and maladaptive (*medium evidence, high agreement*) (Sections 4.7.4; 4.8.3). These barriers include the lack of recognition of Indigenous Peoples' sovereignty and exclusion of Indigenous Peoples from decision-making institutions (Ford et al., 2017; Labbé et al., 2017; Eira et al., 2018; McLeod et al., 2018; MacDonald and Birchall, 2020) (14.4.4.2.2; 13.8.1.2). At the same time, the rate and scale of climate change can impede the ability of vulnerable communities to turn their adaptive capacity into effective adaptation responses (Ford et al., 2015; Herman-Mercer et al., 2019).

There is *high confidence* that local people are adapting to the cultural impacts of climate-driven glacier retreat and decline in snow cover and ice in polar and high-mountain areas. However, there is also *high confidence* that such adaptation can be detrimental and disrupt local cultures. For example, in the Peruvian Andes, concerns about water availability for ritual purposes has led to restrictions on pilgrims' removal of ice and limiting the size of ritual candles to preserve the glacier (Paerregaard, 2013; Allison, 2015). Relatedly, some local people have questioned the cosmological order and have reoriented their spiritual relationships accordingly (Paerregaard, 2013; Carey et al., 2017). In Siberia (Mustonen, 2015) and northern Finland (Turunen et al., 2016), community-led decisions among herders favour alternative routing, pasture areas and shifts in nomadic cycles in response to changing flood events and permafrost conditions (Box 13.2). However, loss of grazing land and pasture fragmentation pose adaptation limits, and some strategies such as supplementary feeding and new technologies may further affect cultural traditions of herding communities (Risvoll and Hovelsrud, 2016; Jaakkola et al., 2018).

There is *high confidence* that relocation (managed retreat) is an adaptation response for communities in areas impacted by, or at risk of, inundation and other hydrological changes (15.3.4.7; 15.5.3). However, relocation can be culturally, socially, financially, politically and geographically constrained due to the importance of cultural relationships with traditional, customary or ancestral lands (*high confidence*) (Albert et al., 2018; Narayan et al., 2020; Yates et al., 2021). Among Pacific islands, for example, the prospect of migration raises concerns about the loss of cultural identity and IK and practices, which can impact emotional well-being (Yates et al., 2021).

As cultural beliefs influence risk perception, there is *medium confidence* that some cultural understandings can foster a false sense of security among Indigenous Peoples, local communities and traditional peoples regarding climate-driven hydrological changes. For example, some members of the Rolwaling Sherpa community in Nepal believe that mountain deities protect them from GLOFs (Sherry and Curtis, 2017) (Section 4.2.2). Elsewhere, such as in the islands of Fiji and St. Vincent, cultural beliefs can diminish human agency because change is viewed as inevitable and beyond human intervention (Smith and Rhiney, 2016; Currenti et al., 2019). Yet such cultural beliefs are not necessarily maladaptive, as they potentially support other resilience factors, such as IKLK (Section 4.8.5; Ford et al., 2020), as well as cultural connections and social ties (Yates et al., 2021).

In sum, although some Indigenous Peoples, local communities and traditional peoples can adapt, and are adapting to climate-driven hydrological changes, and their impacts on and risks to culturally significant practices and beliefs (*medium confidence*), these strategies are constrained by structural barriers and adaptation limits (*high confidence*).

Box 4.7 | Flood-Related Adaptation Responses

Floods, due to their rapid onset and destructive force, require specific adaptation measures. Historically, to address flood damages and risk protection, retreat and accommodation were most common, emphasizing protecting and retreating (Wong et al., 2014; Bott and Braun, 2019). Figure 4.22 identifies five major adaptation strategies from a meta-review of water-related adaptation responses that helps in protecting, retreating and accommodating (Section 4.7.1).

Globally, structural measures for flood protection through hard infrastructure are the most common measures as they directly manage flood hazards by controlling flow through streams and prevent water overflow (Andrew and Sauquet, 2017; Duží et al., 2017). These measures include dikes, flood control gates, weirs, dams, storage and proper waste management (Barua et al., 2017; Egbinola et al., 2017). Infrastructure measures require high maintenance, such as dredging and clearing channels and overpasses (Egbinola et al., 2017). A negative aspect of protective infrastructural measures is that, while they eliminate the hazard up to a certain magnitude (Di Baldassarre et al., 2013), they also generate an illusion of no risk by diminishing frequent floods (Duží et al., 2017; Logan et al., 2018). In addition, specific engineering solutions that might be introduced from other localities without proper contextual adjustments may lead to maladaptation (Mycoo, 2014; Pritchard and Thielemans, 2014). NbS (Box 4.6) have shifted infrastructure measures from purely grey onto mixed engineering and environmental measures. Examples include SUDS, which aid in decreasing flow peaks and are affordable, aesthetically pleasing and socially acceptable while also reducing heat and hence the production of storms (Chan et al., 2019) (Section 4.6.5).

Non-structural or soft measures for flood adaptation include human actions that generate capacities, information and, therefore, awareness of floods (Du et al., 2020). Soft measures aim to integrate flood resilience within city management and planning (Wijaya, 2015; Andrew and Sauquet, 2017; Abbas et al., 2018). Social support between members of a community and economic mechanisms such as loans or remittances are soft measures that promote recovery or resilience to floods (Barua et al., 2017; Musah-Surugu et al., 2018; Bott and Braun, 2019). Communities with heightened awareness and knowledge of floods are probably going to elect political leaders that will affect flood protection and policies that include adaptation (Abbas et al., 2018). Soft measures can be an anchoring factor for policies that promote early warning systems, infrastructure, flood-resilient housing and environmental restoration (Andrew and Sauquet, 2017; Abbas et al., 2018). However, soft measures, especially at large scale, may also lead to maladaptation, such as lack of synchronisation between international, national and local levels (Hedelin, 2016; Lu, 2016; Jamero et al., 2017), and can further be hampered by bureaucracy (Pinto et al., 2018).

Early warning systems (EWS) are defined as integrated systems of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems to enable individuals, communities, governments and businesses to take timely action to reduce disaster risks in advance of hazardous events (UNISDR, 2021). By this definition, EWS are directly dependent on soft and hard infrastructure measures that increase capacity and reduce hazard (Abbas et al., 2018). Aside from the capacity dependent on soft measures and the monitoring infrastructure, communication at all scales, from national weather services to local leaders, needs to be effective for prompt action (Devkota et al., 2014). In many cases, EWS might be the only option to reduce flood casualties (Kontar et al., 2015).

Accommodating floods has gained popularity as the effects of climate change become more apparent and as notable hydroclimatic events exceed the limitations of protective measures (Pritchard and Thielemans, 2014). NbS measures like wetland restoration can act as modern infrastructure protection with clear mitigation co-benefit and provide opportunities for accommodating floods. For example, initiatives such as 'Room for the River' consider flood safety combined with other values such as landscape, environment and cultural values (Zevenbergen et al., 2015). A popular EbA measure has been wetland restoration, which can control flood peaks, serve as storage

Box 4.7 (continued)

ponds in addition to restoring the environment (Pinto et al., 2018; Saroar, 2018). However, its effectiveness under different conditions is yet to be assessed (Wamsler et al., 2016). Flood resilient housing is another form of accommodating and living with floods. These comprise mostly of elevated homes or different flood protection measures considering vegetation around the house to make those flood resilient (Ling et al., 2015; Abbas et al., 2018; Ferdous et al., 2019).

Despite different degrees of effectiveness, no flood adaptation measure is uniquely effective to eliminate flood risk. Adaptation to floods needs to be considered at a local level, considering the types of floods, community's capacities and available livelihoods (Fenton et al., 2017a). Ideally, flood adaptation strategies need to include short-term actions linked to long-term goals, be flexible, consider multiple strategies and interlink investment agendas of stakeholders (Zevenbergen et al., 2015). Most importantly, flood adaptation and management options have been proven effective to reduce loss of human lives, but not entirely at sustaining livelihoods and reducing infrastructure damages (Rahman and Alam, 2016; Bower et al., 2019; Ferdous et al., 2019).

4.7 Benefits and Effectiveness of Water-Related Adaptations, Their Limits and Trade-Offs

The previous section documented adaptation responses in water use sectors we assess in this chapter (Section 4.6), and noted that in many instances, effectiveness of those responses is not clear. While there are thousands of case studies of implemented adaptation responses (observed adaptation) to water insecurity, there is a lack of synthesised understanding about the effectiveness and benefits of adaptation (Berrang-Ford et al., 2021a) and whether or not those benefits also translate into climate risk reduction (Singh et al., 2021). In contrast, literature on the effectiveness of future projected adaptation in reducing climate risks is limited in number. Yet, even then, the findings are not synthesised across various options to make an overall assessment of the effectiveness of future projected adaptation. In this section, we draw on two meta-review protocols (see SM4.2 for a description of each protocol) and assess the benefits of current adaptation and effectiveness of future projected adaptation in reducing climate risks. We also assess limits to adaptation and trade-offs and synergies between adaptation and mitigation.

4.7.1 Current Water-Related Adaptation Responses, Benefits, Co-benefits and Maladaptation

AR5 (Jiménez Cisneros et al., 2014) concluded that developing countries needed a larger share of adaptation investments for anticipatory adaptation in the water sector (*medium evidence, high agreement*) and that adaptive water management measures were critical in addressing climate-related uncertainty. Noble et al. (2014) listed various examples of adaptation options, and water-related adaptation featured prominently in almost all categories. They also discussed the challenges of developing metrics for measuring adaptation outcomes and stressed the importance of transformational adaptation instead of incremental adaptation. Finally, SR1.5 (de Coninck et al., 2018) made one of the first attempts to systematically assess the feasibility of adaptation options (Singh and Basu, 2020).

4.7.1.1 Current Water-Related Adaptation Responses

We define an adaptation response as a water-related adaptation if the hazard is water-related (e.g., floods, droughts, extreme rainfall events, groundwater depletion, melting and thawing of cryosphere, Figure 4.25) or the adaptation intervention is water-related (e.g., irrigation, rainwater harvesting, soil moisture conservation, etc.). Adaptation responses were implemented across all water use sub-sectors assessed in this chapter (Section 4.6, Figure 4.23). Given the overall interest in assessing adaptations that documents outcomes, we limited our analysis to a set of 359 unique articles that measure outcomes of adaptation across pre-defined outcome categories (SM4.2, Table SM4.5; Berrang-Ford et al., 2021a; Mukherji et al., 2021). A total of 1054 adaptation responses were documented in the 359 case studies; these were categorised into 16 categories (Figure 4.22). These adaptation responses are not always specific to long-term climate change impacts (that is, changes in annual mean fluxes), but rather respond to changes in variability in the water cycle and specific water hazards. Adaptation to internal variability is needed to increase the resilience to projected water cycle changes because water cycle changes primarily manifest as changes in variability (Douville et al., 2021).

There is *high confidence* that a significant share of water-related adaptations is occurring in the agriculture sector. Agriculture accounts for 60–70% of total water withdrawals (Hanasaki et al., 2018; Burek et al., 2020; Müller Schmied et al., 2021) and supports the livelihoods of a large majority of people in the developing countries. Within the agriculture sector, there is *high confidence* in the quality and quantity of evidence of adaptation responses such as improved cultivars and agronomic practices, on-farm irrigation and water management and water and soil moisture conservation, and *medium confidence*, derived from *robust evidence*, and *medium agreement* for other most other adaptation responses (Figure 4.23 and Figure 4.24). Most of these adaptation case studies are from Asia and Africa, and agriculture is the predominant sector where most of these adaptation responses are being implemented (*high confidence*) (Section 4.6.2). However, the sectoral nature of adaptation responses varies across continents. Agriculture is the most important sector in all continents, except Europe and Australasia, where most adaptation occurs in the urban sector (*high confidence*) (Figure 4.24).

Map of selected observed impacts on cultural water uses of Indigenous Peoples of the cryosphere

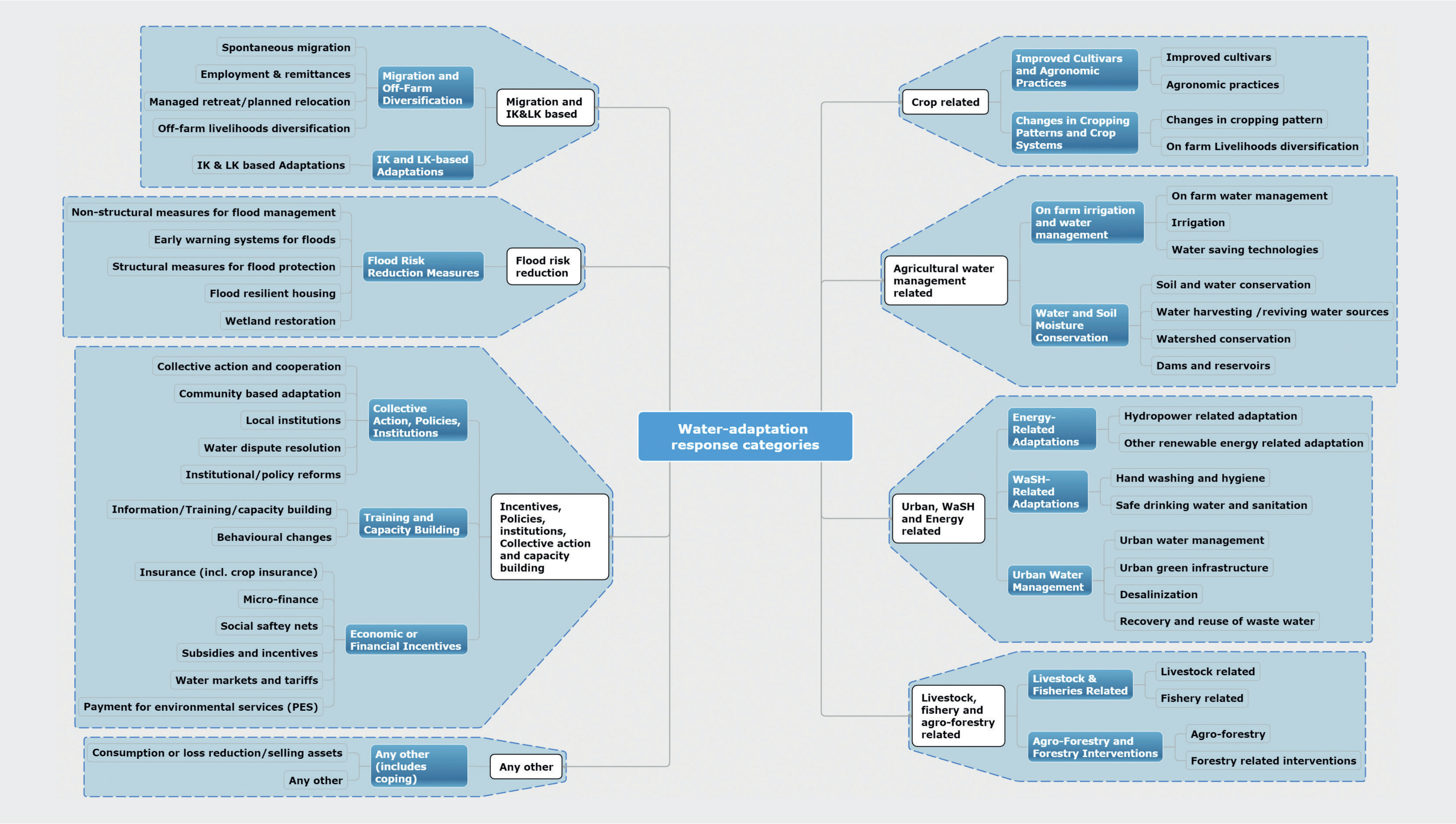


Figure 4.22 | Decision tree, documenting the classification of water-related adaptation responses across 48 subcategories into 16 intermediate and 8 larger categories. We use the 16 intermediate categories of adaptation responses for further analysis in this section.

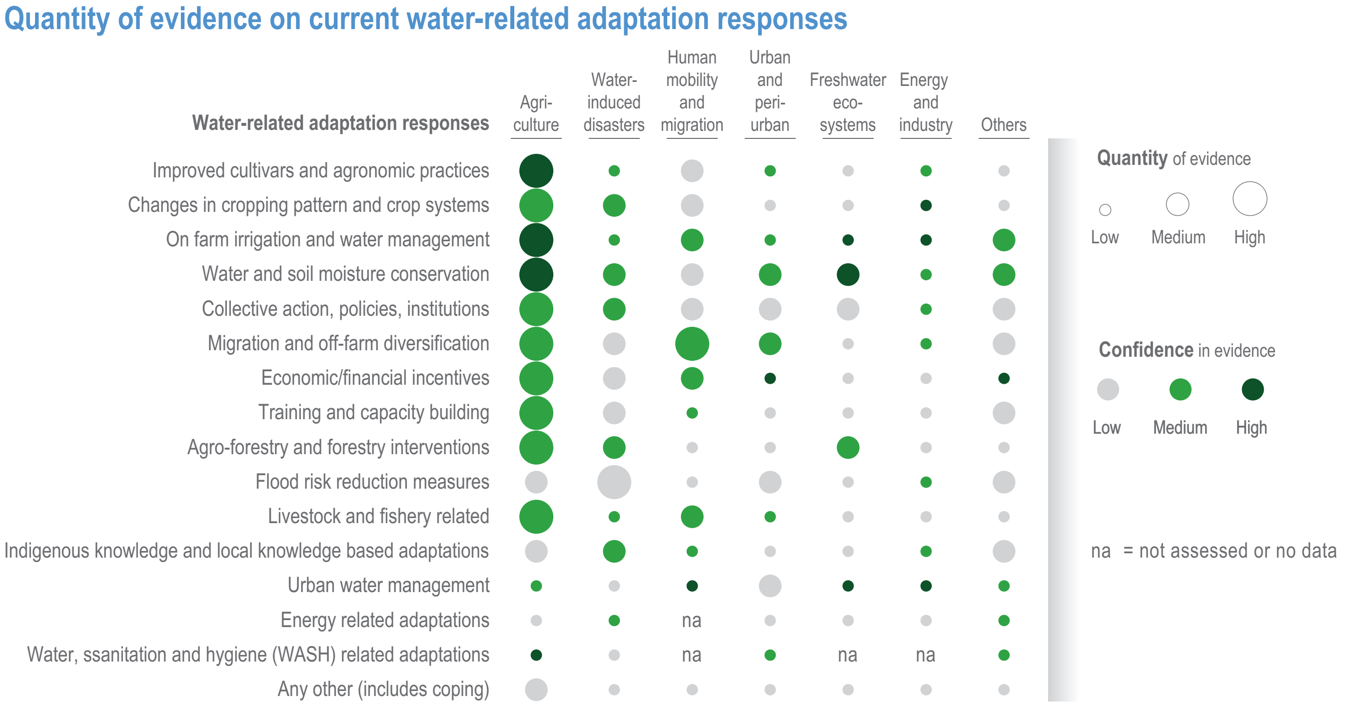


Figure 4.23 | Sectoral distribution of documented water-related adaptation responses (observed adaptation) across the 16 categories derived from Figure 4.22. The quantity of evidence is derived from the number of papers in a particular adaptation response category where high is > 40 papers, medium is 10–40 papers and low is < 10 papers. Confidence in evidence relates to the way the article links outcomes of adaptation with the adaptation response. Category 1: studies causally link adaptation outcomes to the adaptation response by constructing credible counterfactuals; category 2: studies correlate responses and outcomes without causal attribution; category 3: studies describe adaptation outcomes without making any causal or correlation claims between adaptation outcomes and adaptation responses. *High confidence*: more than 67% of the studies fall in categories 1 and 2; *medium confidence*: 50–67% of the studies are in categories 1 and 2, and *low confidence* is less than 50% of studies are in categories 1 and 2.

The top four adaptation responses in terms of frequency of documentation are changes in the cropping pattern and crop systems (145 responses), improved crop cultivars and agronomic practices (139 responses), irrigation and water management practices (115 responses) and water and soil conservation measures (102 responses). These top four responses provide several benefits such as higher incomes and yields, better water use efficiencies and related outcomes (*high confidence*) (Table 4.9 and Figure 4.27). However, those benefits are incremental, that is, they help improve crop production and incomes, at least in the short run, but may not automatically lead to transformative outcomes and climate risk reductions (Pelling et al., 2015; Fedele et al., 2019). One way to move from incremental to transformative adaptation could be to invest gains from incremental adaptation in education and capacity building to improve overall adaptive capacity (Vermeulen et al., 2018). Responses such as migration, including spontaneous and planned relocation, are also relatively well documented (*medium confidence*), as are responses such as collective action, training and capacity building and economic and financial measures for increasing adaptive capacities (*medium confidence*). These categories of adaptation can potentially lead to transformative outcomes, such as a shift to livelihoods that are less exposed to climate hazards. However, transformative pathways are not always straightforward (Pahl-Wostl et al., 2020) (Table 4.8).

Droughts, followed by precipitation variability and extreme precipitation, are the two most common hazards against which adaptation responses are forged. The other three top hazards are general climate impacts, heat-related hazards and inland and riverine flooding (Figure 4.25). The majority of the adaptation responses across all categories were introduced by individuals and households, followed by the civil society, and hence autonomous (Figure 4.26). The private sector (defined as profit-making companies and distinct from individual farmers and households) has played a relatively minor role in initiating adaptation responses. However, the low participation of the private sector in initiating adaptation responses could be partly an artefact of the nature of documentation.

