Stop Floating, Start Swimming

Water and climate change – interlinkages and prospects for future action

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

PIK Potsdam Institute for Climate Impact Research

adelphi

Imprint

As a federally owned enterprise, GIZ supports the German Government in achieving its objectives in the field of international cooperation for sustainable development.

Published by:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices:
Bonn and Eschborn, Germany

Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66
E info@giz.de
I www.giz.de

Sector Programme Water Policy

Contact:
Marcel Servos (GIZ)
I wasserpolitik@giz.de

Authors:
Martin Kerres (GIZ), Marcel Servos (GIZ), Annika Kramer (adelphi), Fred Hattermann (PIK), Dennis Tänzler (adelphi), Tobias Pilz (PIK) and André Mueller (adelphi)

Acknowledgement for Inputs and Review:
Dipankar Aich, Franziska Wende, Frederik Pischke, Jens Hönerhoff, John Matthews, Josef Haider, Kartik Chandran, Maggie White, Michael Schwab, Yong Yian, Mathias Bertram, Hanna Swartzendruber as well as GIZ sector programmes on water, sanitation and climate change, WaCCliM and EbA programs and the sectoral department (FMB).

Design/layout:
creative republic, Thomas Maxeiner Visual Communications, Frankfurt / Germany

Illustration credits:
© shutterstock/Ryger, Melok, Yuravector and Bunyakina Nadya
© Studio Grafico, Berlin

On behalf of
German Federal Ministry for Economic Cooperation and Development (BMZ)

Division 103 – Water-, Sanitation- and Hygiene Management
(previously Division 413 – Water, Urban Development, Mobility)

GIZ is responsible for the content of this publication.

Printed on 100% recycled paper

Printing and distribution:
Braun & Sohn Druckerei GmbH & Co. KG, Maintal

Status:
Bonn, August 2020

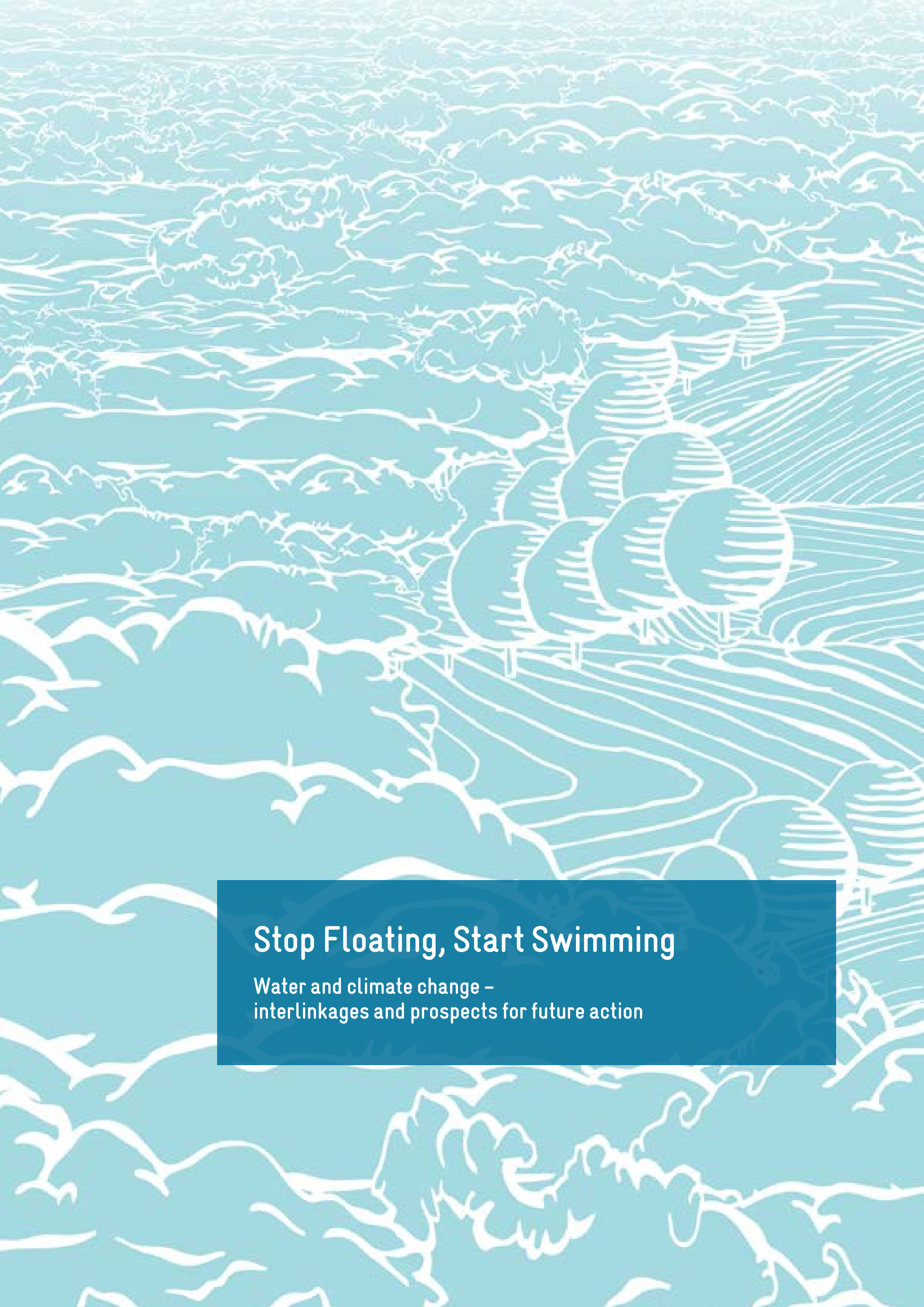
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

On behalf of

Federal Ministry for Economic Cooperation and Development

PIK Potsdam Institute for Climate Impact Research

adelphi



Stop Floating, Start Swimming

Water and climate change – interlinkages and prospects for future action

Contents

List of Figures

List of Tables

List of Abbreviations

a	Annum
AfDB	African Development Bank
AR5	IPCC's Fifth Assessment Report
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMZ	Federal Ministry for Economic Cooperation and Development
CMIP5	Coupled Model Intercomparison Project, Phase 5
COP	Conference of the Parties
CRIDF	Climate Resilient Infrastructure Development Facility
DFID	Department for International Development
DRR	Disaster Risk Reduction
EbA	Ecosystem-based Adaptation
EbM	Ecosystem-based Mitigation
ENSO	El Niño Southern Oscillation
FIB	Forest Investment Fund
GCF	Green Climate Fund
GCM	Global Climate Model
GEF	Global Environment Facility
GERD	Grand Ethiopian Renaissance Dam
GHG	Greenhouse Gases
GHM	Global Hydrological Model
GIDRM	Global Initiative on Disaster Risk Management
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GPD	Global Peatland Database
GWP	Global Water Partnership
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
IWRM	Integrated Water Resources Management
LDC	Least Developed Countries
LEDS	Low Emission Development Strategy
MAR	Managed Aquifer Recharge
N	Nitrogen
NAP	National Adaptation Plan

NAPA	National Adaptation Programme of Action
NBA	Niger Basin Authority
NBI	Nile Basin Initiative
NbS	Nature-based Solutions
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
PIK	Potsdam Institute for Climate Impact Research
RBO	River Basin Organisation
RCP	Representative Concentration Pathway
RHM	Regional Hydrological Model
SAMS	South American Monsoon System
SDGs	Sustainable Development Goals
SSP	Shared Socioeconomic Pathway
TEM-A	Technical Expert Meetings on Adaptation
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organisation
WWF	World Wide Fund for Nature

Executive Summary

Climate change matters to the water cycle – Impacts vary from one region to another, but we often do not know exactly how.

Even small changes in climate can have significant impacts on water availability and extreme events, such as droughts and floods. The water cycle is an essential part of the climate system, and therefore acutely sensitive to climate change and climate variability. Empirical evidence shows that insignificant climate variations can cause significant changes in hydrological flows and water availability. For instance, a global temperature rise of 2°C could increase the number of people suffering from absolute water scarcity by an additional 40%, compared to the effects of population growth alone. Groundwater is particularly affected by droughts, since only precipitation that has not evaporated or drained off reaches deeper layers.

It is imperative to take a closer look at the regional and local levels. In West Africa, for instance, with its main Niger river basin, and in the Upper Amazon region, uncertainty in annual precipitation projections is very high, but there are strong indications that climate variability (more heavy rainfall, but longer dry spells) and seasonal shifts differ in both basins. This means that, even in a wetter climate, there can be more droughts, and that measures to counteract droughts are beneficial, regardless of the direction in general precipitation trends. Droughts are also expected to become more severe in the Limpopo and Tagus basins. Meanwhile, the Blue Nile and Ganges are projected to face increased flood risks.

In some regions, it remains unclear how climate change will impact the water cycle. Overall, climate change adds another element to existing pressures on water resources for drinking, energy, and food. These include population growth and mobility, economic development, international trade, urbanisation, diversifying diets, and cultural and technological change. It is often impossible to specifically tie certain phenomena to one of these pressures. Trends in annual precipitation are highly uncertain in many regions, for example in large parts of the sub-tropics, where many Least Developed Countries are located. In fact, in only about two-thirds of the world's land surface area, at least 80% of climate projections agree on the general trend in precipitation under a high emission concentration pathway. Hydrological model uncertainty decreases once regional models consider catchment-specific characteristics. Some uncertainties will, however, inevitably remain.

Concrete approaches and next steps for water action:

- Maintain and improve hydro-meteorological monitoring stations and information systems, including capacities for transparent analysis and reporting in order to improve long-term weather and climate observations.

- Register, connect and integrate data and information from in situ measurements and remote sensing, as well as socio-economic data including land use and population growth.

- Enhance (coupled) climate and hydrology assessment and modelling capacities including on groundwater in order to improve climate projections and impact scenarios.

Water provides solutions for dealing with uncertainties, e.g. through resilient water infrastructure and robust and flexible storage solutions.

The water sector is the most essential sector for improving the climate resilience of communities and ecosystems. Seeing as the impacts of climate change directly affect water resources, actions in the water sector are crucial for dealing with them. With regard to increasing water scarcity due to climate change, climate action in the water sector includes water demand management, reduction of water losses, and reuse of treated wastewater, to name merely a few approaches. Enhancing climate resilience in the water sector often goes hand-in-hand with potential co-benefits concerning mitigation of greenhouse gases (GHG), sustainable development, and protection of ecosystems including their biodiversity. Water-related climate impacts also affect other sectors, such as agriculture (e.g. impacts on irrigation) and energy (e.g. cooling water), calling for a Water, Energy, Food Security Nexus approach. Water management needs to build on thorough climate risk assessments and factor in multiple uncertainties. The impacts of climate change have been mainstreamed into water planning processes. Today, comprehensive environment and climate risk analyses are required for project planning and design in most development agencies. Tools are also available for activities in the private sector, which has become increasingly aware of water and climate risks. These assessments help to identify climate-resilient, cost-effective, and sustainable solutions for improving climate resilience.

Water resources planners and practitioners have long applied adaptive management and implemented robust solutions to cope with hydro-meteorological variability, now reinforced by a changing climate. Robust solutions are those that perform well over a wide range of climate and non-climate scenarios, or can be flexibly adapted to them. Still, it is essential that climate risks are monitored, allowing for adjustments in case of new insights. Projection uncertainties must not be misused as an excuse to label "business as usual" water measures as adaptation activities.

Nature-based Solutions offer additional opportunities for effective, robust, and flexible climate change adaptation. Water managers have long relied on natural processes, for example by using wetlands to treat wastewater. The water community has also gained experience with governance mechanisms that help implement Nature-based Solutions, including through Water Stewardship approaches.

Safeguarding and providing water storage capacity is crucial for climate adaptation. Water storage offers multiple answers to the impacts of climate change. Storage provides a buffer against both floods and droughts, balances increasing water variability, and compensates for the loss of natural water storage systems, such as glaciers and wetlands. In order to manage climate risks, while safeguarding freshwater ecosystems, it is necessary to rethink how nature-based, "green" (e.g. wetlands, groundwater), and infrastructure-based, constructed "grey" storage systems can best be combined. To this end, the whole range of water storage options needs to be considered.

Transboundary water management complements the country-led climate approach, and it deserves even stronger attention. Neither do rivers nor the impacts of climate change stop at administrative borders. Adaptation in one country can potentially mean maladaptation to a neighbouring country. The success of the Transboundary Water Management approach can be further developed into Transboundary Resilience Management. Innovative activities in this field already exist.

Concrete approaches and next steps for water action:

- Improve water storage capacity and water conservation, e.g. through permeable soils (rainwater management), protection of wetlands, and support of traditional water storage methods, demand management, and reducing water losses.
- Explore the use of alternative water resources, including reuse of treated wastewater and desalination – provided they comply with social and environmental safeguards.
- Apply and mainstream approaches for economic analysis of climate change impacts and climate risk assessments in public and private sector activities. These should combine bottom-up water risk assessments with top-down information on climate impacts as a basis for water adaptation planning.
- Incorporate the potential of Nature-based Solutions by promoting integrated and flexible approaches that combine nature-based and infrastructure-based infrastructure in adaptation planning.
- Integrate the transboundary perspective in NDCs during current and future NDC ambition-raising processes, as well as in the NAP process, and advise on regional initiatives for transboundary climate resilience.

Sustainable water management holds large GHG mitigation potential, part of which is still largely untapped.

Unsustainable water and wastewater management is a major source of GHG emissions. The supply, conveyance, and treatment of water are energy-intensive processes, contributing to carbon emissions, if they are powered by fossil fuels. Energy use by water and wastewater activities accounts for about 4% of the international electricity consumption and might double by 2040. The treatment of wastewater can generate emissions of methane (CH_4) and nitrous oxide (N_2O), both with a much stronger global warming potential than CO_2. Emerging and developing countries are engaging in reducing these emissions, including through improving energy efficiency and upgrading treatment technologies. Such interventions often cut operational costs for utilities. Some activities can generate co-benefits on climate resilience, for instance the reduction of water losses. Existing tools help utilities in all parts of the world to assess, reduce and report their emissions in line with national mitigation goals.

Untreated and poorly treated wastewater and sludge are silent but significant GHG emitters. It is estimated that more than 80% of the global wastewater does not receive any kind of treatment. When disposed into surface waters, the amount of nutrients and organic matter within the respective water body increases. This spurs the formation of CH_4 and N_2O – turning surface waters into a source of GHG with particularly high global warming potential. Watershed management and extended water treatment capacities can positively effect GHG emissions by reducing organic matter and nutrient inputs into surface water bodies. Preventing the inflow of insufficiently treated wastewater can contribute to national climate change mitigation efforts, while protecting water quality and safeguarding aquatic ecosystems.

Natural wetlands are substantial global carbon pools that usually also function as carbon sinks. Particularly peatlands constitute major carbon stocks of global importance. Peatlands store twice as much carbon as the earth's forests in their biomass-making peatlands the most space-effective carbon storage systems of all terrestrial ecosystems. The degradation and destruction of peatlands alone might be responsible for 5% of global anthropogenic CO_2 emissions. Nature-based Solutions, such as Ecosystem-based Mitigation (EbM) approaches, can significantly contribute to global GHG mitigation efforts through water. Safeguarding the integrity of natural wetlands through conservation and rewetting measures is a low-hanging fruit to foster climate ambitions through EbM approaches. The sustainable management of water resources is an essential part of protecting carbon-rich freshwater ecosystems and their ecosystem services, while creating multiple co-benefits for climate adaptation, the conservation of biodiversity and human well-being. Based on the chosen irrigation regime, rice paddies can be significant sources of GHG. The formation of CH_4 and N_2O in flooded rice paddies is estimated to be responsible for at least 2.5% of global GHG emissions. The underlying formation process is essentially influenced by the type of water management strategies and irrigation/flooding regimes in place. In this regard, institutions responsible for water management, such as ministries, agencies as well as other water stakeholders can support and enhance existing efforts by the agricultural sector to reduce GHG emissions.

Concrete approaches and next steps for water action:

- Assist in incentivising and implementing energy efficiency activities in water and wastewater utilities, in line with national mitigation efforts.
- Further increase coverage of low GHG wastewater management to improve human and ecosystem health and reduce GHG emissions.
- Provide and institutionalise accurate, but user-friendly methodologies and tools for assessing, reducing, and reporting GHG emissions and energy costs in the water sector.
- Support data gathering and inventory of CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions due to nutrient inputs into surface water bodies, e.g. through poorly treated wastewater. Also consider GHG formation in dam reservoirs.

- Initiate and support capacity-building in countries and communities to measure and monitor wetlands, in particular peatland ecosystems. Enhance mapping and (carbon) inventory efforts regarding the extent and status of global freshwater ecosystems to assess their mitigation potential and to inform decision-making on climate, conservation, and restoration action.

- Include all water-related GHG emissions in Nationally Determined Contributions (NDCs), while highlighting the untapped mitigation potential of the water sector. In doing so, stress the opportunities of Nature-based Solutions, such as Ecosystem-based Mitigation measures in the water sector, for enhanced GHG mitigation efforts and NDC ambition-raising.

Water is in an ideal position to bridge development and climate agendas by emphasising mutual benefits.

Emerging and developing countries have prioritised water action when it comes to climate resilience. Analyses show that water is the most prioritised sector in the adaptation components of NDCs, underlining both its crucial role and strong demand for water action by the parties. National Adaptation Plan (NAP) processes also often build on water action. Activities should ideally already be included at the NAP level, which in turn might prominently inform the next round of NDCs. Water is less present in national climate strategies when it comes to GHG mitigation, both in NDCs and long-term strategies. Strategy update processes open opportunities for concretising adaptation action and increasing water ambitions for decarbonisation.

Water action stands for achieving multiple climate and development goals. Co-benefits might also support efforts at preserving biodiversity and reducing disaster risks. One activity can contribute to several objectives at once, and the specific impact chains in reaching the respective goals are often interdependent and hard to disentangle. Nonetheless, activities marked as relevant for achieving a particular goal must prove their respective contributions, in particular if finance used is earmarked for that goal.

Resilient Water Management promotes coherence between major global agendas in responding to (climate) risks, including the Paris Agreement, the 2030 Agenda for Sustainable Development, and the Sendai Framework for Disaster Risk Reduction (DRR). About 90% of natural disasters are water- related, mostly droughts and floods. A better understanding and communication of water-related impacts can help identify solutions to minimise risks. Disaster risk reduction and management activities need to be considered for water-related climate action in order to use synergies with existing activities under the Sendai Framework. To this end, different initiatives are already underway, such as the Global Initiative on Disaster Risk Management (GIDRM).

Concrete approaches and next steps for water action:

- Start from the NAP process as a main entry point to ensure the consideration of relevant national adaptation priorities in the water sector.

- Provide guidance and checklists on addressing water adaptation and mitigation issues in climate plans and strategies.

- Promote the inclusion of water-related GHG mitigation contributions, including Ecosystem-based Mitigation activities, in NDCs.

- Promote holistic approaches to address water, climate, and development interlinkages by exploring co-benefits among the Paris Agreement, the 2030 Agenda, and the Sendai Framework on DRR.

1. Introduction

Water and climate change are inextricably linked. As rising temperatures spur the hydrological cycle, climate change will affect water availability and quality, as well as hydrological variability and extremes, such as floods and droughts.

Actions in the water sector, including water resources management, as well as water supply and sanitation services[1], will substantially shape the resilience of communities and ecosystems. Not surprisingly, the water sector has received the largest sectoral share of international public climate adaptation finance in the last years (CPI, 2019).

This report aims at improving the understanding of complex interrelations between climate change and water, and, based on this understanding, at identifying the most adequate water actions for mitigating greenhouse gas (GHG) emissions and improving climate resilience. It does so by synthesising state-of-the-art knowledge and research from a physical as well as from a political perspective, and, on that basis, by recommending appropriate action, while referring to good practices and methodologies.

The report primarily targets water practitioners, and decision-makers in the water sector, and the water expert community, aiming to help them better understand how the water sector and water-related activities can specifically contribute to climate mitigation and adaptation goals through meaningful action. However, serving as a comprehensive knowledge base, the report does not solely provide evidence- based information for water actors, but also for members of the climate change community.

1 As defined by the OECD Development Assistance Committee (DAC) Creditor Reporting System (CRS): water supply and sanitation (DAC 5 code 140), excluding waste management/disposal (OECD, 2019).

Financial and political support also increase the water sector's responsibility to "do the right thing". It is wrong to assume that water action automatically improves climate resilience. For instance, the mere extension of conventional supply from non-renewable water sources might even be counterproductive and increase long-term vulnerability, in particular if climate change causes increasingly severe water stress in a region. Governments and international development partners have been aware that knowledge on the current and future climate conditions and their impacts on water resources in a specific area are indispensable for successful adaptation to climate change. Therefore, *Chapters 2 to 5* of this report provide an overview on climate and water interactions, climate change and impact modelling, including its potential uncertainties, as well as climate change trends at the global level and in selected river basins. The latter were selected in a way that illustrates the wide range of regionally different climate change impacts on river basins, mostly focusing on regions with emerging and developing economies.

With these elements in mind, water management approaches can provide the right answers for addressing climate risks. It is not just about adding climate readiness to "business as usual" solutions. *Chapter 6* shows how water has the potential to proactively advance climate action through emphasising the impacts of its own established and innovative concepts, always in the context of reducing climate vulnerability and GHG emissions, and complying with the criteria for adaptation and mitigation activities and finance.

While water is key to climate resilience, the water sector also contributes to the emission of GHG, with considerable mitigation potential.

Not only does the water sector use a large amount of energy through water treatment and supply processes that might cause CO_2 emissions; wastewater management also contributes to emissions of other highly potent GHG, such as methane (CH_4) and nitrous oxide (N_2O). Technologies and tools to mitigate emissions are already available, including for utilities in emerging and developing countries.

The sustainable management of water-related ecosystems bears additional opportunities. Surface waters exposed to a high influx of untreated domestic, agricultural, or industrial wastewater are substantial sources of CH_4 and N_2O. Moreover, water-related freshwater ecosystems, such as wetlands – particularly peatlands – function as carbon pools and sinks of global relevance. Wetland protection and management activities can significantly reduce GHG emissions, and, at the same time, improve climate resilience and advance sustainable development. Water sector and water-related sources of GHG emissions, and their respective mitigation potential, are described in *Chapter 7.*

Climate change mitigation and adaptation, including cross-cutting activities, are subject to a complex governance regime at the international, regional, national, and sub-national levels. Due to the increasing focus on these overarching policy processes, the implementation of climate action through water also depends on its being considered a crucial step in reaching the respective goals. Therefore, participation in relevant policy processes and coordination with key actors, also on sustainable development and disaster risk management, provides another success factor for low-carbon, resilient societies through water action. *Chapter 8* helps to understand the main policy processes and underpinning institutional frameworks, enabling water actors to precisely address and combine relevant policy processes, adaptation and mitigation opportunities, and co-benefits.

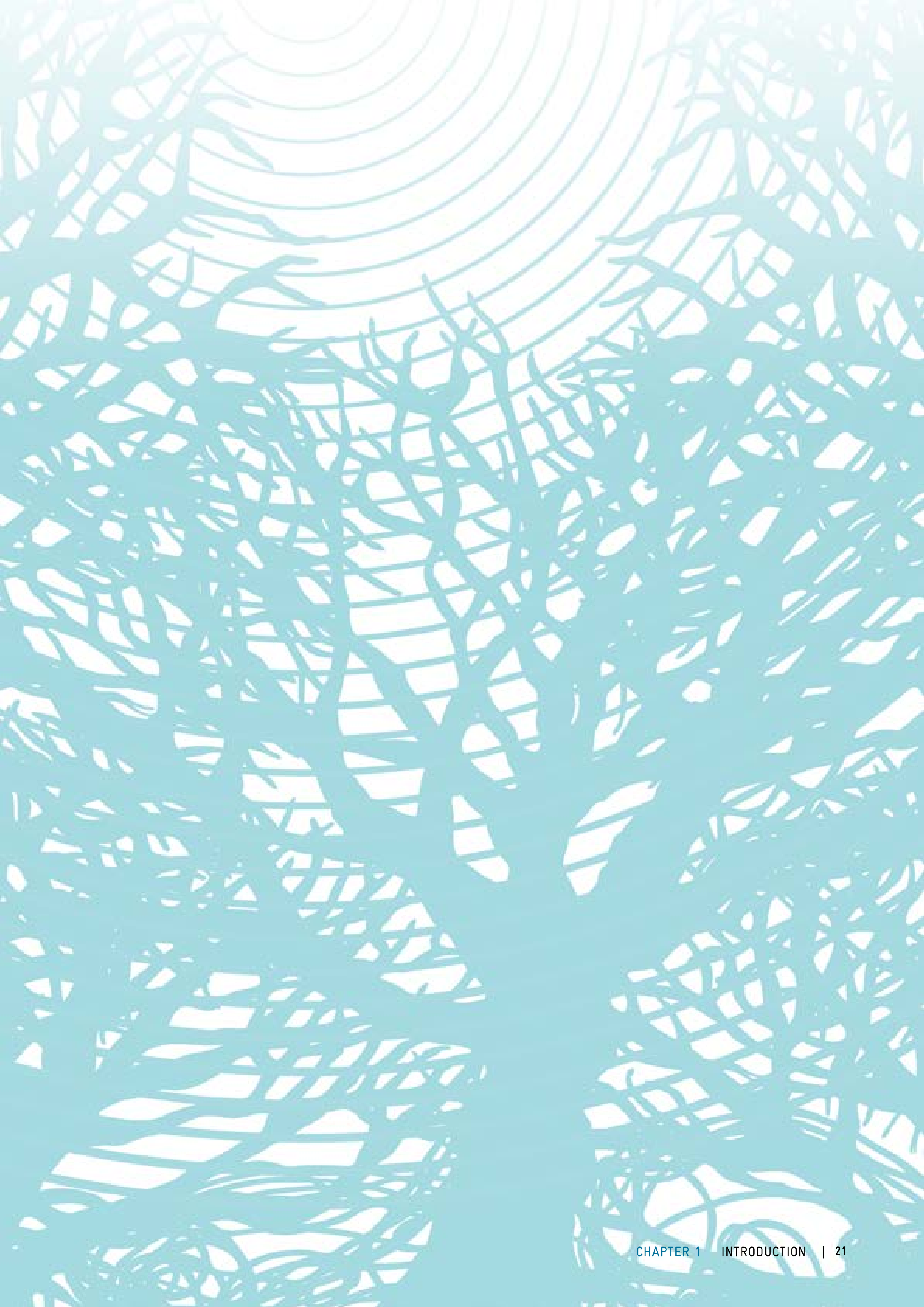
It is time for the water sector to confidently rely on and promote its own strengths, while taking even more responsibility in shaping the future of climate action. For this reason, the present study encourages water stakeholders to further account for the given realities of international and national climate frameworks and structures, while actively developing pivotal water solutions for their successful implementation.