4.7.1.2 Benefits, Including Co-benefits of Water-related Adaptation Responses and Resulting Maladaptation

There is no consensus in the literature about ways of measuring the effectiveness of current adaptation responses in reducing climate-related impacts (Singh et al., 2021). However, various methodologies, including feasibility assessment, have been deployed (Williams et al., 2021). Given the methodological challenges in defining and measuring the effectiveness of adaptation in reducing climate risks, in this section, we focus on outcomes of water-related adaptation across several dimensions. A total of 359 studies were identified to contain sufficiently *robust evidence* of documented adaptation outcomes to form the basis of this assessment (SM4.2, Table SM4.5; Berrang-Ford et al., 2021a; Mukherji et al., 2021). Positive outcomes denote benefits of adaptation, while negative outcomes may mean that adaptation was not effective in bringing any benefits or that it was maladaptive (Schipper, 2020).

We assess outcomes across five indicators: (a) economic and financial indicators, such as improvements in crop yields and resulting incomes; increase in profits, higher savings or lesser losses from hazards; (b)

Observed water-related adaptation responses that measure outcomes

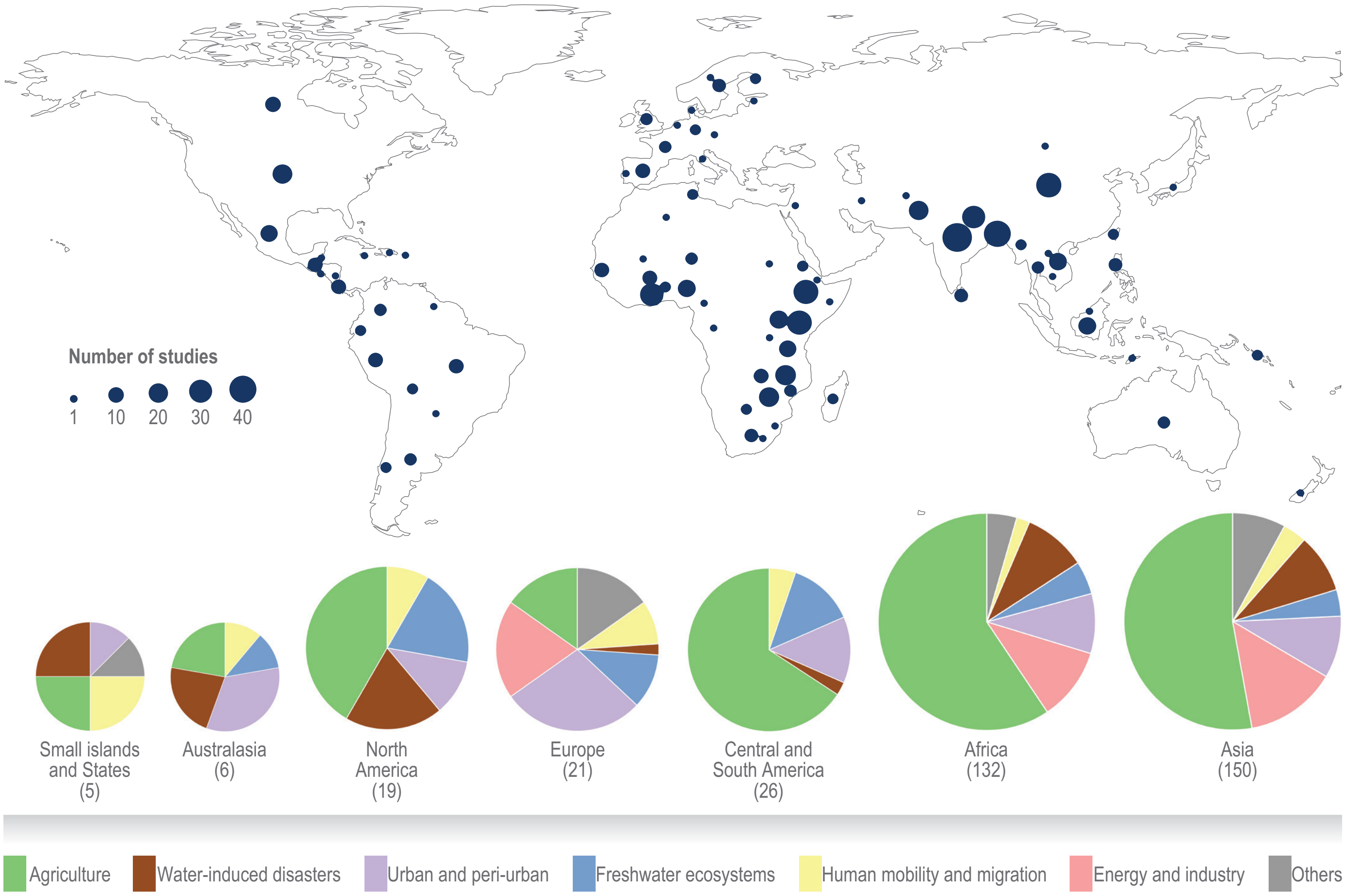


Figure 4.24 | Location of case studies on water-related adaptation which measure adaptation outcomes (*n* = 359) and their sectoral distribution across all regions. Circles denote the number of case studies in a particular location in the continent. The pie chart shows the sectors in which adaptation is taking place. The sectors correspond to water use sectors described in Sections 4.3, 4.5 and 4.6 of this chapter.

impacts on vulnerable people, for example, on women, children and Indigenous Peoples; (c) water-related impacts, for example, improved water use efficiency, water saving, reduction in water withdrawals and application; (d) ecological and environmental impacts such as lesser energy use, better soil structures and better thermal comfort.; (e) institutional and sociocultural impacts such as improved social capital and stronger communities of practice, equity; and strengthening of local institutions or national policies. Of these 359 studies, 319 documented beneficial outcomes across one or more indicators, while the remaining 40 presented no beneficial outcomes. Illustrative examples are shown in Table 4.9, while the distribution of these responses with positive outcomes is shown in Figure 4.27, and indicates that economic benefits of adaptation are more common in developing countries, while benefits along ecological dimensions are more common in the developed countries,

Co-benefits are defined as mitigation benefits resulting from an adaptation response (Deng et al., 2017). Around a quarter of papers that documented positive adaptation outcomes also reported mitigation co-benefits. Agroforestry, community forests and forest-based adaptations are the most oft-cited examples of mitigation co-benefits (Bhatta et al., 2015; Etongo et al., 2015; Weston et al., 2015; Pandey et al., 2017; Sain et al., 2017; Sánchez and Izzo, 2017; Wood et al., 2017; Adhikari et al., 2018a; Hellin et al., 2018; Aniah et al., 2019; Quandt et al., 2019; also see Box 5.11). Other examples include mitigation benefits of climate-smart agricultural practices that reduce input intensity and help in carbon sequestration (Arslan et al., 2015; Somanje et al., 2017), retrofitting buildings in urban areas with energy-efficient devices for lowering electricity bills and emissions (Fitzgerald and Lenhart, 2016) and reuse of treated wastewater for irrigation and urban uses (Morote et al., 2019) (Box 4.5, 4.7.6).

Not all adaptation responses reduce risks, and some may have long-term maladaptive outcomes, even if they are beneficial in the short term. Maladaptation often stems from poor planning and implementation of adaptation responses and because of not addressing the root causes of vulnerability (Schipper, 2020; Eriksen et al., 2021). Of the 319 case studies where adaptation response was found to have some beneficial outcomes, around one third of them also mentioned the possibility of maladaptation. Migration can often have maladaptive outcomes because migration can exacerbate the inherent vulnerabilities of migrants (Section 4.6.8). For example, slum dwellers in cities may earn higher incomes, but their quality of life worsens (Ayeb-Karlsson et al., 2016). In some instances, even wage rates in migration hotspots can remain

Table 4.8 | Illustrative examples of case studies of water-related adaptation responses where outcomes were measured ($n = 359$). These cases include instances where adaptation benefits were positive, negative or neutral. Examples also include studies with or without causal and correlation links between adaptation response and outcomes (categories 1, 2 and 3 studies as described in the caption of Figure 4.23). The purpose of the table is to provide a list of illustrative examples to showcase the wide range of adaptation responses that are being implemented. Table 4.9 zooms into examples where adaptation had positive benefits on any of the selected parameters described in Section 4.7.1.2.

Name of the adaptation response (number of documented responses in that category)	Description of adaptation response	Sources
Changes in the cropping pattern and crop systems (145 responses)	Changes in cropping pattern; e.g., the introduction of sugarcane and rice in Costa Rica; crop diversification in Ethiopia and Zimbabwe; crop diversification in Tanzania	Singh et al. (2014); Warner et al. (2015); Asmare et al. (2019); Lalou et al. (2019); Makate et al. (2019)
	Changes in the timing of sowing and harvesting, e.g., in China; India and Pakistan	Yu et al. (2014); Macchi et al. (2015)
	On-farm diversification, e.g., an integrated crop-livestock system in France	Havet et al. (2014)
Improved crop cultivars and agronomic practices (139 responses)	Improved crop cultivars, e.g., short-duration paddy varieties in Nepal; saline-tolerant rice cultivar in Bangladesh; drought-tolerant maize varieties in Malawi, Nigeria, Zimbabwe and Uganda	Kabir et al. (2016); Wossen et al. (2017); Khanal et al. (2018a); Makate et al. (2019)
	Improved agronomic practices, e.g., conservation agriculture to conserve soil moisture in Malawi and Tanzania; climate-smart agricultural practices in Zambia; alternate wetting and drying and direct seeding of rice in India	Thierfelder et al. (2015); Kimaro et al. (2016); Traore et al. (2017); Kakumanu et al. (2019)
Irrigation and water management practices (115 responses)	Irrigation, e.g., construction of local irrigation infrastructure in Chile; funding of community wells in Canada; drilling of borewells in Thailand; irrigation in Ethiopia; spate irrigation in Sudan; night-time irrigation scheduling to reduce evaporative demand in the UK	Hurlbert and Pittman (2014); Ferchichi et al. (2017); Rey et al. (2017); Pak-Uthai and Faysse (2018); Fadul et al. (2019); Lemessa et al. (2019); Lillo-Ortega et al. (2019); Torres-Slimming et al. (2020)
	On-farm water management and water-saving technologies, e.g., use of surface pipes for irrigation water conveyance in China; drip irrigation in China; and use of water-saving measures in India	Hong and Yabe (2017); Tan and Liu (2017); Deligios et al. (2019); Rouabhi et al. (2019)
Water and soil conservation (102 responses)	On-farm water and soil conservation measures, e.g., in Burkina Faso; terraces and contour bunds in Ethiopia	West Colin et al. (2016); Kosmowski (2018)
	Water harvesting through on-sand dams in Kenya; *in situ* and *ex situ* water harvesting in Uganda and India	Ngigi et al. (2018); Sullivan-Wiley and Short Gianotti (2018); Kalungu et al. (2021)
	Watershed conservation programmes, e.g., in Ethiopia	Siraw et al. (2018)
	Revival of water bodies; e.g., creation of artificial lakes in Portugal	Santos et al. (2018)
Collective action, policies and institutions (95 responses)	Collective action and cooperation; e.g., grassroots-level collective action for conflict resolution in Guatemala; collective decision to reduce water withdrawals during drought in Japan	Hellin et al. (2018); Tembata and Takeuchi (2018)
	Community-based adaptation in Bangladesh, community-based management of rangelands in Mongolia	Fernández-Giménez et al. (2015); Roy (2018)
	Local institutions, e.g., multi-stakeholder platforms for disaster risk reduction and agriculture in Peru and several African countries; Adaptation Learning Programme.	Mapfumo et al. (2017); Lindsay (2018)
	Water dispute resolution; e.g., water conflict mitigation in Costa Rica.	Kuzdas et al. (2016)
	Institutional and policy reforms; e.g., local water and land use planning instruments in Australia; the Dutch Delta Programme in the Netherlands; implementation of EU Flood Directives in Sweden	Fallon and Sullivan (2014; Zevenbergen et al. (2015; Hedelin (2016)
Migration and off-farm diversification (92 responses)	Spontaneous migration, e.g., voluntary relocation in the Solomon Islands and rural to urban migration in Ethiopia and Pakistan.	Birk and Rasmussen (2014); Iqbal et al. (2018)
	Employment and remittances, e.g., in Senegal.	Romankiewicz et al. (2016)
	Planned relocation; e.g., the Massive Southern Shaanxi Migration Programme in China; resettlement of flood-prone communities in Bangladesh.	Islam et al. (2014); Lei et al. (2017)
	Off-farm diversification; e.g., migration to towns and engaging in off-farm labour wage-earning in Niger, Ghana Bangladesh; shifting to non-pastoral livelihoods in Ethiopia	Mussetta et al. (2016); Basupi et al. (2019)
Livestock and fishery-related (63 responses)	Livestock related, e.g., livestock species diversification in Ethiopia and Kenya; insuring livestock in Pakistan; changes in range management practices in the USA.	Opiyo et al. (2015); Yung et al. (2015); Wako et al. (2017); Rahut and Ali (2018)
	Fishery related, e.g., non-destructive fishery gears and techniques in Ghana and Tanzania	Yang et al. (2019a)

Name of the adaptation response (number of documented responses in that category)	Description of adaptation response	Sources
Training and capacity building (57 responses)	Information, training and capacity building; e.g., climate information services in Kenya and Senegal; training contributed new learning about digging canals to avoid prolonged water logging in the Philippines; soil conservation training programme in Ethiopia	Bacud (2018); McKune et al. (2018); Chesterman et al. (2019)
Agroforestry and forestry-related responses (56 responses)	Agroforestry-related measures in India, Kenya, Nigeria; farmer-managed natural regeneration (FMNR) in Ghana.	Weston et al. (2015); Pandey et al. (2017); Fuchs et al. (2019); Okunlola et al. (2019)
	Forestry related; e.g., coastal afforestation by planting salinity-resistant trees in Bangladesh and Colombia	Pandey et al. (2016); Barrucand et al. (2017); Barua et al. (2017)
Economic and financial incentives (54 responses)	Insurance; rice crop insurance programme in Indonesia; agricultural insurance programme in South Africa.	Dewi et al. (2018); Elum et al. (2018)
	Micro-finance and credit programmes, e.g., in Bangladesh.	Fenton et al. (2017b)
	Social safety nets; e.g., food-based safety net programmes in Brazil, food for work programmes in Ethiopia.	Mesquita and Bursztyn (2017); Sain et al. (2017); Tesfamariam and Hurlbert (2017); Gao and Mills (2018)
	Subsidies and incentives, e.g., farm input subsidy programme in Malawi; financing programmes in Canada to help producers with resources to improve/maintain the quality of soil, water, biodiversity for drought mitigation.	Hurlbert (2014); Kawaye and Hutchinson (2018)
	Water markets and tariffs; e.g., urban water tariffs in Zaragoza, Spain; informal groundwater markets in China.	Kayaga and Smout (2014); Zhang et al. (2016b)
	Payment for ecosystems services, e.g., in Mexico	Newsham et al. (2018)
IKLK based adaptations (41 responses)	Use of TK of Konda Reddy's in India to shift agroforestry practices; and among *Khasia* and Tripura communities in Bangladesh; use of local ecological knowledge is by small-scale fisher-farmers in the Amazon floodplains, Brazil; traditional water sharing system '*bethma*' in Sri Lanka; indigenous methods of water harvesting in India	Sarkar et al. (2015); Burchfield and Gilligan (2016); Kodirekkala (2018); Ahmed and Atiqul Haq (2019)
Flood risk reduction measures include (40 responses)	Non-structural measures for flood management; e.g., changes in day-to-day practices in Indonesia; place-specific social structures in the UK.	Petzold (2018); Bott and Braun (2019)
	Structural measures for flood management; improvement of the drainage system in Indonesia; flood walls in Beira, Mozambique; dredging and construction of culverts in Nigeria.	Bahinipati and Patnaik (2015); Wijaya (2015); Egbinola et al. (2017); Spekker and Heskamp (2017)
	Early warning systems; e.g., flood forecasting in Nepal, Indonesia, Nigeria.	Ajibade and McBean (2014); Devkota et al. (2014); Sari and Prayoga (2018)
	Flood-resilient housing; e.g., houses on stilts in Guyana, in Pakistan, Vietnam, Philippines.	Mycoo (2014); Ling et al. (2015); Abbas et al. (2018)
	Wetland restoration; e.g., in the USA and Netherlands	Zevenbergen et al. (2015); Pinto et al. (2018)
Urban water management (22 responses)	Urban water management, e.g., incorporating low impact development and urban design features for sustainable urban drainage systems in Spain and Malaysia; demand management and tariff reforms in several European countries.	Flyen et al. (2018); Rodríguez-Sinobas et al. (2018); Stavenhagen et al. (2018); Chan et al. (2019)
	Green infrastructure; e.g., ecological stormwater management and re-naturalisation processes in Sweden; pavement watering in France, Ghana, India, Kenya, Bangladesh	Hendel and Royon (2015); Wamsler et al. (2016); Tauhid and Zawani (2018); Birtchnell et al. (2019)
	Desalinisation for water supplies in Spain	Martínez-Alvarez et al. (2016); Morote et al. (2019)
Energy-related adaptations (eight responses)	Hydropower related; e.g., hydropower benefit-sharing in the Mekong basin and Nepal	Balasubramanya et al. (2014); Suhardiman et al. (2014); Shrestha et al. (2015)
	Other renewable energy-related, e.g., "Raising Water and Planting Electricity project" in Taiwan province of China	Lin and Chen (2016)
WaSH-related adaptations (five responses)	Hand washing and hygiene, e.g., provision of latrines and washing hands with soap in Bangladesh	Dey et al. (2019)
	Safe drinking water and sanitation; e.g., piped water supply in China	Su et al. (2017)
Any other including coping strategies (20 responses)	Reduction in consumption, selling off assets, etc.; e.g., selling of household property and livestock in Nigeria; consumption smoothing in Ghana; reducing consumption in Nepal	Musah-Surugu et al. (2018); Rai et al. (2019)

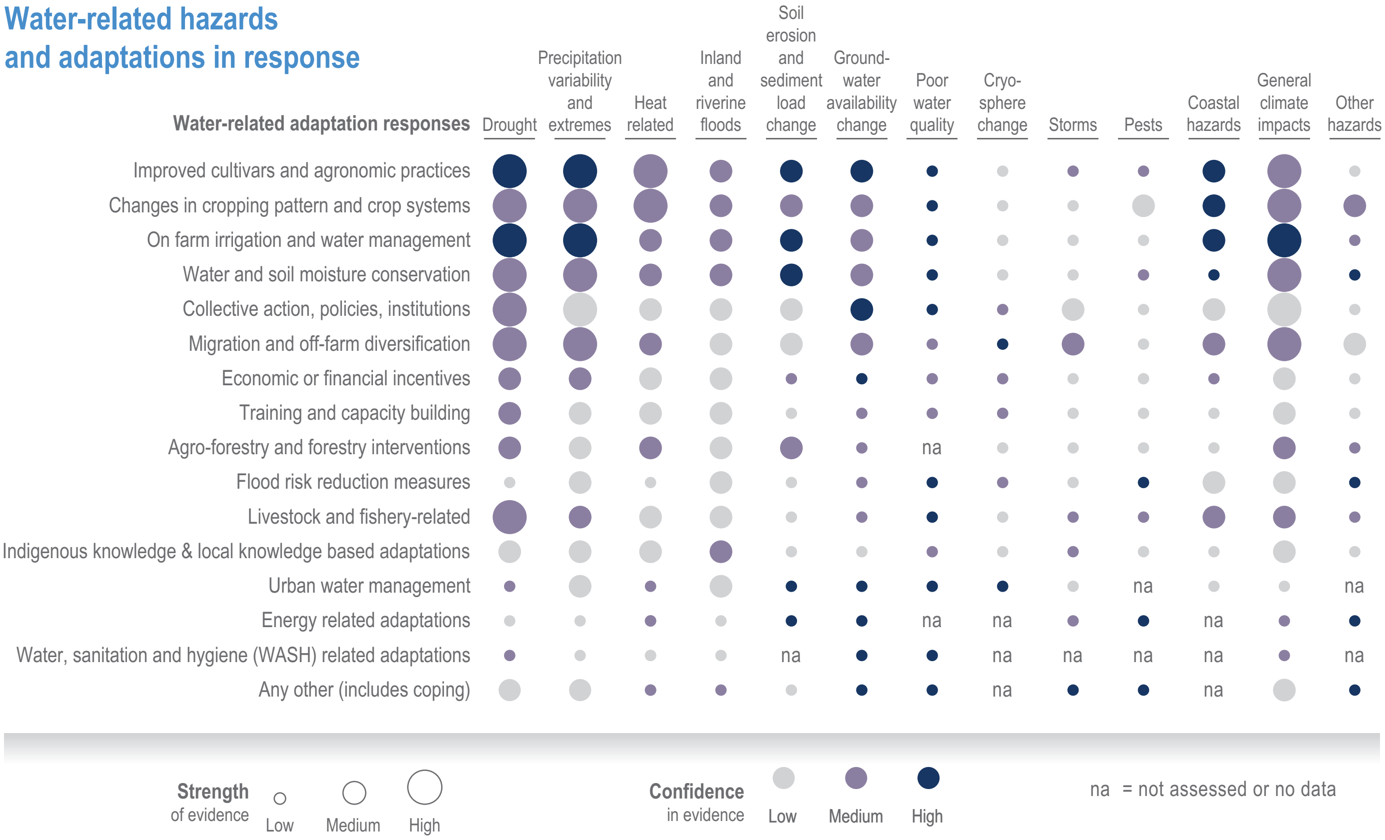


Figure 4.25 | Water-related adaptations and climate hazards against which adaptation responses are forged. Evidence and confidence are derived in the same way as in Figure 4.23.

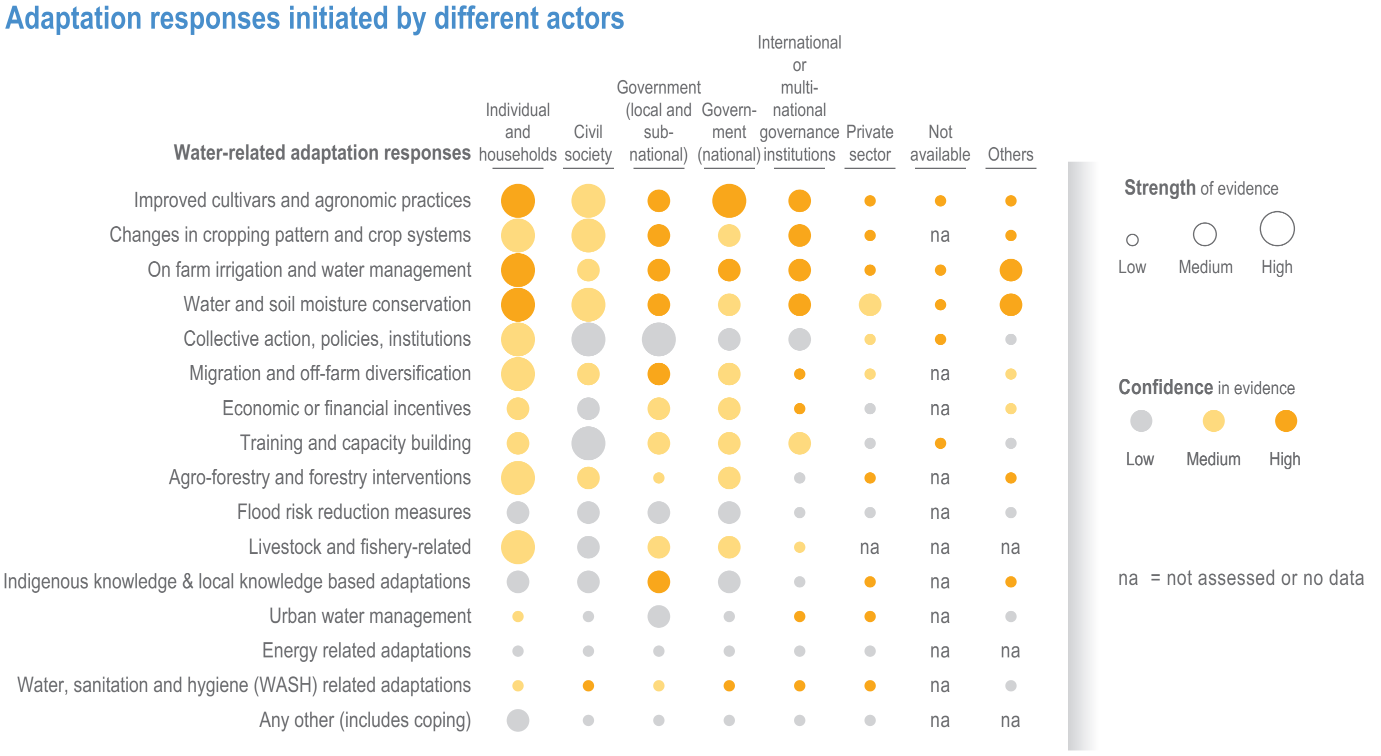


Figure 4.26 | Water-related adaptations and their initiators. The initiator of adaptation is defined broadly and includes the entities who initiate a response, implement that response or engage in that response in any way, including leading, financing or enabling. Evidence and confidence are derived in the same way as in Figure 4.23.

Table 4.9 | Illustrative examples of adaptation responses and their benefits across different outcome indicators. All these studies are either category 1 or category 2 studies in that the link between adaptation response and the outcome is either causal or correlated with one another. These benefits notwithstanding, links of adaptation benefits to climate and associated risk reduction are not always clear. Some of these adaptation responses can have beneficial outcomes in one of the five parameters, but can have maladaptive outcomes in others.

Hazard	Adaptation responses	Outcome category	Adaptation outcome	Reference
Droughts, floods, and general climate impacts in Nepal	Improved crop cultivars, agronomic practices, irrigation, soil water conservation measures	Economic and financial outcomes	Farming households that adapted produced about 33% more rice than households that did not adapt after controlling for all heterogeneity.	Khanal et al. (2018a)
Increased rainfall variability in India	Farmer's training on agronomic measures, for example, alternate drying and wetting (ADW), modified system of rice intensification (MSRI) and direct-seeded rice (DSR)		The capacity building and water saving increased crop yields by 960 kg ha^{-1}, 930 kg ha^{-1} and 770 kg kg^{-1} through the adoption of AWD, MSRI and DSR, respectively. The three practices have increased farmers' income and decreased the cost of cultivation by up to USD 169 ha^{-1}.	Kakumanu et al. (2019)
Droughts and changes in the seasonality of rainfall in Pakistan	Adjusting sowing time of wheat		Household income and wheat yields were higher for households who adjusted the sowing time to cope with climate risks than those who did not, after controlling for other factors.	Rahut and Ali (2017)
Droughts in North China Plains	Irrigation		Adding one extra irrigation could increase wheat yield by up to 12.8% in a severe drought year.	Wang et al. (2019a)
Soil degradation; extreme rainfall events and high runoff causing erosion in Mali	Soil and water conservation using contour ridges and improved millet and sorghum cultivars		Millet grain yield during 2012–2014 was statistically higher in contour ridge terrace plots than the control, with yield differences ranging from 301 kg ha^{-1} in 2012 to 622 kg ha^{-1} in 2013. Improved varieties produced on average 55% more yield than the local ones.	Traore et al. (2017)
Drought, floods, hailstorm and erratic rainfall, Ethiopia	On-farm agricultural water management		The net revenue from adopting a combination of agricultural water management and modern seeds or inorganic fertiliser is significantly higher by 7600 and 1500 Birr ha^{-1}, respectively, than adopting modern seeds or inorganic fertiliser alone. Birr is the Ethiopian currency.	Teklewold et al. (2017)
Droughts and general climate impacts, South Africa	Crop insurance and irrigation		Farmers who insured their farm business and had access to irrigation had relatively higher net revenue than those who did not, but this link is not causal. Instead, it shows causality could go either way, including those farmers who were better off getting their business insured.	Elum et al. (2018)
Droughts and floods in Kenya	Migration		Remittance income enables uptake of costlier adaptation measures such as a change in livestock species, which also have higher returns for households. Therefore, the study was not causal in its inference.	Ng'ang'a et al. (2016)
Droughts in Nigeria	Drought-tolerant varieties		Per capita, food expenditure of those who adopted drought-tolerant maize was significantly lower than those who did not after controlling for everything else and causal inference.	Wossen et al. (2017)
General climate impacts, including rainfall variability in Brazil	Agroforestry systems as land use in rural municipalities		The land value in the municipalities with agroforestry was higher than that of the municipalities where the agroforestry scheme was not implemented.	Schembergue et al. (2017)
Water quality deterioration due to floods in Bangladesh	Water, sanitation and health WaSH programme	Outcomes for vulnerable people	Children: prevalence of childhood diarrhoea reduced by 35% in midline prevalence, 8.9% and by 73% in end line prevalence, 3.6% compared to baseline prevalence 13.7%.. Inferences are causal.	Dey et al. (2019)
Droughts in Zimbabwe	Adoption of drought-tolerant maize varieties by smallholder farmers		Smallholder farmers: Smallholder farmers practising conservation agriculture (CA) were as likely to adopt drought-tolerant maize varieties as other farmers and thus benefit from increased yields and incomes.	Makate et al. (2019)
General climate impacts, including droughts in Niger	Crop diversification		Poor households: Crop diversification mainly benefits the most vulnerable households; the impact on the poorest group ranges from double to triple the impact on the wealthiest group.	Asfaw et al. (2018)
Droughts and general climate impacts in Malawi and Zimbabwe	Conservation agriculture; drought-tolerant maize and improved legume varieties		Female farmers: Yield and income effects on the adoption of conservation agriculture and improved varieties of maize and legumes were both positive for men and women.	Makate et al. (2019)
Historically widespread and severe droughts in Ethiopia in 1999, 2002, 2003, 2005 and 2008.	Government safety net programme called Productive Safety Net Programme (PSNP)		Poor households: PSNP transfers reduce chronic poverty level from 15.7% to 10.6% and increase the never poor share from 11.5% to 15.8%.	Gao and Mills (2018)

Hazard	Adaptation responses	Outcome category	Adaptation outcome	Reference
Droughts in Kenya	Water harvesting structures, for example, sand dams	Water-related outcomes	Sand dams increase groundwater storage in riverbanks by up to 40%, which is maintained throughout the year.	Ryan and Elsner (2016)
Millennium drought in Australia	Water trading		Irrigation application rates fell in the dairy industry from 4.2 million litres ha^{-1} in 2000–2001 to 3.5 million litres ha^{-1} in 2005–2006	Kirby et al. (2014)
Droughts, floods and soil erosion and sediment load in a river basin in France	Agreement signed between water and electricity utilities and farmers		Agreement between water and electricity utilities to compensate farmers for reducing water use resulted in a decrease in water demand from 310 Mm^3 in 1997 to 220 Mm^3 in 2012 in the Durance Valley irrigation system in France.	Andrew and Sauquet (2017)
Drought in India	The reducing area under irrigated rice crop		Reduced rice irrigation resulted in over 60 mm ha^{-1} of water savings compared to irrigated rice crops on that land.	Hochman et al. (2017b)
Floods due to cyclonic storms and tidal inundation in Bangladesh	Planting of vetiver grass for stabilising coastal embankments	Ecological and environmental outcomes	Households that planted vetiver grass around their homestead and nearby road managed to save their houses and assets from the recent cyclonic storm and tidal inundation.	Barua et al. (2017)
General climate impacts, including rainfall variability in Brazil	Agroforestry systems as land use in rural municipalities		Trees planted as a part of the agroforestry programme provide thermal comfort to both animals and humans.	Schembergue et al. (2017)
Drought in 2015 in Ethiopia	Contour ridge terraces as soil water conservation measure		Contour ridge terraces primarily controlled water runoff and soil erosion and acted as a buffer during the 2015 Ethiopian drought.	Kosmowski (2018)
Drought and rainfall variability in Pakistan	Climate-smart agricultural practices	Institutional and sociocultural outcomes	Farmers who adopted climate-smart practices also tended to form a better relationship with local extension agents and reached out to them more frequently. Again, however, causality might as well lie the other way round.	Imran et al. (2019)
Droughts, Mexico	Strengthening of local water users' associations through external assistance programmes		Local water user's associations were able to reduce water abstractions during years of severe droughts.	Villamayor-Tomas and García-López (2017)
Rainfall variability in Niger	Community-based adaptation and through adaptation learning programmes		More robust social networks where women were able to take important decisions	Vardakoulias and Nicholles (2015)

low due to the high volume of the migrant population (Fenton et al., 2017b); as such, it does not help buffer consumption against rainfall shocks (Gao and Mills, 2018). Migration also has gendered impacts, with girls from migrating families being taken out of school (Gioli et al., 2014) or interrupting children's education overall (Warner and Afifi, 2014). In planned relocation from vulnerable urban slums, relocation sites can be far from job sites and increase social conflicts (Tauhid and Zawani, 2018).

Adaptation responses that focus on improving incomes through production intensification can have maladaptive outcomes. An oft-cited example of this is groundwater overuse as a result of irrigation intensification. There is widespread evidence of groundwater overuse in many countries in Africa (Mapfumo et al., 2017), in the Middle East and North Africa (Petit et al., 2017; Daly-Hassen et al., 2019), in Asia (Burchfield and Gilligan, 2016; Zhang et al., 2016b; Kattumuri et al., 2017), in Spain (Petit et al., 2017) and in Australia (Kirby et al., 2014) (Sections 4.2.6, 4.6.2, Box 4.3). Intensification-based approaches also increase costs of cultivation (Mussetta et al., 2016; Wang and Chen, 2018; Quan et al., 2019), and can lead to more use of fertilisers and herbicides (Thierfelder et al., 2015; Sujakhu et al., 2016; Khanal et al., 2018a; Yamba et al., 2019). Diversification away from food crops can also compromise domestic food security (Kloos and Renaud, 2014; Brüssow et al., 2017).

Even interventions that have positive carbon co-benefits like forestry and agroforestry can have maladaptive consequences on land and water resources, especially if inappropriate species (Etongo et al., 2015) with higher water demands are grown (Krishnamurthy et al., 2019) (Section 4.7.6).

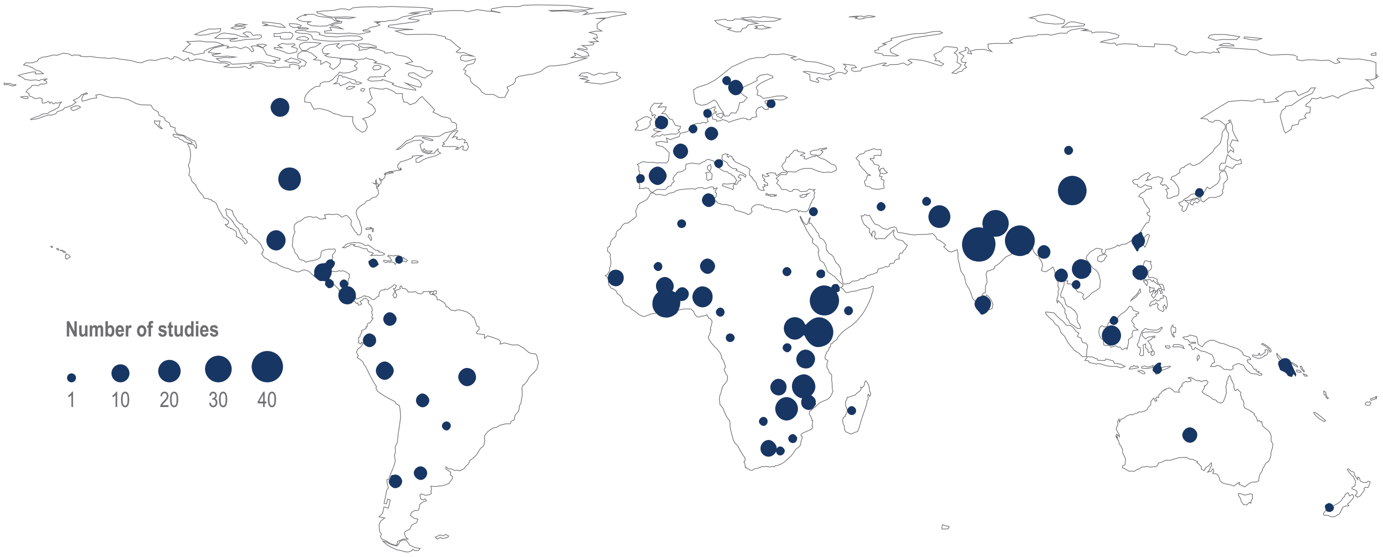
In summary, current adaptation responses have benefits across several dimensions. In developing countries, most adaptation measures improve economic outcomes (*high confidence*). Adaptation responses also have benefits in terms of water outcomes and environmental and ecological parameters, and these benefits are more commonly manifested in developed countries (*high confidence*). Of the papers assessed for water-related adaptation, roughly one fourth reported adaptation co-benefits (*high confidence*). In contrast, one third of studies reported maladaptive outcomes, now or in the future (*high confidence*), emphasizing the importance of looking at synergies and trade-offs. Despite many adaptation case studies, there is a knowledge gap in understanding if the benefits of adaptation also translate into a reduction of climate impacts, and if so, to what extent, and under what conditions (*high confidence*). In view of this critical knowledge gap, our assessment is limited to benefits of current adaptation responses.

4.7.2 Projections of Future Effectiveness of Adaptation Responses

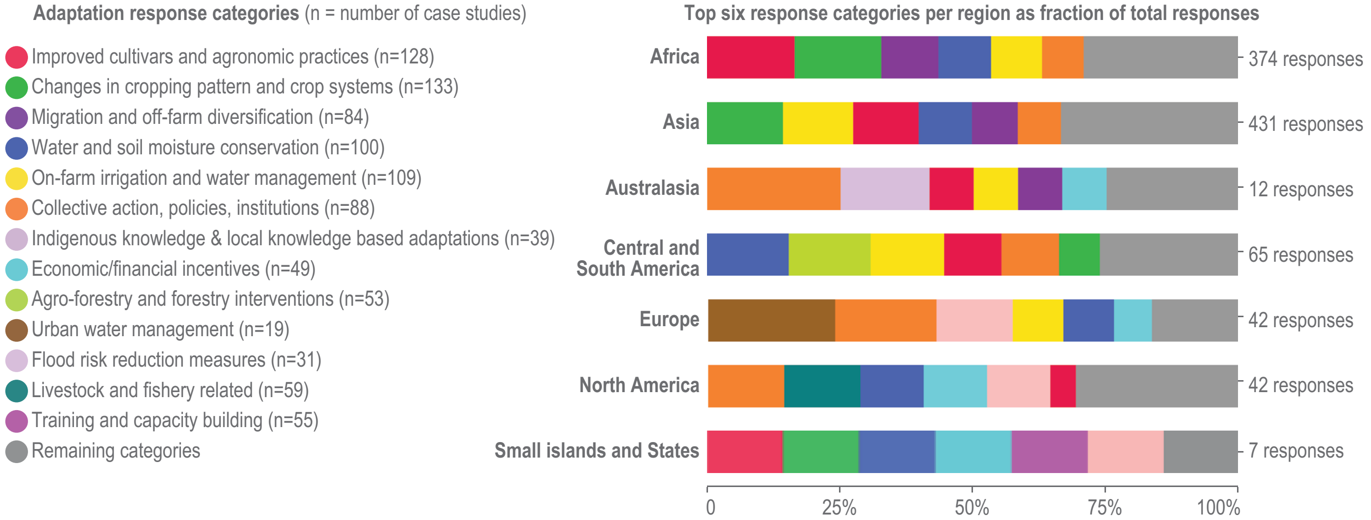
Several adaptation options have been shown to have beneficial effects on societally relevant outcomes under current climate conditions (Section 4.7.1.2) and will remain critical to adapt to future climate change.

Observed water-related adaptation responses with positive outcomes

(a) Map depicting 319 case studies of current water related adaptation responses with documented beneficial outcomes of adaptation



(b) Fraction of top six adaptation responses to total responses



(c) Beneficial outcomes of adaptation per region across five dimensions. Innerlines correspond to the top six adaptation response categories from previous panel.

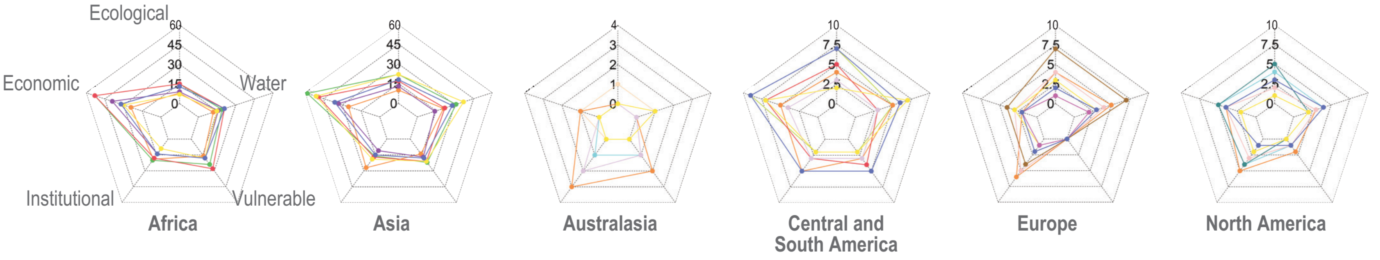


Figure 4.27 | Top panel: location of case studies of water-related adaptation responses (996 data points from 319 studies). In these 996 data points, at least one positive outcome was recorded in one of the five outcome indicators. These outcome indicators are economic/financial, outcomes for vulnerable people, ecological/environmental, water-related, and sociocultural and institutional. Middle panel: the top six documented adaptation options per region as a fraction of the total of reported studies, with grey bars containing the share of all other adaptation responses. In most instances, the top six adaptation categories include nearly 3/4 of the studies. Bottom panel: The spider diagrams show the number of studies reporting beneficial outcomes for one or more dimensions for the top six adaptation options identified in each region. Due to a small number of studies in small island states, a spider diagram was not generated for the small island states.