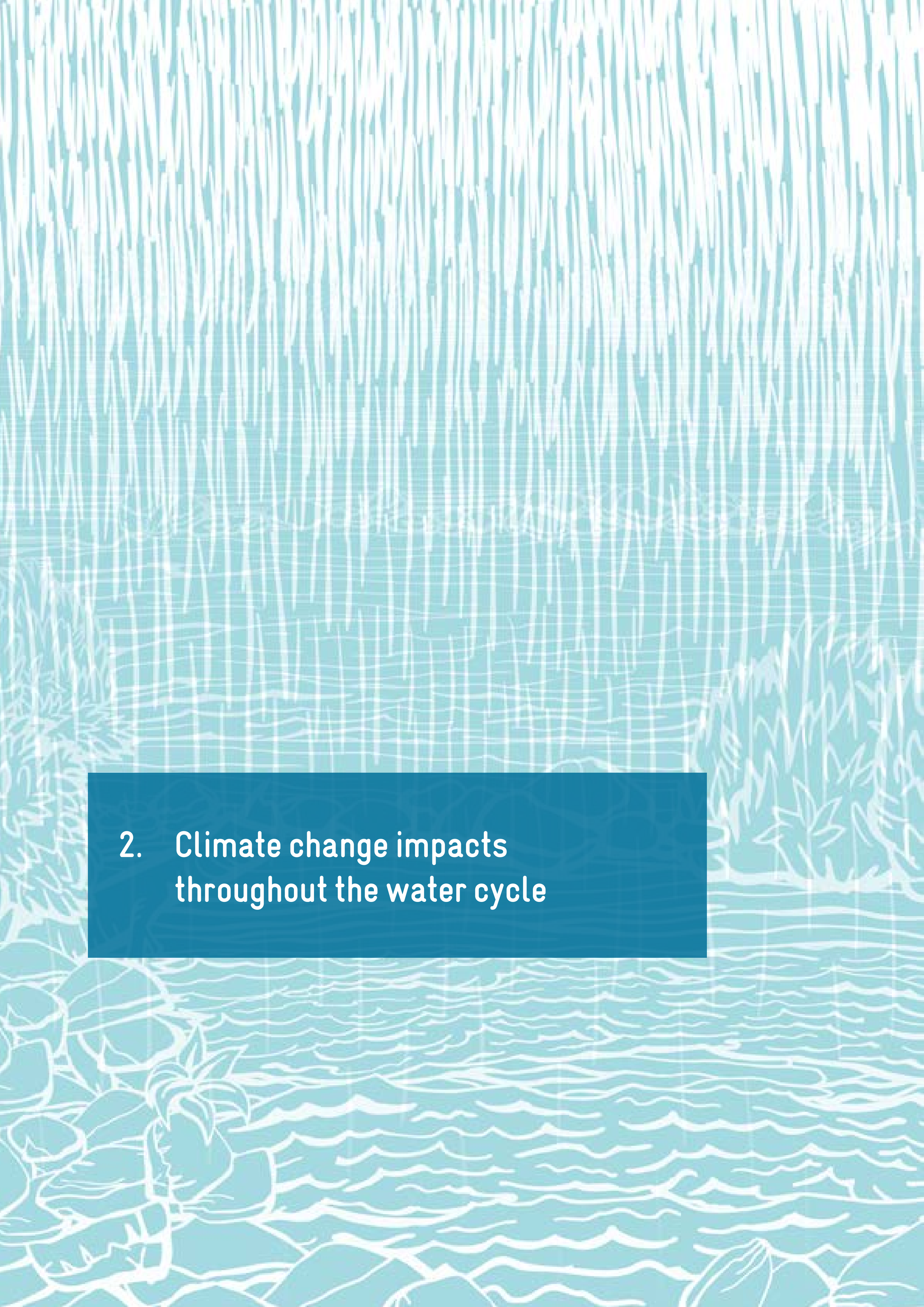
In other words – **Stop floating, start swimming!**

1.1 References

CPI (Climate Policy Initiative) (2019): **Global Landscape of Climate Finance 2019.**
https://climatepolicyinitiative.org/wp-content/uploads/2019/11/2019-Global-Landscape-of-Climate-Finance.pdf

OECD (Organisation for Economic Co-operation and Development) (2019):
Purpose codes list for 2019 reporting on 2018 flows.
https://www.oecd.org/dac/financing-sustainable-development/development-finance-standards/DAC-CRS-PPC-2019.xls





2. Climate change impacts throughout the water cycle

Climate change is one of the main global challenges of the twenty-first century. GHG emissions do not only lead to an increase in global temperatures, but also have an impact on precipitation levels and global water resources. This chapter introduces climate change impacts on the hydrological cycle, as well as indicators commonly used for the quantification of climate change impacts on water availability and hydroclimatic extremes. As most large-scale climate impact studies, the present report focuses on changes in precipitation, evapotranspiration, local runoff, and river discharge.

Key Messages of Chapter 2

- Natural water storage (e.g. in ice and snow as well as groundwater and wetlands) and hydrological processes will be heavily affected by climate change impacts.
- Climate change is leading to an increase in average global temperatures, and consequently to the presence of more energy in the hydro-climatic system. This will eventually cause an increase in evapotranspiration, as well as an intensification of the water cycle.
- The global increase in precipitation is not evenly distributed across continents; in fact, many regions might even receive less precipitation. Moreover, the local increase in evapotranspiration could be higher than the potential increase in precipitation.
- Higher temperatures, extreme weather events, and changes in water availability will also affect water quality. However, relevant data is often not available, and future impacts remain mostly unclear.

2.1 Climate change and the hydrological cycle

The global water cycle describes the continuous movement and storage of water on, above and below Earth's surface (*see Figure 1*). Only ~3% of Earth's water is fresh water: Most of it is stored in icecaps and glaciers (~63%) as well as groundwater (~36%), while all lakes, rivers and swamps combined account for only a small fraction (~0.4%) of total freshwater reserves (fractions based on numbers in *Figure 1*, extracted from Trenberth et al., 2011). Water enters the atmosphere as water vapour through evaporation, plant transpiration and sublimation.

The primary energy input stimulating the water cycle is solar radiation. The anthropogenic increase of GHG concentration in the atmosphere has resulted in a net increase of radiation input. This increase in energy has already caused a rise in global temperatures by almost 1°C in comparison to pre-industrial times (IPCC, 2013).

It is necessary to make a distinction between man-made global climate change and natural climate variability in order to account for the broader picture of water and climate relations. Climate variability is characterized by naturally occurring cycles, such as seasonal variations or periodic changes in solar activity, or climate events, such as the El Niño phenomenon. It is expected that a warmer climate (more energy in the hydro-climatic system) will lead to an intensification of the water cycle, mostly because of the increase in evapotranspiration (Kundzewicz and Schellnhuber, 2004).

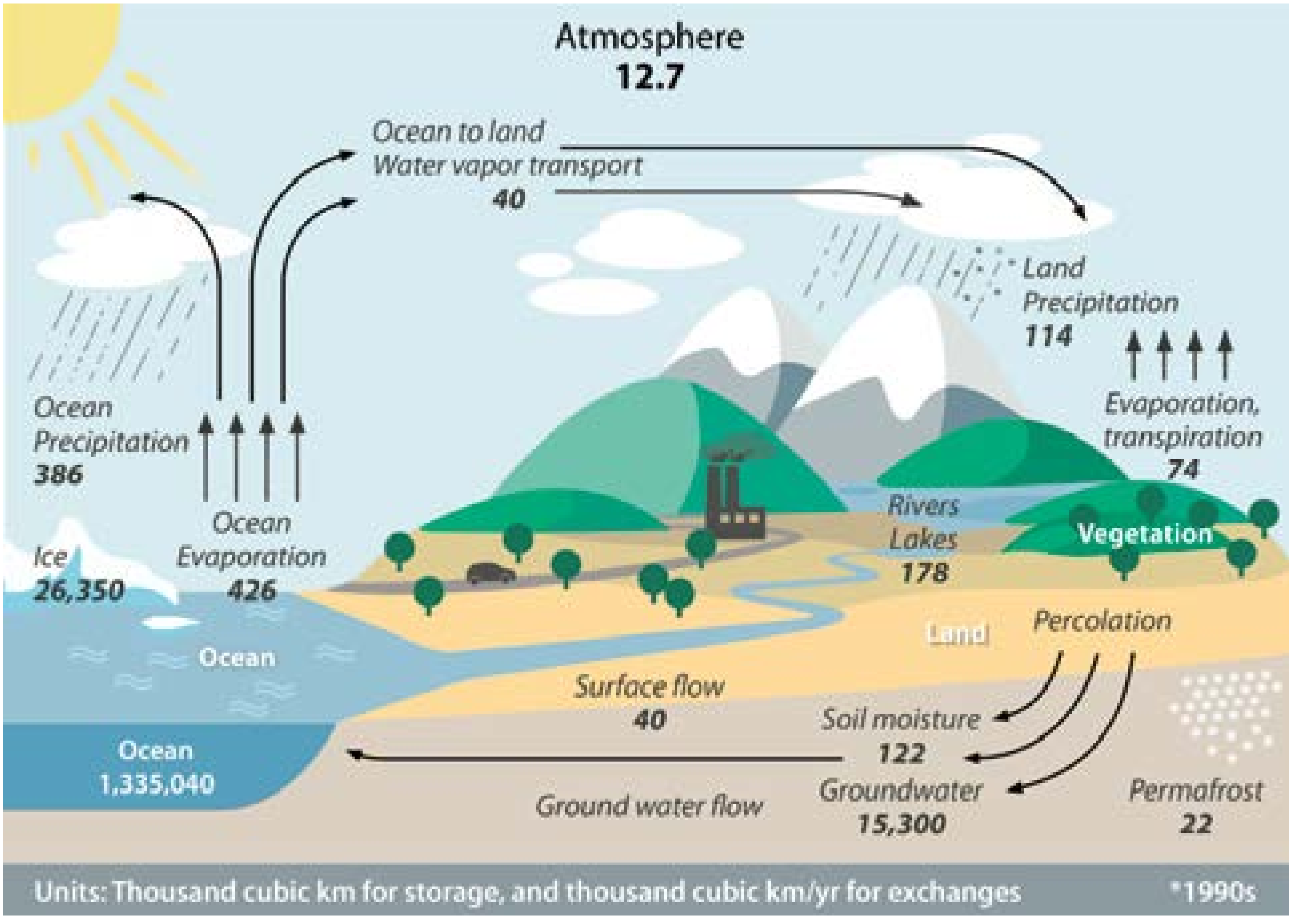


Figure 1: The global water/ hydrological cycle with estimates of the current global water budget and its annual flow using observations from 2002-2008 (units: 1000 km^3 for storage and 1000 km^3/yr for exchanges (Royal Meteorological Society, data based on Trenberth et al., 2011)).

Indeed, observations show that since the late nineteenth century, the mean global water vapour concentration in the lower atmosphere has increased by ~7%, and **global mean precipitation** has increased by 1-3%. However, precipitation and associated changes are difficult to quantify on a global scale, and the latter number is associated with a large degree of uncertainty (Wentz et al., 2007). The generation of precipitation is controlled by the temperature of the troposphere, which determines how much condensation, and thus precipitation occurs. In addition, wind systems transporting wet and dry air masses affect the amount of rainfall a region receives.

There are strong indications that the global temperature increase, which is higher over continents, in high latitudes and in high mountains, has already led to changes in small- and large-scale weather patterns (Di Capua and Coumou, 2016; Coumou et al., 2015). As a result, the global increase in precipitation is not evenly distributed over continents; in fact, many regions now tend to receive even less precipitation than before. Moreover, an increase in precipitation does not translate directly into more river discharge in a certain region, since the higher energy input stimulates evapotranspiration, and the local increase in evapotranspiration can be higher than the potential increase in precipitation.

➔ *Natural water storage will be heavily affected by climate change.*

Especially in mountainous areas, **water stored in ice and snow** is an important component of the water cycle, as well as a source of freshwater for river basins inhabited or exploited by humans. Such regions can be heavily affected by climate change. Scientists are observing a retreat of glaciers and a decrease of the share of water stored in snow and ice in many parts of the world. This could change both the seasonality of discharge (e.g. elevated discharge from rainfall in winter instead of spring flow induced by snow melt) and water availability (e.g. reduced summer discharge when less water from glaciers is present). Only in those few areas, in which the increase of precipitation in the winter is larger than the increase in snow melt do glaciers exhibit a positive trend in terms of mass.

Variations in the hydrological cycle stimulated by changes in precipitation and evapotranspiration have effects on **river discharge**. However, expected climate change impacts vary considerably around the globe and are associated with a large degree of uncertainty. For some regions, such as northern Europe, shifts in the hydrological regime are projected to result in a different seasonality of annual discharge dynamics caused by, for instance, earlier snow melt and replacement of snow by rainfall under increasing temperatures. In other regions, such as the Mediterranean, projected increases in evapotranspiration and decreases in rainfall are likely to result in less river discharge. Likewise, hydrological extremes, such as droughts and floods, are expected to change as well.

Another essential part of the hydrological cycle is **groundwater storage and flow**. Sustainable use of renewable groundwater resources has the potential to reduce the impact of surface water deficits by temporarily providing water for domestic and agricultural uses when surface water is insufficiently available (Kundzewicz and Döll, 2009). The specific effects of climate change on groundwater are not clear yet. Uncertainties caused by downscaling, hydrologic models and groundwater recharge estimation can reinforce each other. Studies show that, in general, groundwater is very sensitive to climate variability and change, depending on climatic conditions, depth and thickness of the aquifer and other factors (ibid.). This is due in part to the consequences of climate change: Increased evaporation from the soil surface, transpiration by plants, as well as surface runoff will all reduce the amount of water that remains available for infiltration into the ground.

➔ *Climate change will also alter water quality.*

Climate change also **affects water quality**. The impacts of climate change on water quality are subject to a large variety of specific factors and therefore even more difficult to project than impacts on water quantity.

- **Higher temperatures** stimulate the growth of algae and bacteria, with adverse effects on aquatic ecology and humans. Another negative effect on the ecological integrity of aquatic systems is that the oxygen solubility of water decreases with warmer temperatures. During low flow and drought conditions, i.e. when water stagnates in rivers and lakes and reservoirs with very shallow water levels, both effects are aggravated, which has a severe negative impact on both aquatic communities and humans dependent on surface water resources. A general rise in temperatures will also translate to shallow aquifers, where higher potential evapotranspiration will increase recharge salinity.

- **A reduction in water quantity** will reduce the water's dilution capacity of pollutants and sediments, while an increase will have the opposite effect.

- **Extreme events** might also cause water pollution, for instance through flooding and landslides, affecting water quality.

- **Sea level rise** may contribute to groundwater salinization, even though abstraction seems to have a stronger impact on this process at the global level.

It should be noted that effects are often indirect, particularly when it comes to water quality. For instance, increased irrigation due to drought can lead to unmanaged infiltration of salty, nutrient-rich, but low-quality water into an aquifer.

2.2 Indicators for investigating changes in water availability and hydroclimatic extremes

Different indicators are normally applied to investigate trends and changes in water resources (e.g. groundwater, surface water, glacier water), water availability (the quantity of water resources) and hydrological extremes (floods and droughts). *Table 1 below* provides a list of hydrological indicators often used in climate impact studies. Their advantage is that they are mostly easy to monitor. These indicators are commonly used as outputs of hydrological models applied to simulate climate change impacts. However, data availability and quality vary. In addition, some of the indicators can be used to analyse impacts on components of the water cycle for which much less information is available (e.g. recharge for renewable groundwater resources), or for which impacts of climate change are more difficult to estimate (e.g. actual evapotranspiration as an indicator for plant productivity).

Due to restrictions in data availability, case studies featured in this report focus on air temperature, precipitation, river discharge including monthly distribution, evapotranspiration and changes in 100-year return period discharge levels.

Indicator	Unit	Relevance	Used for report's case studies
Precipitation as Rain and Snow	mm per time unit (year, month)	Determines the maximal amount of available water, used to investigate annual trends and seasonal shifts	yes
Potential Evapotranspiration	mm per time unit (year, month)	Potential amount of water evaporated from the land surface (soil, lakes, reservoirs, etc.) and transpirated by plants under unlimited water supply; Indicator for water demand of plants and available energy in the hydro-climatic system	yes
Actual Evapotranspiration	mm per time unit (year, month)	Actual amount of water consumed by plant transpiration and surface evaporation; Additional indicator for changes in plant productivity	yes
Local Runoff	mm per time unit (year, month)	Local water yield (precipitation minus actual evapotranspiration)	no
Groundwater Recharge	mm per time unit (year, month)	Water which percolates through the unsaturated soil layers and reaches the groundwater table. Indicator to quantify impacts on renewable groundwater resources	no
River Discharge	m^3 per time unit	Integrates all water flows in a river catchment, indicator for surface water availability, changes in seasonality and trends in extremes (floods and droughts)	yes
Return Period	Time unit (year)	Average time interval between events, such as floods or droughts exceeding a specific magnitude. The higher the value, the more extreme the event (e.g. a 30-year flood is still a moderate flood, which occurs on average every 30 years, while a 100-year flood is an extreme event)	yes
Frequency of Exceedance	1 per time unit (year)	Inverse of return period, i.e. number of times a certain threshold is exceeded over a specific time interval (e.g. a discharge value which is exceeded on average once per year is an indicator for high flows, while a discharge value which is exceeded on average 99% of the time is an indicator for low flows).	no
Water Temperature	°C	Water quality indicator determining oxygen concentration and growth of algae and bacteria; Information often not available or difficult to obtain	no
Nutrient and Algae Concentration (nitrogen, phosphorous)	mg l–1	Water quality indicator determining growth of algae and bacteria; Information often not available or difficult to obtain	no

Table 1: List of selected hydrological indicators to analyse climate change impacts on water resources, water availability, seasonality, and extremes

The main components of the water cycle are precipitation, evapotranspiration, local runoff and river discharge. The hydrological cycle with associated water flows and storages is very sensitive to any changes in precipitation and evapotranspiration (Hirabayashi et al., 2013; Prudhomme et al., 2014). Especially in arid and semi-arid regions, actual evapotranspiration nearly equals precipitation or is even higher, and only a small fraction of precipitation reaches the surface water storages and groundwater. Actual (evapo) transpiration can further be used as a proxy for plant-available water in a certain region, and hence for plant productivity.

River discharge refers to water flows in a river. River discharge should not be confused with river runoff that is the amount of water concentrated in a river, reaching the river through surface, sub-surface, and groundwater runoff. Runoff is subsequently often stored in lakes and reservoirs, making it available for human consumption. It integrates all flow components and processes in the upstream river catchment. Knowledge of river discharge characteristics is essential for water resources planning and management, flood forecasting and routing, and floodplain regulation. Long-term average river discharge is a suitable indicator for studying the general and per capita water availability in a basin. Moreover, discharge data with a higher temporal resolution are suitable for the analysis of changes in seasonal patterns, flood frequency and intensity, and low flow (drought) conditions.

There are various possible approaches to characterizing hydrological extremes. High and low flows are commonly distinguished as events in which discharge is above or below a certain threshold. The severity of the event is then determined statistically, by counting the number of events over a certain period (frequency of exceedance, e.g. six times during 30 years), or by using the inverse of this value, e.g. after how many years such an event occurs on average (return period, e.g. five years).

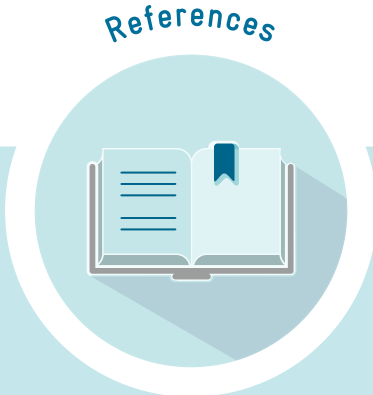
In order to assess a change in hydrological extremes over time, two options are available: The first is to measure the change in magnitude of an event with a previously determined return period (e.g. the discharge of a 100-year flood). The second is to assess how the return period of a certain discharge level changes.

A specific approach for droughts entails counting the number of days over a certain period, for example 30 years, in which generated runoff remains below a certain threshold, and analysing how this number changes in future projections.

➔ ***Most large-scale climate impact studies on hydrology focus on changes in precipitation, evapotranspiration, local runoff and river discharge.***

In order to investigate the hydrological conditions of a region and possible changes, the state of different types of natural and built water storage systems, such as soil moisture, groundwater, water in reservoirs, lakes and wetlands, are important indicators. However, data availability on sub-surface water resources, in particular, is limited, partly due to complex geological structures and incomplete knowledge on sub-surface conditions. This explains why large-scale climate impact studies, including the present report, mostly focus on changes in precipitation, evapotranspiration, local runoff and river discharge when quantifying impacts on hydrology.

While groundwater recharge is a useful indicator for investigating and quantifying impacts on groundwater resources, it is mostly only available from hydrological models. A decrease in groundwater recharge indicates a trend towards lower groundwater availability.



2.3 References

Coumou, D., Lehmann J., and Beckmann J. (2015): **The Weakening Summer Circulation in the Northern Hemisphere Mid-latitudes. Science, 348 (6232), 324-327**, DOI: *https://doi.org/10.1126/science.1261768*

Di Capua, G., and Coumou, D. (2016): **Changes in meandering of the Northern Hemisphere circulation. Environ. Res. Lett., 11 (9), 094028**, DOI: *https://doi.org/10.1088/1748-9326/11/9/094028*

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

IPCC (Intergovernmental Panel on Climate Change) (2013): **Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change by Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.). Cambridge/New York: Cambridge University Press.**

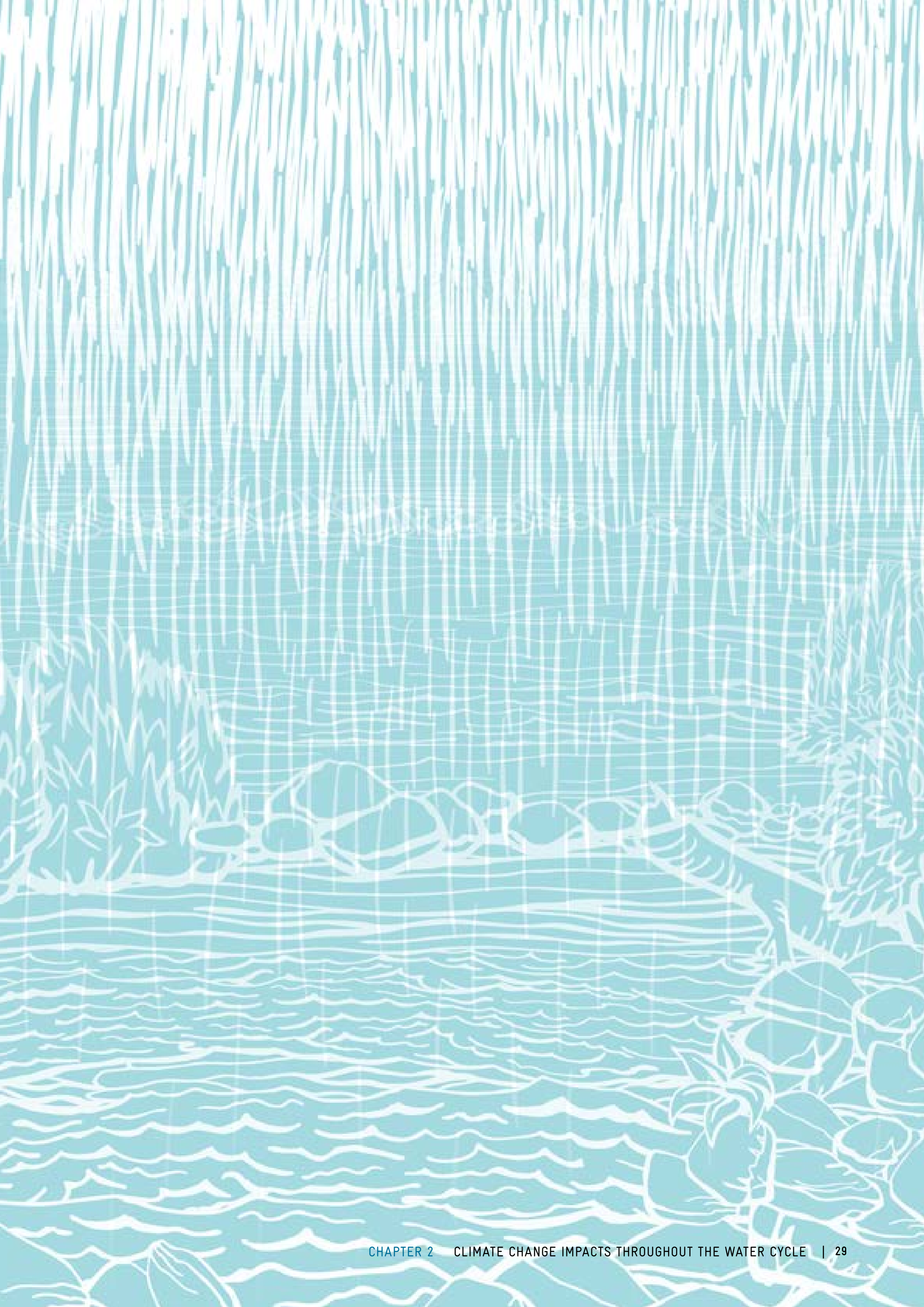
Kundzewicz, Z. W., and Döll, P. (2009): **Will groundwater ease freshwater stress under climate change? Hydrological Sciences Journal, 54 (4), 665–675**, DOI: *https://doi.org/10.1623/hysj.54.4.665*

Kundzewicz, Z. W., and Schellnhuber, H.-J. (2004): **Floods in the IPCC TAR Perspective. Natural Hazards, 31 (1), 111-128**, DOI: *https://doi.org/10.1023/B:NHAZ.0000020257.09228.7b*

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arneli, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., and Stacke, T. (2014): **Hydrological droughts in the 21st century: hotspots and uncertainties from a global multi-model ensemble experiment. PNAS, 111 (9), 3262–3267**, DOI: *https://doi.org/10.1073/pnas.1222473110*

Trenberth, K. E., Fasullo, J., and Mackaro, J. (2011): **Atmospheric Moisture Transports from Ocean to Land and Global Energy Flows in Reanalyses. J. Climate, 24, 4907-4924**, DOI: *http://dx.doi.org/10.1175/2011JCLI4171.1*

Wentz, F. J., Ricciardulli, L., Hilburn, K., and Mears, C. (2007): **How Much More Rain Will Global Warming Bring? Science, 317 (5835), 233-235**, *https://doi.org/10.1126/science.1140746*



3. Critical review of climate impact modelling on water resources

Computer models are invaluable tools for the estimation of climate change and its associated impacts on water resources. However, uncertainties along the impact model chain are a major challenge in assessing the hydrologic effects of climate change. Sources of uncertainty include Global Climate Models (GCMs), GHG emission and concentration scenarios (e.g. Representative Concentration Pathways (RCPs)), downscaling methods, and hydrological models. This chapter introduces the modelling of climate change and its associated impacts. Furthermore, it discusses possible sources of (projection) uncertainty and their relevance for the assessment of water resources, availability and hydrological extremes, both now and in the future. At the end of the chapter, options for improving the underlying data in order to increase the robustness of hydrological impact assessments are presented.

Key Messages of Chapter 3

- **Despite advances in climatological and hydrological modelling, significant uncertainties regarding the specific impacts of climate change on water resources remain.**
- **GCMs, hydrological models and scenarios of future GHG concentrations (e.g. RCPs) contribute to uncertainties associated with climate change impact projections for the water sector.**
- **Individual contributions by uncertainty sources may change under different hydro-climatological conditions with respect to both spatial (e.g. different altitudes) and temporal patterns (e.g. dry vs. wet season).**
- **In order to improve hydro-climatic data – in terms of quantity and quality – it is necessary to increase the coverage of hydro-meteorological monitoring networks, ensure the necessary maintenance of existing stations and set up efficient data quality control procedures. As a consequence, information and subsequent applicability for end-users could improve the robustness of hydrological model projections.**
- **There is a strong demand for improved hydro-climatic information, such as interlinked in situ and remotely sensed data, e.g. from satellites and socio-economic data, for instance on land and energy use, which may further improve future scenarios.**
- **Some uncertainties will inevitably remain, thus, creating further challenges for development as well as adaptation strategies.**

Definition of terms

Adaptation "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities".[a]
Generally, adaptation measures can reduce the risk by reducing vulnerability and in certain cases also exposure. Vulnerability can be reduced either by decreasing sensitivity or by increasing capacity.[b]

Adaptive capacity The combination of the strengths, attributes, and resources available to an individual, community, society, or organization that can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities.[a,c]

Climate variability "refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)".[a]

Exposure "The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected." [a]

Flexible adaptation plans Flexible adaptation plans allow decision-makers to select a course of action to adjust to shifting or emerging conditions while ensuring a near-term action does not rule out potentially critical future actions. Flexible plans cope with uncertainty by adapting to changing conditions (some times referred to as adaptive management).[a, b, c]

Hazard "The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts".[a]

No/low-regret "In the absence of accurate climate prediction models, the "no-regret" or (perhaps more aptly named "low-regret") approach gives priority to actions that are prudent regardless of future climate conditions." [b]

Robustness The ability of a system to remain functioning under a large range of disturbance magnitudes.[c] In addition to being a characteristic of a system, robustness can also be a characteristic of decision making itself (e.g., robust decision making), meaning a plan is performing well across a large range of uncertainties.[b]

Resilience The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions. [a, c]

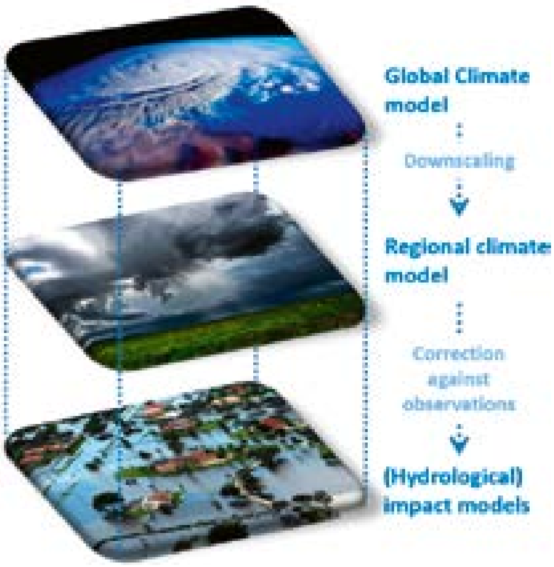
Risk The likelihood over a specified time period "for consequences [= impacts] where something of value is at stake and where the outcome is uncertain. […] Risk results from the interaction

	of vulnerability, exposure, and hazard”.[a]
Uncertainty	An expression of the degree to which a value or relationship is unknown. Uncertainty “can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts)”.[a]
Vulnerability	“The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt”.[a]

3.1 Introduction to climate change impact modelling

Climate models are essential tools to understanding and quantifying climate variability, climate change, and related impacts (IPCC, 2013). In climate change impact modelling, a chain of computer models translates global scenarios for GHG emissions and atmospheric concentrations into regional impacts, such as effects on water resources, hydrological processes and extremes (e.g. floods and droughts). A simplified model chain is shown in *Figure 2 (left)*.
The chain begins with the physically-based Global Climate Models (GCMs), whose results are transformed into regional climate and weather simulations by statistical means or physically based regional climate models – a process also called “downscaling”.

Global Hydrological Models (GHMs) are mostly driven directly by global climate model output, after the correction of systematic errors (“bias-correction” against observations). **Regional Hydrological Models (RHMs)** are usually driven by regional climate model outputs. In most cases, this also includes a bias-correction of the climate data. Additional spatial information is needed to initialize a hydrological model in order to take into account specific regional features of the catchment area, such as soil and geological characteristics, land use, surface elevation, as well as land and water management (optional): *see Figure 2 (right)*.



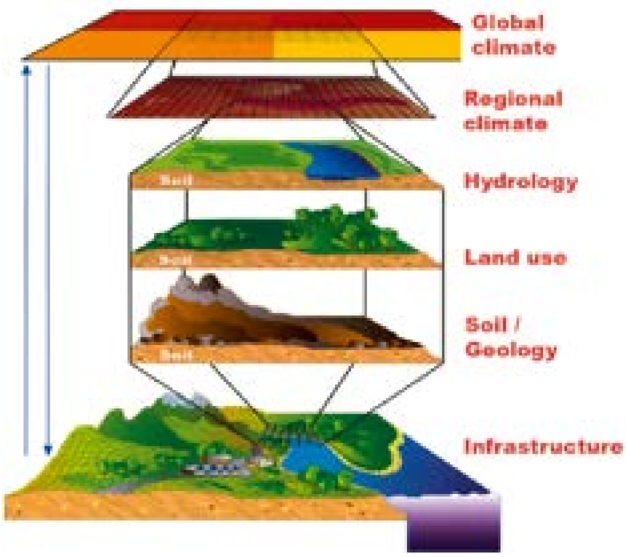


Figure 2 (left): Simplified model chain from global climate to regional impact models.

Figure 2 (right): Layers of information applied in climate impact models (Hadley Climatic Research Unit, changed).

Global socio-economic scenarios and GHG concentration pathways can be imagined as stories of possible futures describing factors that are difficult to quantify or determine, such as governance, social structures, institutions, and GHG emissions. In different forms, these have been a basis for the regularly published Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC), which provide a summary of the current scientific, technical, and socio-economic understanding of climate change and its associated impacts.

The present report uses the latest scenarios as defined for the IPCC's Fifth Assessment Report (AR5), namely, **Representative Concentration Pathways (RCPs)**. RCPs do not constitute socio-economic scenarios but project the development of radiative forcing at the end of the 21st century (van Vuuren et al., 2011). In consequence, higher amounts of GHG emissions throughout this century relate positively to radiative forcing values. The IPCC AR5 relies on the following four RCPs (IPCC, 2013):

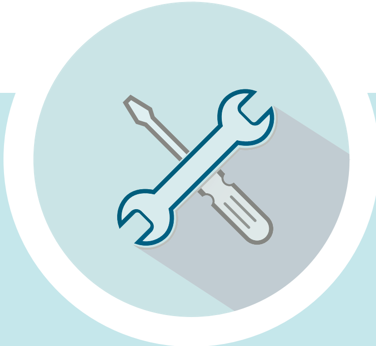
- **RCP2.6:** Radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines;
- **RCP4.5:** Radiative forcing is stabilised at approximately 4.5 W/m^2 after 2100;
- **RCP6.0:** Radiative forcing is stabilised at approximately 6 W/m^2 after 2100;
- **RCP8.5:** Radiative forcing exceeds 8.5 W/m^2 by 2100 and continues to rise.

Radiative forcing refers to changes in Earth's energy budget (the balance of incoming and outgoing radiation) at the top of the atmosphere (IPCC, 2013). For instance, scenario RCP8.5 assumes an increase in radiative forcing, exceeding 8.5 W/m^2 by the end of the century relative to pre-industrial levels. In many studies, including this report, the most extreme scenarios (namely, the low-concentration RCP2.6 and the high-concentration RCP8.5) are analysed under the assumption that their investigation will cover a broad range of possible impacts associated with future climate change.

Climate models translate the RCPs into climate change signals. In this context, AR5 relies heavily on the **Coupled Model Intercomparison Project, Phase 5 (CMIP5)** (Taylor et al., 2013), which provides the results for an ensemble of GCM applications. The outcomes of five selected CMIP5 models were used in the **Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)** (Warszawski et al., 2014) to run hydrological models and quantify climate change impacts for the water sector. The results of CMIP5 and ISIMIP are also used for the analyses performed in the present report.

In addition to the RCPs, researchers have recently developed **Shared Socioeconomic Pathways (SSPs)** in order to include narratives of future socio-economic developments (Riahi et al., 2017). There are five SSP narratives, ranging from a future in which the world focuses on sustainable development, to a middle road, to a future marked by inequality and fossil-fuel intense development. RCPs and SSPs were combined to form a matrix of possible future pathways characterized by a certain climate forcing and associated socio-economic development, e.g. a pathway of 2.6 W/m^2 radiative forcing until the end of the twenty-first century under sustainable development, a pathway of 6.0 W/m^2 in a world characterized by inequality, and so on. The SSPs are being considered for the sixth CMIP phase (CMIP6), which will be the basis of the next IPCC report (AR6) that is expected to be published in 2021-2022 in several parts.

Tools



The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)

Until recently, the scientific knowledge about expected climate change impacts remained to a large extent fragmentary. Many studies have analysed potential impacts on specific regions and sectors, and scientists have published numerous papers on this issue. However, the studies were mostly undertaken using different climate scenarios and impact models, an approach that complicates direct comparisons and quantitative syntheses of impacts together with a consistent estimation of uncertainties.

Consequently, ISIMIP was launched in 2013 as a community-driven modelling effort to bring together impact modellers across sectors and scales. The goal was to create consistent and comprehensive projections of impacts of different levels of global warming (https://www.isimip.org/; see Warszawski et al., 2014). ISIMIP offers a framework and protocol for a consistent analysis of climate change impacts across affected sectors and spatial scales. In this way, an international network of modellers contributes to a comprehensive and consistent picture of the world under different climate change scenarios. Within the first phase of ISIMIP, an intercomparison of multiple global impact models driven by climate projections for different emission scenarios was initiated, covering various sectors, including the water sector (e.g. Haddeland et al., 2014; Schewe et al., 2014; Prudhomme et al., 2014; Hattermann et al., 2017), agriculture, biomes, etc.

One can use both global-scale and regional-scale (or river basin-scale) models to assess climate change impacts on hydrological processes. Global-scale modelling studies provide global overviews on impacts and inform policy-makers. However, global-scale modelling outputs are often not reliable at the regional or local scale. Consequently, projections of climate change impacts should be accompanied by studies conducted at the regional scale.

The objective of the intercomparison of multiple impact models is to compare projected climate change impacts and quantify uncertainties from different sources in a systematic way. This strategy leads to more robust results and constitutes a sound basis for the development of adaptation and mitigation strategies. Furthermore, the intercomparison of regional-scale impacts for one sector can contribute to the integration of impacts for specific regions, when results for different sectors are combined.

Most of the results shown in Chapters 4 and 5 of this report were published in the context of ISIMIP and have been complemented by selected additional recent publications.

3.2 Sources of uncertainty in projections of climate change impacts

The top-down flow of information from RCPs over global and regional climate models towards regional impacts induces a **cascade of uncertainty**. This arises as uncertainty from one layer is transferred to the next and thereby picks up that next layer's individual uncertainty, eventually resulting in a multitude of combined uncertainties at the bottom of the cascade (Wilby and Dessai, 2010). It is difficult to account for such uncertainties and thus decision-makers often have trouble interpreting the implications for projections of future climate change impacts. Therefore, researchers use different strategies to aggregate the information about uncertainties (Smith et al., 2018).

Furthermore, also GCMs and GHMs can be major sources of uncertainties. Both model groups add their own contributions of inherent uncertainty during their application. To address this circumstance researchers commonly employ ensembles of models instead of single ones. However, often it remains difficult to assess which model stage (i.e. GCMs or GHMs) contributes the lion's share of total uncertainty in an individual case. *Figure 3* provides an overview of different sources of uncertainty in climate impact modelling on water resources, namely GHG concentration pathways, GCM and GHM, and suggests some actions for uncertainty reduction.

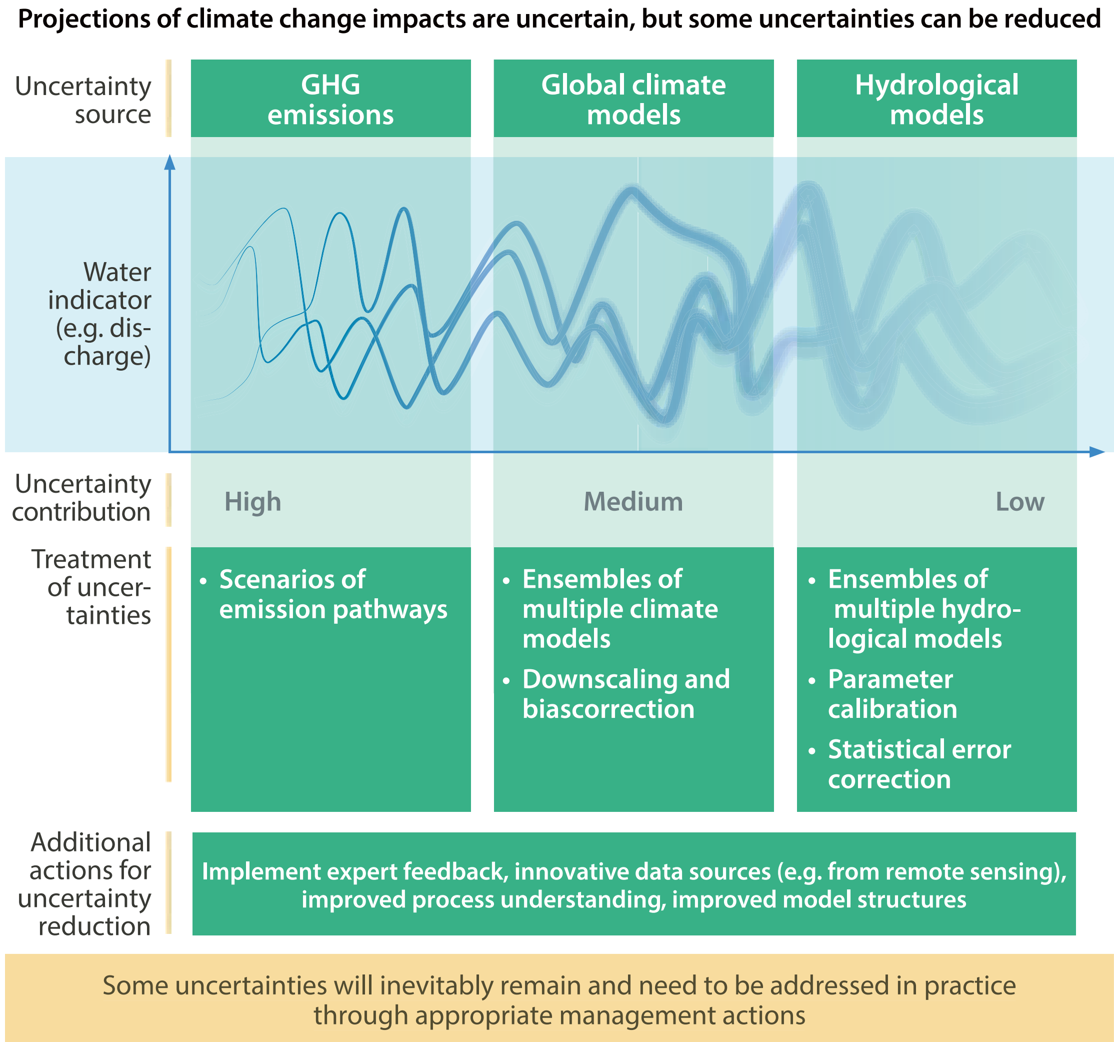


Figure 3: Overview of major sources of uncertainty in climate change impact modelling.

➔ *Shares of uncertainty sources vary according to region and season.*

There is a relation between the shares of GCM and GHM as sources for uncertainty and the regional application of these models. These shares may regionally vary across different parts of the world, as Schewe et al. (2014) found (*Figure 4*). Their results indicate that GCM uncertainty is particularly high in tropical and northern regions, which are characterised by high amounts of precipitation, while in rather dry sub-tropical and arid regions, GHMs are responsible for the lion's share of the uncertainty of projections. Hattermann et al. (2018) found that GCM uncertainty is often even larger than the influence of the selection of a specific GHG concentration scenario.

In addition, uncertainty contributions may vary depending on the time of year. As such, uncertainty attributed to the hydrological model can be considerable in times when the hydrological processes largely determine river discharge. In dry periods, evapotranspiration and groundwater processes dominate the river discharge pattern, and the different hydrological models use different formulations to determine the impact of these processes (Hattermann et al., 2018; Hagemann et al., 2013). This is also the case for snow melt processes (Gelfan et al., 2017).

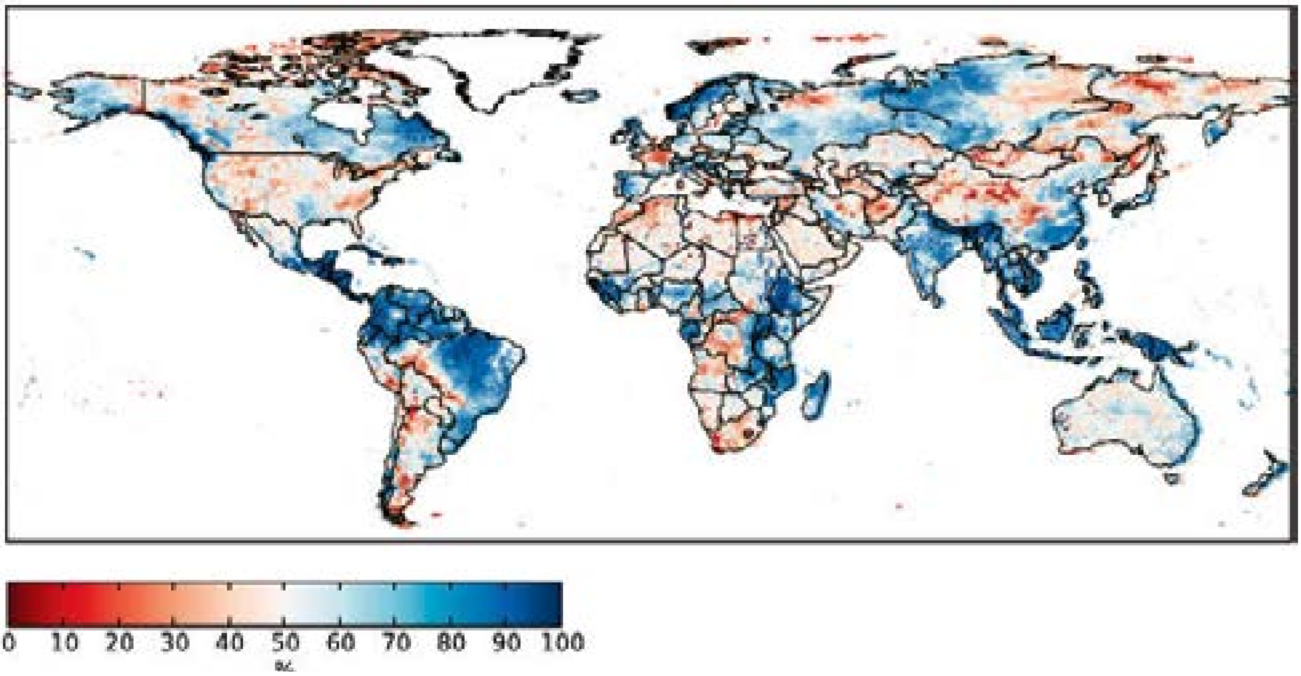


Figure 4: Ratio of GCM variance to total variance as a measure of uncertainty. In red areas, GHM uncertainty predominates, and in blue areas, GCM uncertainty predominates. Greenland has been masked. (Schewe et al., 2014)

3.3 Development and improvement of databases and methods

The potential for uncertainty reduction depends on the respective source of uncertainty. While potential in the field of GHG concentration scenarios is low, due to a lack of clarity concerning future developments, climate models have a larger share of potential in this regard – and hydrological models may be even more promising. Both model groups would certainly benefit from an improved understanding of processes and, as a result, from an improved implementation of the models, as well as enhanced computational resources. In general, improved methods for downscaling and bias-correction could enhance local impact projections. This holds especially true for the analysis of extreme values (e.g. extreme precipitation and flood events), which are often poorly reflected by global models and further distorted by insufficient bias-correction schemes. Moreover, adequate model parameter calibration and the validation of modelling results could also improve the performance of hydrological models. However, regarding calibration and validation, it is essential to have enough high-quality data available.

In order to improve data quantity and quality, it is necessary to increase the coverage of hydro-meteorological monitoring networks, ensure the necessary maintenance of existing stations and set up efficient data quality control procedures. Improving data quality and quantity will increase the robustness of hydrological impact assessments. However, observation density and data quality in meteorology, hydrology, land cover and use as well as socio-economic figures are often limited in many of the countries that are particularly vulnerable to climate change impacts. Furthermore, in many regions, storage of water in snow and ice characterises the water cycle, eventually determining the water supply. Yet monitoring networks are often underdeveloped at the high altitudes where snow and ice are of particular importance.

The development of well-maintained databases is an important pre-condition for climate scenario and impact research. This requires making use of innovative data sources (e.g. remote sensing or crowd-sourced data), the ongoing collection of new data, the sustainable maintenance of existing monitoring networks and ideally the availability or recovery of long-term historical data. In general, data suitable for impact modelling should be quality-controlled, standardised, combined with spatially and temporally complementary data, if available, and digitised in an accessible and shareable format in case the data is only available on paper.

Maintaining such databases in the long term requires strong national and local ownership for data collection, processing, and storage. On the other hand, collaboration with international agencies, such as the World Meteorological Organization (WMO), is advised in order to ensure compliance with international standards, the exchange of data and knowledge, and the development of regional capacities.

➔ ***To enhance datasets, a combination of in situ and remote sensing assessments is needed. Available data should be integrated into databases with user-friendly interfaces.***

An important element in the creation of hydrological and meteorological datasets is the interlinking of in situ and remote sensing observations, e.g. through satellites. This is highly important especially in developing countries, where ground-based observational networks often do not cover all regions. Combining various data gathering methods, such as remote sensing and in situ, can lead to significant improvements in observation density, and thus more suitable data for climate impact modelling.

In the long run, one major aim with respect to newly gathered or available data should be their integration into preferably freely accessible databases with user-orientated interfaces. Hence, processing and providing information to interested users (e.g. in the agriculture, energy, water planning, aviation, and education sectors) is one of the most important tasks in this context. This requires strengthening of agency capacities at the national and even regional levels, such as training personnel and improving infrastructure, including in the IT sector. Support for more user-oriented data applications could, for example, be delivered in the form of advice, examples for good practices, as well as warning and forecasting products, including seasonal forecasting. These user-oriented applications should support climate change adaptation planning and the development of cross-sectoral adaptation strategies.

However, even with improved data, some uncertainties about future developments will inevitably remain. This presents challenges for the development of adaptation strategies in water-related sectors and demands appropriate management actions.

3.4 References

Coumou, D., Lehmann J., and Beckmann J. (2015): **The Weakening Summer Circulation in the Northern Hemisphere Mid-latitudes. Science, 348 (6232), 324-327**, DOI: *https://doi.org/10.1126/science.1261768*

García, L.E., Matthews, J.H., Rodriguez, D.J., Wijnen, M.,DiFrancesco, K. N., and Ray, P. (2014): **Beyond Downscaling: A Bottom-Up Approach to Climate Adaptation for Water Resources Management. AGWA Report 01. Washington, DC: The World Bank.**

Gelfan, A., Gustafsson, D., Motovilov, Y., Arheimer, B., Kalugin, A., Krylenko, I., and Lavrenov, A. (2017): **Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues. Climatic Change, 141 (3), 499-515**, DOI: *https://doi.org/10.1007/s10584-016-1710-5*

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z. D., Wada, Y., and Wisser D. (2014): **Global water resources affected by human interventions and climate change. PNAS, 111 (9), 3251-3256**, DOI: *https://doi.org/10.1073/pnas.1222475110*

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Hanasaki, N., Heinke, J., Ludwig, F., Voss, F., and Wiltshire, A. J. (2013): **Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth Syst. Dynam., 4, 129-144**, DOI: *https://doi.org/10.5194/esd-4-129-2013*

Hattermann, F. F., Krysanova, V., Gosling, S. N., Dankers, R., Daggupati, P., Donnelly, C., Flörke, M., Huang, S., Motovilov, Y., Buda, S., Yang, T., Müller, C., Leng, G., Tang, Q., Portmann, F. T., Hagemann, S., Gerten, D., Wada, Y., Masaki, Y., Alemayehu, T., Satoh, Y., and Samaniego, L. (2017): **Cross-scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins. Climatic Change, 141 (3), 561-576**, DOI: *https://doi.org/10.1007/s10584-016-1829-4*

Hattermann, F. F., Vetter, T., Breuer, L., Su, B., Daggupati, P., Donnelly, C., Fekete, B., Flörke, F., Gosling, S. N., Hoffmann, P., Liersch, S., Masaki, Y., Motovilov, Y., Müller, C., Samaniego, L., Stacke, T., Wada, Y., Yang, T., and Krysnaova, V. (2018): **Sources of uncertainty in hydrological climate impact assessment: A cross-scale study. Environmental Research Letters, 13 (1), 015006**, DOI: *https://doi.org/10.1088/1748-9326/aa9938*

IPCC (2013): Climate Change 2013: **The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change** by Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.). **Cambridge/New York: Cambridge University Press.**

IPCC (Intergovernmental Panel on Climate Change) (2014): **Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change**, by Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al.(Eds). Cambridge/New York: Cambridge University Press.

Poff, N. L., Brown, C. M., Grantham, T. E., Matthews, J. H., Palmer, M. A., Spence, C. M., ... and Baeza, A. (2016): **Sustainable water management under future uncertainty with eco-engineering decision scaling.** Nature Climate Change, 6(1), 25.