However, there is limited quantitative information on the future viability of available responses to reduce projected climate impacts effectively. However, the context-specific nature of adaptation on the ground and the uncertainties associated with future climate outcomes, both in terms of policy decisions around mitigation and model-inherent uncertainties, make long-term projections of adaptation effectiveness of limited use for decision-making on the ground. However, such projections are still needed to understand the efficacy of current technical and managerial solutions to reduce climate risk. Consequently, an increasing body of literature focuses on the effectiveness of specific interventions to reduce projected climate risks in a local to regional setting.

This section provides a quantitative aggregate assessment of effectiveness of projected water-related climate adaptations at different levels of GWLs (SM4.2). Effectiveness is defined as the potential of a given adaptation measure to address projected changes in climate and return the system under analysis to baseline conditions. If the measure cannot fully compensate for the projected climate risk, residual risks remain, defined as the fraction of risk remaining after adaptation. For example, in many regions, projected temperature-driven yield loss can be reduced by shifting to or increasing irrigation. However, yields often do not always fully return to baseline conditions without climate change, leaving residual risk after adaptation. Assessed options are limited to technical solutions, which have quantitative entry points to global climate impact models.

Most adaptation projections focus on water-related interventions in the agricultural sector, including irrigation-related responses, shifting planting dates, changing crops and cultivars, and water and soil conservation. Sectoral projections of adaptation effectiveness are limited in forestry- and agroforestry-related responses, flood protection measures (excluding here options that are solely related to effects of sea level rise), urban water-related adaptation and energy-related responses. The majority of assessed studies focus on comparing different variations of one or several response options in terms of timing or duration, for example, a shift in planting dates of 10 d and 20 d, relative to present-day practice and provide results for a range of scenarios and (or) timeframes.

A total of 45 studies were identified for this assessment, based on their quantitative assessment of the effects of adaptation on projected impacts (SM4.2 for the method of future projected effectiveness assessment). From each study, the distinct combinations of specific variations of adaptations, scenarios and timeframes assessed were considered as individual data points, providing a total of 450 unique data points for the assessment (Table SM4.6). The study-specific temperature increase was classified relative to the 1850–1900 baseline for each data point, based on the model and scenario specifications provided and grouped into outcomes at 1.5°C, 2°C, 3°C and 4°C. The effectiveness is assessed based on the fraction of risk that an option can reduce. Co-benefits are defined as a situation where outcomes improve relative to baseline conditions, whereas maladaptive outcomes describe a situation where risks increase after adaptation has been implemented.

Several studies assess the future effectiveness of improved cultivars and agronomic practices, such as changing fertiliser application or switching to drought-resistant crops (five studies; 85 data points). Results show a range of effectiveness levels across regions and warming levels and vary depending on the tested response options (Qin et al., 2018) (Figure 4.29), with moderate to small effectiveness, large residual impacts or potential maladaptive outcomes, as well as decreasing effectiveness with increasing warming (Figure 4.28) (*high confidence*). For studies testing results across a range of scenarios, approaches show increasingly mixed (Qin et al., 2018) and limited effects (Amouzou et al., 2019) with higher warming, with overall reductions across warming levels for most tested responses (Qin et al., 2018).

Changes in cropping patterns and crop systems (Figure 4.28) (five studies; 31 data points) indicate limited potential to reduce projected climate risks, with the majority of studies providing results of up to 1.5°C of warming and limited evidence for higher warming levels. At 1.5°C, effectiveness in Africa is mostly insufficient, with substantial maladaptive potential (Brouziyne et al., 2018). Over Asia, effectiveness is mostly small at 1.5°C with substantial residual impacts, further reducing to insufficient effectiveness at large residual risks at 4°C (Figure 4.28 Projected effectiveness) (*robust evidence; medium agreement*) (Boonwichai et al., 2019; Dai et al., 2020; Mehrazar et al., 2020). Amongst the options related to changes in cropping patterns and crop systems, shifting planting dates is projected to retain moderate to high residual risks under some specifications in Iran (Paymard et al., 2018) and Morocco (Brouziyne et al., 2018), while high effectiveness is reported for similar specifications in Thailand (Boonwichai et al., 2019), Australia (Luo et al., 2016), Morocco ((Brouziyne et al., 2018) and Iran (Mehrazar et al., 2020). Of the assessed adaptation options, changes in cropping patterns and cropping systems appear least effective in reducing climate risk, with decreasing effectiveness at higher levels of warming.

Studies assessing the future effectiveness of irrigation-related responses (Figure 4.28) focus on a range of specific approaches, including increasing irrigation efficiency, deficit irrigation, irrigated area expansion or shifting from rain-fed to irrigated agriculture, as well as specific types of irrigation (21 studies; 103 data points). As a frequently implemented option with direct entry points to agricultural models, this option provides the most robust set of data points across regions and warming levels. For all regions, a reduction in effectiveness is apparent from 1.5°C to higher levels of warming, leading to increased residual risk with increasing warming (*high confidence*). Irrigation can increase yield relative to present day, showing co-benefits for some regions, though the share of co-benefits decreases with higher warming (*high confidence*) (Figure 4.28). However, since many of these studies rely on global agricultural models which do not fully represent the actual availability of water, further expansion of irrigation at the scale assumed in those studies may not be realistic (Sections 4.3.1.2. 4.3.1.3) (Elliott et al., 2014).

A wide range of water and soil management-related options (Figure 4.28), including mulching, no tilling or contour farming, has been assessed for future effectiveness (eight studies; 49 data points). Results underline the context-specific nature and need to carefully adjust the specific options to a regional setting, with variations of options leading to effective outcomes or residual impacts within individual studies (Qiu et al., 2019) and across regions and warming levels.

Similar to observed adaptation, studies assessing combinations of the agricultural adaptation options outlined above (11 studies; 36 data

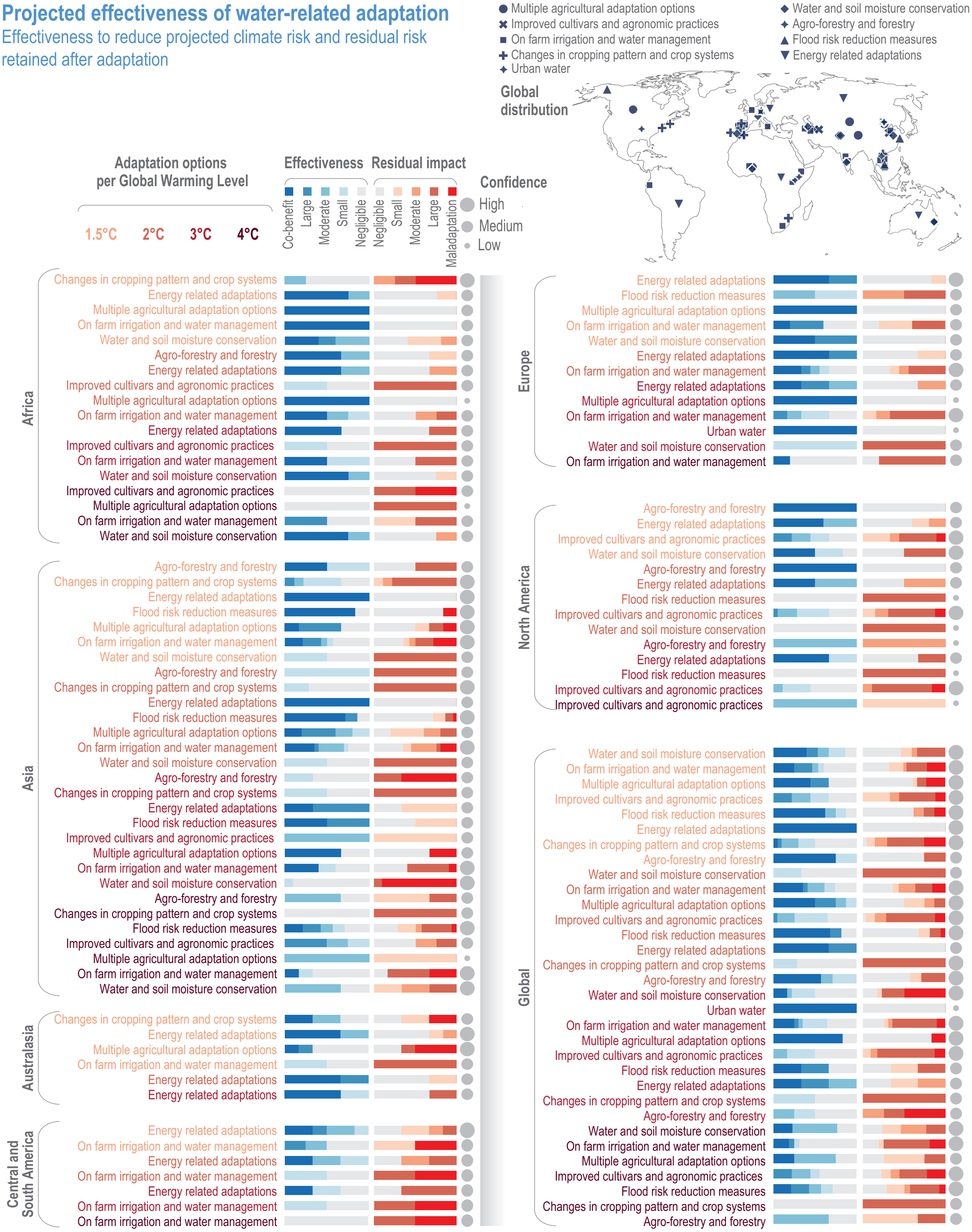


Figure 4.28 | Projected effectiveness of adaptation options in returning the system to a study-specific baseline state relative to the projected climate impact; and level of residual risk retained after adaptation, relative to baseline conditions. Regional summaries are based on IPCC regions. Warming levels refer to the

global mean temperature (GMT) increase relative to an 1850–1900 baseline. For each data point, the study-specific GMT increase was calculated to show effectiveness at 1.5°C, 2°C, 3°C and 4°C. Based on the ability of an implemented option to return the system to its baseline state, the effectiveness is classified based on the share of risk the option can reduce: large (>80%); moderate (80–50%); small (<50–30%); insufficient (<30%). Where the system state is improved relative to baseline, co-benefits are identified. Residual impacts show the share of remaining impacts after adaptation has been implemented: negligible (<5%); small (5 to <20%); moderate (20 to <50); large (≥50%). Where risks increase after adaptation, data points are shown as maladaptation. All underlying data is provided in Table SM4.6.

points) show the highest effectiveness across agricultural adaptation outcomes and generally project moderate to high effectiveness with the potential for co-benefits (Figure 4.28). Though maladaptive outcomes are also documented, residual risks are limited, also at higher levels of warming. Therefore, developing integrated plans of synergistic options linked to adequate monitoring and evaluation approaches and designed to adjust to changing conditions continuously is desirable to minimise climate risk and ensure food security (Babaeian et al., 2021).

Globally, agroforestry-related adaptation (four studies; 18 data points) is moderately to highly effective, with the potential for substantial co-benefits at 1.5° and 2°C of warming, with a sharp decline in effectiveness at 3°C and 4°C and a substantial increase in residual risk and maladaptive outcomes (Figure 4.28).

Flood risk-related adaptation (four studies; 47 data points) is associated with the potential for substantial co-benefits relative to present-day flood risk, indicating a current adaptation gap larger than for other impact areas. These co-benefits decline with increasing warming. Limits to the tested options become increasingly apparent at 3°C and 4°C of warming, where residual risks increase for most assessed cases (Figure 4.28).

Adaptation projections for urban water risks as well as the energy sector are limited to one study each, with one data point for urban adaptation (Rosenberger et al., 2021) and 80 data points for different variations of adaptation outcomes across regions and scenarios for the energy sector (van Vliet et al., 2016c). Sustainable stormwater management, focusing on a combination of nature-based solutions, is shown to be highly effective and yields co-benefits at 3°C. However, these results were gained in a specific case study setting in a European city with limited generalizability (Figure 4.28).

The assessment of adaptation in the hydropower and thermoelectric power-generation sector indicates high effectiveness and co-benefits across all regions for 1.5°C, with decreasing effectiveness and increasing residual risks for 2°C and 3°C of warming and highest reductions in effectiveness for Central and South America (Figure 4.28).

Quantitative projections of future adaptation depend on available impact models to analyse the effect of specific adaptation interventions. However, since not all possible future adaptation responses can be incorporated in climate impact models, this is a major limitation to assessing the full scope of options available in the future. For example, many frequently implemented measures showing effective outcomes, such as behavioural and capacity building-focused responses or migration and off-farm diversification (Section 4.7.1.2), are not incorporated in quantitative water-related climate impact projection models. In addition, projections of future adaptation depend on currently available technologies or approaches, but new methods and technologies will probably emerge. Thus, improving the representation of adaptation in future projections is a significant knowledge gap that remains to be addressed.

Whether specific adaptation responses are shown to be effective and even lead to co-benefits or are associated with residual impacts is highly contextually, location- and crop-specific. In addition, the specific climate-impact-scenario combinations play an important role in determining assessed outcomes.

In practice, responding to increasing climate risk will need to be context-specific and sufficiently agile to respond to ever-changing realities on the ground. The adaptive pathways approach underline that a sequence of different options responding to climate change over time may be most effective (Babaeian et al., 2021). In addition, impact models generally underestimate or underrepresent climate extremes (Schewe et al., 2019), limiting the ability of the present analysis to reflect adaptation requirements to extremes, which are likely to push systems to their limits (Section 4.7.4). While currently known structural adaptation responses can reduce some of the projected risks across sectors and regions, residual impacts remain at all levels of warming, and effectiveness decreases at higher levels of warming. Adaptation generally performs more effectively at 1.5°C, though residual damages are projected at this warming level across sectors and regions (*high confidence*). A range of options also shows the potential for further increasing negative effects (maladaptation) across sectors, regions and warming levels, further underlining the need for contextualised approaches.

4.7.3 Comparing Current and Future Water-Related Adaptation Responses

Water-related adaptation is being observed across sectors and regions (Section 4.6), and beneficial outcomes are documented across different dimensions (Section 4.7.1). A limited set of frequently documented adaptation responses is also represented in quantitative projections of adaptation effectiveness (Section 4.7.2, Figure 4.29). However, due to the largely different assessment methodologies for measuring beneficial outcomes for current adaptations and effectiveness to reduce impacts for future adaptations, comparing current and future adaptation outcomes is not straightforward. For current adaptation responses, beneficial outcomes may or may not translate to climate risk reduction, making risk reduction potential of observed adaptation a significant gap in our current understanding. The large diversity of outcomes across regions and assessed options becomes apparent for future adaptation options, with the group of 'inconclusive' outcomes indicating a large spread of results across regions. This underlines the contextual nature of adaptation and boundary conditions for implementation that can determine the success of adaptation outcomes, now or in the future.

Documented implemented adaptations show several beneficial outcomes, with most studies (319 of 356) documenting positive rather

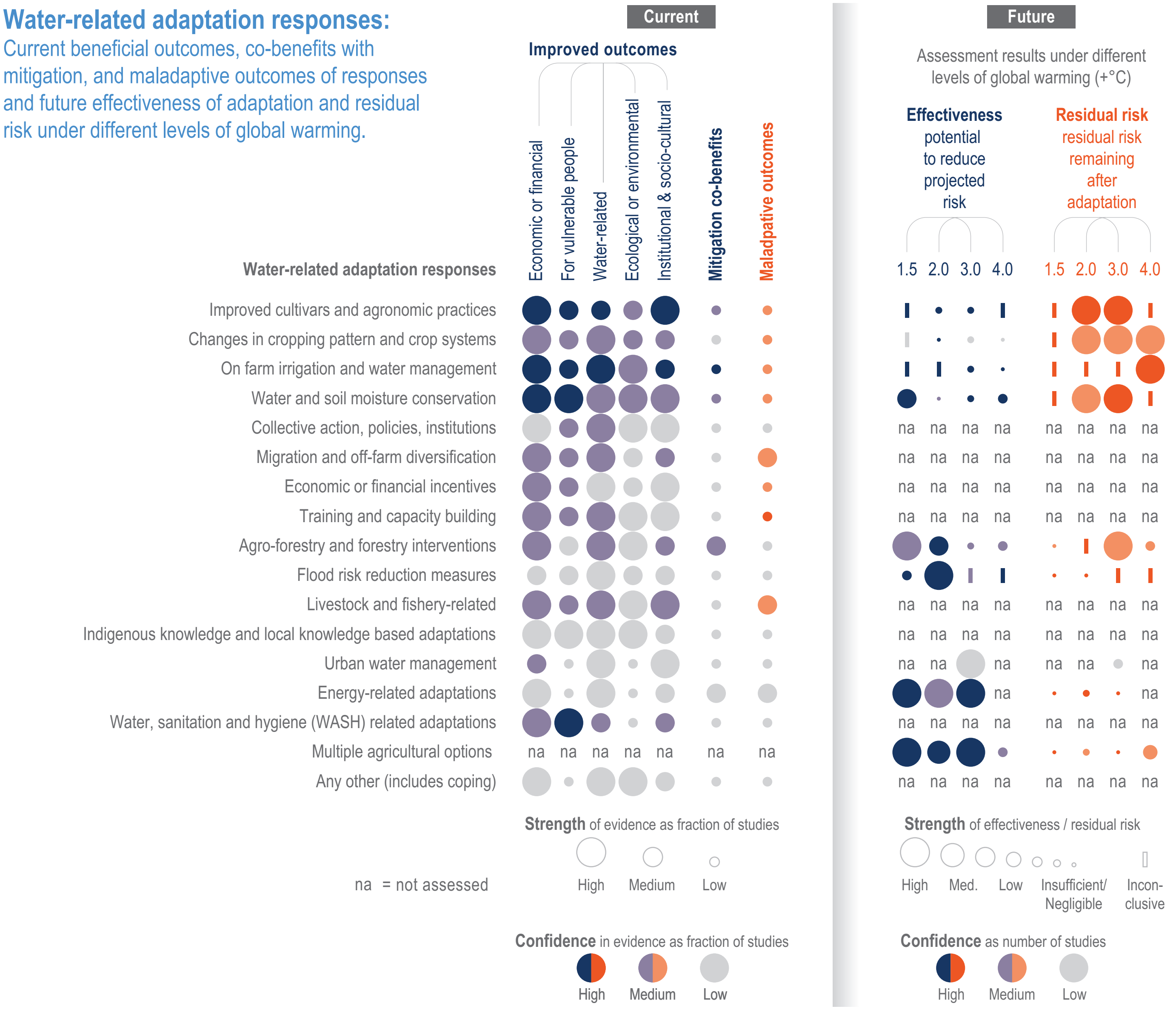


Figure 4.29 | The panel on the left side shows observed benefits of adaptation. Observed outcomes are reported across five dimensions of benefits, co-benefits and maladaptation outcomes. Benefits are measured across five dimensions. Strength of evidence is high if >80% of adaptation responses in that category have at least one beneficial outcome; medium if between 50 and 80% of adaptation responses in that category have at least one beneficial outcome, and low if <50% of adaptation responses have at least one beneficial outcome. Confidence in evidence relates to the way the article links outcomes of adaptation with the adaptation response. Category 1: studies causally link adaptation outcomes to the adaptation response by constructing credible counterfactuals; category 2: studies correlate responses and outcomes without causal attribution; category 3: studies describe adaptation outcomes without making any causal or correlation claims between adaptation outcomes and adaptation responses. *High confidence*: more than 67% of the studies fall in categories 1 and 2; *medium confidence*: 50–67% of the studies are in categories 1 and 2; *low confidence* is less than 50% of studies are in categories 1 and 2. The panel on the right-hand side shows the effectiveness of future adaptations. Future outcomes are assessed in terms of their effectiveness to reduce climate impacts at 1.5°C, 2°C, 3°C and 4°C of global temperature increase relative to 1850–1900. Effectiveness is defined as the fraction of adaptation that the option is able to reduce; residual risk is the fraction of risk remaining after adaptation. If >66% of assessed data points agree on the effectiveness class, a response–temperature combination is shown as belonging to that class. Where results diverge, the result is inconclusive, with studies showing high and low effectiveness across regions and studies. Confidence is based on the number of data points available for each response–temperature combination with *high confidence*: 5 or more data points; *medium confidence*: 2–4 data points; *low confidence*: 1 data point. Also, see Figure 4.28 for further explanations, and Tables SM4.5 and SM4.6 provide underlying data.

than negative outcomes. However, there may be a positive reporting bias in the literature, as positive outcomes are more likely to be reported than negative ones. Also, positive outcome in one parameter does not preclude negative outcomes in others, so maladaptation is still possible even when an adaption has some positive benefits (Section 4.7.1.2). In addition, much of the adaptation happening on the ground may not be published in peer-reviewed publications and, therefore, not covered by the literature assessed in this report. Further, there is limited knowledge about the effectiveness of current adaptation in reducing climate-related risks due to documentation and methodological challenges elaborated in Section 4.7.1.2 (SM4.2).

In contrast, evaluating the effectiveness for future projected adaptations is methodologically possible (Section 4.7.2, and SM4.2), but every adaptation that is happening now cannot be modelled for the future. Therefore, projections of future adaptation effectiveness are limited to those options that can be incorporated into (global) quantitative climate impact models. Unfortunately, an extensive range of options, such as capacity building or training, migration and employment, which are essential building blocks in the portfolio of available (water-related) adaptation options, are currently not quantitatively represented in adaptation projections. In addition, the future will probably bring further development in technical solutions, which are currently also not modelled. While implementing the modelled technical options may be feasible in general, several barriers and constraints (Section 4.7.4) and enabling conditions, which influence adaptation action in practice, are not included in current modelling studies. Therefore, the modelling studies may present optimistic assessments of adaptation effectiveness for the future.