References

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arneli, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., and Stacke, T. (2014): **Hydrological droughts in the 21st century: hotspots and uncertainties from a global multi-model ensemble experiment. PNAS, 111 (9), 3262-3267**, DOI: *https://doi.org/10.1073/pnas.1222473110*

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... , and Lutz, W. (2017): **The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change, 42, 153-168**, DOI: *https://doi.org/10.1016/j.gloenvcha.2016.05.009*

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F. Warszawski, L., and Kabat, P. (2014): **Multimodel assessment of water scarcity under climate change. PNAS, 111 (9), 3245-3250**, DOI: *https://doi.org/10.1073/pnas.1222460110*

Smith, K. A., Wilby, R. L., Broderick, C., Prudhomme, C., Matthews, T., Harrigan, S., and Murphy, S. (2018): **Navigating Cascades of Uncertainty – As Easy as ABC? Not Quite… Journal of Extreme Events, 5 (1), 1850007**, DOI: *https://doi.org/10.1142/S2345737618500070*

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., et al. (2013): **Ground water and climate change. Nature Climate Change, 3 (4), 322-329**, DOI: *https://doi.org/10.1038/nclimate1744*

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., and Rose, S. K. (2011): **The representative concentration pathways: an overview. Climatic Change, 109** (5), DOI: *https://doi.org/10.1007/s10584-011-0148-z*

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., and Schewe J. (2014): **The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework. PNAS, 111 (9), 3228-3232**, DOI: *https://doi.org/10.1073/pnas.1312330110*

Wilby, R. L., and Dessai, S. (2010): **Robust adaptation to climate change. Weather, 65** (7), **180-185**, DOI: *https://doi.org/10.1002/wea.543*

4. Climate change impacts on hydrology and water resources: global trends

The determination of certain impacts on water resources due to climate change remains one critical challenge for the water sector now and in the future. A broader scientific understanding of what is known and what is unknown with respect to global trends is needed. Therefore, this chapter will reflect on potential temperature and precipitation alterations and associated consequences of their interplay. It will also show that some trends – particularly those concerning precipitation – are not easy to determine, resulting in a variance of possible future changes. The chapter continues with a discussion of projected global trends in temperature and precipitation until the end of the century.

Lastly, an analysis of associated climate impacts on water resources and hydrological extremes (floods and droughts) is performed.

Key Messages of Chapter 4

- The water cycle is an essential part of the climate system, and therefore very sensitive to climate variability and change. Empirical evidence shows that seemingly insignificant variations in climate patterns often lead to significant changes in hydrological flows and regional water availability.
- While most GCM projections agree regarding an expected increase in temperature, the direction of the precipitation trend (negative or positive) is unclear for large parts of the world.
- Temperature rise leads to enhanced evapotranspiration, potentially increasing pressure on local water resources – even in regions with increasing amounts of precipitation.
- Climate change might lead to a severe decrease in water availability: An additional 40% of people might suffer from absolute water scarcity due to the impacts of climate change at a global warming of 2°C above present, compared with the effects of population growth alone.
- Trends in hydro-climatic extremes and climate variability can be more robust (higher model agreements) with regard to their trend direction, often indicating an increase in droughts.
- In some regions, groundwater storage has the potential to reduce the pressure on surface water resources, if withdrawals stay below recharge rates. However, groundwater storage is also affected by a changing climate, thus, expected impacts on renewable groundwater resources can be significant.

4.1 Trends in global temperature and precipitation

The following simulations on temperature and precipitation build upon the consideration of RCPs, which were introduced in the previous chapter. Based on RCP2.6 and RCP8.5, the simulations show that there is little disagreement regarding temperature increases simulated by different Global Climate Models (GCMs) under specific scenario conditions. However, similar agreement on trend direction is not perceivable regarding precipitation changes. Consequently, there is much more variability and uncertainty in projecting precipitation trends. *Figures 5 on the right* and *Figure 6 on page 46* provide more detail on mean temperature and precipitation trends until the end of the century, based on RCP2.6 and RCP8.5.

➔ ***The direction of the precipitation trend (less or more precipitation) is unclear for large parts of the world.***

For only about 66% of land surface area, at least 80% of precipitation projections agree on the direction of the trend under high-GHG concentration conditions (RCP8.5, *see Figure 5 on the next page* under low-concentration conditions (RCP2.6, *see Figure 6 on page 46*), similar levels of agreement can only be seen for 19% of the land surface area. Nevertheless, an increase in precipitation dominates generally for both scenarios. However, many of the world's largest river basins are located in regions in which precipitation trends do not match up in magnitude, or even show opposing trends, for example the Niger or the Amazon (*see Chapter 5*).

➔ ***Overall, if climate change is kept at a moderate level, impacts on precipitation will be less pronounced.***

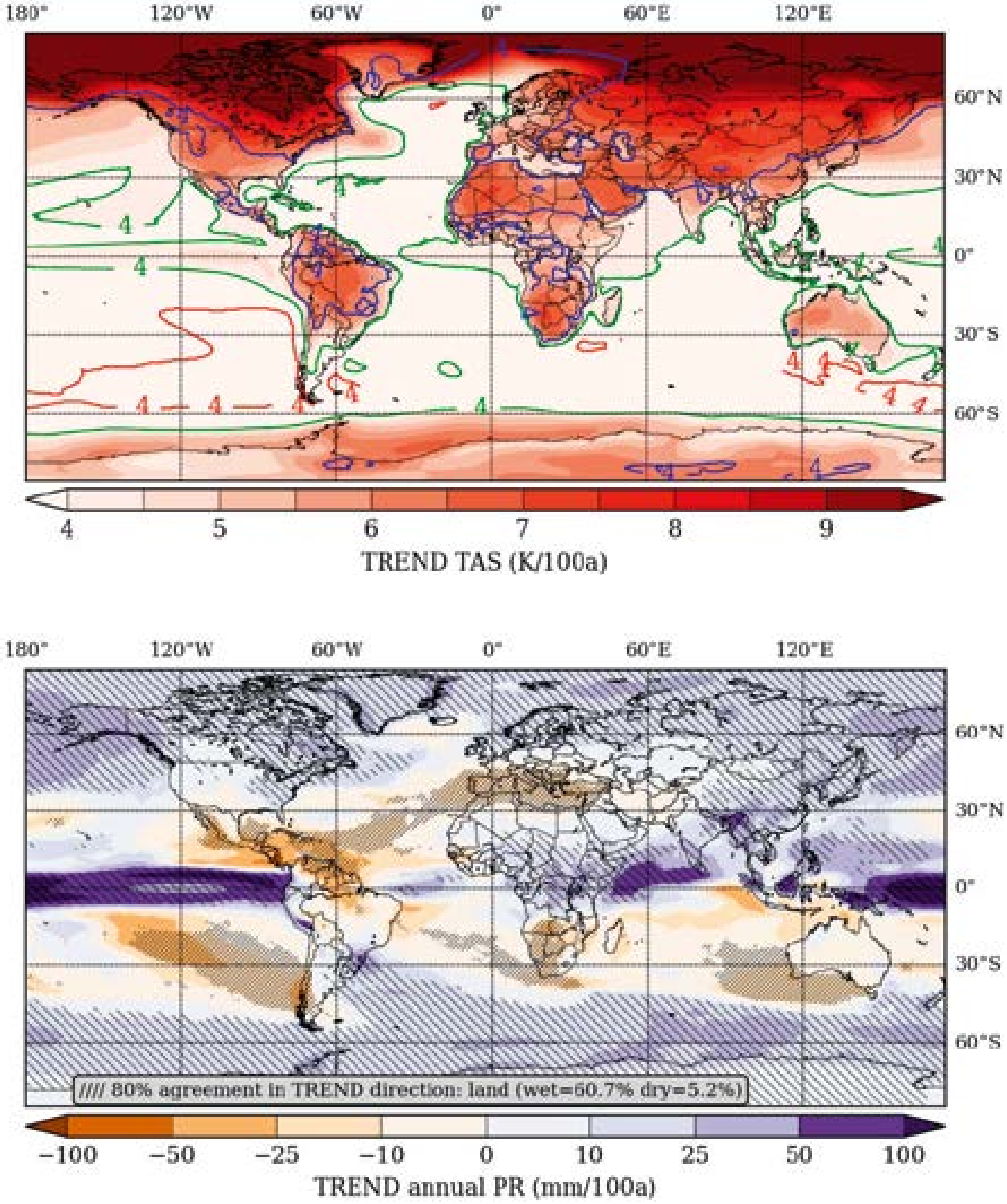
Regardless of these challenges associated with the determination of trends, a general statement in terms of prospective alterations is possible: Impacts on temperature and precipitation are expected to be less pronounced if climate change is kept at a moderate level, that is, if it follows an RCP2.6 concentration scenario, instead.

In addition, further global key trends on temperature and precipitations can be observed:

- By the end of the century, the global temperature might increase by another 1°C compared to the current state under the most optimistic projections (RCP2.6), and by another 6°C in the most pessimistic scenario (RCP8.5).
- In general, a temperature increase is more distinct in high latitudes and high mountain and dryland areas, and less pronounced in the tropics and over water surfaces.
- Precipitation trends are mostly positive due to the intensification of the water cycle, as more radiative forcing leads to more energy in the hydro-climatic system.
- Higher precipitation does not necessarily translate into enhanced water availability, because more precipitation can be compensated by an increase in evapotranspiration reinforced by warmer temperatures.

➔ ***To enhance datasets, a combination of in situ and remote sensing assessments is needed. Available data should be integrated into databases with user-friendly interfaces.***

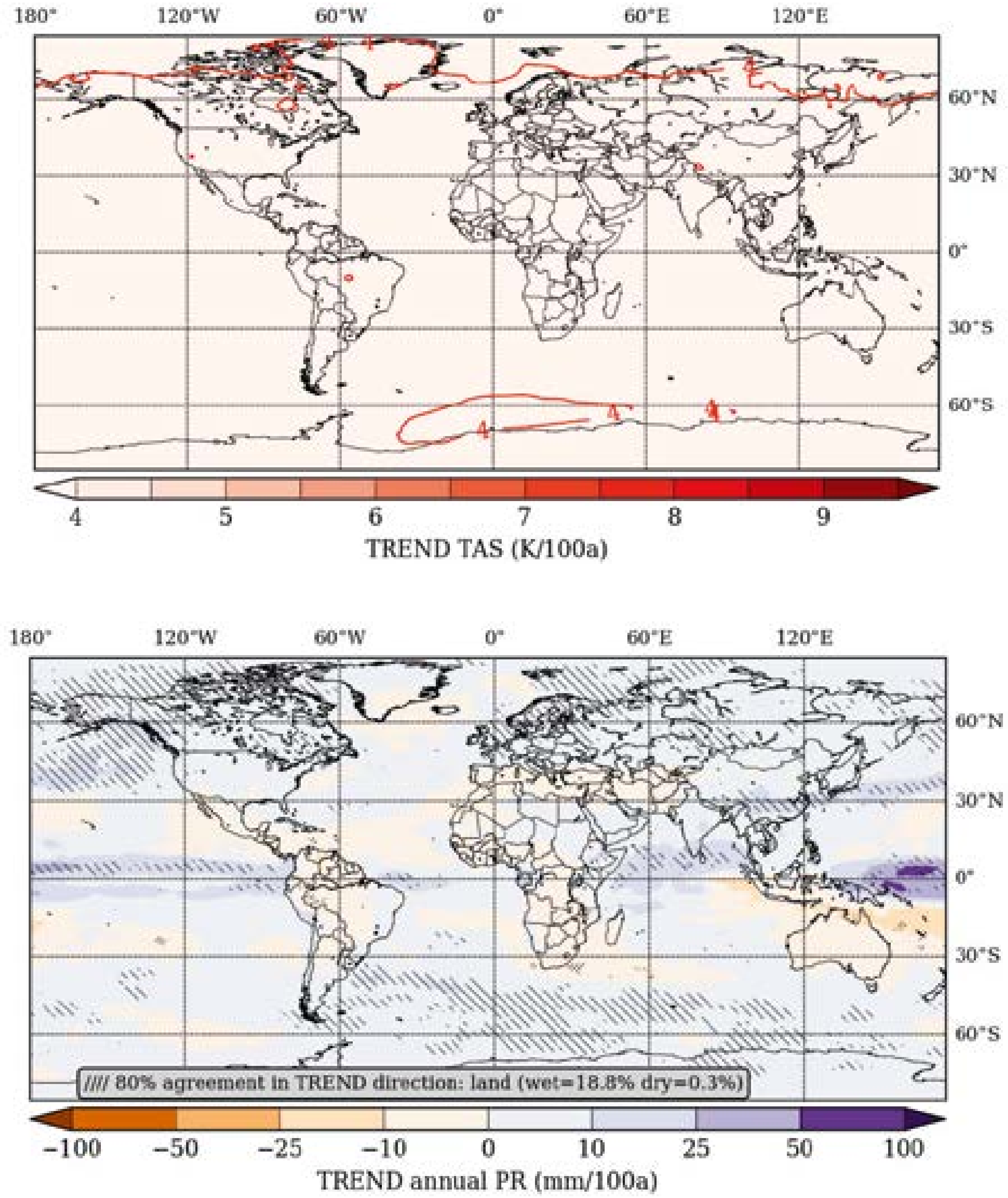
CMIP5 GCM ENSEMBLE MEAN TREND (RCP 8.5), 2006–2100, Global average: 6.3 K/100a



In the upper graphic, green lines encircle areas, for which the mean of the model ensemble projects a warming rate of 4 K / 100a, while red and blue lines refer to the single warmest and coldest model of the ensemble. In the lower graphic, shaded areas indicate where at least 80% of the model ensemble agrees in the direction of the trend (\\\ indicates positive, /// negative trend).

Figure 5: Mean trend in average annual temperature and average annual precipitation until the end of this century under RCP8.5 (high radiative forcing and temperature increase) (Data processed at Potsdam Institute for Climate Impact Research).

CMIP5 GCM ENSEMBLE MEAN TREND (RCP 2.6), 2006–2100, Global average: 1.0 K/100a



Same illustration features as *Figure 5*

Figure 6: Mean trend in average annual temperature and average annual precipitation until the end of this century under RCP2.6 (low radioactive forcing and temperature increase) – Data processed at Potsdam Institute for Climate Impact Research.

4.2 Global-scale trends in per capita water availability

From a global perspective, a key takeaway of most reports and publications on climate change impacts on water is that climate change might eventually lead to a severe decrease in water availability, thereby increasing the number of people living under absolute water scarcity (see, for example, IPCC, 2013; World Bank, 2014).

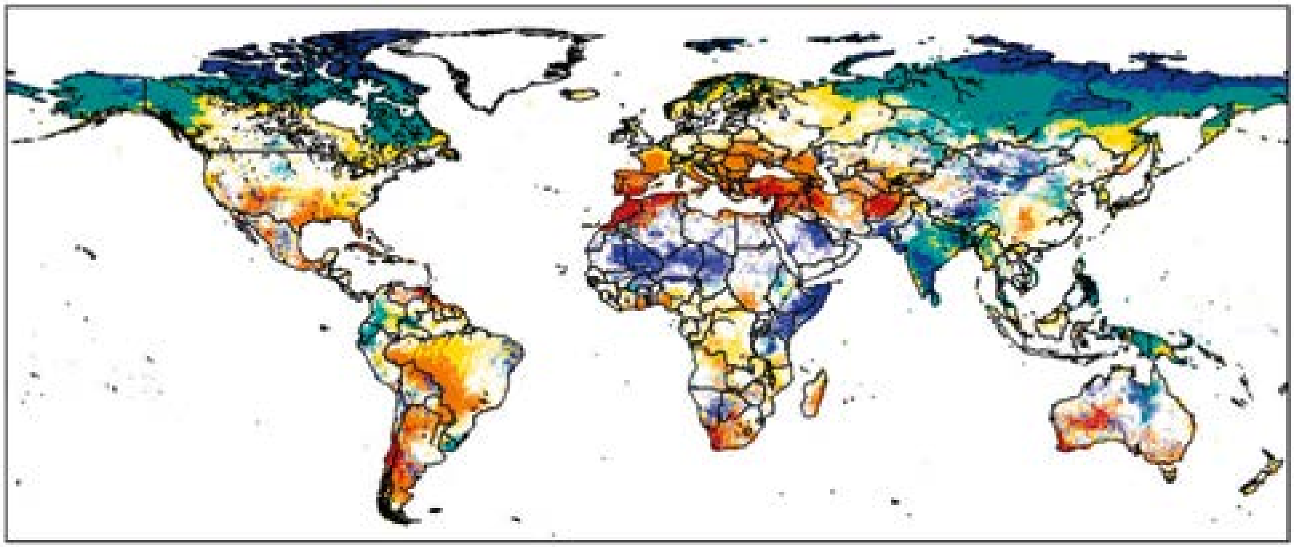
A comprehensive global assessment of future water availability that considers changing water demand due to population growth under climate change is presented in Schewe et al., 2014. The authors use a large ensemble of GHMs provided by the ISIMIP project, which were driven by five GCMs and the RCPs to synthesize current knowledge on climate change impacts on water resources and availability. Population dynamics were considered according to the Shared Socioeconomic Pathways (SSPs).

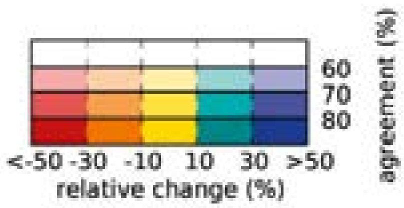
➔ ***An additional 40% of people might suffer from absolute water scarcity due to the impacts of climate change at a global warming of 2°C above present.***

Their model ensemble average projects that a global warming of 2°C above present (approximately 2.7°C above preindustrial) conditions will mean that an additional 15% of the global population might face a severe decrease in water resources, and that 40% more people might live under absolute water scarcity (< 500 m^3 per capita per year) compared with the effect of population growth alone (ibid.). In the event of unmitigated climate change beyond 2°C, the negative impacts are even more profound. This is in line with the findings of other recent publications (see e.g. Döll et al., 2018).

In conclusion, climate change – in combination with expected future population growth – might significantly increase the pressure on available water resources on a global scale. Therefore, climate change is expected to exacerbate water scarcity in many regions worldwide (*see Figure 7*).

Nonetheless, current research highlights large uncertainties associated with such estimates on future conditions, as already discussed in the previous chapter (*see Chapter 3.2 and Figure 3*).





Color hues show the multimodel mean change, and saturation shows the agreement on the sign of change across all GHM–GCM combinations (Schewe et al., 2014)

Figure 7: Relative change in per capita water availability when 2°C temperature increase is reached, compared with present-day temperatures, under RCP8.5.

➔ Groundwater storage is affected by a changing climate, thus, expected impacts on renewable groundwater resources can be substantial.

The impacts of climate change on renewable groundwater resources are expected to be significant (Portman et al., 2013). To date, several investigations have been undertaken at different geographical locations and at different spatial scales to assess the vulnerability of groundwater resources to the direct and indirect impacts of climate change. However, researchers still know little about the impacts of climate change on groundwater recharge, and regional projections are uncertain (Aslam et al., 2018).

Groundwater resources have the potential to reduce the impact of surface water deficits by providing water, for instance, for domestic or agricultural use when surface water is insufficiently available (Kundzewicz and Döll, 2009). For regions with enough consumable (e.g. fresh and high-quality) groundwater, groundwater resources provide a secure source of water, so long as the amount withdrawn is less than the level of groundwater recharge.

According to Kundzewicz and Döll (2009), withdrawals are likely to increase in areas where surface water becomes scarcer (including as a result of climate change), thus decreasing consumable groundwater resources, such as in northeastern Brazil, southwestern Africa, and the Mediterranean region. In addition, overpumping and sea level rise may contribute to saltwater intrusion, thereby limiting the usability of groundwater resources in coastal regions. Already today, groundwater storage is of strategic importance to global water and food security. Its role will probably become even more important under climate change, as more frequent and intense climate extremes (droughts and floods) are associated with an increase in the variability of precipitation, and consequently, surface water availability (Taylor et al., 2013).

Reducing GHG emissions would incur substantial benefits to renewable groundwater resources. Estimates show that the share of the population suffering from water scarcity due to moderately decreasing groundwater recharge by the end of the century is 24% under RCP2.6, compared with 38% under RCP8.5. At the same time, the share of the population spared from any significant changes in groundwater recharge would be 47% (RCP2.6) compared with 29% (RCP8.5) (Portmann et al., 2013). Despite this correlation between GHG concentrations and groundwater recharge, projection uncertainties remain significant, and depend on socio-economic aspects. However, one robust result of Portmann et al. across all employed GCMs is that severe decreases of groundwater recharge (more than 30%) would especially affect dryland regions and, therefore potentially aggravate droughts.

4.3 Global-scale trends in droughts

Climate change will almost certainly lead to an increase in water shortages and severe droughts at the global level (IPCC, 2013; World Bank, 2014; Döll et al., 2018). An ISIMIP- related study by Prudhomme et al. (2014) investigates droughts (defined here as runoff shortage, e.g., instances in which total runoff remains below a given threshold), their hotspots, and related uncertainties. The authors projected a likely increase in the frequency of droughts for most parts of the globe by the end of the twenty-first century, with effects being more pronounced under higher emission scenarios (*see Figure 8*). In addition, nearly half of the considered model simulations under RCP8.5 projected that hydrological droughts could exceed more than 40% of the analysed land area.

➔ Some water-scarce areas might experience even more profound water insecurity in the future due to climate change impacts.

The robustness of the multi-model ensemble, i.e. the degree to which the models agree in their projections, varies across the globe. While for most regions there is a high degree of uncertainty in the projections, some areas with more robust results can be identified. This includes the Mediterranean area, the Middle East, the southeastern United States, Chile, and southwestern Australia – all possible hotspots for a future increase in days under hydrological drought conditions (Prudhomme et al., 2014). Consequently, profound water security issues may arise in some regions that already suffer from droughts. The extent of associated climate impacts will depend in part on water governance structures and regionally specific adaptation options (*see Chapters 5 and 6*).

Moreover, there are also some regions in which the number and/or severity of droughts may decrease, for example in parts of eastern Africa, Siberia, and the northernmost region of North America (*see Figure 8*). This can possibly be explained by the increase in precipitation in these areas; still, projections remain associated with a high degree of uncertainty (Liersch et al., 2018).

Year mean change

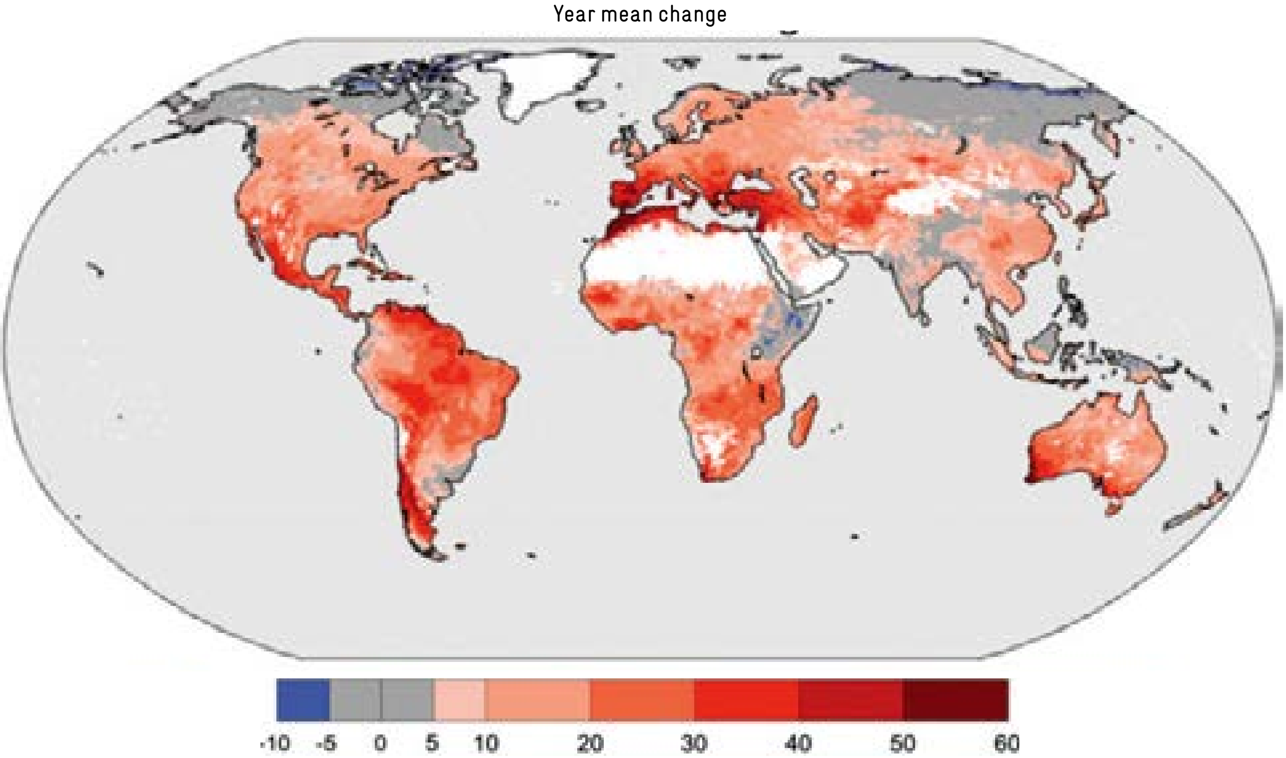


Figure 8: Percentage change of the number of days under hydrological drought conditions for the period 2070–2099 relative to 1976–2005. The figure shows the average of a multimodel ensemble under RCP8.5, with five GCMs and seven GHMs (Courtesy Prudhomme et al., 2014)

Q30 mean change

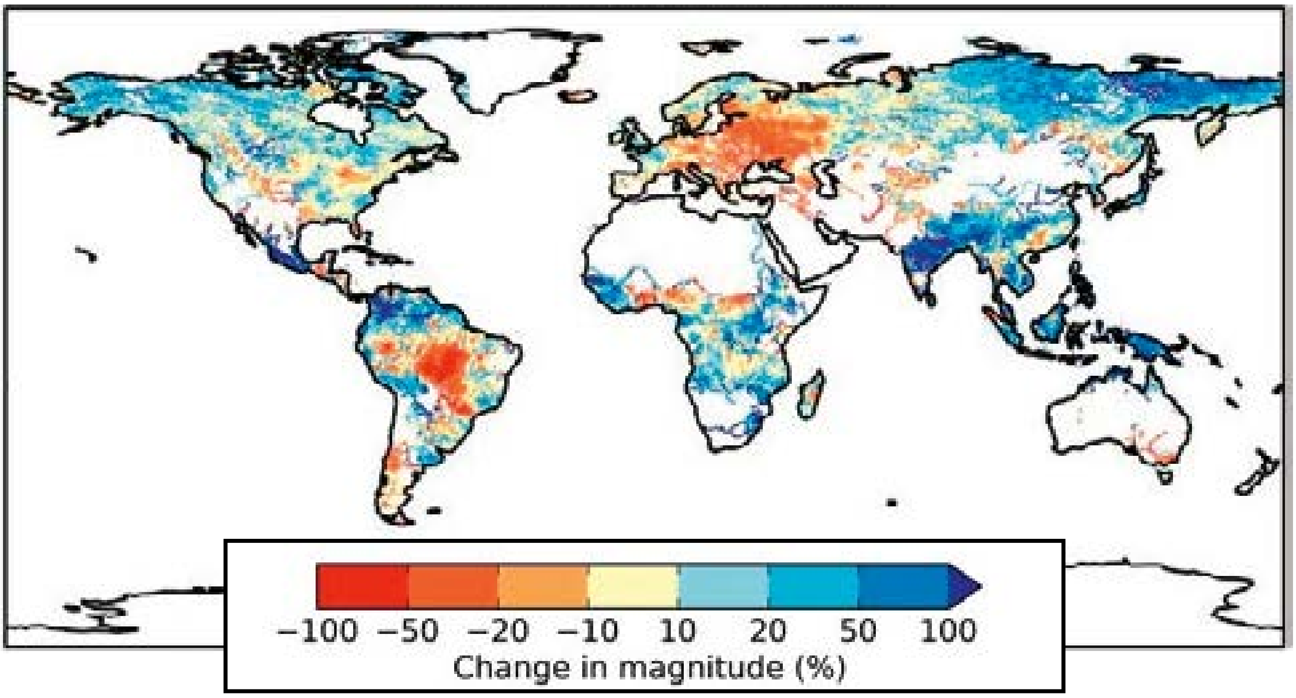


Figure 9: Global changes in discharge levels of moderate floods occurring, on average, every 30 years (Q30) in 2070–2099 under RCP8.5, compared with 1971–2000 (Courtesy of Dankers et al., 2014)

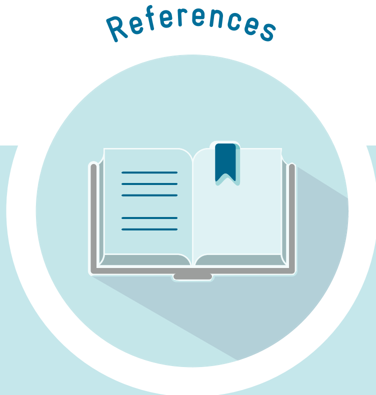
4.4 Global-scale trends in floods

Recent research suggests that climate change will lead to an increase in flood hazards globally (Hirabayashi et al., 2013; Dankers et al., 2014; Willner et al., 2018). Changes in flood hazards-based on ISIMIP simulations – are shown in *Figure 9 on the previous page*, obtained from Dankers et al. (2014). In their analysis, the authors looked at five-day peak flow levels occurring, on average, every 30 years (a quantifier for a moderate flood), and quantified changes in this flood level until the end of the twenty-first century under the RCP8.5 scenario.