Adaptations that are beneficial now (e.g., crop- and water-related ones) are also projected to be effective to varying extents in reducing future risks, with the degree of effectiveness strongly depending on future GWLs. For example, beyond a certain level of warming (2°C and upwards), the effectiveness of most options is projected to reduce, and residual impacts are projected to increase. Reduction in the effectiveness of future adaptation at higher global warming levels emphasises the need for limiting warming to 1.5°C, as space for adaptation solution starts to shrink beyond that for most options for which future projections exists (*high confidence*).

To sum up, there are two significant knowledge gaps in our understanding of water-related adaptations. First, the nature of literature on current adaptation makes it challenging to infer their effectiveness in reducing climate risks, even though the benefits of adaptation are clear (*high confidence*). Second, not all adaptation responses that are possible in the future can be modelled because of inherent limitations to what can be modelled. Thus, advancement in tools and metrics for measuring the effectiveness of current adaptation in reducing climate risks and suitable downscaled climate and impact models that incorporate economic, social, cultural and management aspects for an extensive range of future adaptation options is needed.

4.7.4 Limits to Adaptation and Losses and Damages

The core constraints identified in AR5 (Klein et al., 2014) for freshwater-related adaptation were lack of governance, financial resources and information, while water availability was singled out as a core constraint to diversifying options for water-dependent sectors. SR1.5 showed that increasing aridity and decreased freshwater availability, including limited groundwater supply in fossil aquifers in conjunction with rising sea levels may pose hard limits to adaptation for small islands (Roy et al., 2018). SR1.5 also shows that water-related risks can be reduced substantially by limiting warming to 1.5°C (*high confidence*) (Hoegh-Guldberg et al., 2018), thereby also reducing the potential to reach hard limits to adaptation. SROCC highlighted that several barriers and limits to adapt to reduced water availability in mountain areas, such as lack of finance and technical knowledge (Hock et al., 2019b). The SRCCL further highlighted the critical importance of water-related climate change adaptation and potential limits to adaptation in the land sector when extreme forms of desertification lead to a complete loss of land productivity (*high confidence*) (Mirzabaev et al., 2019).

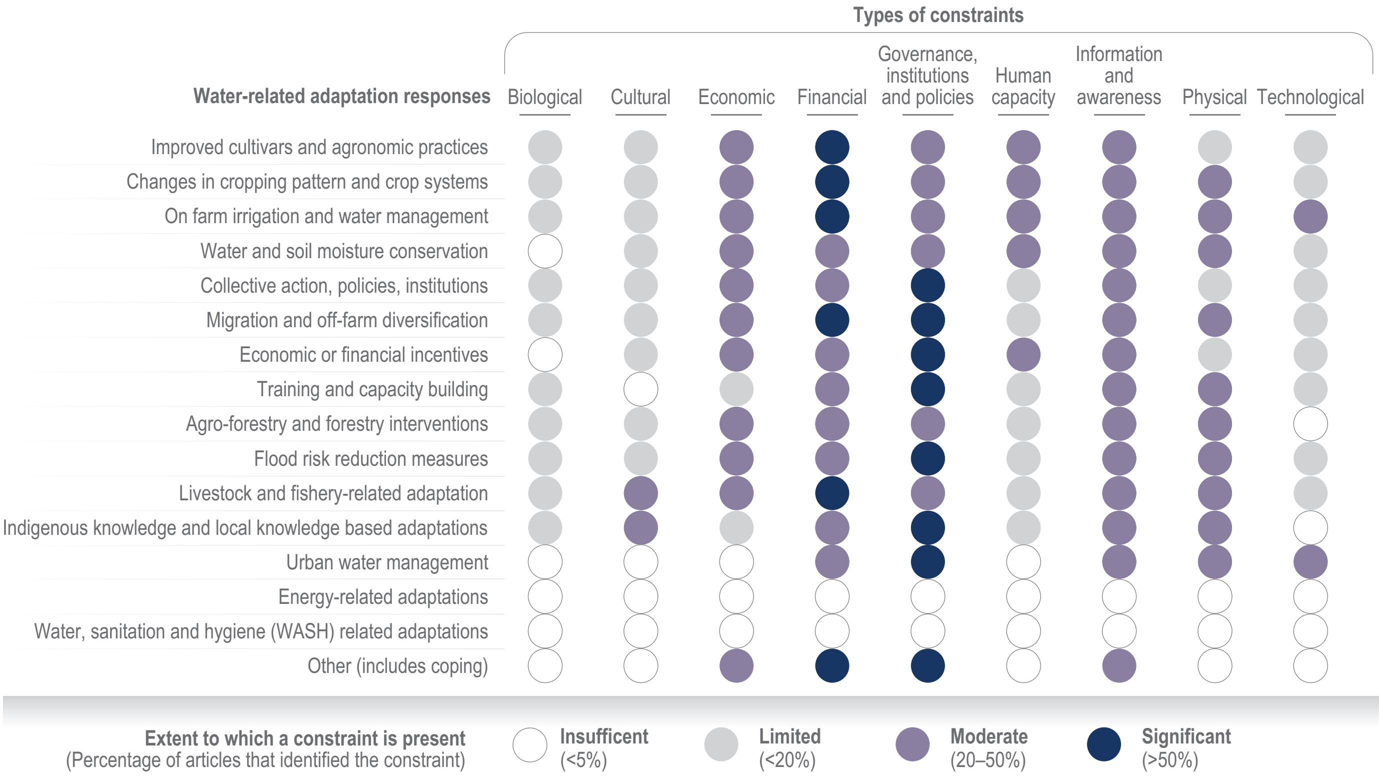
Institutional constraints, including path dependency and lengthy decision-making processes, remain major limitations to successful adaptation globally (*high confidence*) (Barnett et al., 2015; Oberlack, 2017), as well as for the water sector (Kingsborough et al., 2016; Oberlack, 2017; Azhoni and Goyal, 2018). For example, a lack of institutional support has limited the ability of farmers to implement adaptation, even if information about the benefits is acknowledged (Nambi et al., 2015). A lack of inter-sectoral coordination and communication within institutions and conflicting interests between water sectors limit the potential for integrated policies. For all water-related adaptation options, which have shown to be effective in one or more dimensions (Section 4.7.1.2), governance and institutional constraints were identified to be the most commonly encountered to a moderate or significant extent (Figure 4.30). Water–energy–food nexus approaches can help overcome these inter-sectoral barriers (Box 4.8) (Rasul and Sharma, 2016; Ernst and Preston, 2017). In addition, trade-offs between different policy goals must be considered to ensure the broader significance of the implemented adaptation strategies, such as water quality implication of adaptation efforts in the agricultural or energy sectors (Section 4.7.6) (Fezzi et al., 2015).

The lack of financial and technological resources constrains adaptation implementation (Castells-Quintana et al., 2018; Iglesias et al., 2018) and was identified as significant or moderate across all water-related adaptation responses, with significant constraints especially present in options related to the agricultural sector (Figure 4.30). For example, financial resources were significant constraints to implementing Climate Smart Agriculture in Guatemala, a relevant adaptation strategy to improve food security, resilience, and low emission development (Sain et al., 2017).

While financial barriers played an important role in adopting new technologies at the farm level in Spain, acceptance, common understanding and awareness were amongst the most frequently identified barriers across different adaptation options (Esteve et al., 2018). Limitations in knowledge and understanding of complex processes, feedback effects and interconnections in the water sector pose challenges to effective adaptation and adaptation decision-making (Kundzewicz et al., 2018). Such constraints are identified as moderate across the range of options assessed in this chapter (Figure 4.30). For tropical and mountainous regions and the African continent, in particular, significant uncertainties in available data and a lack of reliable climate projections remain one of the biggest obstacles in long-term adaptation planning (Antwi-Agyei et al., 2015), especially in the water sector (Watson et al., 2017; Azhoni and Goyal, 2018; Hirpa et al., 2018; González-Zeas et al., 2019). There is also often a discrepancy between the level of awareness among different stakeholders, for example, between affected farmers whose agency is limited by the lack of knowledge by local authorities (Chu, 2017).

For some regions of the world, such as small islands (Karnauskas et al., 2016; Karnauskas et al., 2018) (Box 4.2) and the Mediterranean (Cross-Chapter Paper 4) (Schleussner et al., 2016), aridity increases have the potential to pose hard adaptation limits. In mountain and polar regions, changes in the cryosphere (Sections 4.2.2, 4.4.2) may

Adaptation constraints for water related adaptation across different dimensions



Types of constraints

Water-related adaptation responses	Biological	Cultural	Economic	Financial	Governance, institutions and policies	Human capacity	Information and awareness	Physical	Technological
Improved cultivars and agronomic practices	◔	◔	◑	●	◑	◑	◑	◔	◔
Changes in cropping pattern and crop systems	◔	◔	◑	●	◑	◑	◑	◑	◔
On farm irrigation and water management	◔	◔	◑	●	◑	◑	◑	◑	◑
Water and soil moisture conservation	○	◔	◑	◑	◑	◑	◑	◑	◔
Collective action, policies, institutions	◔	◔	◑	◑	●	◔	◑	◔	◔
Migration and off-farm diversification	◔	◔	◑	●	●	◔	◑	◑	◔
Economic or financial incentives	○	◔	◑	◑	●	◑	◑	◔	◔
Training and capacity building	◔	○	◔	◑	●	◔	◑	◑	◔
Agro-forestry and forestry interventions	◔	◔	◑	◑	◑	◔	◑	◑	○
Flood risk reduction measures	◔	◔	◑	◑	●	◔	◑	◑	◔
Livestock and fishery-related adaptation	◔	◑	◑	●	◑	◔	◑	◑	◔
Indigenous knowledge and local knowledge based adaptations	◔	◑	◔	◑	●	◔	◑	◑	○
Urban water management	○	○	○	◑	●	○	◑	◑	◑
Energy-related adaptations	○	○	○	○	○	○	○	○	○
Water, sanitation and hygiene (WASH) related adaptations	○	○	○	○	○	○	○	○	○
Other (includes coping)	○	○	◑	●	●	○	◑	○	○

Extent to which a constraint is present
(Percentage of articles that identified the constraint)

○ **Insufficent** (<5%)
◔ **Limited** (<20%)
◑ **Moderate** (20–50%)
● **Significant** (>50%)

Figure 4.30 | Adaptation constraints manifest across a range of dimensions and here are assessed based on a meta-review of water-related adaptation (Section 4.7.1, SM4.2, and Table SM4.5). Where less than five articles are available for assessment, data is insufficient to assess the extent to which a constraint is present. Where less than 20% of the articles reporting on the respective adaptation option identify the presence of a constraint, it is classified as 'limited', where 20 to 50% report on a specific constraint it is considered as 'moderate'. Where more than 50% of articles report on the presence, the constraint is considered 'significant'. This assessment is based on the available peer-reviewed literature assessing adaptation benefits in the water sector—in practice, these or other constraints may still be significant, but have not have been identified in peer-review sources.

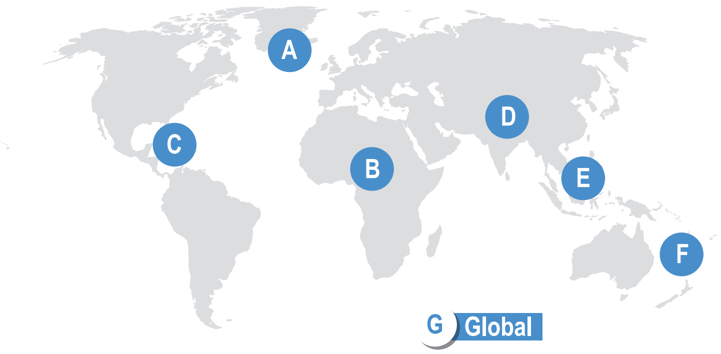
limit water availability for irrigation systems that depend on meltwater (Section 4.5.1) (Qin et al., 2020). Biophysical limits may also be reached through impacts of hydrological extremes, such as crop loss as a consequence of extreme precipitation events (Huggel et al., 2019; van der Geest et al., 2019). Such limits are reported to a limited to moderate extent across all adaptation options assessed (Figure 4.30). However, knowledge gaps remain about physical and biological constraints to adaptation in the water sector. Climate impacts, such as droughts in East Africa or glacier melt in the cryosphere, indicate that biophysical limits to adaptation may exist, even under current climate conditions (Figure 4.31) (Warner and van der Geest, 2013; Huggel et al., 2019; van der Geest et al., 2019). A lack of investment in relevant infrastructure, such as dikes for example, as well as maladaptive effects of certain measures could increase existing risks and exacerbate impacts (van der Geest et al., 2019).

Integrated approaches, such as linking land use and water policies (Mehdi et al., 2015), inter-institutional networks (Azhoni et al., 2017), nexus approaches (Box 4.8) (Conway et al., 2015) as well as consideration of linkages to the SDGs (Section 4.8) (Gunathilaka et al., 2018) are crucial to overcoming constraints in water adaptation. In addition, monitoring and evaluating the effectiveness of adaptation measures, policies and actions can contribute to knowledge, awareness and data to support adaptation implementation in the future (Sections 4.7.1; 4.8) (Klostermann et al., 2018). Although the information on climate change adaptation that has beneficial impacts, including enabling conditions and success factors specific to the water sector, is emerging, significant knowledge gaps remain (Section 4.7.1.2) (Gotgelf et al., 2020). Further understanding the constraints and limits that exist with regard to adaptation in the water sector is becoming urgent in light of increasing slow (e.g., droughts) and rapid (e.g., floods) onset impacts associated with climate change.

Taking action towards adaptation critically determines the outcomes and impacts of climate change processes across space and time. Where efforts to reduce risk do not effectively occur, losses and damages occur as a consequence of climate change, some of which can have irreversible and existential effects (van der Geest and Warner, 2015; Page and Heyward, 2016; Thomas and Benjamin, 2018a; Mechler et al., 2019). Water-related impacts that occurred despite implemented adaptation have been documented across all world regions (*high confidence*) (Figure 4.31).

Advances in climate change attribution (Section 4.2; SM4.3; Figure 4.20) show the direct effects of anthropogenic climate change, also with regard to climate extremes. These advances also provide the basis for climate litigation (Marjanac and Patton, 2018) to hold countries/companies accountable for climate change impacts, for example, concerning risks of glacial lake outburst in Peru (Frank et al., 2019).

Examples of regional studies where communities experienced negative impacts despite or beyond implemented adaptation have been documented



	Hazard	Adaptation	Losses and Damages
A	Temperature increase, permafrost thawing	Outmigration	Loss of livelihoods, ecosystems and infrastructure
B	Drought	Crop-livestock integration, soil fertility management, crop variety, migration	Loss of food security
	Drought, climate variability	Pastoralism (moving cattle to regions with abundant pasture)	Loss of food security
C	Hurricanes, storms, droughts	Using savings, borrowing, government assistance	Loss of income sources, loss of access to finance, depletion of assets, health problems, damage to housing and agriculture
D	Landslides	Diversify livelihoods, physical barriers, house adjustments, migration	Loss of life, loss of property and infrastructure
	Changing monsoon patterns	Irrigation channels, water sharing mechanisms, crop diversification	Loss of access to water and loss of crops
	Floods, cyclones, surges, coastal flooding	Physical protection, creating buffers, build safety nets	Loss of livelihoods, harvest failure and damage to infrastructure
E	Floods, storms and drought	Irrigation, diversification of crops, regeneration of degraded forests, animal husbandry	Loss of food security, crops, income, livelihoods and land
	Floods, landslides, typhoons	Food relief, temporary shelter and loaning money	Loss of livelihoods, infrastructure and ecosystems
F	Freshwater scarcity, aridity, cyclones, El Nino, flooding	Seasonal work and outmigration, early warning systems	Loss of life, livelihoods, homes, crops, contamination of drinking water, displacement
G Global	Changes in glacier runoff, permafrost thawing, GLOFs	Outmigration, new livelihoods (e.g. tourism)	Loss of cultural heritage, loss of income, loss of lives

Figure 4.31 | Examples of regional studies where communities experienced negative impacts despite or beyond implemented adaptation have been documented. Panels indicate the climate hazard that leads to the need for adaptation, the adaptation option implemented and the recorded impacts per region (A – Arctic (Landauer and Juhola, 2019), B – Africa (van der Geest et al., 2019), C – Caribbean (Lashley and Warner, 2015), D – South Asia (Kusters and Wangdi, 2013; van der Geest and Schindler, 2016; Bhowmik et al., 2021), E – Southeast Asia (Acosta et al., 2016; Beckman and Nguyen, 2016), F – Pacific the Small Island States (Gawith et al., 2016; Handmer and Nalau, 2019), G – Global effect: Mountain Cryosphere (Huggel et al., 2019)). Presented examples are limited to the available peer-reviewed literature that focuses explicitly on impacts that have been documented despite documented evidence that adaptation in relation to water hazards had previously been implemented. Section 4.3 provides a full assessment of observed impacts across sectors and regions.

A further increase in the frequency and/or intensity of water-related extremes (Section 4.4) will also increase consequent risks and associated losses and damages (Section 4.5), primarily for exposed and vulnerable communities globally (Bouwer, 2019). After assessing the future potential of currently available technologies to reduce projected water-related climate impacts, there is evidence that residual impacts will remain after adaptation for most adaptation options and levels of warming, with increasing residual risks at higher warming levels (Section 4.7.2). Financial, technical and legal support will be needed when hard limits are transgressed and loss and damage occurs (Mechler et al., 2020). Knowledge gaps remain regarding quantified information on limits and constraints to adaptation in the water sector.

In summary, institutional constraints (governance, institutions, policy), including path dependency and financial and information constraints, are the main challenge to adaptation implementation in the water sector (*high confidence*). Water-related losses and damages that manifest despite or beyond implemented adaptation have been observed across world regions, primarily for exposed and vulnerable communities (*high confidence*). Hard limits to adaptation due to limited water resources will emerge for small islands (*medium evidence, high agreement*) and regions dependent on glacier- and snowmelt (*medium evidence, high agreement*).

4.7.5 Costs of Adaptation and Losses due to Non-Adaptation

Estimating adaptation costs for climate change impacts on the various water use sectors is vital for decision-making, budgeting, and resource allocation (Chambwera et al., 2014). However, in AR5, studies on adaptation costs for water were deemed to have 'limited coverage' and mainly focused on 'isolated case studies'; costs in agriculture were 'extremely limited' (Chambwera et al., 2014).

One estimate on observed losses due to climate change from the UK notes that almost 50% of freshwater thermal capacity is lost on extreme high-temperature days, causing losses in the range of average GBP 29–66 million/year (Byers et al., 2020). However, global estimates of current losses because of climate change impacts on water resources remain few. Most of the evidence is focused on projected damages rather than actual ones (World Bank, 2016; Rozenberg and Fay, 2019).

Without adaptation, water-related impacts of climate change are projected to reduce global GDP by 0.49% in 2050 under SSP3, with significant regional variations for the Middle East (14%); Sahel (11.7%); Central Asia (10.7%), and East Asia (7%) (World Bank, 2016). In Asia, water-related impacts of climate change on all sectors of the economy are projected to reduce GDP by 0.9% (in high-income Asia) to 2.7% (in low-income Asia) by 2050 without adaptation or mitigation. Under the A1B scenario, real GDP is projected to fall by 0.78% by 2030 in South Asia (Ahmed and Suphachalasai, 2014). In Sub-Saharan Africa, damages from floods in 2100 are projected at 0.5% of GDP under a 2°C temperature rise without adaptation; and will be non-uniformly spread across countries (Markandya, 2017; Dottori et al., 2018). In Europe, annual damages due to coastal flooding are projected at €93 billion by 2100 under RCP8.5-SSP3 (Ciscar et al., 2018). Global direct damages from fluvial floods are projected to rise to €1250 billion yr^{-1} under a 3°C global warming level and SSP5 socioeconomic scenario (Dottori et al., 2018). A model-based study of selected water-related sectors like fluvial and coastal flooding, agricultural productivity of major crops, hydroelectric power generation, and thermal power generation provides much conservative estimates of GDP loss (Takakura et al., 2019). The study shows that without adaptation, loss of global GDP could be 0.094% under RCP8.5 and SSP5 and 0.013% under RCP2.6 and SSP1 scenarios in 2090 (2080–2099), with regional values for Africa (0.017 to 0.286%), Asia (0.015 to 0.104%), Australasia (-0.012 to 0.003%), North America (-0.002 to 0.005%) and South and Central America (0.011 to 0.055%) (Takakura et al., 2019). So, while there is general agreement about negative impacts on GDP due to water-related risks in the future, the magnitude of GDP loss estimates varies substantially and depends on various model assumptions (*high confidence*). Updating costs while improving the modelling of uncertainties is essential for evidence-based decision-making (Ginbo et al., 2020).

Costs of water-related infrastructure in adaptation have received attention at the global and regional level to bridge the 'adaptation gap' (Hallegatte et al., 2018; UNEP, 2018; Dellink et al., 2019; GCA, 2019). For example, (Rozenberg and Fay, 2019) estimated that subsidising capital costs to extend irrigation to its full potential would cost 0.13% of the GDP per year of low-and middle-income countries between 2015 and 2030. The coastal and riverine protection cost was between 0.06% and 1% of these countries' GDP per year over the same period. Projected economic damage due to coastal inundation was USD 169–482 billion in 2100 under RCP8.5-SSP3 without adaptation, but USD 43–203 billion cost to raise dike height will reduce 40% of the total damage (Tamura et al., 2019). Hard infrastructure for river floods, costing $4–9 billion yr^{-1}, can reduce damage by USD 22–74 billion yr^{-1} (Tanoue et al., 2021). Damages are estimated to be up to six-time larger than the cost of implementing efficient adaptation measures (H2020., 2014). (GCA, 2019) reported that investing USD 1.8 trillion globally, for example, in early warning systems, climate-resilient infrastructure; dryland crop production; mangrove protection; and improving the resilience of water resources between 2020 and 2030 could generate USD 7.1 trillion in benefits.

Comparatively, less attention has been paid to low-regret options, especially at the national and local levels. Conservation agriculture and integrated production systems, early-warning systems, restoration of wetlands, and zoning are postulated to have lower investment and lock-in costs than engineering-based options (Mechler, 2016; Cronin et al., 2018; Johnson et al., 2020). However, they require regular maintenance and high technical and human capacity, which are likely to vary by scale, location, and context (Chandra et al., 2018; Khanal et al., 2019; Mutenje et al., 2019; Rahman and Hickey, 2019). Global studies suggest improvements in returns on adaptation investments by delivering better services and reducing water wastage through appropriate water pricing and regulations (Damania et al., 2017; Bhave et al., 2018). For example, under scenarios SSP1 and SSP3, water pricing and regulation are projected to reverse losses in expected 2050 global GDP of 0.49% to gains of 0.09%. GDP losses are projected to drastically reduce in the Middle East, eliminated in the Sahel and Central Africa, and reversed into gains in Central Asia and East Africa, with benefits concentrated in worst-affected regions (World Bank, 2016). More local and national studies are needed to identify low regret options and their benefits and

Box 4.8 | Water-Energy-Food (WEF) Nexus Approaches for Managing Synergies and Trade-Offs

The WEF nexus is an approach that recognises 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; Liu et al., 2018b; Märker et al., 2018). For instance, agricultural production requires significant energy inputs due to intensive groundwater pumping (Siddiqi and Wescoat, 2013; Gurdak, 2018; Putra et al., 2020). Similarly, hydropower production often has trade-offs with irrigation, affecting food production, carbon emission and forest protection (Meng et al., 2020). New technologies, such as desalination plants for urban water supply against future climate change and drought, are also very energy-intensive (Caldera et al., 2018) (Box 4.5). Quantifying the complex interdependencies among food, energy and water is critical to achieving the SDGs and reducing trade-offs (Liu et al., 2018a; Liu et al., 2018b; UN, 2019). A key benefit of the nexus approach is to leverage the interconnection of WEF and achieve the most efficiency in the overall systems. Hence, this approach allows for widening the set of salient stakeholders and, therefore, 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; Mercure et al., 2019).

The WEF nexus approach thus opens up possibilities for strategic interventions across sectors through a better understanding of trade-offs (Albrecht et al., 2018). Policies and strategies aiming to cope with climate change may amplify rather than reduce negative externalities and trade-offs within the nexus: low carbon transition, the shift to non-conventional water resources, and agricultural intensification, all implemented to mitigate and adapt to climate change, are not always nexus-smart. Hence, a nexus approach that integrates management and governance across these three sectors can enhance WEF security by minimising trade-offs and maximising synergies between sectors. At the same time, renewable energy offers the opportunity to decouple water and food production from fossil fuel supply, leading to several advantages from both a socioeconomic and environmental point of view (Cipollina et al., 2015; Pistocchi et al., 2020). WEF nexus approaches can achieve overall system efficiency when maximising the use and recovery of water, energy, nutrients and materials (Pistocchi et al., 2020; Tian et al., 2021). These types of holistic system thinking of WEF show promising strategies to catalyse transformative changes. Suppose that the specific types and extent of WEF linkages in a region are well understood. In that case, it becomes possible to intervene through one element to cause an effect on another connected component that may have proven difficult for direct intervention (Mukherji, 2020).

Several challenges remain for sound operationalisation of the nexus, notably insufficient data, information and knowledge in understanding the WEF inter-linkages and lack of systematic tools to address trade-offs involved in the nexus and to generate future projections (Liu et al., 2017a; Liu et al., 2018b). There are recent signs of progress in developing models and tools for addressing the nexus trade-offs, for example, the bioenergy–water nexus (Ai et al., 2020). There is a need to move beyond viewing the WEF nexus as a way of problem identification to seek integrated solutions to interconnected problems.

actual costs (Blackburn and Pelling, 2018; Abedin et al., 2019; Brown et al., 2019; Momblanch et al., 2019; Page and Dilling, 2020) (*limited evidence, high agreement*).

In summary, climate change impacts on water resources are projected to lower GDP in many low-and middle-income countries without adequate adaptation measures (*high confidence*). However, estimating the exact quantum of future GDP loss due to water-related impacts of climate change is fraught with several methodological challenges. Adaptation measures that focus on reducing water-related impacts of climate change will help stem losses further. Still, more work needs to be done on actual benefits and costs of adaptation strategies and residual impacts and risks of delaying adaptation action (*medium confidence*). In addition, better evidence on the costs and benefits of low-regret solutions, such as water pricing, increasing water use efficiency through technology and service improvements, and enhanced support for autonomous adaptation, is also needed for informed decision-making (*high confidence*).

4.7.6 Trade-Offs and Synergies between Water-Related Adaptation and Mitigation

In AR5, there was *medium evidence* and *high agreement* that some adaptation and mitigation measures can lead to maladaptive outcomes, such as a rise in GHG emissions, while further exacerbating water scarcity leading to increased vulnerability to climate change, now or in the future (Noble et al., 2014). In addition, SR1.5 (Hoegh-Guldberg et al., 2018; IPCC, 2018a) and SRCCL (IPCC, 2019b) reiterated the challenge of trade-offs that may undermine sustainable development. Conversely, adaptation, when framed and implemented appropriately, can synergistically reduce emissions and enhance sustainable development.

Different mitigation pathways can either increase or decrease water withdrawals or water consumption (or both, or either) depending on the specific combination of mitigation technologies deployed (*high confidence*) (Fricko et al., 2016; Jakob and Steckel, 2016; Mouratiadou et al., 2016; Fujimori et al., 2017; Parkinson et al., 2019). For example, the impacts of climate change mitigation on future global water demand depend largely on assumptions regarding socioeconomic and water policy conditions and range from reduction of 15,000 km^3 to an increase of more than 160,000 km^3 by the end of century (Mouratiadou et al., 2016). This section assesses some of the mitigation and adaptation measures from a water trade-off and synergy lens.

Solar pumps for irrigation are increasingly introduced where conventional energy is not available (Senthil Kumar et al., 2020) or supply is intermittent or expensive (Shah et al., 2018), for example, in Africa (Schmitter et al., 2018), Europe (Rubio-Aliaga et al., 2016) and South Asia (Sarkar and Ghosh, 2017). Solar pumps can replace diesel and electric pumps (Rajan et al., 2020), potentially reduce 8–11% of India's carbon emissions (~45.3–62.3 MMT of CO_2) attributable to groundwater pumping while also boosting agricultural productivity (Gupta, 2019). However, in the absence of incentives to deter groundwater over-exploitation (Shah et al., 2018), solar pumps may exacerbate groundwater depletion (Closas and Rap, 2017; Gupta, 2019) (*low evidence, medium agreement*).

In many places, treatment and reuse of wastewater from urban residential and industrial sources may be the principal supply option under acute water scarcity (US EPA, 2017) and help reduce other freshwater withdrawals (Tram Vo et al., 2014; Diaz-Elsayed et al., 2019). While reuse may recover valuable nutrients, capture energy as methane, and save water, effluent containing heavy metals may degrade land and surface and groundwater quality and pose a salinisation risk in semiarid regions (*medium evidence, high agreement*). Agricultural reuse of poor-quality wastewater will become increasingly necessary, but treatment is energy-intensive and may contribute to further GHG emissions (Qadir et al., 2014; Salgot and Folch, 2018) (Box 4.5).

Desalination of seawater or brackish water is an adaptation measure in many coastal water-scarce regions (Hanasaki et al., 2016; Jones et al., 2019). Solar desalination is developing rapidly, and it lessens the carbon footprint of conventional, fossil-fuel-powered desalinisation plants (Pouyfaucon and García-Rodríguez, 2018) (also see Box 4.5). However, the desalinisation process is energy-intensive (Caldera et al., 2018); it ejects brine that is difficult to manage inland, has high salinity and other contaminants (Wilder et al., 2016) (*medium evidence, high agreement*) (Box 4.5).

Negative-emission technologies, such as direct air capture (DAC) of CO_2, could reduce emissions up to 3 $GtCO_2$/year by 2035, equivalent to 7% of 2019 global emissions. However, they can increase net water consumption by 35 $km^3\ yr^{-1}$ in 2050 (Fuhrman et al., 2020) under the low-overshoot emissions scenario. According to other estimates, capturing 10 Gt CO_2 could translate to water losses of 10–100 km^3, depending on the technology deployed and climatic conditions (temperate vs. tropical) (Chapter 12, WGIII). Some DAC technologies that include solid sorbents also produce water as a by-product, but not in quantities that can offset total water losses (Beuttler et al., 2019; Fasihi et al., 2019) (*medium confidence*).

Developing countries are projected to witness the highest increase in future energy demand under 2°C global warming leading to significant increases in water use for energy production (Fricko et al., 2016) (Section 4.5.2). Results from a simulation study on retrofitting coal-fired power plants built after 2000 with carbon capture and storage (CCS) technologies show an increase in global water consumption, currently at 9.66 $km^3\ yr^{-1}$, by 31–50% (to 12.66 $km^3\ yr^{-1}$ and 14.47 $km^3\ yr^{-1}$, respectively) depending on the cooling and CCS technology deployed, and hence are best deployed in locations which are not water scarce (Rosa et al., 2020c) (*medium confidence*). In Asia, the near-term mitigation scenario with high CCS deployment increases the average regional water withdrawal intensity of coal generation by 50–80% compared to current withdrawals (Wang et al., 2019b). Carbon can be 'scrubbed' from thermoelectric power plant emissions and injected for storage in deep geological strata (Turner et al., 2018), but this can lead to pollution of deep aquifers (Chen et al., 2021) and have health consequences (*low confidence*).

Bio-energy crop with carbon capture and storage (BECCS) involves CO_2 sequestration as biofuel or forest bioenergy (Creutzig et al., 2015). BECCS has profound implications for water resources (Ai et al., 2020), depending on factors including the scale of deployment, land use, and other local conditions. Evaporative losses from biomass irrigation and thermal bioelectricity generation are projected to peak at 183 $km^3\ yr^{-1}$ in 2050 under a low overshoot scenario (Fuhrman et al., 2020). (Senthil Kumar et al., 2020) projected that while BECCS strategies like irrigating biomass plantations can limit global warming by the end of the 21st century to 1.5°C, this will double the global area and population living under severe water stress compared to the current baseline. Both BECCS (Muratori et al., 2016) and DAC can significantly impact food prices via demand for land and water (Fuhrman et al., 2020). The direction and magnitude of price movement will depend on future carbon prices, while vulnerable people in the Global South will be most severely affected (*medium evidence, high agreement*).

Afforestation and reforestation are considered one of the most cost-effective ways of storing carbon. An additional 0.9 billion ha of canopy cover in suitable locations could store 205 Gt of carbon (Bastin et al., 2019), but this estimate is deemed unrealistic. Aggressive afforestation and reforestation efforts can result in trade-offs between biodiversity, carbon sequestration, and water use (Smith et al., 2008). In northern China, ecological restoration by regreening drylands resulted in several environmental and social benefits (Mirzabaev et al., 2019) but also led to increased freshwater use in some pockets (Zhao et al., 2020). Afforestation and reforestation with appropriate broad-leaf species in temperate Europe (Schwaab et al., 2020) can offer water quality and quantity-related benefits, mitigate extreme heat, and buffer against drought (Staal et al., 2018). A global assessment on forest and water showed that forests influence the overall water cycle, including downstream water availability via rainfall-runoff dynamics and downwind water availability via recycled rainfall effects (Creed and van Noordwijk, 2018). The study concluded that afforestation and reforestation should be concentrated (Ellison et al., 2017) in water-abundant locations (to offset downstream impacts) and where transpiration can potentially be captured downwind as precipitation (Creed et al., 2019) (Cross-Chapter Box NATURAL in Chapter 2). Overall, extensive BECCS and afforestation/reforestation deployment can alter the water cycle at regional scales (*high confidence*) (Cross-Chapter Box 5.1 in Chapter 5, WGI, (Canadell et al., 2021)).

On the other hand, demand-side mitigation options, such as dietary changes to more plant-based diets, reduced food waste (Aleksandrowicz et al., 2016; Springmann et al., 2018; Kim et al., 2020), can reduce water use (*medium evidence, high agreement*).

In summary, many adaptation and mitigation measures have synergistic or maladaptive consequences for water use, depending on associated incentives, policies, and governance that guide their deployment. Many mitigation measures have a considerable water footprint (*high confidence*), which must be managed in socially and politically acceptable ways to reduce the water intensity of mitigation while increasing synergies with sustainable development (*medium evidence, high agreement*).

4.8 Enabling Principles for Achieving Water Security, Sustainable and Climate Resilient Development Through Systems Transformations

Sustainable development is a global policy priority and commitment, as is keeping temperatures well below 2°C as per the Paris Agreement. Water is central to almost all SDGs (Box 4.1). Water is explicitly referred to in SDG6 (clean water and sanitation) and SDG11 (sustainable communities and cities) (UN, 2015) (Section 4.1). SDG1 (no poverty) is statistically linked to SDG6 (clean water and sanitation) (Pradhan, 2019), since reducing poverty can help increase adaptive capacity in line with the Paris Agreement adaptation goals (see Chapter 1 and Chapter 18). SDG2 (zero hunger) cannot be achieved without access to adequate water for agriculture. Meeting SDG3 (health and well-being) will rely on access to basic infrastructure like water and sanitation (Delany-Crowe et al., 2019; see Cross-Chapter Box HEALTH in Chapter 7, Sections 4.3.3, 4.3.5), while SDG7 (affordable and clean energy) will need water for hydropower production under a changing climate (Berga, 2016; Byers et al., 2016) (Section 4.5.2). Meeting SDG11 (sustainable cities and communities) will require reducing the impacts from water-related disasters.

Water is also fundamental to all systems transitions, namely, transitions in energy, industrial, land and ecosystem and urban systems. Within energy and industrial system transitions, water stress for electricity generation has already caused impacts (Section 4.3.2). Therefore, water efficiency measures are increasingly applied in both energy and industrial systems with benefits for mitigation and adaptation (Section 4.6.3). Water is inextricably entwined with land and ecosystems transitions, with forested areas and ecosystems being integral components of the water cycle, regulating streamflow, fostering groundwater recharge and contributing to atmospheric water recycling (Takata and Hanasaki, 2020) (Section 4.2). However, mitigation action of large afforestation, can have negative water impacts (Cross-Chapter Box 1 in Chapter 5 of WGI report, 4.7.6), making it imperative to consider water footprint of land- and forest-based mitigation (Muricho et al., 2019; Seddon et al., 2020) (Section 4.7.6). Sustainable forest management and NBS are promising alternatives for good water management (Muricho et al., 2019; Seddon et al., 2020). Water will also play a crucial role in sustainable urban transitions. Cities are already facing water-related impacts (Section 4.3.4), which are projected to intensify with every degree of global warming (Flörke et al., 2018; Nazemi and Madani, 2018) (Section 4.5.4). Mitigation and adaptation measures in urban spaces, such as green infrastructure (Liu and Jensen, 2018), sustainable water supply management through recycling of wastewater and storm water runoff (Box 4.5) and NbS like sponge cities, are fundamentally about water (Box 4.6).

Thus, water remains central to achieving SDGs and will play a fundamental role in systems transitions needed for climate resilient development. We outline a set of seven enabling principles that are needed to achieving water security and will also help in achieving SDGs and facilitate systems transitions.

4.8.1 Appropriate Technologies

AR5 concluded that successful adaptation across all sectors depends on access to technology, and technology transfer can play an essential role in building up adaptive capacity (Noble et al., 2014). SR1.5 discussed the role of efficient irrigation technologies in adaptation (de Coninck et al., 2018).

Technologies that reduce carbon emissions by promoting the efficient use of water can support successful adaptation (Biagini et al., 2014), provided they do not have adverse distributional outcomes (*medium evidence, high agreement*). Water management in agriculture has long seen the use of technology. For example, the use of technology to improve access to water, for example, through the diffusion of groundwater pumps in the 1970s in South Asia, had several livelihood benefits, but made agriculture more carbon-intensive (Zaveri et al., 2016). More recently, technology has been used to improve water use efficiency in agriculture through the adoption of drip and sprinkler irrigation (Zhuo and Hoekstra, 2017; Grafton et al., 2018), and the use of the Internet of Things (IoT) (Keswani et al., 2019). In addition, innovations to reuse water through various wastewater recovery technologies (Diaz-Elsayed et al., 2019; Capodaglio, 2020), create potable water through desalinisation (Caldera et al., 2018) and reuse of wastewater in agriculture (Salgot and Folch, 2018) are also on the rise (Box 4.5). Solar technologies are increasingly used for irrigation, wastewater recovery, desalinisation and water harvesting (Algarni et al., 2018; Pouyfaucon and García-Rodríguez, 2018; Tu et al., 2018; Zhao F. et al., 2020). Machine learning and artificial intelligence technologies (Doorn, 2021) have started being used in many water-use sectors, such as urban settings (Nie et al., 2020), wastewater management (Abdallah et al., 2020; Ben Ammar et al., 2020) and agricultural water management, but mostly in high-income countries mostly on an experimental basis (Tsang and Jim, 2016; González Perea et al., 2018). Technology is being increasingly used in hydrological sciences for measurements and monitoring (SM4.1), as well as for creating comprehensive hydrometeorological warning systems (Funk et al., 2015). Lack of technology and knowledge transfer, especially related to remote sensing, is an adaptation barrier in states with less resources (Funk et al., 2015).

Adoption of technologies depends on the availability of finance (Section 4.8.2). The effectiveness of technology in reducing climate-related risks depends on its appropriateness to the local context (Biagini et al., 2014; Mfitumukiza et al., 2020) and other factors, including institutional and governance frameworks (*high confidence*). Water technologies can also have unintended outcomes, leading to maladaptation in some cases. For example, efficient irrigation technologies like drip and sprinkler irrigation, while reducing water application rates per unit of land, can increase overall water extraction by increasing total land under irrigation (van der Kooij et al., 2013; Grafton et al., 2018; Mpanga and Idowu, 2021). Water-related technologies can also have adverse distributional outcomes when gains from technology adoption accrue disproportionately to a small section of the population; for example, only rich and male farmers can adopt high-cost technologies like solar irrigation pumps (Gupta, 2019) (*medium confidence*).

In summary, technology is an important part of water adaptation response, and outcomes of technology adoption are mediated through other societal factors, including institutions, governance frameworks and equity and justice issues (*medium evidence, high agreement*).

4.8.2 Adequate and Appropriate Financing

Although AR5 did not explicitly mention finance for water-related adaptation actions, it considered urban adaptation (Revi et al., 2014) and risk financing (Arent et al., 2014). SR1.5 (de Coninck et al., 2018) discussed governance and finance limitations, while SRCCL discussed finance in adapting to floods and droughts (Hurlbert et al., 2019).

Mitigation garners the significant share of committed climate finance. For example, of the total USD 15.4 billion climate finance commitments through 'green bonds', 79% accrued to mitigation and the rest to adaptation (World Bank, 2017). However, within adaptation finance, water garners a significant share of adaptation funds, with 13% of the Adaptation Fund's investments were for water management, 12% for coastal management and 10% for disaster risk reduction (Adaptation Fund, 2018). Similarly, within the urban adaptation landscape, which got ~3–5% of total adaptation finance flows of USD 30.8 billion tracked in 2017–2018 (Richmond et al., 2021), water and wastewater management projects received the largest share of urban adaptation finance (USD 761 million annually) followed by disaster risk management (USD 323 million) (Richmond et al., 2021). However, more frequent tracking of public financing is required, with a greater focus on transparency and accountability (Ciplet et al., 2018; Khan et al., 2020) and justice and social equity (Emrich et al., 2020) (also see Cross-Chapter Box FINANCE in Chapter 17).