From a regional perspective, climate change will not increase flood hazards everywhere. In fact, decreases in the magnitude and frequency of floods occur on roughly one-third (20-45%) of global land surface, particularly in areas where floods are generated mainly through spring snow melts. In most of the model runs, however, an increase in 30-year flood magnitudes was found for more than half of the globe.

An increase in flood hazard does not necessarily lead to an equal increase in flood risk. Flood risk is the combination of flood hazard and exposure and, as such, regions with only moderate flood hazards but high exposure (e.g. large cities in low-lying, flood-prone areas) exhibit a large flood risk, and vice-versa. Willner et al. (2018) used the results of the ISIMIP GHMs to calculate the increase in flood protection that is required to keep river flood risk at present levels. They analysed how flood hazards and, consequently, the required adaptation efforts evolve due to climate change, in comparison to the present state. The analysis was carried out worldwide for sub-national administrative units. They report that strong adaptation efforts are required in (most of) the United States, Central Europe, northeastern and western Africa, and large parts of India and Indonesia. Thus, the need for adaptation against increasing river floods is a global problem, affecting both industrialised and developing countries.

As mentioned before, flood projections by GHMs are associated with strong uncertainty, mostly because both GCMs and GHMs often have problems reproducing the relevant features that lead to flooding (Kundzewicz et al., 2017). For example, the projections presented in Dankers et al. (2014), which use a combination of GCMs and GHMs, show ambivalent trends of moderate floods for Central Europe. However, the projections by Hattermann et al. (2018), which use an ensemble of regional climate models in combination with RHMs, show stronger and mostly positive trends for the same region.



4.5 References

Aslam, R. A.; S. Shrestha, Pandey V. P. (2018): **Groundwater vulnerability to climate change: A review of the assessment methodology. In: Science of The Total Environment 612, pp. 853–875** DOI: *https://doi.org/10.1016/j.scitotenv.2017.08.237*

Dankers, R., Arneli, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D. (2014): **First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. PNAS, 111 (9), 3257-3261**, DOI: *https://doi.org/10.1073/pnas.1302078110*

Döll, P., Trautmann, T., Gerten, D., Müller Schmied, H., Ostberg, S., Saaed, F., and Schleussner, C.-F. (2018): **Risks for the global freshwater system at 1.5 °C and 2 °C global warming. Environmental Research Letters, 13 (4), 044038**, DOI: *https://doi.org/10.1088/1748-9326/aab792*

Hattermann, F. F., Wortmann, M., Liersch, S., Toumi, R., Sparks, N., Genillard, C., Schröter, K., Steinhausen, M., Gyalai-Korpos, M., Máté, K., Hayes, B., del Rocío Rivas López, M., Rácz, T., Nielsen, M. R., Kaspersen, P. S., and Drews, M. (2018): **Simulation of flood hazard and risk in the Danube basin with the Future Danube Model, Climate Services, 12, 14-26**, DOI: *https://doi.org/10.1016/j.cliser.2018.07.001*

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

IPCC (Intergovernmental Panel on Climate Change) (2013): **Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change by Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.). Cambridge/New York: Cambridge University Press.**

Kundzewicz, Z.W., Krysanova, V., Dankers, R., Hirabayashi, Y., Kanae, S., Hattermann, F.F., Huang, S., Milly, P.C.D., Stoffel, M., Driessen, P.P.J., Matczak, P., Quevauviller, P., and Schellnhuber, H.-J. (2017): **Differences in flood hazard projections in Europe–their causes and consequences for decision making. Hydrological Sciences Journal, 62 (1), 1-14**, DOI: *https://doi.org/10.1080/02626667.2016.1241398*

Kundzewicz, Z. W., and Döll, P. (2009): **Will groundwater ease freshwater stress under climate change? Hydrological Sciences Journal, 54 (4), 665-675**, DOI: *https://doi.org/10.1623/hysj.54.4.665*

Liersch, S., Tecklenburg, J., Rust, H., Dobler, A., Fischer, M., Kruschke, T., Koch, H., and Hattermann, F. F. (2018): **Are we using the right fuel to drive hydrological models? A climate impact study in the Upper Blue Nile. Hydrology and Earth System Sciences, 22 (4), 2163-2185**, DOI: *https://doi.org/10.5194/hess-22-2163-2018*

Portmann, F. T., Döll, P., Eisner S., and Flörke M. (2013): **Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. Environmental Research Letters, 8 (2), 024023**, DOI: *https://doi.org/10.1088/1748-9326/8/2/024023*

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arneli, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., and Stacke, T. (2014): **Hydrological droughts in the 21st century: hotspots and uncertainties from a global multi-model ensemble experiment. PNAS, 111 (9), 3262-3267**, DOI: *https://doi.org/10.1073/pnas.1222473110*

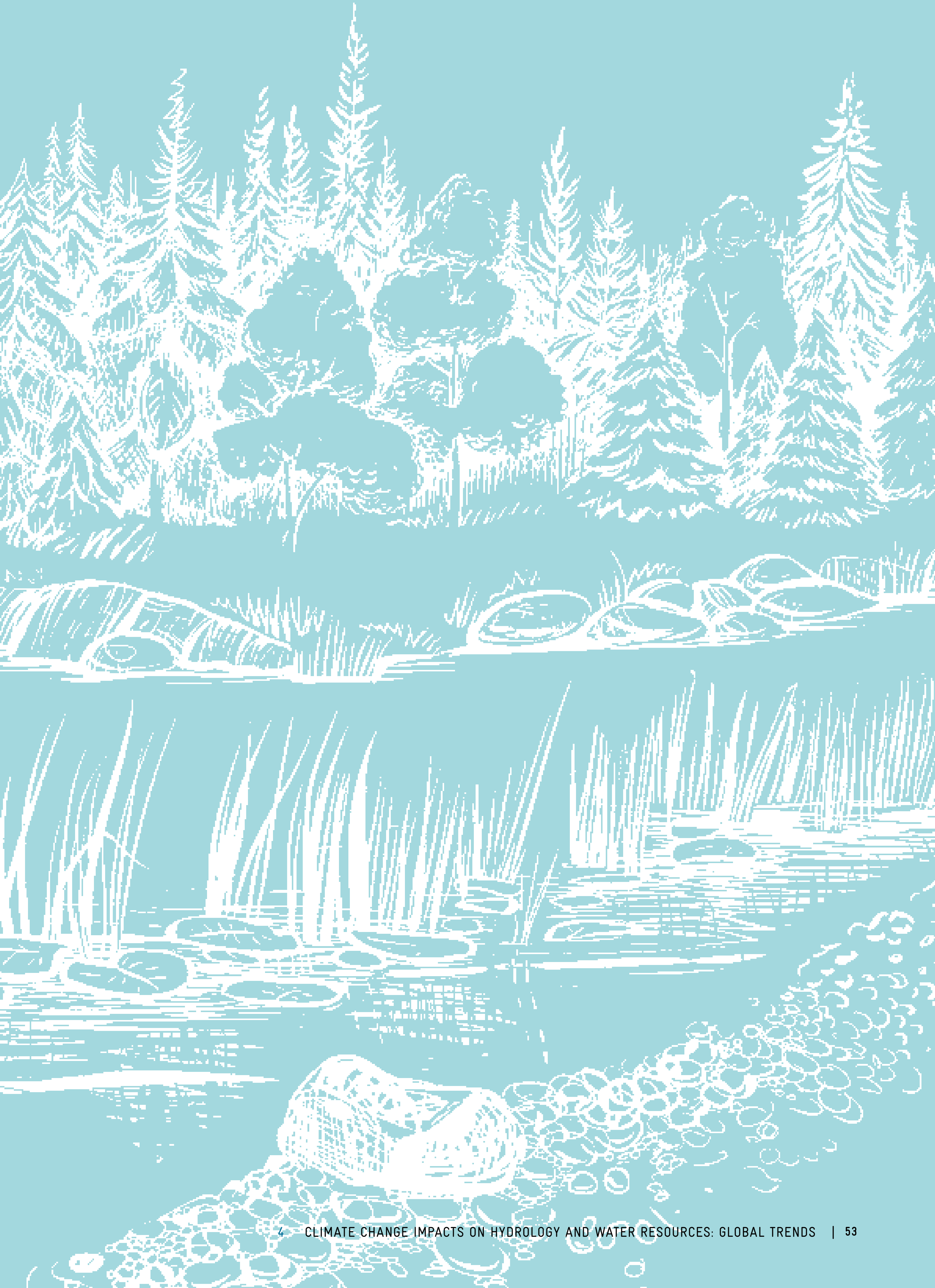
References

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F. Warszawski, L., and Kabat, P. (2014): **Multimodel assessment of water scarcity under climate change. PNAS, 111 (9), 3245-3250**, DOI: *https://doi.org/10.1073/pnas.1222460110*

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., et al. (2013): **Ground water and climate change. Nature Climate Change, 3 (4), 322-329**, DOI: *https://doi.org/10.1038/nclimate1744*

Willner, S. N., Levermann, A., Zhao, F., and Frieler, K. (2018): **Adaptation required to preserve future high-end river flood risk at present levels. Science Advances, 4 (1), eaao1914**, DOI: *https://doi.org/10.1126/sciadv.aao1914*

World Bank (2014): **Turn Down the Heat: Confronting the New Climate Normal. Washington, DC: The World Bank**.



5. Climate change impacts on hydrology and water resources: regional case studies

The previous chapters presented and discussed the impacts of climate change on water resources and extremes mostly on a larger geographic scale. The focus of this chapter lies in six specific river basins, namely: the Blue Nile, Ganges, Upper Amazon, Upper Niger, Limpopo, and Tagus. The chapter describes the case study areas, as well as the projected impacts of climate change on water resources. The above basins were selected in a way that represents different continents and climate zones, most of them in developing and emerging regions, with a specific focus on Africa.

Analysed catchment areas are projected to experience different impacts from climate change on water availability, water-related activities, and extremes. Morever, they are affected by human interventions to different degrees. For instance, the Upper Amazon is still relatively unaffected by human regulations and land-use changes. In contrast, the Limpopo, Tagus, and Ganges basins are partly regulated by dams, reservoirs, irrigation, and land management. Such human influences are partly, though not fully, considered in below model setups.

Key Messages of Chapter 5

- Temperature is expected to increase towards the end of the century in all case study areas. Unlike the other basins, strong seasonal differences in temperature increase are projected for the Tagus basin.
- Precipitation is projected to increase in the Blue Nile and Ganges basins. For the Upper Amazon and Upper Niger, trends are unclear, while for the Limpopo and Tagus, trends are negative.
- There is a large variability in the models' projections for river discharge. It is more likely to decrease in the Tagus basin, and to increase in the Ganges area. Trends for the other basins are less distinct.
- Peak discharge, as a measure of flood risk, is likely to decrease in the Tagus and Limpopo basins. Increases in peak discharge seem more likely in the other basins. Droughts are expected to become more frequent, and/or more severe in the Tagus, Limpopo, and Upper Niger basins.
- Climate variability, including more heavy rainfall and longer dry spells, and seasonal shifts are projected to be most relevant for the Upper Niger and Upper Amazon basins.
- All projections on temperature, precipitation, river discharge, and floods are more pronounced towards the end of the century.

Regional impacts of climate change on the water sector are diverse

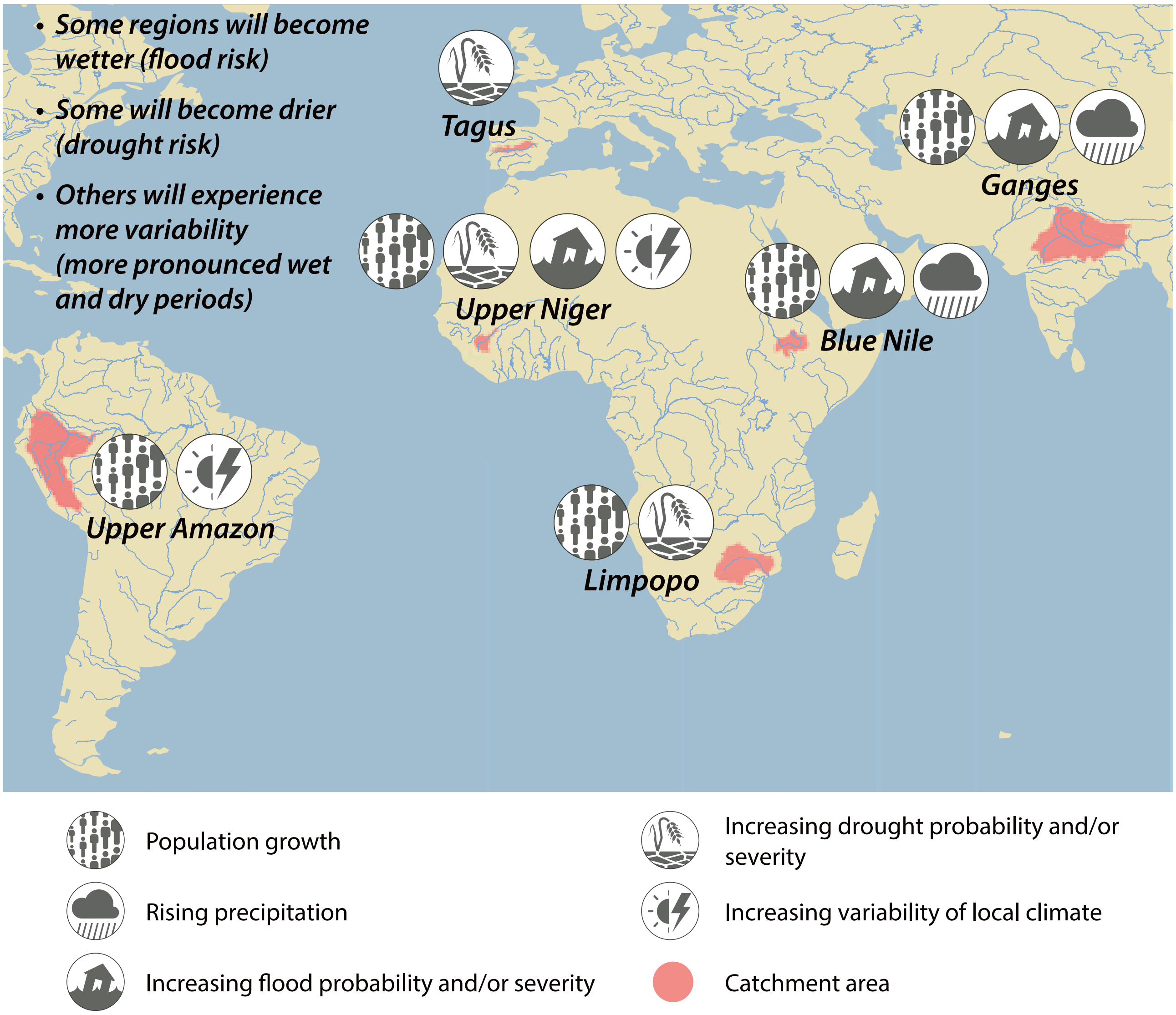


Figure 10: Location of the six case study areas together with the projected changes for the local water sectors towards the end of the twenty-first century

5.1 Blue Nile

The Upper Blue Nile is the Ethiopian segment of the Blue Nile (*Figure 11*). It is the second-longest tributary to the Nile River (after the White Nile). Yet, it contributes up to 80% of the mean annual discharge to the combined Nile, which enters Egypt.

The source of the Blue Nile is Lake Tana and its tributaries. From Lake Tana, the Blue Nile flows across northwestern Ethiopia through numerous incised valleys and canyons, and crosses the border to Sudan at El Diem.

The Blue Nile was selected as a case study because of its importance for water availability in the downstream countries, mainly Sudan, Egypt, and Ethiopia itself. In 2011, Ethiopia started building a dam at the outlet of the river to Sudan, the Grand Ethiopian Renaissance Dam (GERD). Once completed, it will be the largest hydroelectric power plant in Africa, and the seventh-largest in the world, with a very strong impact on the downstream flow regime. Major influences on the hydrological regime of the catchment area are a distinct topography and a wide range of climatic conditions.

The altitude within the basin ranges from 4050 m.a.s.l. in the Ethiopian highlands, to 500 m.a.s.l. at the outlet at El Diem. At the selected gauge, it comprises an area of 240,000 km^2. Apart from the influence of the landform, the effects of the summer monsoon determine the climate in the basin.

Annual precipitation ranges from 1077 mm/yr to over 2000 mm/yr in the highlands, with an average of 1400 mm/yr and an average temperature of 19.4 °C (Conway, 2000). Only a small share of precipitation is converted into river flow (11%). The main type of land use is cropland (58%), followed by heather (26%), and bare soil (5%).

Climate change impact summary: The analysis of climate change impacts shows a robust signal towards higher precipitation and discharge (*Table 2 and Figure 12 on the next page*). In addition, most models project higher levels of extreme floods (*Figure 13 on the next page*). Droughts do not seem to be an issue for this region.

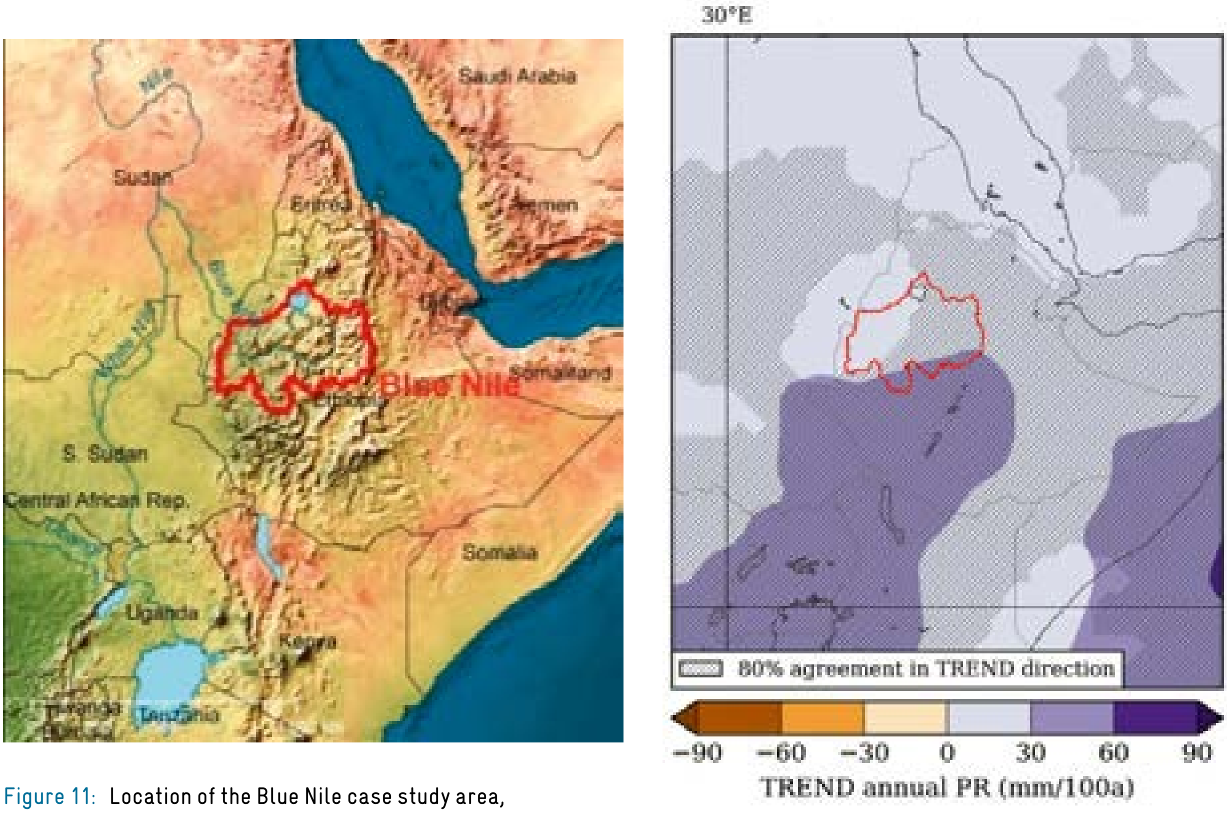


Figure 11: Location of the Blue Nile case study area, with projected spatial trends in precipitation until the end of the twenty-first century

Table 2: **Baseline conditions and projected changes in hydrological and climatological indices for the Blue Nile basin.** Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential evapotranspiration is derived from hydrological model simulations (ISIMIP dataset). RCP values are projected changes relative to baseline obtained from GCM runs of the CMIP5 project (temperature, precipitation), and hydrological models from ISIMIP. Small inconsistencies in the figures can result from the use of these different sources.

Years	1971 – 2000	2071 – 2100	
	Baseline	RCP2.6	RCP8.5
Temperature (°C)	19.40	+1.33	+4.23
Precipitation (mm per year and % change)	1405	+5.31%	+11.58%
Potential evapotranspiration (mm per year and % change)	1221	+7.00%	+21.00%
Actual evapotranspiration (mm per year and % change)	1292	+8.00%	+19.00%
River discharge (mm per year and % change)	113	+10.70%	+27.90%

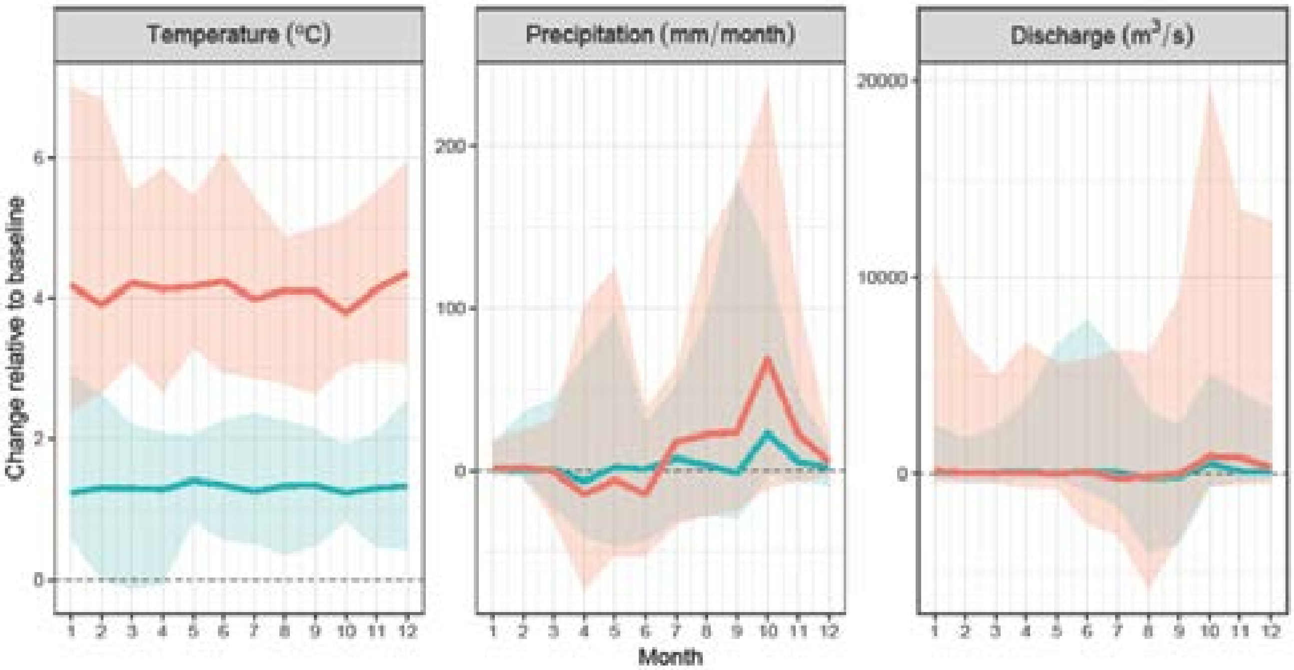
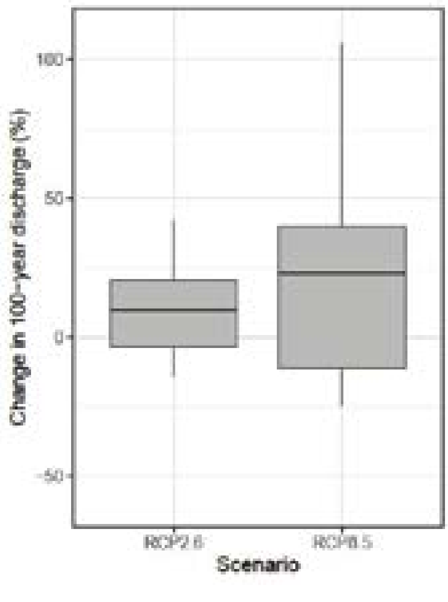


Figure 12: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

Figure 13: (right) Projected change in 100-year discharge levels for the period 2071-2099, relative to 1971-2000. Data derived from the ISIMIP data set.