Private financing remains a minor source of adaptation financing (World Bank, 2019). Around 39% of green bonds issued in 2017 were for water, wastewater and solid waste management (World Bank, 2017). In 2018, USD 100.5 billion of water-themed bonds were issued, mainly in Europe (63%), the Asia Pacific (19.6%) and North America (14.9%) (Filkova et al., 2018; World Bank, 2019). Such financing focuses on returns and scale (Cholibois, 2020), and as such, local needs, especially those of the poor, may not be adequately represented (Manuamorn et al., 2020; Williams, 2020) (*medium confidence).*

COVID-19 will probably affect adaptation financing in water. Countries will be fiscally stretched to finance public investments domestically and through international development aid (Barbier and Burgess, 2020). However, investments in flood and drought management (Phillips et al., 2020) and water and sanitation (Armitage and Nellums, 2020b; Bhowmick et al., 2020) are critical for building resilience against pandemics, and are also crucial elements of adaptation in water. Therefore, integrated approaches that achieve both goals need to be deployed (Barbier and Burgess, 2020; Newell and Dale, 2020) (Box 4.4., Cross-Chapter Box COVID in Chapter 7).

In summary, water garners a significant share of public and private adaptation funds (*high confidence*). However, current COVID-19-related cuts in adaptation financing may further impede developing countries' ability to invest in adequate water adaptation.

4.8.3 Gender, Equity and Social Justice

SR1.5 acknowledged that the adaptive capacity of a population was going to reduce with each degree of warming and that vulnerability to climate change was due to gender, race and level of education, which can compound existing and future vulnerabilities (IPCC, 2018a).

Gender, class, race, age, physical ability and educational level determine access to water and financial and societal resources, potentially adverting climate-induced water hazards, reducing vulnerability and facilitating adaptation. However, insufficient attention has been given to the role of improving equity in access to water (Abedin et al., 2019; Eakin et al., 2020). Not all water adaptation strategies are accessible to the poorest, who may turn to maladaptive strategies if their access to water is negatively affected (Eakin et al., 2016). Consequently, there have been calls for mainstreaming equity considerations into adaptation (Blackburn and Pelling, 2018) (*medium evidence*, *high agreement*). It has been shown that people living in poverty, racial minorities and those ageing are more vulnerable to climate-induced water hazards and that their adaptive capacity is limited (Szewrański et al., 2018; Winsemius et al., 2018; Nyantakyi-Frimpong, 2020; Erwin et al., 2021). Among these categories, gender is the one that has been most analysed in the context of water and climate change.

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, which makes them more vulnerable to climate-related hazards (Caretta and Börjeson, 2015; Djoudi et al., 2016; Sultana, 2018; Yadav and Lal, 2018). In most societies in developing countries, women and girls are in charge of fetching water. The necessity of water collection takes away time from income-generating activities and education (*high confidence*) (Fontana and Elson, 2014; Kookana et al., 2016; Yadav and Lal, 2018). In addition, the distances women and girls would have to walk as a result of growing water scarcity due to climate change may increase (*limited evidence, high confidence*) (Becerra et al., 2016) (Sections 4.3.3, 4.5.3). 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; Sinharoy and Caruso, 2019).

Although women are often depicted as victims of climate change-induced water scarcity (Huynh and Resurreccion, 2014; Djoudi

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et al., 2016; Gonda, 2016; Yadav and Lal, 2018), they are also proactive adaptation actors (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 or generalisable (Carr and Thompson, 2014; Djoudi et al., 2016; Gonda, 2016; Sultana, 2018). Coping responses and adaptation mechanisms to climate change are profoundly gendered. Women and men approach the diversification of agricultural and pastoral livelihoods differently in response to climate change (Caretta and Börjeson, 2015; Kankwamba et al., 2018; Singh et al., 2018; Basupi et al., 2019). For example, reliance on women's self-help groups and associations has proven successful in ensuring women's participation in decision-making in adaptation interventions as a response to climate change-induced shifting precipitation patterns and increasing droughts (Chu, 2017; Mersha and van Laerhoven, 2018; Phuong et al., 2018; Walch, 2019). Studies feature water harvesting, crop diversification, cash transfer programmes and food subsidies as adaptation measures that enhance gender equality. Adaptation to climate change in these instances promoted gender equality because it allowed women to reap the benefits of these new measures in terms of economic and health well-being (Tesfamariam and Hurlbert, 2017; Lindoso et al., 2018; Walch, 2019).

Meanwhile, adaptation interventions such as drip irrigation, the adoption of more labour-intensive crops and livelihood diversification through male out-migration have proven to increase women's burden (Caretta and Börjeson, 2015; Kattumuri et al., 2017). Hence, a lack of gender-sensitive analysis before implementing water management projects can lead to maladaptation and increase gender vulnerability (Phan et al., 2019; Eriksen et al., 2021) (*high confidence)*.

Acknowledging and understanding the implications of climate-related water adaptation policies in terms of equity and justice is a prerequisite for ensuring their legitimacy and inclusiveness and promotes social justice (Carr and Thompson, 2014; Djoudi et al., 2016; Jost et al., 2016; Sultana, 2018). Furthermore, integrating the principle of gender inclusivity in adaptation is morally and ethically appropriate and effective because women hold much of the local and TK in many agricultural communities and can fruitfully provide insights on how to design and implement adaptation responses (Fauconnier et al., 2018; James, 2019).

In summary, there is *high confidence* that the effects of climate change-induced water insecurity are not evenly felt across populations. Particularly vulnerable groups are women, children, disabled and Indigenous Peoples whose ability to access adequate water is limited and varies across race, ethnicity and caste. Equity and justice are central to climate change adaptation and sustainable development, as the world's poorest people and countries feel the adverse impacts of a changing climate most acutely. These groups can become even more vulnerable due to adaptation actions that are not equitable.

4.8.4 Inclusion of Indigenous Knowledge and Local Knowledge

AR5 concluded that there is *robust evidence* that mutual integration and co-production of local, traditional and scientific knowledge increase adaptive capacity and reduce vulnerability (Adger and Pulhin, 2014). SROCC stated with *medium confidence* that IKLK provide context-specific and socioculturally relevant understandings for effective climate change responses and policies (Abram et al., 2019). SRCCL found that IKLK contribute to enhancing resilience against climate change and combating desertification (*medium confidence*). The combination of IKLK with new sustainable land management techniques, SRCCL stated with *high confidence*, can contribute to raising resilience to the challenges of climate change and desertification (Mirzabaev et al., 2019).

There is *high confidence* that adaptation efforts benefit from the inclusion of IKLK (Mustonen et al., 2021). IKLK can inform how climate change impacts and risks are understood and experienced. Holders of IKLK can also help to develop place-based and culturally appropriate adaptation strategies that meet their community's expectations (Comberti et al., 2019; Martinez Moscoso, 2019) (Cross-Chapter Box INDIG in Chapter 18).

There is *high confidence* that genuine partnerships with Indigenous Peoples and local communities can assist in decolonising approaches to freshwater management (Arsenault et al., 2019; Wilson et al., 2019), which recognise the importance of knowledge that is not grounded on the technocratic division between nature and society (Goldman et al., 2018). There is also *high confidence* that Indigenous Peoples-led freshwater management can facilitate culturally inclusive decision-making and collaborative planning processes at the local and national levels (Somerville, 2014; Harmsworth et al., 2016; Parsons et al., 2017). However, market-based models of water rights regimes can impede the ability of Indigenous Peoples to exercise their rights and deploy traditional ecological knowledge regarding freshwater protection (Nursey-Bray and Palmer, 2018) (*medium evidence, high agreement*).

Community-led actions and restoration measures are helping to ameliorate climate impacts and provide 'safe havens' to affected freshwater species (*high confidence*). For example, the Skolt Sámi of Finland have introduced adaptation measures to aid survival of culturally significant Atlantic salmon stocks in the Näätämö watershed. Atlantic salmon had declined as northern pike, which preys on juvenile salmon, expanded its range in response to warmer water temperatures. Indigenous co-management measures included increasing the catch of pike and documenting important sites (such as lost spawning beds) to ensure that ecological restoration encourages further habitat and increased salmon reproduction (Pecl et al., 2017; Mustonen and Feodoroff, 2018).

Community-led applications of IKLK in conjunction with external knowledge and funding can improve water security (*high confidence*). For example, Borana pastoralists in Ethiopia (Iticha and Husen, 2019) and Ati and Suludnon people (Philippines) (Nelson et al., 2019) utilise both IK and technical information for weather forecasting, while Calanguya people (Philippines) collaborated with local government and nongovernmental organisations (NGOs) to diversify crops and protect the watershed (Gabriel and Mangahas, 2017). With assistance from municipalities, Indigenous Peoples are rehabilitating springs and traditional water wells in Bangladesh hill tracts (Sultana et al., 2019) and Micronesia (McLeod et al., 2019). In response to changing cryospheric conditions in the Peruvian Andes, indigenous Quechua farmers use IK and technical information in community-led research to preserve biocultural knowledge and emblematic crops (Sayre et al., 2017). In Galena, Alaska (USA), a flood-preparedness and response programme has benefitted from the long-term cooperation between emergency management and tribal officials (Kontar et al., 2015) (12.5.3.2 Main concepts and approaches). IKLK can enhance the visibility of Indigenous Peoples and local communities that are excluded from official decision-making processes. In southwest Burkina Faso, for example, Indigenous Peoples are using IKLK to balance (and sometimes resist) official technical estimates of water availability, which enhances their political visibility and enables them to address water scarcity (Roncoli et al., 2019).

There are structural and institutional challenges in knowledge co-production between holders of IKLK and 'technical' knowledge. These challenges include issues of water rights, language, extractive research practices (Ford et al., 2016; Simms et al., 2016; Stefanelli et al., 2017; Arsenault et al., 2019) and colonial uses of IKLK (Castleden et al., 2017), which can produce distrust among holders of IKLK (David-Chavez and Gavin, 2018). In addition, some IK is sacred and cannot be shared with outsiders (Sanderson et al., 2015).

In summary, IKLK are dynamic and have developed over time to adapt to climate and environmental change in culturally specific and place-based ways (*high confidence*). Ethical co-production between holders of IKLK and technical knowledge is a key enabling condition for successful adaptation measures and strategies pertaining to water security, as well as other areas (*medium evidence, high agreement*). Knowledge co-production is a vital and developing approach to the water-related impacts of climate change that recognises the culture, agency and concerns of Indigenous Peoples and local communities. It is critical to developing effective, equitable and meaningful strategies for addressing the water-related impacts of global warming (Cross-Chapter Box INDIG in Chapter 18).

4.8.5 Participative, Cooperative and Bottom-Up Engagement

Participation, cooperation and bottom-up engagement are critical to optimal adaptation (*medium evidence*, *high agreement*). There is *high confidence* that many of the countries and social groups most threatened by climate change have contributed the least to global emissions and do not have not the 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*).

There is *medium evidence* and *high agreement* that optimal adaptation depends critically on inter-state cooperation (Banda, 2018), which in turn requires trust and norms of reciprocity among all those involved (Ostrom, 2014). Reciprocity is central 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 Oppenheimer, 2016). Indeed, cooperation at the international level is less probable to occur if participants do not trust each other (Hamilton and Lubell, 2018). In climate-related water adaptation, transboundary cooperation is essential, as 60% of global freshwater resources contained in 276 river and lake basins are shared between countries (Timmerman et al., 2017). Yet, more than 50% of the world's 310 international river basins lack any type of cooperative framework (McCracken and Meyer, 2018).

SDG6 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 and national water policy and law (McCracken and Meyer, 2018) and possibly help build an environment of trust among riparian states. Moreover, although the 2030 Agenda for Sustainable Development (A/RES/70/1) makes it clear that without the participation of local communities (e.g., SDG6, Target 6b) 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 participation, 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 affected by climate change—including women and Indigenous Peoples—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). Moreover, incentives for bottom-up and participative decision-making in the water sector can facilitate effective stakeholder engagement (OECD, 2015), which helps build public confidence and trust in water governance.

4.8.6 Polycentric Water Governance

SR1.5 concluded with *high confidence* that cooperation and coordinated actions at various governance levels are vital to ensuring participation, transparency, capacity building and learning among different actors (IPCC, 2018a). According to SRCCL, adaptive governance builds on multi-level and polycentric governance (Hurlbert et al., 2019), where efforts taken by multiple actors across different scales provide learning opportunities for all (Hurlbert, 2018).

Polycentrism is characterised by the absence of a unique centre of authority. Therefore, the legitimacy of the decisions taken by multiple decision-makers at different levels of water governance derives from the perceived fairness of the decision-making process (Baldwin et al., 2018) and the inclusion of women, Indigenous Peoples and young people (Iza, 2019) (*medium confidence*). Evidence-based approaches can also enhance the legitimacy of polycentric governance (Boelens et al., 2015; Arriagada et al., 2018) by generating knowledge to support localised and multi-leveled decision-making, as in the case of water user communities in Peru (Buytaert et al., 2014; Buytaert et al., 2016).

The advantages of polycentric approaches to climate governance include improved communication, inclusiveness, consensus and better outcomes (Ostrom, 2014; Cole, 2015; Keohane and Victor, 2016; Morrison et al., 2017; Tormos-Aponte and García-López, 2018) (*high* *agreement*). However, polycentric governance systems require cross-scale information sharing, coordination and democratic participation to work appropriately (Pahl-Wostl and Knieper, 2014; Carlisle and Gruby, 2017; Morrison et al., 2017; Biesbroek and Lesnikowski, 2018; Frey et al., 2021) (*high confidence*). For example, efficient information sharing has been necessary to implement groundwater governance in transboundary contexts (Albrecht et al., 2017).

Empirical studies that examined the potential of polycentric governance to address water challenges in the face of climate change showed that polycentrism could encourage and support participatory, decentralised and deliberative adaptation. These, in turn, can produce better environmental outcomes and improve water governance outcomes (*high confidence*). Polycentric water governance can be an effective enabler for adaptation when it ensures interconnectedness with multiple public and private actors across the different sectors (e.g., irrigation users, domestic users, industrial users, watershed institutions, etc.) and across different levels (e.g., local, regional and national governments) to help come up with well-coordinated water adaptation responses (*high confidence*) (Pahl-Wostl and Knieper, 2014; McCord et al., 2017; Baldwin et al., 2018; Hamilton and Lubell, 2018; Kellner et al., 2019).

Questions remain about the extent to which polycentrism can result in either greater climate justice or exacerbate existing inequalities due, for example, to existing power inequalities which may affect the performance and effectiveness of a polycentric system (Pahl-Wostl and Knieper, 2014; Morrison et al., 2017; Hamilton and Lubell, 2018; Okereke, 2018). For instance, historical inequities and injustices due to settler colonialism and top-down water policies, governance and laws (Collins et al., 2017; Arsenault et al., 2018; Johnson et al., 2018; Robison et al., 2018) have resulted in long-term water insecurity in many indigenous communities in North America (Simms et al., 2016; Medeiros et al., 2017; Conroy-Ben and Richard, 2018; Diver, 2018; Emanuel, 2018) (*high confidence*) (Section 4.6.9). Additionally, studies highlight that power dynamics can undermine the success of those initiatives. For example, in the Sao Paulo water crisis, polycentric governance did not fully realise its potential when it was guided by authoritarian governance favouring political interests over social, territorial and environmental justice (Frey et al., 2021). Likewise, in the Thau basin (France), the most important and influential actors shaped policy measures in response to climate change, thus limiting the potential for radical changes in water use (Aubin et al., 2019).

In summary, polycentric governance can enable improved water governance and effective climate change adaptation (*medium confidence*). However, it can also exacerbate existing inequalities as long as less powerful actors, such as women, Indigenous Peoples and young people, are not adequately involved in the decision-making process (*high confidence*).

4.8.7 Strong Political Support

According to AR5 (Jiménez Cisneros et al., 2014), barriers to adaptation in the water sector include lack of institutional capacity, which, together with political support, constitutes one of the feasibility dimensions towards limiting global warming to 1.5°C (de Coninck et al., 2018). As the IPCC SROCC (IPCC, 2019a) and SRCCL (Shukla et al., 2019) suggest, limited institutional support can challenge adaptation efforts in water management.

Climate adaptation planning approaches can be constrained by several economic, institutional, developmental and political barriers (Anguelovski et al., 2014; Eisenack et al., 2014), including strong political support, that is, the lack of collective willingness to take action. Despite the ongoing accumulation of scientific evidence as to the seriousness of the impact of climate change on water resources, state action has not always been effective. There are now a rising number of case laws addressing the state's failure to implement adaptation policies and resultant climate change litigation (Setzer and Vanhala, 2019; Peel and Osofsky, 2020), including in the water sector, as in the leading case Leghari v Federation of Pakistan (2015 WP. No. 25501/201), in which a farmer sued the national government for failure to carry out national climate change policies impacting on the constitutional right to life (Preston, 2016).

The 2015 Paris Agreement made a significant impact on the status quo, with almost all the countries agreeing to limit global warming to 2°C or less. The preparation of NDCs under the Paris Agreement contributed positively to national climate policies and helped focus on the centrality of water in adaptation planning (Röser et al., 2020). In total, 92% of countries that mention adaptation in NDCs also include water (GWP, 2018). Low-income countries make specific reference to rain-fed or irrigated agriculture and livestock. In contrast, middle- and high-income countries include developing management, governance mechanisms and increased disaster risk reduction in their NDC pledges (GWP, 2018). Floods were the critical climate hazards identified in the adaptation components of NDCs, followed by droughts (85 out of 137 countries for floods and 80 out of 137 for drought). Also, the water sector was identified as the top priority sector for adaptation actions in the NDCs for 118 out of 137 countries, followed closely by the agricultural sector with 100 out 137 (GWP, 2018) based on data from UNFCCC (2017). Many developing countries have included quantitative targets for adaptation in the water sector (Pauw et al., 2018). Similarly, water-related impacts and adaptation often feature prominently in NAPs (DEFRA, 2018).

Evidence suggests that adaptation failure in the water sector is due to policy and regulatory failures (Keohane and Victor, 2016; Oberlack and Eisenack, 2018; Javeline et al., 2019), reflecting political myopia (Muller, 2018; Empinotti et al., 2019; Pralle, 2019) (*high confidence*).

International donors and supranational/transnational legislation (e.g., EU law) can support the capacity of national and sub-national governments to act and remove possible barriers to the effective implementation of climate change adaptation policies in the water sector, including obstacles posed due to lack of financial support for the developing countries (Massey et al., 2014; Tilleard and Ford, 2016; Biesbroek et al., 2018; Rahman and Tosun, 2018) (*medium confidence*).

Frequently Asked Questions

FAQ 4.1 | What is water security, and how will climate change affect it?

Water is essential for all societal and ecosystems needs. Water security is multi-dimensional and not just about water availability. Water needs to be available in sufficient quantity and quality and needs to be accessible in an acceptable form. Accordingly, a situation of water security indicates the availability and accessibility of sufficient clean water to allow a population to sustainably ensure its livelihoods, health, socioeconomic development and political stability. Many socioeconomic factors, such as population growth and food consumption patterns, play an important role in determining water security. Still, climate change is increasingly shown to be an important contributor to water insecurity worldwide, with some regions more at risk than others.

Climate change can affect these different dimensions of water security in different ways. Most directly, climate change is affecting the overall availability of water across regions and during important seasons. More extended periods of dry spells and droughts are already affecting water availability, especially in the arid areas of India, China, the USA and Africa. Other extremes, such as heavy precipitation and flooding, can affect water quality, making water unsafe for drinking, for example. In coastal regions and small islands, the combined effects of higher sea levels and more intense storms affect water security by increasing the salinisation of groundwater resources. Indirect effects of climate change on water security include impacts on infrastructure for the provision and recovery of water resources, which can affect the safe access to adequate water resources, both in terms of quality and quantity.

In terms of assessing the extent of water scarcity, studies estimate that currently, between 1.5 and 2.5 billion people live within areas exposed to water scarcity globally. These numbers are projected to increase continuously, with estimates of up to 3 billion at 2°C and up to 4 billion at 4°C by 2050. Many socioeconomic factors, such as population growth and food consumption patterns, determine water scarcity. Still, climate is increasingly shown to be an important component that drives scarcity across the world. Water scarcity is often a seasonal occurrence, and climate change is projected to increase seasonal extremes. Often, consecutive years with drier conditions lead to a long-term decrease in groundwater tables, affecting water availability directly and soil moisture in the longer term.

As an essential component of water security, climate change will affect water quality in different ways. Drier conditions lead to a reduction in water availability, causing a potential increase in the concentration of contaminants. Increasing runoff and floods can wash pollutants into water bodies. With climate change projected to increase the variability of rain over space and time, such impacts on water quality are becoming increasingly likely. Higher temperatures add to deteriorating water quality by reducing oxygen levels.

Another critical component to ensure secure access to water resources is adequate water infrastructure for access, disposal and sanitation. Unfortunately, increasing extremes due to climate change, especially floods and increasing storm activity, have great potential to damage such infrastructure, especially in developing world regions, where infrastructure is much more susceptible to damage and pollution.

There are substantial differences in the distribution of risks across regions, with some areas facing a much higher risk burden than others. Also, projections of the potential impacts of climate change on water security vary across regions. However, patterns of projected water-related extremes are emerging more clearly globally with increasing confidence.

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Frequently Asked Questions

FAQ 4.2 | Which places are becoming wetter and which are becoming drier, and what risks do these bring to people?

Due to climate change, substantial numbers of people are now living in climates with average precipitation levels significantly different to the average over the 20th century. Nearly half a billion people are living in unfamiliar wet conditions, mostly in mid- and high latitudes, and over 160 million people are living in unfamiliar dry conditions, mostly in the tropics and subtropics. In addition to changes in average precipitation, precipitation patterns over time are also changing, as well as river flows. Societal impacts and increased risks from both wetter and drier conditions are starting to emerge.