5.2 Ganges

The Ganges rises in the western Himalayas in the Indian state of Uttarakhand and flows south and east through the Gangetic Plain of North India into West Bengal (Bangladesh, *Figure 14*). A significant portion of discharge from the Ganges originates in the Himalayan mountains, which have a high mountainous climate, with water stored in glaciers and snow during winter. Meanwhile, the lower parts of the Ganges are influenced by the Indian monsoon and are located in sub-tropical to tropical climates.

The average precipitation amount is about 1200 mm/yr, and temperatures are high, at 21.1°C. The Ganges is the most important river of the Indian sub-continent. Its fertile soils are essential to the agricultural economies of India and Bangladesh. Nearly 95% of the original natural vegetation in the Ganges basin has been replaced by human land use, mainly through agriculture, but also through urban areas. Therefore, the main type of land use is cropland (77%), followed by grassland (10%), and forest (3%).

A major barrage was built in 1975 close to the point at which the Ganges enters Bangladesh, and its water flow management was laid out in the 1996 Indo-Bangladesh Ganges Water Treaty. Temperatures in the Himalayas seem to rise faster than the global average, and the Tibetan glaciers seem to retreat at a higher speed. These glaciers are a vital lifeline for Asian rivers, including the Indus and the Ganges, and their retreat is a major concern for the water supply and hydrological regimes in the region. Therefore, the Ganges has been selected down to gauge Farakka, draining an area of more than 800,000 km², as a case study.

Due to high precipitation and water from the Himalayan mountains, the share of precipitation converted into river flow is moderately high (40%).

Climate change impact summary: Like the Blue Nile, the Ganges is located in an area with robust projections towards increasing precipitation, which will likely result in more seasonal discharge and, hence, enhanced annual water availability (*Table 3 and Figure 15 on the next page*).

There are indications that the overall variability might also increase, meaning there could be more droughts in some parts of the basin. At the same time, almost all considered models point towards strongly increased levels of extreme floods, which might pose a serious issue towards the end of the twenty-first century (*Figure 16 on the next page*).

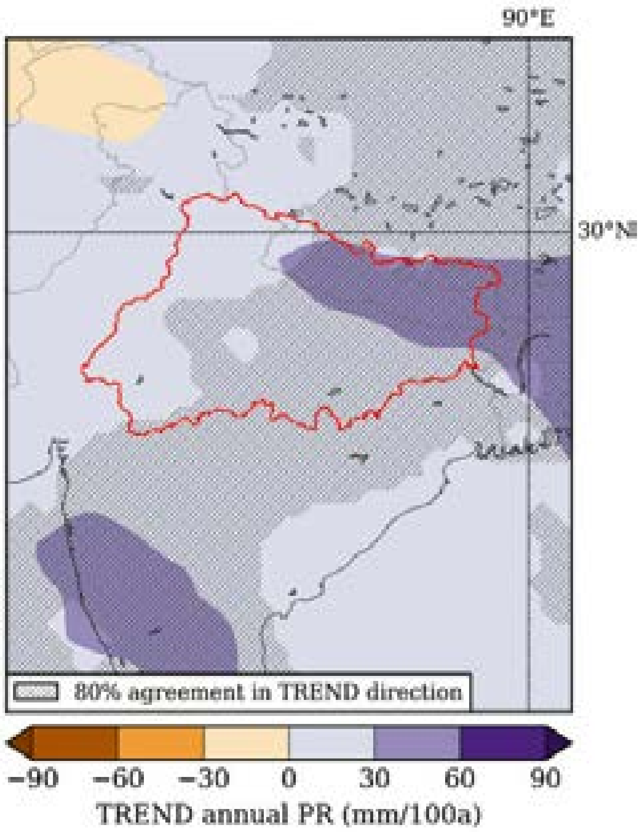


Figure 14: Location of the Ganges case study area, with projected spatial trends in precipitation until the end of the twenty-first century

Table 3: **Baseline conditions and projected changes in hydrological and climatological indices for the Ganges basin.** Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential evapotranspiration is derived from hydrological model simulations (ISIMIP dataset). RCP values are projected changes relative to baseline obtained from GCM runs of the CMIP5 project (temperature, precipitation), and hydrological models from ISIMIP.

Years	1971 – 2000	2071 – 2100	
	Baseline	RCP2.6	RCP8.5
Temperature (°C)	21.10	+1.48	+4.83
Precipitation (mm per year and % change)	1173	+5.66%	+13.65%
Potential evapotranspiration (mm per year and % change)	1515	+8.00%	+20.00%
Actual evapotranspiration (mm per year and % change)	702	+7.00%	+10.00%
River discharge (mm per year and % change)	471	+16.10%	+31.50%

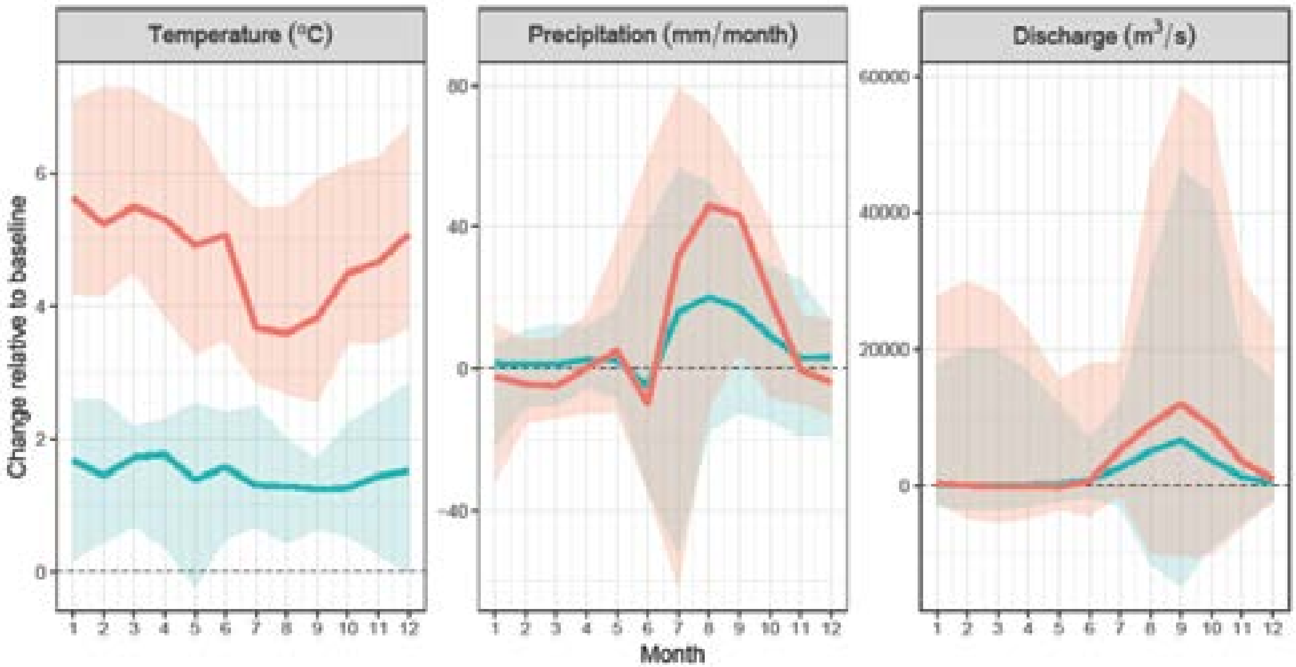
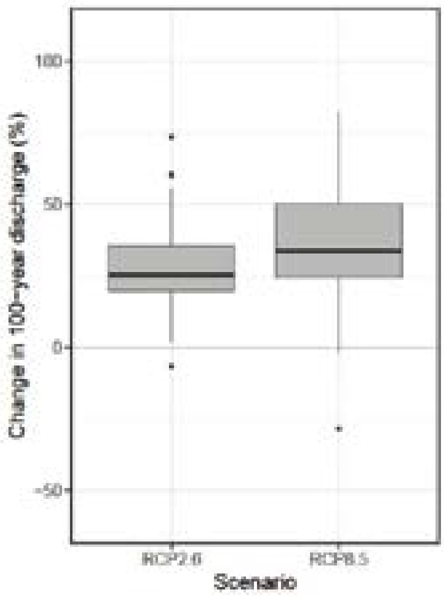


Figure 15: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

Figure 16: (right) Projected change in 100-year discharge levels for the period 2071-2099, relative to 1971-2000. Data derived from the ISIMIP data set.



5.3 Upper Amazon

The headwaters of the Amazon are located in the Andes, at an elevation range of almost 6600 m, with 40% of the area lying above 500 m.a.s.l (*Figure 17*).

While tropical rainforest dominates the Amazonian lowlands, the Andean region is highly diverse in terms of vegetation, with montane forests in lower altitudes, and both shrublands and montane grasslands dominating in higher altitudes. Precipitation regimes vary across latitudes and timescales, and are influenced by large-scale meteorological phenomena, such as the South American Monsoon System (SAMS), and the El Niño Southern Oscillation (ENSO). The lower northern and north-eastern parts of the basin receive a relatively high level of rainfall, on average more than 3000 mm yr-1. The rainfall peak (>3500 mm yr-1) lies at a mean elevation of 1300 ± 170 m.a.s.l. along the eastern slopes of the Andes.

The long-term mean annual precipitation over the Upper Amazon until the gauge of São Paulo de Olivença in the period 1981-2010 was 2204 mm, of which 1476 mm, or 67%, ran off as streamflow. Peru is planning to build dams and reservoirs in its headwaters, while land-use change, mainly deforestation, is another major concern.

Climate change impact summary: Annual precipitation levels are projected to increase slightly in the headwaters of the Amazon. However, evapotranspiration will also increase, and the projections indicate a seasonal shift (*Table 4 and Figure 18 on the next page*). Consequently, it remains uncertain whether annual water availability will increase. There are some indications that, under stronger global warming, the number and severity of droughts may increase, as will the severity of floods (*Figure 19 on the next page*).

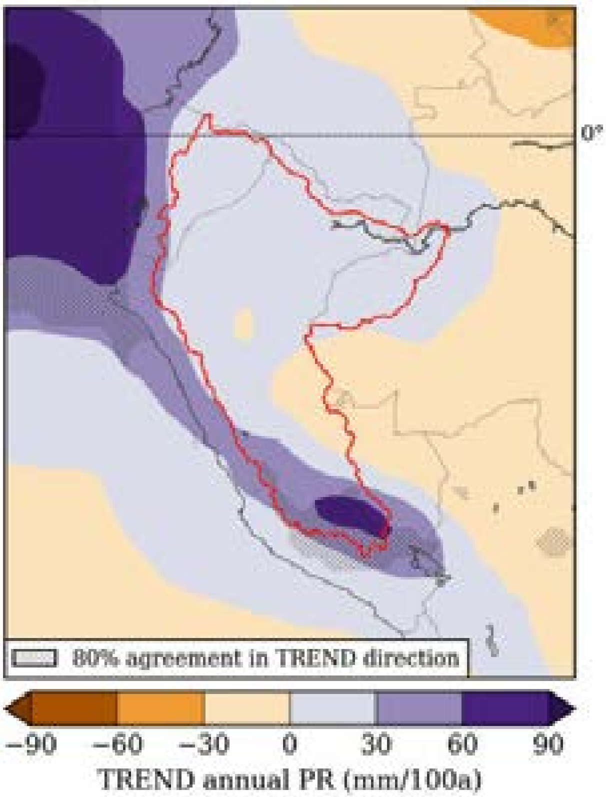


Figure 17: Location of the Upper Amazon case study area, with projected spatial trends in precipitation until the end of the twenty-first century

Table 4: **Baseline conditions and projected changes in hydrological and climatological indices for the Upper Amazon basin.** Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential evapotranspiration is derived from hydrological model simulations (ISIMIP dataset). RCP values are projected changes relative to baseline obtained from GCM runs of the CMIP5 project (temperature, precipitation), and hydrological models from ISIMIP.

Years	1971 – 2000	2071 – 2100	
	Baseline	RCP2.6	RCP8.5
Temperature (°C)	21.70	+1.53	+4.60
Precipitation (mm per year and % change)	2122	+1.04%	+4.05%
Potential evapotranspiration (mm per year and % change)	1509	+8.00%	+24.00%
Actual evapotranspiration (mm per year and % change)	663	+8.00%	+16.00%
River discharge (mm per year and % change)	1459	-2.00%	+10.00%

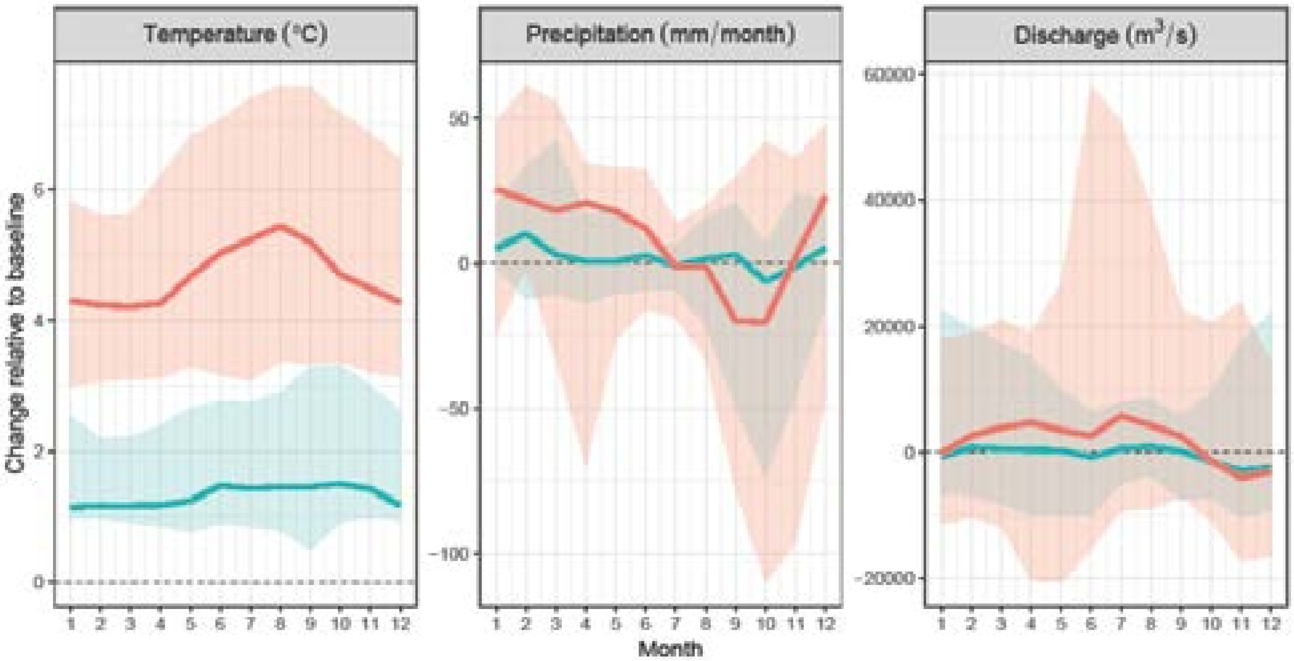
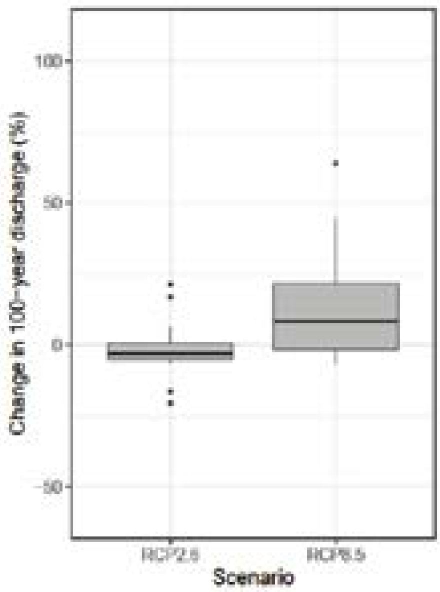


Figure 18: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

Figure 19: (right) Projected change in 100-year discharge levels for the period 2071-2099, relative to 1971-2000. Data derived from the ISIMIP data set.



5.4 Upper Niger

The Niger River is the longest and largest river in western Africa. Its source is located in the Guinean highlands (*Figure 20*), from whence the Niger flows in a northern arc through the dry Sahelian zone, until it re-enters the wetter tropical region north of the Gulf of Guinea. Topographically, the basin also includes larger parts of Algeria, but from this northernmost part in the Central Sahara, no water contributes to the streamflow. Geographically, the Niger basin spreads over six different, large agro-climatic and hydrographic regions. These range from the Central Sahara, with less than 100 mm/yr average annual rainfall, to tropical rain forests in the Guinean zone, with more than 1400 mm/yr. Apart from this broad range of climates, the streamflow pattern of the Niger is substantially influenced by the Inner Niger Delta, which delays the peak runoff and smooths the hydrograph.

In this report, the Niger basin is analysed at gauge Koulikoro, and therefore covers just the Upper Niger basin (around 120,000 km^2). This part is mainly characterised by a wetter climate, with about 1500 mm of rainfall per year, and some tributaries, particularly the Benue. However, the influence of the dynamics of the Inner Niger Delta and the Guinean headwaters on the river flow is still noticeable. The temperature is high, 26.5°C on average. Consequently, evapotranspiration is high, resulting in a low runoff coefficient (the share of rainfall converted into streamflow) of about 18%. The dominant land uses are forest (34%), savanna (30%), and cropland (24%). The main course of the Niger flows through Guinea, Mali, Niger, Benin, and Nigeria, some of which are recognized by the UN as Least Developed Countries. One reason why the Upper Niger River was selected as a case study area is that several severe droughts over the last few decades have demonstrated the region's strong vulnerability to climate variability and climate change, for instance in 2012, when the Republic of Niger suffered from a severe drought followed by intense flooding of the Niger River.

Increased water abstraction for irrigation, new dams for hydropower generation, and the impact of climate change increase the pressure on available water resources. Another, often underestimated threat in the basin are floods, which are affecting an increasing number of people.

Climate change impact summary: By the end of the century, temperatures are projected to increase by 1.3 to 4.6°C, depending on the GHG concentration pathway (*Table 5 and Figure 21 on the next page*). Yearly precipitation sums are expected to remain mostly unchanged under RCP2.6, and to decrease slightly, by about 7%, under RCP8.5. However, seasonal changes can be expected, for instance, an enhanced wet season both in terms of precipitation and river discharge (*Figure 21 on the next page)*. In addition, severe droughts might increasingly occur, while at the same time, extreme floods are expected to become more severe (*Figure 22 on the next page*).

Figure 20: Location of the Upper Niger case study area, with projected spatial trends in precipitation until the end of the twenty-first century

Table 5: **Baseline conditions and projected changes in hydrological and climatological indices for the Upper Niger basin.**
Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential evapotranspiration is derived from hydrological model simulations (ISIMIP dataset). RCP values are projected changes relative to baseline obtained from GCM runs of the CMIP5 project (temperature, precipitation), and hydrological models from ISIMIP.

Years	1971 – 2000	2071 – 2100	
	Baseline	RCP2.6	RCP8.5
Temperature (°C)	26.50	+1.34	+4.60
Precipitation (mm per year and % change)	1495	-1.33%	-7.00%
Potential evapotranspiration (mm per year and % change)	1734	+7.00%	+24.00%
Actual evapotranspiration (mm per year and % change)	1221	+4.00%	+7.00%
River discharge (mm per year and % change)	274	+8.40%	+2.00%

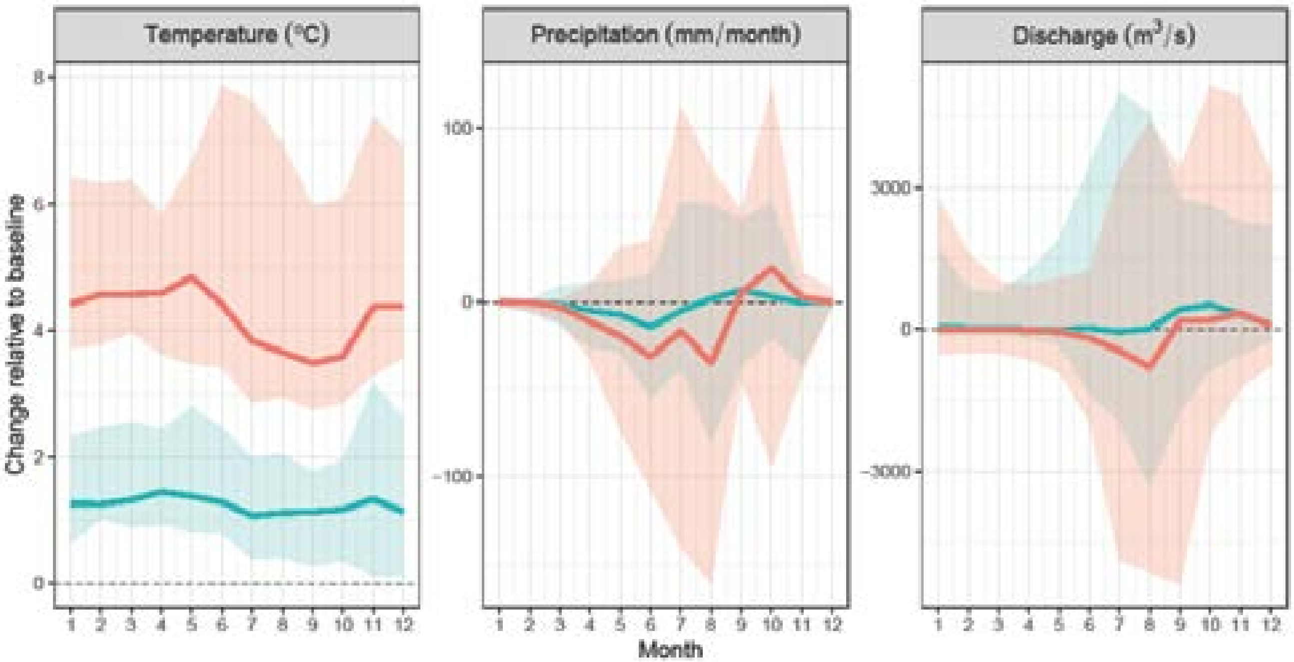
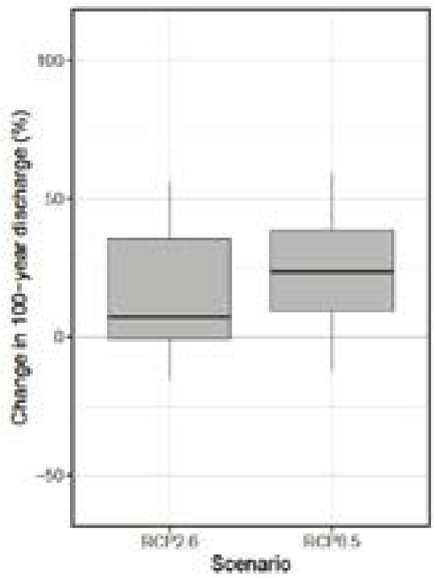


Figure 21: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

Figure 22: (right) Projected change in 100-year discharge levels for the period 2071-2099, relative to 1971-2000. Data derived from the ISIMIP data set.



5.5 Limpopo

The Limpopo River originates in Witwatersrand, South Africa, from whence it flows in a northern arc, acting as a border between South Africa and Botswana, later between South Africa and Zimbabwe, and then enters Mozambique, where it reaches the Indian Ocean (*Figure 23*). At the selected gauge, close to the mouth into the Indian Ocean, the basin comprises an area of about 410,000 km^2. The hydrology of the Limpopo is characterised by its location in the transition zone between the intertropical convergence zone and the tropical dry zone, with additional maritime influence in the east. Rainfall is low, at about 500 mm/yr, and temperature is rather high, 21 °C on average. Its topography is dominated by higher altitude plains in the inland, and lower coastal plains, both separated by the Great Escarpment, which runs through the centre of the basin from north to south. This geographical setting results not only in a typical subtropical intra-annual, but also a very distinct inter-annual variability of flow.

The Limpopo basin serves as a case study in Southern Africa, with important human regulation (mining activities, reservoirs for irrigation, and electricity generation). Heavy floods (e.g. the extreme flood in Mozambique in 2000), as well as the 2017 drought in South Africa serve as a reminder that both types of weather extremes may increase in number and intensity in the region.

Climate change impact summary: Climate change will likely lead to a reduction in precipitation in the area, but projections point towards river discharge increasing (*Table 6 and Figure 24 on the next page*). However, droughts are likely to become more severe, while the intensity of extreme floods is projected to decrease (*Figure 25 on the next page*).

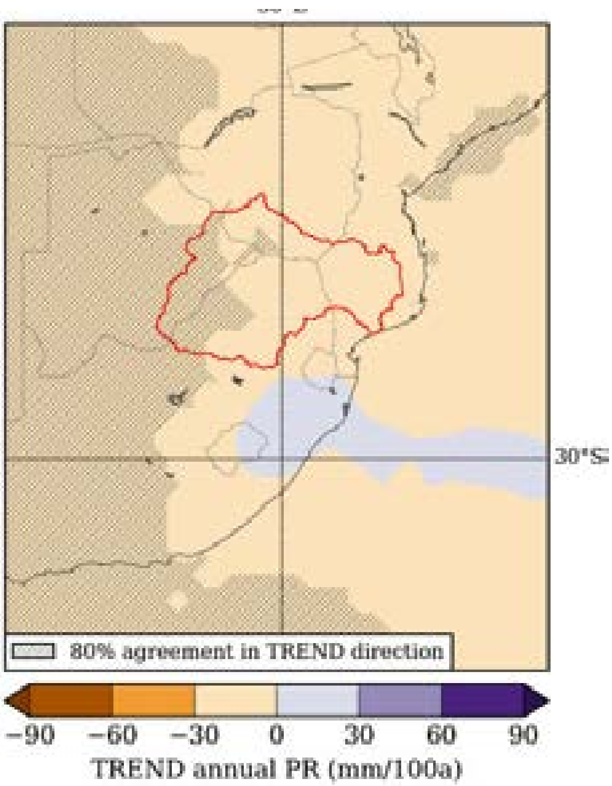


Figure 23: Location of the Limpopo case study area, with projected spatial trends in precipitation until the end of the twenty-first century

Table 6: **Baseline conditions and projected changes in hydrological and climatological indices for the Limpopo basin.** Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential evapotranspiration is derived from hydrological model simulations (ISIMIP dataset). RCP values are projected changes relative to baseline obtained from GCM runs of the CMIP5 project (temperature, precipitation), and hydrological models from ISIMIP.