Some parts of the world are becoming wetter, and some are becoming drier, in terms of either changes in precipitation and/or the water available in the soil, in rivers or underground. Soil moisture, river water and groundwater are affected by changes in precipitation and also by changes in evaporation, which is affected by temperature and by uptake by vegetation.

All these factors are affected by climate change. Rising temperatures drive higher evaporation, which dries the landscape, although this can be offset in some areas by reduced uptake of water from the soil by plants in response to rising CO_2 concentrations. A warming climate brings more precipitation overall, although changes in global wind patterns mean that some areas are seeing less precipitation.

As a result, substantial numbers of people are now living in climates with average precipitation levels significantly different to the average over the 20th century. Nearly half a billion people are living in unfamiliar wet conditions, mostly in mid- and high latitudes, and over 160 million in unfamiliar dry conditions, mostly in the tropics and subtropics (Figure FAQ4.2.1).

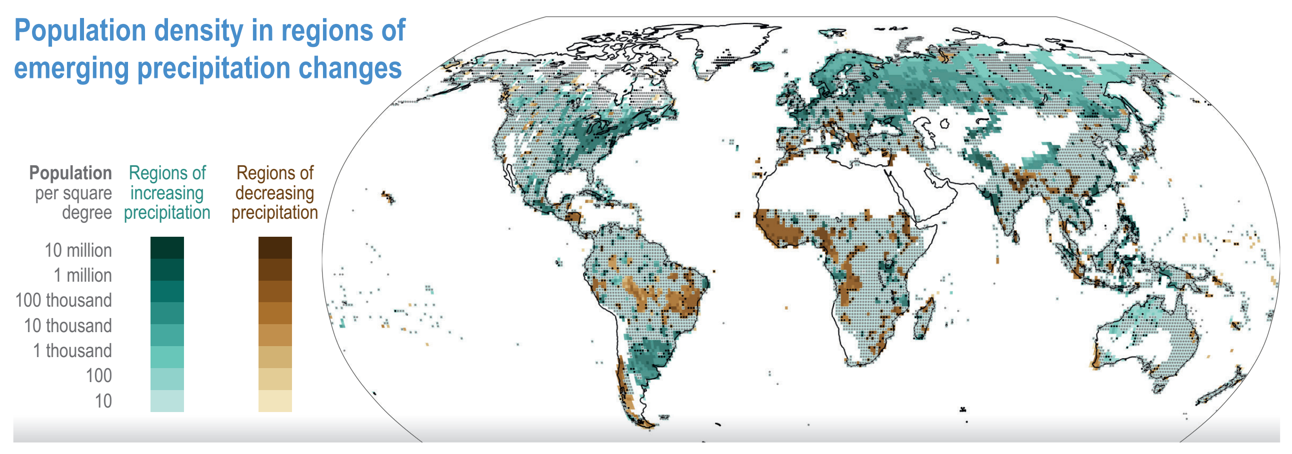

Figure FAQ4.2.1 | Numbers of people seeing increases and decreases in precipitation.

In addition to changes in average precipitation, the patterns over time are also changing, such as the length of dry spells and the amount of precipitation falling in heavy events. Again, these changes vary across the world due to shifting wind patterns. Approximately 600 million people live in places with longer dry spells than in the 1950s, mostly in West Africa, south Asia and parts of South America. Approximately 360 million people experience shorter dry spells, in North America, northern Asia and other parts of South America.

In contrast, far more people (about 600 million people) are seeing heavier precipitation than less heavy precipitation (80 million). A more widespread increase in heavy precipitation is expected in a warming world, where the warmer atmosphere takes up more moisture and hotter ground drives more intense storms.

River flows are also changing in many parts of the world, often due to changes in precipitation, although direct human impacts are also important. Generally, the most widespread increased river flows are seen in high latitudes, while decreasing flows are seen in mid- and low latitudes, although there are major exceptions to these trends and data is sparse in many regions (Figure FAQ4.2.2).

FAQ 4.2 (continued)

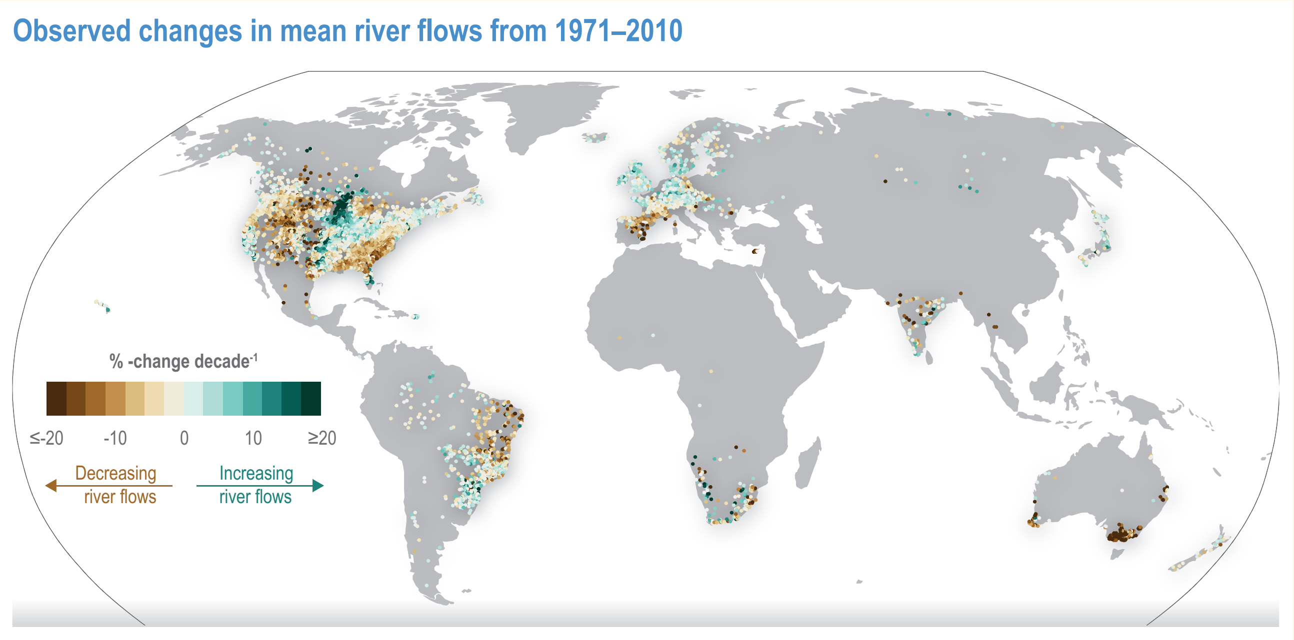

Figure FAQ4.2.2 | Observed changes in mean river flows from 1971 to 2010

Some of these changes are starting to have impacts on society. For example, increasing rainfall in the USA has led to increased crop yields. Heavy rainfall and long periods of rainfall lead to flooding, causing deaths, injuries, infrastructural damage, spread of disease, disruptions to employment and education, psychological trauma and territorial displacement. The weather conditions associated with many recent major flooding events were made *more likely* by climate change, although non-climatic factors remain the dominant driver of increased flooding.

Drier soils have made heatwaves more severe. A drying of the landscape has increased the length of the fire season across much of the world, contributing to unprecedented severity of wildfires in recent years. In recent years, several major drought events with impacts on agriculture were made *more likely* by climate change.

Overall, the general picture is of increased average precipitation and/or longer periods of precipitation in the mid and high latitudes, but decreased precipitation and/or longer times between precipitation across much of the tropics and subtropics. Where heavy precipitation is changing, this is mostly towards increasing intensity. Societal impacts and increased risks from both wetter and drier conditions are starting to emerge.

Frequently Asked Questions

FAQ 4.3 | How will climate change impact the severity of water-related disasters, such as droughts and floods?

Climate change will lead to populations becoming more vulnerable to floods and droughts due to an increase in the frequency, magnitude and total area affected by water-related disasters. Floods and droughts will also affect more people in the course of this century as a result of population growth and increased urbanisation, especially if warming cannot be limited to 1.5°C. The impact of floods and droughts are expected to increase across all economic sectors, resulting in negative outcomes for the global production of goods and services, industry output, employment, trade and household consumption. Floods will pose additional risks to people's lives and health through inundation, facilitating the further spread of waterborne diseases. At the same time, droughts can have adverse health impacts due to the limited availability of food and water for drinking and hygienic purposes. All losses, both in terms of lives and in economic terms, will be more limited in a 1.5°C than in a 3°C warmer world.

Anthropogenic land use changes and climate change will exacerbate the intensity, frequency and spatial extent of floods and droughts, leading to populations becoming more vulnerable. According to projections, these increases

FAQ 4.3 (continued)

in extreme events will be more significant with higher levels of global warming. However, the location and severity of floods and droughts are context-dependent and complex phenomena.

The processes that lead to droughts include lack of or less frequent precipitation, increased evapotranspiration and decreased soil moisture, snow cover, runoff and streamflow. For example, warming temperatures may result in higher evapotranspiration, in turn leading to drier soils. In addition, reduced soil moisture diminishes the amount of water filtering into rivers in both the short and long term while also increasing the aridity that can foster the conditions for fire. Moreover, decreased snow cover represents less runoff supply to downstream areas during warmer seasons. Depending on this process and the propagation of a meteorological drought onto further systems, a drought can be defined as hydrological, agricultural or ecological. Agricultural drought threatens food production through crop damage and yield decreases, and consequent economic impacts, and therefore, can be the most impactful to humans. Geographically, the likelihood of agricultural drought is projected to increase across most of southern Africa, Australia, the majority of Europe, the southern and western USA, Central America and the Caribbean, northwest China, parts of South America, and the Russian Federation; but due to increased precipitation, it is projected to decline in southeastern South America, central Africa, central Canada, western India and the south of the Arabian Peninsula.

Flood hazard natural processes usually result from increases in heavy precipitation events, but they can also be caused by saturated soils, increased runoff and land use changes. A warming climate usually causes greater energy for the intense upward motion for storm formation and increases evapotranspiration, which leads to heavier precipitation. Many places around the world will experience more-than-average rainfall, which may increase soil moisture. Wetter soils saturate faster during precipitation events, resulting in increased runoff that can muddy the waters and lead to floods. Anthropogenic land use changes, such as urbanisation, deforestation, grasslands and agricultural extension, can also reduce the amount of water infiltrating the soil and leading to frequent flooding. Floods are expected to increase in Asia, the USA and Europe, particularly in areas dependent on glacier water where melting will lead to earlier spring floods. Additionally, fluvial floods are projected to be more frequent in some regions in central Africa and northern high latitudes and less frequent in the southern areas of North America, southern South America, the Mediterranean, parts of Australia and southern parts of Europe.

Globally, socioeconomic development will lead to heightened societal hazards. Due to population growth and increased urbanisation, floods and droughts will affect more people in the course of this century, especially if warming cannot be limited to 1.5°C. All losses, both in lives and in economic terms, will be more limited in a 1.5°C than in a 3°C warmer world. The impacts of floods and droughts are expected to increase across all economic sectors, from agriculture to energy production, resulting in negative outcomes for our global production of goods and services, industry output, employment, trade and household consumption. Landslides, sinkholes and avalanches arising from heavy rainfall events will increasingly threaten infrastructure and agricultural production. In cities, increased flood frequency could disrupt waste management systems, resulting in the clogging of waterways. In addition, unprecedented flood magnitudes could overwhelm hydraulic infrastructure, affecting the energy, industry and transportation sectors. An expansion in inundation area, coupled with urban sprawl, would increase flood damage. Floods will pose additional risks to people's lives and health through inundation, thus facilitating the spread of waterborne diseases. At the same time, drought can have adverse health impacts due to the limited availability of food and water for drinking and hygienic purposes. Although there are no agreed-upon projections for migration and displacement due to water-related disasters, it is known that drought and desertification cause harvest failures, which may lead subsistence farmers to relocate to urban areas. Whether temporary or permanent, displacement is often mired with diminished safety, loss of social ties, and a weakened sense of place and cultural identity.

Finally, vulnerable groups such as people living in poverty, women, children, Indigenous Peoples, uninsured workers and the elderly will be the most affected by water-related disasters.

Frequently Asked Questions

FAQ 4.4 | Globally, agriculture is the largest user of water. How will climate change impact this sector, and how can farmers adapt to these changes?

Climate-induced changes in the global hydrological cycle are already impacting agriculture through floods, droughts and increased rainfall variability, which have affected yields of major crops such as maize, soybeans, rice and wheat. These changes are projected to continue in a warmer world, which will cause yields of rain-fed crops to decline and reduce the amount of water available for irrigation in water-stressed regions. Farmers already use adaptation and coping strategies to manage agricultural water use. Some of the most important adaptation responses are the application of irrigation, on-farm water and soil conservation; changing cropping patterns; adopting improved cultivars; and improved agronomic practices. In many parts of the world, farmers increasingly use Indigenous knowledge and local knowledge to inform their decisions of what to grow, when to grow and how much to irrigate. To offset the risks of market-related volatility coupled with climate change, farmers also adopt economic and financial instruments such as index-based crop insurance. Training and capacity-building programmes and social safety nets are other forms of adaptation that farmers are using to respond to these changes.

Worldwide, and especially in developing countries, agriculture (including crop cultivation and livestock and fisheries) is the largest water user, accounting for 50–90% of all water use. Moreover, a substantial part of the water used in agriculture is 'consumptive' use, which means that the water is 'consumed' for crop growth and is not immediately available for other uses. This is different from other sectors, such as energy production, where only a fraction of the water is consumed, and other downstream users can reuse the rest. Agriculture also accounts for a large share of employment in developing countries, with 60–80% of the rural population dependent on agriculture for their livelihoods. Agriculture provides food security for all. This makes farmers and agriculture particularly vulnerable to climate change.

Climate-induced changes in the global hydrological cycle are already impacting agriculture through floods, droughts and increased rainfall variability. For example, loss in yields has been reported for major crops such as maize (by 4.1%), soybeans (by 4.5%), rice (by 1.8%) and wheat (by 1.8%) due to changes in precipitation between 1981 and 2010. In addition, drought has affected both the area under cultivation and the yields of major crops. According to one estimate, globally, there has been a loss of 9–10% of total cereal production due to droughts and other weather extremes. Similarly, floods are one of the significant reasons for crop losses worldwide. Climate change-induced losses in livestock and fisheries have also been documented. In some parts of the world, especially in cold temperate zones, agro-climatic zones have become more conducive to yield growth in crops like maize and soybean due to increases in summer precipitation. Yet, negative impacts far outweigh positive impacts.

Projected impacts on agriculture due to changes in water availability are also severe. For example, yields of rain-fed crops such as maize are projected to decline by one fifth to one third by the end of the century. In contrast, many areas which currently support multiple crops may become unsuitable for rain-fed farming or support only one crop in a year. Irrigation, which is often one of the most effective adaptive strategies against water-induced stress, is also projected to be affected by a reduction of the amount of water available for irrigation in some parts of the world that are already water-stressed or as a result of groundwater depletion in places such as India, North China and the northwestern USA. Overall, future droughts and floods will pose a major risk to food security, and agriculture and impacts will be more severe on countries and communities that are already food insecure.

Given that farmers are already dealing with variability in the amount and timing of rainfall. In many places, demand for agricultural water is greater than supply, and farmers are using many adaptations and coping strategies to meet water demands for their crops, fish and livestock. Some of the most popular adaptation responses around crops and water include:

- changing cropping patterns to less water-intensive crops, and changes in the timing of sowing and harvesting to respond to unfamiliar trends in the onset of rains
- adoption of improved cultivars, such as drought and flood-resistant seed varieties
- improved agronomic practices, including conservation agriculture that helps reduce water application rates
- irrigation and water-saving technologies such as efficient irrigation and on-farm water management techniques
- on-farm water and soil moisture conservation

Most of these measures are beneficial across multiple indicators (water saving, increased incomes, etc.); however, whether they also reduce climate-related risks is not well understood and remains a knowledge gap. Irrigation and changes in crop choices and cultivars are also shown to be effective for future adaptation, especially at 1.5°C global warming, but much less effective at 2°C and 3°C when these responses will not mitigate a large part of the climate risk. Most of these

FAQ 4.4 (continued)

adaptation measures mentioned above are autonomous. However, some, such as improved seeds and cultivars, are supported by national agricultural research agencies, international research coalitions such as the CGIAR [Consultative Group on International Agricultural Research], and private seed companies. In many parts of the world, farmers are also increasingly using IKLK to inform these decisions of what to grow, when to grow and how much to irrigate.

Figure FAQ4.4.1 | Water-related adaptation responses in agriculture sector: benefits, co-benefits with mitigation, and possible maladaptation

FAQ 4.4 (continued)

Given the predominance of market economies worldwide, most farmers also depend on the market to sell their produce, and market fluctuations affect their incomes. In addition, market-related volatility coupled with climate change is a source of increased risk for farmers. Several economic and financial instruments are being used with varying levels of success to offset some of these interlinked impacts. Index-based crop insurance is one such instrument that compensates farmers for losing crops due to hazards such as floods and droughts. However, several limitations in their implementation remain.

In cases of severe droughts and floods, which have debilitating impacts on already poor and vulnerable populations, national governments provide social safety programmes, such as food or cash-for-work programmes, which are shown to be successful in reducing risks for the most vulnerable people, even though there are often concerns with targeting efficiency. Providing training and capacity building of farmers to adopt new farming practices and technologies to manage risk better are also known to be effective when the training is conceptualised, targeted and implemented in consultation with farmers. Planned adaptation practices include managing weather and market risks through insurance products, social safety nets for vulnerable populations, and providing the right mix of training and capacity building. These adaptation practices are generally implemented by civil society, governments and the private sector.

Frequently Asked Questions

FAQ 4.5 | Which principles can communities implement to sustainably adapt to the ways that climate change is impacting their water security?

For communities to sustainably adapt to climate impacts on water security, their participation, cooperation and bottom-up engagement are critical in all stages of decision-making processes. In addition to enhancing the legitimacy of the decision-making process, the community's involvement can increase the equitability and effectiveness of the adaptation approach. As water insecurity disproportionately affects marginalised social groups, their participation in water governance and implementation can help improve their water security. Combining and integrating local, indigenous and traditional ecological knowledge with Western understandings of climate change can enhance the effectiveness of adaptation measures and strategies while ensuring that the adaptation is equitable and just. Improving water security is fundamental to achieving many of the 17 Sustainable Development Goals (SDGs).

For decades, communities worldwide have already been adapting to climate change-induced hydrological changes to maintain their livelihood and safety. Adaptation is a multi-faceted process that is implemented differently depending on the sector affected by changes in the hydrological cycle and the region where these changes happen. For instance, farmers in the semiarid areas might adapt to changing rain patterns through irrigation (see also FAQ4.4). At the same time, urban dwellers can adopt measures such as rainwater harvesting and other nature-based solutions. Several principles have been documented as crucial for achieving sustainable adaptation as they support communities in becoming more resilient to climate change. However, these principles can be implemented singularly or in tandem, and it is essential to acknowledge that long-term adaptation success is context-specific. Therefore, it is critical to involve local communities in co-designing effective adaptation responses.

For communities to sustainably adapt to climate impacts on water security, participation, cooperation and bottom-up engagement are critical in all stages of the decision-making processes, from planning to full implementation. Many of the countries and social groups most threatened by climate change have contributed least to global warming and do not have access to adequate resources to adapt. Effective participation of these actors in water-related climate change adaptation planning can contribute to more equitable adaptation actions. The involvement of the most vulnerable in the design of adaptation responses makes it more probable that these solutions will suit their needs and have therefore a higher chance of being effective. Accessible, inclusive and well-coordinated efforts to enhance water security will improve the legitimacy of water governance and work synergistically with reducing inequalities (UN SDG, SDG 10) and encouraging more sustainable communities (SDG 11). Communities can also be involved in sector-specific adaptation responses. These are often water-related and help ensure that climate action (SDG 13) is well aligned with clean water and sanitation (SGD 6).

FAQ 4.5 (continued)

The participation of traditionally excluded groups such as women and marginalised communities and Indigenous Peoples and ethnic minorities contributes to more equitable and socially just adaptation actions. Water insecurity disproportionately affects these marginalised groups, and their participation in water governance and implementation can help alleviate this burden.

Recognising the importance of Indigenous knowledge and local knowledge in improving water security is vital to ensuring that decisions and solutions align with the interests of Indigenous Peoples and local peoples and benefit their communities culturally and economically. Furthermore, the effectiveness of adaptation measures and strategies improves when Indigenous knowledge and local knowledge and traditional ecological knowledge are combined and integrated with technical understandings of climate change.

The climate adaptation plans led by national governments and local authorities will only be accepted and adequately implemented when supported by the community. Therefore, strong political and societal support is necessary to ensure effective policy changes, whether local or national. Significantly, access to financial assistance from private and public sources expands the range of strategies that communities can consider for enhancing their water security.

These principles are also conducive to the achievement of the United Nations SDGs. Actions that reduce climate risk and enhance water security can positively interact with sustainable development objectives (synergies). Therefore, improving water security is fundamental to achieving many of the 17 SDGs.

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