Years	1971 – 2000	2071 – 2100	
	Baseline	RCP2.6	RCP8.5
Temperature (°C)	21.00	+1.48	+4.75
Precipitation (mm per year and % change)	513	-3.65%	-11.26%
Potential evapotranspiration (mm per year and % change)	1578	+6.00%	+27.00%
Actual evapotranspiration (mm per year and % change)	513	+1.00%	-10.00%
River discharge (mm per year and % change)	13	+22.80%	+5.90%

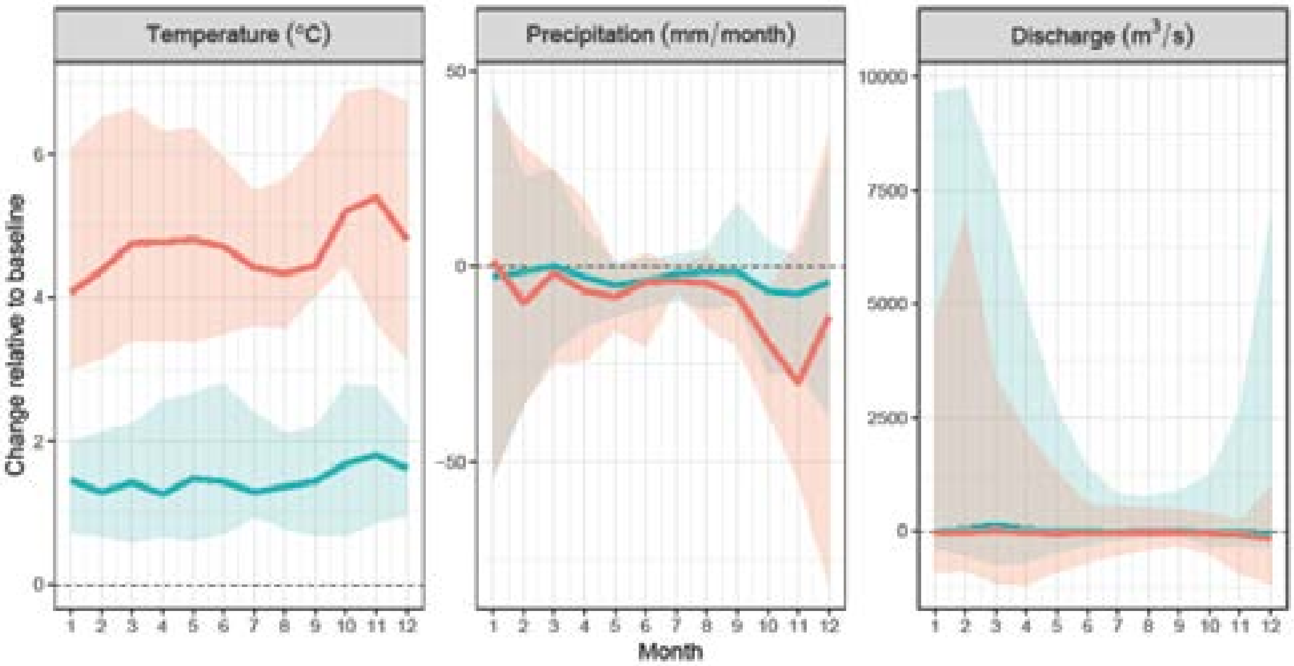


Figure 24: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

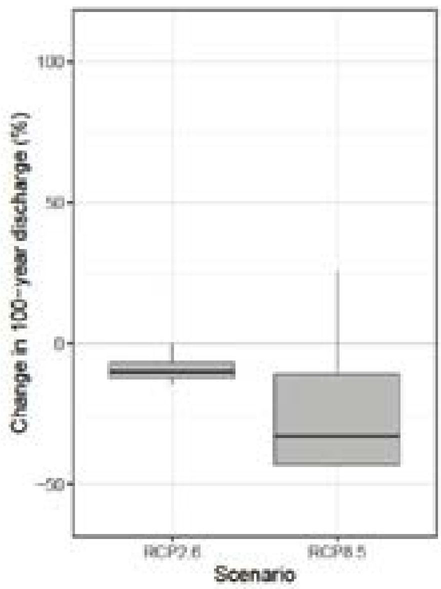


Figure 25: (right) Projected change in 100-year discharge levels for the period 2071-2099, relative to 1971-2000. Data derived from the ISIMIP data set.

5.6 Tagus

The climatic conditions in the Tagus River vary from Mediterranean, in the eastern part of the basin, to Atlantic, in the western part (*Figure 26 below*). Precipitation patterns exhibit high variability, with headwaters receiving around 1100 mm yr-1, and middle reaches in the southern part only 450 mm yr-1. The average temperature is 14 °C.

The Tagus River was studied until gauge Almurol, covering an area of 70,000 km^2. About 23% of precipitation is converted into runoff. The main land uses are cropland (45%), forest (29%), and heather (13%). The basin is an important water source for hydropower production, as well as urban and agricultural water supply in Spain and Portugal. Growing demand for electricity and water, over-regulation of the river and the construction of new dams, and large inter-basin and intra-basin water transfers, increased by the catchment area's strong natural climate variability, have already exerted significant pressure on the river. A substantial reduction in discharge can be observed today, and expected climate impacts are projected to further alter the water budget of the catchment area.

Climate change impact summary: Under RCP 8.5, projected trends indicate a strong decrease in precipitation for the Tagus basin, in particular, and in the entire Mediterranean, more generally (*Table 7 and Figure 27 on the next page*). In addition, the seasonal pattern of temperature increase is the most pronounced in comparison to the other study areas: an increase of up to 7.5°C in summer and about 3.5°C in winter (*Figure 27 on the next page*). As a result, projections for river discharge point towards a decreasing trend, especially under a high GHG concentration scenario. Droughts are also expected to become more severe, while the trend of heavy flood levels remains unclear and partly depends on the respective concentration pathway (*Figure 28 on the next page*).

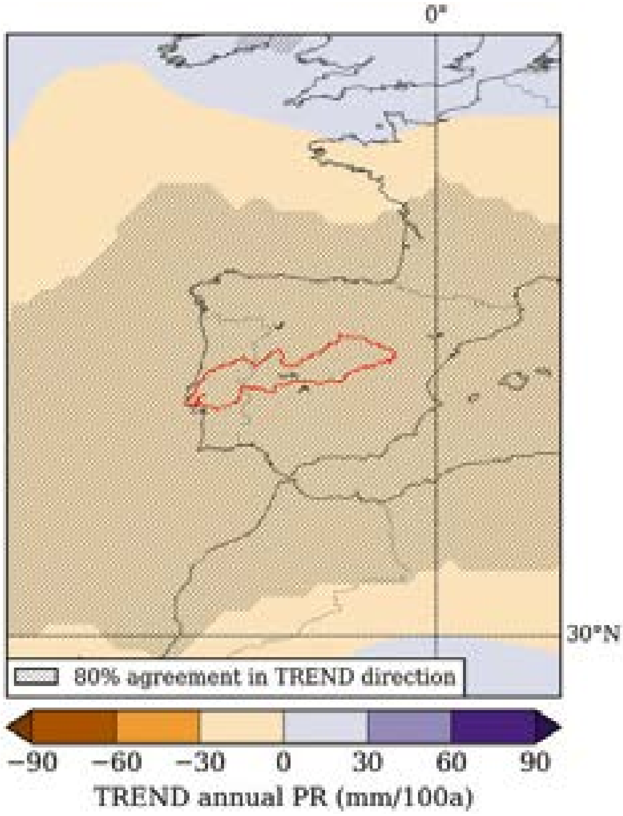


Figure 26: Location of the Tagus case study area, with projected spatial trends in precipitation until the end of the twenty-first century

Table 7: **Baseline conditions and projected changes in hydrological and climatological indices for the Tagus basin.**
Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential evapotranspiration is derived from hydrological model simulations (ISIMIP dataset). RCP values are projected changes relative to baseline obtained from GCM runs of the CMIP5 project (temperature, precipitation), and hydrological models from ISIMIP.

Years	1971 – 2000	2071 – 2100	
	Baseline	RCP2.6	RCP8.5
Temperature (°C)	14.00	+1.57	+5.03
Precipitation (mm per year and % change)	671	-3.97%	-23.26%
Potential evapotranspiration (mm per year and % change)	1106	+11.00%	+35.00%
Actual evapotranspiration (mm per year and % change)	519	+4.00%	-10.00%
River discharge (mm per year and % change)	152	+3.60%	-52.20%

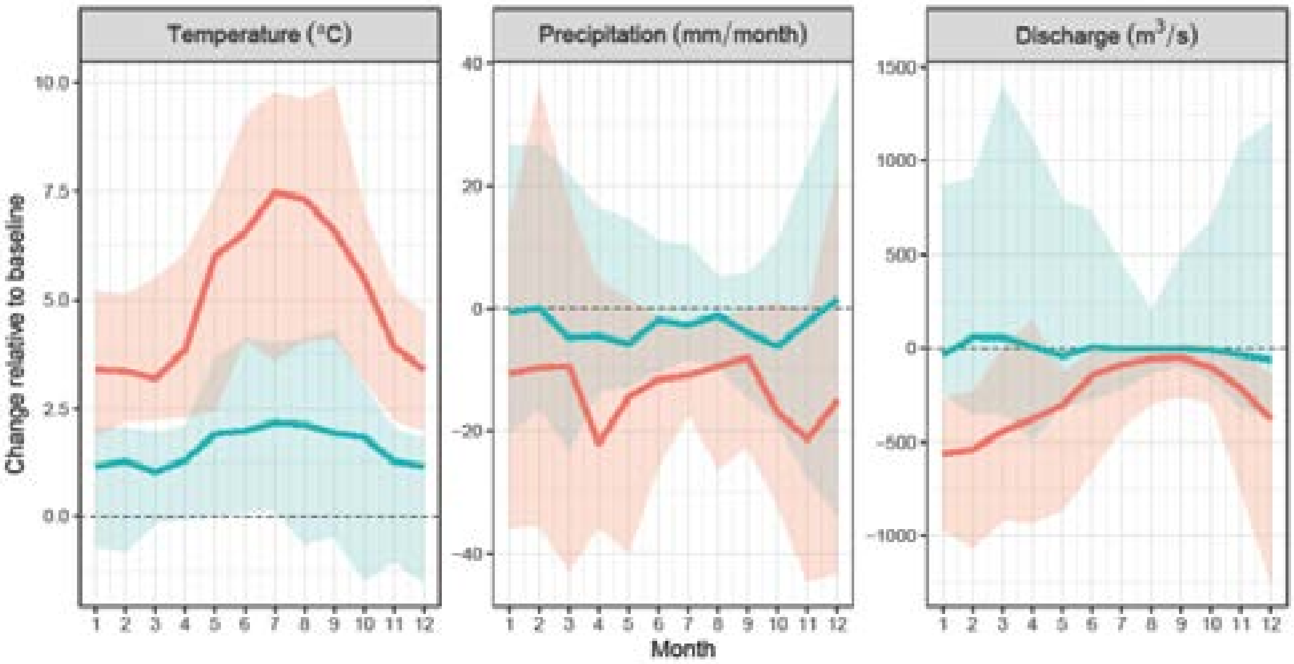
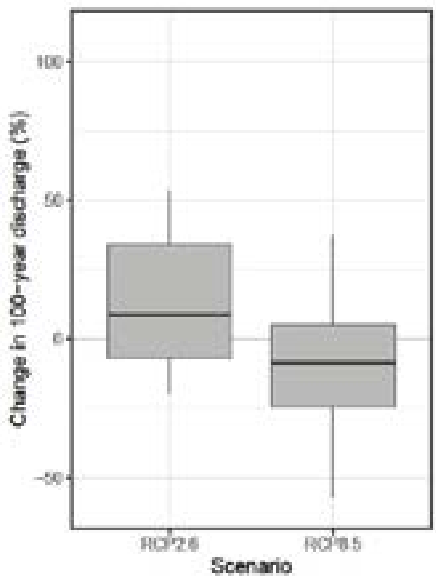


Figure 27: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

Figure 28: (right) Projected change in 100-year discharge levels for the period 2071-2099, relative to 1971-2000. Data derived from the ISIMIP data set.



5.7 References

Conway, D. (2000): **The Climate and Hydrology of the Upper Blue Nile River.** The Geographical Journal, 166 (1), 49-62, DOI: *https://doi.org/10.1111/j.1475-4959.2000.tb00006.x*

6. Climate resilience through water – coping with uncertainties

Humans experience climate change first and foremost through changes in the air and water, for instance through seasonal changes in precipitation, or through too much or too little water. The previous chapters have shown that even minor changes in climate can have profound impacts on the water cycle.

In turn, sustainable water management is essential for climate change adaptation strategies and their successful implementation, with positive effects in various sectors. Consequently, the water sector, including water resources management as well as water supply and sanitation, plays a crucial role in fostering the climate resilience of societies and ecosystems. Proven water sector concepts, such as improving water demand management, reducing water losses, and reusing treated wastewater, can effectively contribute to advancing climate resilience and might also help to reduce GHG emissions.

This chapter focuses on methods and concepts by and in the water sector that help to address water management issues, even if significant uncertainties about future conditions prevail.

Key Messages of Chapter 6

- Resilient water management is a prerequisite for successful climate change adaptation across sectors. Conversely, climate change impacts are likely to slow or undermine the progress made on safely managed water and sanitation.
- Depending on expected climate change impacts, different water management approaches, such as rainwater management and wastewater reuse, have proven to be effective and efficient in reducing vulnerabilities.
- Approaches that deal with uncertainties about future climate conditions need to be combined with socio-economic vulnerability assessments and water management knowledge in order to develop robust, but flexible water management solutions. Optimised and robust hardware to sustain shocks as well as adaptive management to withstand disturbances both increase the resilience of sanitation systems.
- Integrated water storage concepts, including groundwater, surface reservoirs, soil moisture and other elements, provide solutions to multiple climate change impacts and help to replace natural water storage threatened by climate change, such as glaciers and lakes.
- Healthy ecosystems are vital elements of climate resilience. Approaches that come with multiple co-benefits beyond climate considerations include Ecosystem-based Adaptation (EbA) and other Nature-based Solutions (NbS), for instance in the area of flood and drought risk management.
- Existing transboundary water cooperation mechanisms help to combine the long-standing experience of regional water management and governance with climate policy approaches. By more closely integrating water and climate interventions, decision-makers can help create synergies and co-benefits in transboundary basins. However, doing so will require upgrading existing transboundary water cooperation into Transboundary Resilience Management (TRM).

6.1 Cooperation across sectors

Water-related climate change impacts go beyond the water sector. For instance, climate change-induced water scarcity affects the availability of water for agricultural irrigation and cooling water for energy generation purposes. Developing efficient and effective climate adaptation (and mitigation) strategies will create challenges for the water, agriculture, health, energy, industry, and other sectors. Thus, one key governance challenge posed by climate change relates to the cross-sectoral nature of both climate vulnerabilities and adaptive responses. Successful cooperation among sectors, such as proposed by the **Water, Energy, Food Security Nexus (WEF-Nexus)** concept, is a prerequisite for implementing the adaptation actions in the following sections. Furthermore, the Integrated Water Resources Management (IWRM) process provides tools and approaches for cooperation across sectors and stakeholders and can be used in order to jointly improve climate resilience and decarbonization.

As the WEF-Nexus approach proposes, the conflicting interests and trade-offs between different actors and sectors will have to be successfully and equitably managed. It is also important to achieve synergies by identifying multiple benefits (co-benefits) for different sectors as well as adaptation and mitigation initiatives. This requires mainstreaming climate change aspects into the portfolio, and improving coherence between sector strategies and policies. Improved coordination, often the responsibility of environmental ministries, can facilitate the identification of trade-offs and synergies between sectors and their adaptation strategies.

In order to fully utilise water expertise to foster effective climate resilience, water activities need to account for essential climate considerations, including the following elements:

- Consideration of the specific climate vulnerability and risk context in the project design.
- Appropriately using available climate change and impact information, while clearly addressing related uncertainties.
- Designing water management measures in a way that they effectively and transparently increase the climate resilience of people and ecosystems.

In order to coordinate the needs and interests of all stakeholders in a flexible and equitable way, policymakers can directly build flexibility into management instruments, such as sectoral water allocation or land use plans. To account for increasing variability, such plans should contain specific provisions for times of floods and drought. For example, decision-makers could shift water allocation from hydropower and irrigation to drinking water supply in times of water scarcity. Priority should always be given to foundational issues, such as the human rights to safe drinking water and sanitation.

The WEF-Nexus: A cross-sectoral approach

The scarcity of resources, such as water, land or energy, is a major constraining factor for sustainable development that can increase vulnerabilities to climate change and variability, and have immediate implications for local, national and regional security concerns. Interdependent and complex stakeholder constellations and competition over resources can spur scarcity, instability and conflict – potentially even forming a vicious cycle by mutually reinforcing each other. The WEF-Nexus approach fosters a paradigm shift away from separate, sectoral approaches towards holistically managed food, water, and energy sectors. The aim is to establish an integrated resource use approach based on horizontally and vertically integrated interventions. Thereby, the WEF-Nexus considers the totality of available sources of food, energy and water security to use resources more efficiently, while serving human and environmental needs through holistic, coordinated planning. A WEF-Nexus approach to resource use and project planning in a river basin avoids undesired impacts on other sectors, mitigates conflicts between them, and improves the efficient use of natural resources for human livelihoods while also ensuring ecosystem conservation.

Nexus platforms include the Nexus Regional Dialogues Programme (*www.water-energy-food.org*) which showcases concrete solutions to this integrated approach in five regions: Latin America and the Caribbean, Middle East and Northern Africa, the Niger Basin, Southern Africa and Central Asia.

Tools

Development of a specific analytical assessment tool through a WEF-Nexus approach

The link between natural resources and conflict is not as easy, straightforward and self-evident as popular discourses often indicate. Instead, water security and related risks (including those associated with food and energy security, which themselves heavily rely on water) as well as conflict, instability and insecurity each represent complex concepts. Climate change might make each of them – and the complex interdependencies they form – even more difficult to grasp and to control through means of management and governance.

In this context, GIZ has been commissioned by the European Union and the German Federal Ministry for Economic Cooperation and Development (BMZ) to implement the FREXUS project "Improving security and climate resilience in a fragile context through the Water, Energy and Food Security Nexus". Working in the Sahel region (Mali, Niger and Chad), the project aims at turning the vicious cycle of resource scarcity and conflicts over resources into a virtuous cycle of climate-resilient, secure and sustainable development through the application of nexus approaches at local, national and transboundary levels. In this context, it aims at enabling authorities and communities in fragile areas, who are facing the consequences of climate change, to tackle these issues in a peaceful, cooperative and integrated way. Such an approach requires the identification and understanding of vicious cycles, as well as the development of approaches to turn them into virtuous cycles. This provides the basis for further engagement of the FREXUS project in developing nexus-based action plans for climate-resilient resources management for conflict prevention and the promotion of peace.

GIZ is working with the Water, Peace and Security Partnership to further develop its analytical tools at both the global and local levels by integrating water, food and energy security concerns – especially in light of climate change and affiliated risks:

- **The global hotspot identification and early warning tool** aims at identifying areas that could suffer from natural resources-related conflicts in the future (water, energy and food security). The identification is based on the combination of different factors that typically determine whether natural resources-related challenges could lead to conflicts.

- **The local nexus and conflict analysis:** Once a hotspot has been identified, further analysis will be conducted through a localised zoom-in tool in order to identify the key drivers of conflict and develop adequate and problem-specific responses to them. To support decisions in the context of dialogue and decision-making – considered as key means for conflict prevention, mitigation and resolution – the analysis not only supports, but also relies on dialogue and participation with stakeholders. On top of that, the analytical tool will be adapted to new areas in Niger and Chad on a local level, as it has already been tested in Mali (Inner Niger Delta).

Implementing and strengthening a multi-level governance approach is key to delivering climate resilience

Finding the right climate adaptation solutions requires examining the specific local and regional contexts, but it also requires looking beyond administrative borders: the best solutions for increasing climate resilience, e.g. water storage options, such as afforestation in catchment areas, may be located in neighbouring administrative units (*see Chapter 6.6*). While implementing basin-wide strategies for climate adaptation may allow policymakers to efficiently address adaptation challenges, these strategies should be coordinated with national adaptation plans and account for international climate policy processes (*see Chapter 8*). It is therefore necessary to support effective governance mechanisms, not only for horizontal (across different sectors), but also for vertical (across different levels of administration) coordination and cooperation. Improving these mechanisms requires adequate governance capacities at all levels, including processes and institutional structures, as well as human capacity.

Criteria for climate-resilient water projects

Water-related activities can create co-benefits ranging from economic and social priorities (such as income opportunities) to health or economic development. Several additional aspects can help to establish a direct link between improving resilience to the impacts of climate change and potentially reducing GHG emissions. These include the following:

- Following a clear climate rationale in a resilience-building project.
- Basing projects on a proper assessment of climate risks and vulnerabilities to make adequate use of available climate information and, as appropriate, local stakeholder knowledge.
- Considering potentially negative effects on other sectors, societal groups, neighbouring communities or states, and taking a basin-wide perspective, as appropriate.
- Ensuring long-term flexibility in terms of adaptable water infrastructure, management solutions, governance structures and policy instruments.
- Involving adaptive governance approaches that include mechanisms for regular review and learning in order to adapt selected solutions to potentially changing conditions.
- Identifying and inducing multiple (co-)benefits, including GHG mitigation effects, as well as benefits in terms of biodiversity and sustainable socio-economic development.
- Ensuring alignment with national climate priorities, strategies, plans and overall development objectives.
- Considering gender aspects and the needs of vulnerable communities and ecosystems.

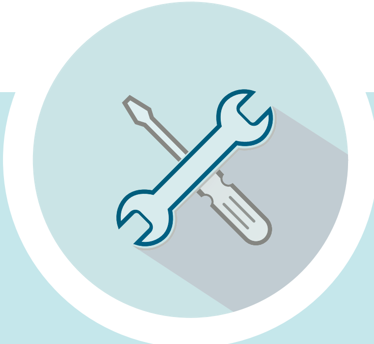
Involving the private sector in collective action for increased climate resilience

In some countries, more than 80% of critical infrastructure services (e.g. energy, water, sanitation, transport, food supply, etc.) are delivered by private actors (Schneider, 2014). Moreover, private actors, e.g. in the agricultural sector, determine both land-use and water-use efficiency. Private sector action can also have significant impacts on water-related ecosystems. In turn, climate change impacts on water resources are equally challenging for the private sector as for individuals, households and the public sector. Consequently, the private sector also needs to increase its resilience and adapt to changes. Furthermore, by investing in climate adaptation activities, the private sector can increase the resilience of surrounding communities and local governments (Schaer and Kuruppu, 2018).

➔ ***Private actors, including in the agricultural sector, are often among the largest water users. Their action can leverage water resilience.***

Moreover, private financial institutions and investors, such as banks, pension funds, insurance companies or impact investors, might invest in resilience or provide funding for others to adapt, e. g. through (micro-) loans, bonds or venture capital (Druce et al., 2016). In efforts to increase climate resilience, the water sector (and other sectors) can thus benefit from partnerships between the private and public sectors to support effective implementation. Existing approaches for involving the private sector in collective action are outlined in the boxes below.

Tools



Initiatives to address water risks involving all stakeholders – Water Stewardship approach

The private sector is increasingly aware of water risks. The Water Stewardship approach can be an effective means for non-state actors to overcome climate- and water-related challenges. It is a collaborative and multi-stakeholder approach that aims to achieve social, environmental and economic benefits.

Several Water Stewardship initiatives exist, such as the Alliance for Water Stewardship, the WWF Water Stewardship programme, as well as the Interna-tional Water Stewardship Programme (IWaSP) and its follow-up programme NatuReS (Natural Resources Stewardship Programme), funded by the German Federal Ministry for Economic Cooperation and Development (BMZ) and the UK Department for International Development (DFID).

Within the framework of these initiatives, several risk assessment tools have been developed. For instance, IWaSP prepared the Water Risk and Action Framework (https://ceowatermandate.org/wraf/about) that allows public bodies, private actors and civil society to jointly identify measures aimed at reducing shared water risks, including risks related to climate change. IWaSP initiated and set up partnerships between these three distinct stakeholders, and coordinates them with the support of GIZ bilateral and regional water programmes.

Considerable progress in Water Stewardship approaches has been made in recent years. However, in order to achieve further success, leading companies need to set an example and advance new approaches. Also, companies will need to mobilise new forms of finance, cooperate with peers, support suppliers, and drive coordination to the next level (Morgan, 2018).

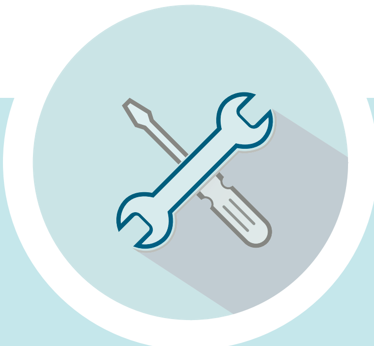
6.2 Risk-based management for dealing with uncertainties

The Global Risk Report of the World Economic Forum has counted water crises among the five top risks in terms of impact for nine consecutive years – also in its 2020 edition, where water crises was listed a top five risk, together with failure on climate action and extreme weather (World Economic Forum et al., 2020). This indicates a high level of awareness on water risks and calls for their appropriate management.

Although improved data, strengthened monitoring and better information exchange can help to reduce uncertainties in climate change projections to a particular degree (*see Chapter 3*), significant uncertainties and risks will remain. While decision-makers on water-related activities have always had to deal with climate variability and uncertainty, the combination of climate change and rapid demographic, economic, institutional, social and environmental developments is expected to increase uncertainty to an unprecedented level (Sadoff and Mueller, 2009).

In consequence, water management systems need to be designed in a way that ensures continuous performance, even under increasingly unknown future conditions. Thus, they need to include considerations of uncertainty and potential risks. A central step to ensuring a desired performance under unknown future climate conditions is to assess climate-related risks, that is, the likelihood that a certain impact resulting from climate-induced hazards will occur.

Tools



Private sector initiatives to address water risks – Water Risk Filter

Water risks can constitute a major threat for private actors. It is estimated that agriculture accounts for about 70% of global water withdrawals, mostly for irrigation. Users include smallscale farmers, cooperatives, private businesses, as well as large companies. The latter's water use can significantly affect water availability and quality for its own business continuity, as well as for societies and the environment. Industrial water use, including a large private sector share, accounts for another 20% of global water withdrawals (figures from WWAP/UN-Water, 2018).

Such a strong water dependency entails responsibility for sustainable water use, but also vulnerability to the water-related impacts of climate change and other trends. Even though private actors are increasingly aware of these water risks, appropriate water risk management know-how, guidelines and regulations are often missing.

In order to assist private actors in assessing and mitigating water risks, the World Wildlife Fund for Nature (WWF) and the German development finance institution DEG jointly developed the **Water Risk Filter**. The freely accessible online tool allows investors and companies from all sectors to assess and quantify water-related risks. The risk assessment considers the location of a company (basin-related risks) as well as its impact and performance based on several variables (company-/commodity-specific risk). The filter translates the underlying data sets into risk metrics. Several map layers visualise the specific risk dimensions. In another step, the tool suggests actions for risk mitigation and developing a water stewardship strategy.

https://waterriskfilter.panda.org (WWF and DEG, 2018)

Risk and vulnerability assessments as baselines for monitoring adaptation effects

Appropriate risk assessments and management can help to define specific objectives to reduce climate risks, while elaborating measures to accomplish these objectives. In addition, it evaluates possible risks against costs for a range of different stakeholders (Hall et al., 2013). As a result, the consideration of risks is a crucial part of climate adaptation strategies – with a relevance for the water sector.

Thereby, risk and vulnerability assessments, involving the appropriate use of existing climate projections as well as the thorough consideration of climate-related risks and socio-economic vulnerabilities, provide a necessary foundation for sound planning of climate resilience measures and strategies. In addition, they help to set a baseline against which adaptation effects can be monitored and evaluated in the future.

The latter is important for tracking and assessing climate change adaptation activities and progress, eventually improving climate adaptation efforts by and in the water sector.

Tools

Standard Guidance on Climate Risk and Vulnerability Assessments

The IPCC has formulated a conceptual and widely recognised basis for identifying and dealing with climate risks in their reports. While the focus was originally on vulnerability, this was replaced by a focus on risks (with vulnerability being one of three elements), introduced with the 2012 Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). It was then used in the IPCC's Fifth Assessment Report (AR5) (IPCC, 2014). Based on these concepts, experts have designed and applied comprehensive vulnerability and risk assessment approaches to provide decision-makers with a sound basis for policy making.

The IPCC has conceptualised risks as "the potential for consequences [= impacts] where something of value is at stake and where the outcome is uncertain […]. Risk results from the interaction of vulnerability, exposure, and hazard […]." This concept is also illustrated as part of the conceptual risk framework (see Figure 29 on the next page). It was informed by the risk concept of Disaster Risk Reduction (DRR) frameworks and puts a stronger focus on hazards and the role of uncertainty of the outcomes, also due to the interrelation of hazard and exposure of affected groups.

As outlined by the risk supplement to the vulnerability source book (published by GIZ in 2017), there is a need to specify the risk focus of an assessment as a starting point. Users need to identify the type of hazards and climate impacts that lead to risk – and who or what is at risk. One example for risks in this context is the risk of water scarcity for small-holder farmers.

There are several guidelines and handbooks that provide best practices for analysing vulnerability and climate risks (Morgan, 2011; UNEP, 2013a; Fritzsche et al., 2014). In recent years, efforts have focused on standardising assessment approaches to provide a sound basis for policies at all levels.

Tools

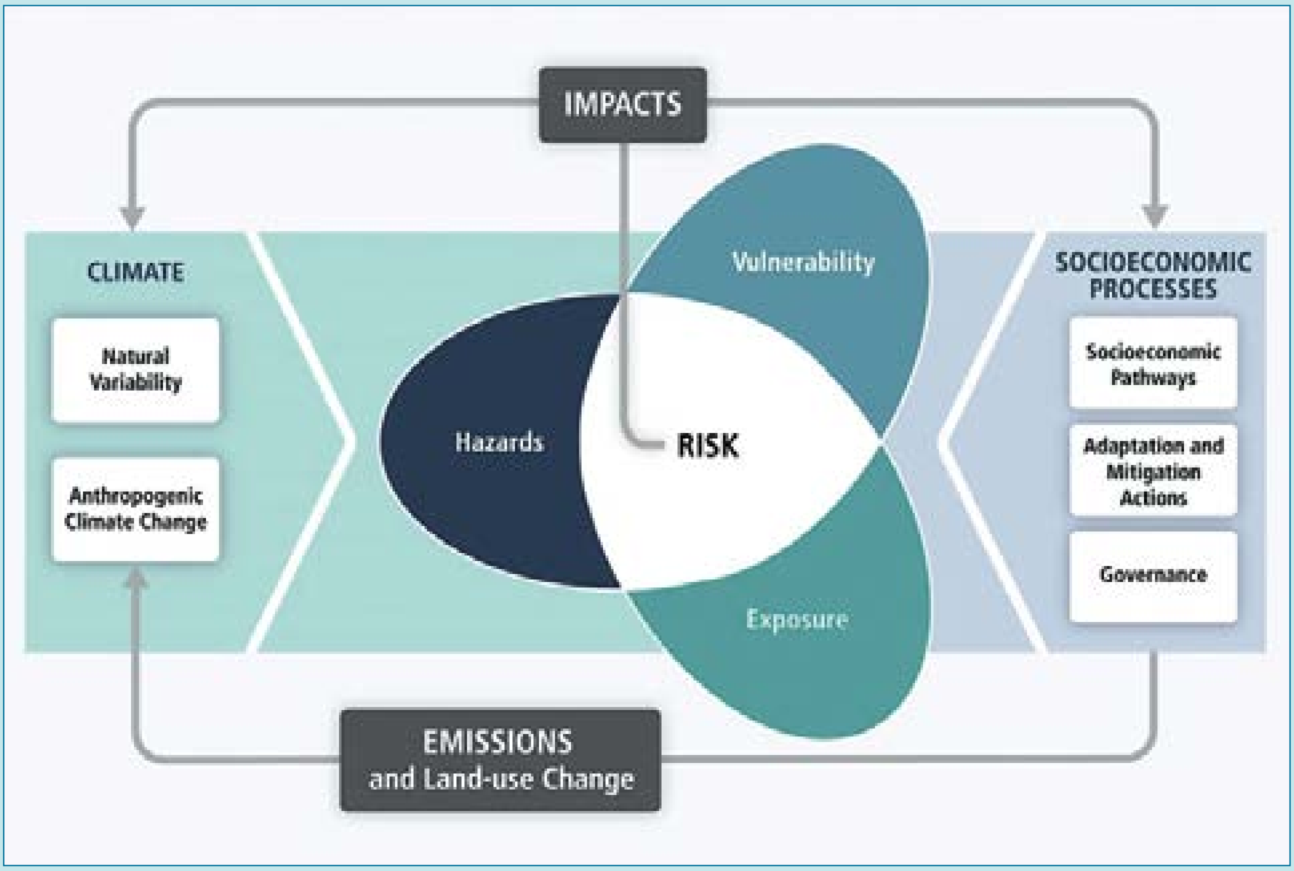


Figure 29: The IPCC AR5 conceptual risk framework; source: IPCC, 2014

Assessing climate-related risks

Assessing climate-related risks and finding robust solutions to increasing climate resilience is not only a technically complex task, but also a highly contextual one. Given the uncertainty associated with climate impact projections, it is difficult to identify an optimal adaptation solution. Furthermore, the question of which solution is best very much depends on stakeholders' risk perception and preferences. Decision-making in the field of climate adaptation requires difficult choices regarding the right policy instruments to support implementation, the right administrative level, geographical scale and timing to act – all in the face of multiple uncertainties. As a response to climate- related challenges, different approaches and assessments within the water sector have evolved over time. The most relevant challenges are:

A stationary approach in water resources management derives future seasonal water availability and occurrence of extremes in a certain region from experiences with hydro-climatic conditions in the past. Even though natural climate variability has always occurred, climate change and socio- economic developments constitute additional uncertainties in terms of factors influencing water availability and use in the future. This bears the potential to increase risks for water management, rendering stationary approaches more inadequate (Milly et al., 2008). New approaches have thus become necessary to assess how future risks affect the performance of water management systems (Hallegatte, 2009).

➔ ***Climate risk assessments have been applied since the 1990s.***

Unlike stationary approaches, newer concepts have started to consider potential future changes of climatic and hydrological conditions and affiliated risks. As a result, water planners have begun accounting for climate risks since the 1990s, including through **top-down climate risk assessments**. Traditional top-down climate risk assessments often begin with downscaling global climate models (*see Chapter 3.1*) to project how climate change will affect the water cycle in a specific region. The analysts then determine whether the performance of a specific water management system will still be acceptable under the modelled conditions. Thus, the assessment examines whether the system still complies with defined minimum standards, fulfilling social, economic, environmental and other benefits. Top-down approaches have proven useful for water-related analyses at the global or regional scale. However, their outputs often lack the required level of detail for local/site-specific water resources management or water infrastructure decisions (García et al., 2014). Therefore, they can only inform water management institutions and policy-makers to a degree of detail that is limited (Ray and Brown, 2015). Another drawback of top-down approaches is that uncertainties are transferred and possibly magnified from the global level to the multiple-model stages, as explained in *Chapter 3* (Matthews et al., 2015).

Bottom-up analyses and probabilistic approaches to climate risk assessments

Uncertainty about future conditions should not be used by decision-makers as an excuse to do nothing, while waiting for better information to become available. Planning documents should communicate transparently both existing uncertainties related to climate projections as well as socio-economic factors, with the aim of providing flexibility to adapting strategies as new information becomes available. Furthermore, the costs of inaction might be greater than any possible benefits that may result from delaying intervention until actors are better informed. Nevertheless, the presence of uncertainties and the corresponding need for adaptation measures that provide benefits under different climate scenarios are also no excuse for simply implementing standard water activities that have been used to deal with hydro-climatic variability in the past (Schiermeier, 2014).

Good practice example

Zambia: Lusaka Water Security Action and Investment Plan. Considering evidence-based climate variability

Supporting climate- and economically resilient cities: The rapidly growing demand for water by Lusaka's population and industry is fast exceeding what both the Lusaka Water and Sewerage Company (LWSC) and the local environment can currently supply. In addition to water supply challenges, there are issues with sanitation, (groundwater) pollution, wastewater, drainage and flood protection within the city. Furthermore, the impacts of climate change are leading to a more water-insecure future. Apart from a 1 to 1.5 degree increase in temperature, there are projections of varied seasonality, which is already being experienced. The city of Lusaka, in particular, is expected to receive reduced rainfall, but more frequent extreme weather events ranging from storms to droughts.

Currently, there is an absence of effective planning, and issues are dealt with as they arise. More cohesive planning, investment in infrastructure and overall management of the system and its governance could significantly help to improve water security and climate resilience. For this purpose, the Lusaka Water Security Initiative (LuWSI) and other partners have recognised the need to develop a concrete investment and action plan to address the city's water risks: the Lusaka Water Security Action and Investment Plan (WSAIP). WSAIP is funded by DFID with the objective of providing hydrogeological, economic and financial support to LuWSI, while at the same time contributing to stakeholder capacity-building and empowerment.

WSAIP has delivered:

1. Two visual online story maps that present the case for action and investments into water security in Lusaka.

2. An online digital atlas that contains important maps to support decision-making on water security in Lusaka.

3. A strategic framework explaining the rationale behind the Water Security Action and Investment plan and the selection process of the 27 projects and actions has been elaborated in 2-pagers and concept notes.

Apart from climate change and variability, the tools developed to determine the city's water security also take into account population growth, economic growth, infrastructure developments, and communities' activities influencing water insecurity and city growth.

In 2015, GIZ's IWaSP Programme initially hosted LuWSI's secretariat during its development phase and mobilised resources to work with actors from the public sector, private sector, civil society and international organisations towards carefully shaping LuWSI's governance and strategy, while initiating the first projects in parallel. The initiative was officially launched in December 2016.

It is evident that **bottom-up climate risk assessments** offer one response to addressing uncertainties and the inherent limitations of top-down assessments described above. While top-down approaches observe how selected future climate scenarios will affect a water system, bottom-up approaches (as defined in Ray and Brown, 2015) start by assessing the vulnerability of such systems. The vulnerability is determined by examining historical and recent data. Building on this information, analysts then tailor the information derived from GCMs based on what is needed to best inform decisions to reduce vulnerability. In the next step, this tailored climate information is used to evaluate if the water system's performance can be sustained under different climate and non-climate conditions in the future. Subsequently, analysts draw on tailored climate projections to assess the probability that these conditions will occur. Probabilistic (as opposed to deterministic) approaches allow analysts to quantify the uncertainty of assessments. This helps decision-makers to adjust their strategy depending on actors' willingness or adversity to take certain risks.

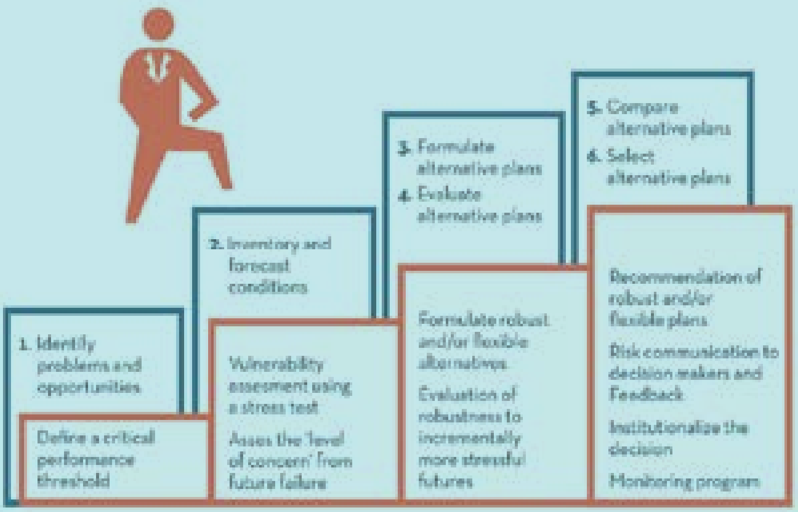
➔ ***Probabilistic approaches allow analysts to quantify the uncertainty of assessments.***

Decision-Scaling (Brown et al., 2012) is a known method for bottom-up climate risk assessments that has also been a core component of the World Bank's "decision tree" approach. Decision-Scaling was developed to assist water project planning through a pragmatic process for risk assessment (Ray and Brown, 2015). Decision-Scaling was also used in the recent Climate Risk Informed Decision Analysis (CRIDA) (Mendoza et al., 2018). CRIDA is explained in more detail in the box below.

Tools

The Climate Risk Informed Decision Analysis (CRIDA)

The Climate Risk Informed Decision Analysis (CRIDA) (Mendoza et al., 2018) is a bottom-up vulnerability assessment methodology. It was designed to evaluate various future uncertainties related to a changing climate, demographics, environment or economics for water resource planning and management. Through extensive stakeholder involvement, it seeks to find robust and flexible solutions, for example for droughts or water shortages, that are capable of reducing risks. This way, it also endeavours to support a paradigm shift in water resource planning and decision-making that focuses more on "what is known" (the risks) instead of "what is unknown" (the exact impacts of climate change).



The progressive and modular methodology includes several of the approaches mentioned in the present chapter and can be adopted to the demands of individual organisations or projects and their contexts. The application of CRIDA is particularly suited for developing countries and data-poor regions, as it uses local knowledge and stakeholder engagement at the early stages of engineering projects.

Figure 30: CRIDA tasks within a typical planning framework. Blue boxes show widespread planning framework steps; orange boxes show CRIDA steps. Source: Mendoza et al., 2018.

Robust and flexible solutions for risk management

The nature of managing climate change impacts means that not all climate risks and projection uncertainties can be eliminated, as discussed above. Therefore, to prevent prospective failures of water (management) systems, solutions developed to increase climate resilience will have to account for remaining uncertainties and residual climate risks. Even in areas where the impact of climate change can be projected with relatively high certainty, such as in the Mediterranean or the Blue Nile Basin, long-term water management investments (e.g. large infrastructure) will have to perform appropriately and sustainably under changing climatic conditions during their lifetime.

Climate-resilient water management entails developing **robust solutions** that perform well over a wide range of climate (and non-climate) scenarios. They are **designed flexibly** enough to be easily adapted to changing conditions if required; thus, they can take many forms.

➔ ***Robust solutions perform well over a wide range of scenarios.***

The Decision-Scaling approach introduced above is one way to develop robust solutions by assessing the vulnerability of certain solutions to various climate conditions. In order to account for various aspects of robust solutions, Hallegatte et al. (2012) have proposed the following typology:

- **Multiple-benefit solutions** (also refered to as co-benefits in the present study; sometimes also as no-regret solutions) provide benefits even in the absence of negative future climate change impacts. This applies especially to adaptation approaches that provide multiple benefits beyond climate resilience, such as water demand management to reduce pressure on scarce water resources as well as reducing costs for treatment and pumping. In this context, Nature-based Solutions (NbS) can be highly beneficial, for instance, the conservation of floodplains or other wetlands can strengthen flood protection, while creating co-benefits for biodiversity, human well-being or enhanced water storage capacities (*see Figure 32 on page 90*).
- **Reversible or flexible solutions** can be adapted to changing conditions at relatively low cost. Most governance approaches fall into this category. Examples include institutionalising the use of early warning systems or evacuation planning that accounts for climate risks, but also building modular infrastructures that can easily be amended or deconstructed.
- **Safety-margin approaches** base water management decisions on higher (or lower) targets than currently expected. This is especially important for decisions that are not reversible or flexible, such as the zoning of settlements in floodplains. In acknowledging the uncertainty inherent in climate projections, it might be wise to add a safety margin to areas considered prone to flooding, where settlement is prohibited.
- **Solutions that reduce decision-making time horizons** can increase robustness. For example, because uncertainty increases with the length of projections, and investments can have a long lifetime, it can be beneficial to choose solutions with shorter lifetimes like decentral solutions for water supply and sanitation or easy-to-retrofit or modular flood defence.

Good practice example

Using the Economics of Climate Adaptation (ECA) method to reduce climate risks in urban areas in Bangladesh

Bangladesh is among the most vulnerable countries to climate risks. While the North of the country is affected by long periods of drought, the southern coastal parts suffer from recurring floods caused by heavy rainfall, storm tides and cyclones. Together with a rising sea level, these trends contribute to the intrusion of salinity into inland water bodies, groundwater and soils. Therefore, people from rural areas seek refuge in cities, often finding themselves in slum areas of big cities, which are also exposed to the effects of climate change.

Barisal, the second-largest coastal town in the Southeast of the country, has experienced rapid population growth in recent decades (7.7% per year). It is estimated that more than 110,000 people live in slums. Canals and ponds are used as garbage dumps or have been filled in order to create more living space. About 150 km of water canals running through the city are dumped with garbage and rubble, increasing the risk of flooding.

With the help of the Economics of Climate Adaptation (ECA) method introduced by the reinsurance company Swiss Re, the damage caused by climate change can be determined, taking into account economic trends and population dynamics for future decades. The German development bank KfW has applied the method for a risk analysis in Barisal as part of a programme on behalf of the Federal Ministry for Economic Cooperation and Development of Germany (BMZ). The application resulted in the identification of cost-benefit priority measures for climate-resilient urban development, also considering socio-economic aspects, such as poverty and vulnerability. The resulting measures will be implemented in line with existing national adaptation strategies.

In order to decrease climate risks for the most vulnerable, the project's focus will be on expanding and increasing the capacity of the drainage network as well as on the renewal and elevation of low-lying sections of prioritised roads, which function as evacuation routes during extreme weather events. Including the population in the planning and implementation phases of the project ensures that ownership and identification with the programme are strengthened. The City of Barisal is given the opportunity to build up expertise within the framework of pilot projects and, at the same time, to increase its own personnel and financial capacities.

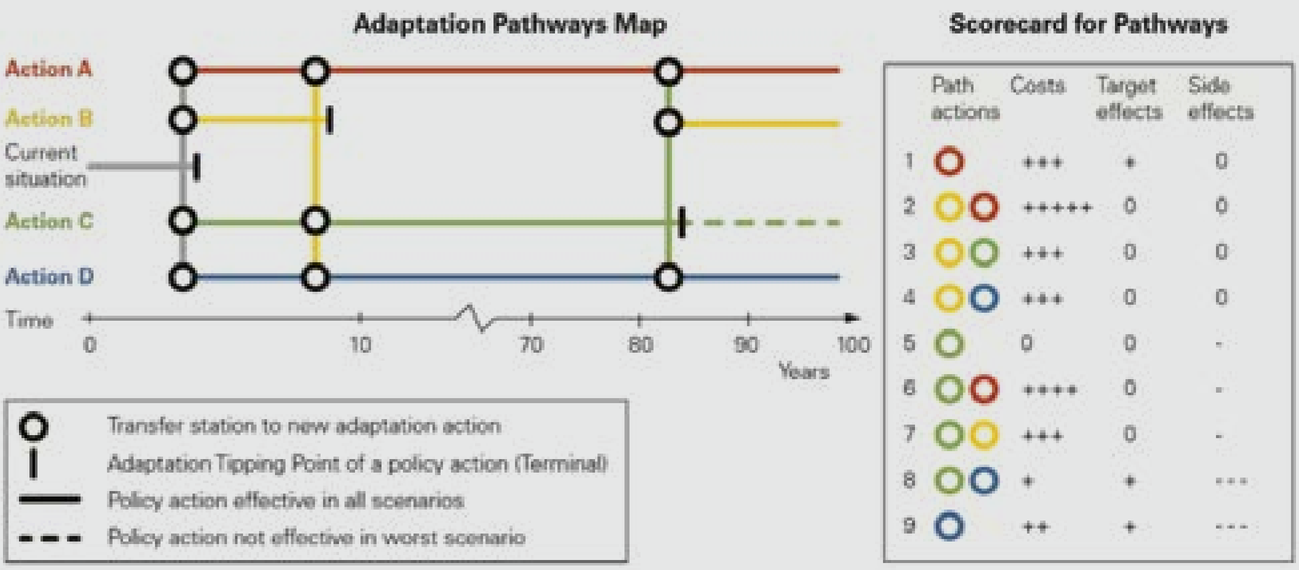
Adaptation Pathways

The long-term robustness of adaptation strategies can further be strengthened by embracing adaptive management approaches. **Adaptive management** allows shifting from one water management solution to another in order to account for altered conditions. For instance, such strategy adjustments could be based on a continuous iterative process of revising previously chosen solutions or learning from newly available information.

Adaptation Pathways are based on the premise that, under strong uncertainty, not all solutions can be known now, but they have to be flexibly identified and implemented over time. They constitute an adaptive – though structured – approach to adaptation planning (Haasnoot et al., 2013). Thus, Adaptation Pathways allow for the development of adaptive plans containing strategies and activities that can still be changed or adjusted in the future. As they enable prospective adjustments in the design of water actions, making use of adaptation pathways avoids "locking in" a single adaptation strategy to achieve pre-defined objectives, such as costs or benefits. A group of Adaptation Pathways are alternatives that can be implemented when pre-defined "tipping points" are reached by identifying the benefits and costs of each possible option at a given time (*see Figure 31*).

Already today, there are various practical examples of Adaptation Pathways being used by water actors: Among others, they have been used to help small municipalities to plan for future sea-level rise in Sweden (Carstens et al., 2019), to evaluate forest adaptation to climate change in England (Petr and Ray, 2017), to assess the performance of the municipal water system of Miami in the USA (Bouwer et al., 2018), and to determine long-term adaptation responses of the flood risk management system of the city Can Tho in Vietnam (Radhakrishnan et al., 2018). An example of an Adaptation Pathways diagram and a scorecard for each of the pathways is presented in *Figure 31*.

Figure 31: Example of an Adaptation Pathways diagram and a scorecard for each of the pathways. Source: Ray and Brown 2015.



In the figure, starting from the current situation, targets begin to be missed after four years; an adaptation tipping point is reached. Following the grey lines of the current plan, one can see that there are four options. Actions A and D should be able to achieve the targets for the next 100 years in all scenarios. If Action B is chosen, a tipping point is reached within about five more years; a shift to one of the other three actions (A, C, or D) will then be needed to achieve the targets. If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed after approximately 85 years in the worst-case scenario (follow the solid green lines). In all other scenarios, the targets will be achieved for the next 100 years. The colours in the scorecard refer to the actions: A (red), B (orange), C (green), and D (blue). The point at which the paths start to diverge can be considered as a decision point. Taking into account a lead time e.g. for implementation of actions, this point lies before an adaptation tipping point. *Source: Matthews et al. (2015)*

Complex risks need collective action and appropriate governance

Finally, increasing climate resilience in the water sector regularly involves changing water allocations and water use practices, e.g. to ensure water security during drier periods and drought. It also often involves adjusting land use and agricultural practices, e.g. where floodplains are to be rehabilitated as part of integrated storage systems. Finding solutions for increased climate resilience therefore requires accommodating and balancing stakeholders' diverging interests. Many aspects of climate adaptation require collective action (Termeer et al., 2017) and thus the establishment of partnerships between the private and public sectors to support effective implementation (*see Chapter 6.1*). Adapting to climate change, while accounting for climate risks and and increasing climate resilience, thus remains a technically complex problem that requires appropriate governance and cooperation.

Good practice example

Applying a web-based tool for developing Climate Change Mitigation and Adaptation Plans (PMACC) in Peru

With its low coastal areas, arid and semi-arid areas, exposure to natural disasters, drought and desertification as well as highly polluted urban areas and fragile ecosystems, Peru's population and ecosystems are highly vulnerable to climate risks. Almost two-thirds (62%) of the country's population lives in the Pacific watershed, with only 2.2% of total water availablity. In this context, many utilities still struggle to deliver basic and equitable water and sanitation services. Growing urbanisation and a lack of wastewater treatment coverage both lead to an increasing water demand and pollution of water bodies. The expected impacts of climate change and variability might further worsen these existing challenges and add new ones. These climate risks will increasingly require proactive planning and implementation for delivering sustainable water and sanitation services.

Through a web-based tool for developing Climate Change Mitigation and Adaptation Plans (PMACC; Planes de Mitigación y Adaptación al Cambio Climático), water and wastewater utilities have received assistance in reporting climate risks and identifying effective short- and long-term adaptation measures, considering multiple benefits. This enables them to improve day-to-day operations and make resilient operational and investment decisions. The PMACC tool allows utilities to draw up climate change plans suitable to their different capacities, sizes and local operating contexts. The PMACC initiative has been implemented by GIZ, through the **Programme for Modernisation and Strengthening Water and Sanitation Sector (PROAGUA II)** on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ).

This planning approach has enabled water utilities in Peru to start implementing adaptation measures, such as the water utility in Moquegua increasing its water metering from 36% to 90% (improving water demand management), reducing water losses from 46% to 31%, and thus reducing daily per-capita water production from 386 to 258 liters, becoming more resilient to longer-term climate change-related water shortages. In order to enhance urban water supply security, PROAGUA II focuses on boosting climate resilience and helps build capacities to protect water resources from domestic and industrial pollution, ensuring that technical and professional staff qualification meets the sector's demands and that climate change adaptation is mainstreamed into sectorial policy and planning. Thereby, it establish a functional monitoring system for SDG 6 and water-related Nationally Determined Contributions (NDCs).

6.3 Resilient water management

While climate change and other trends often increase water-related risks in frequency and intensity, specific incidents including water scarcity, flooding, and increased water variability have been known for centuries. Farmers, planners, engineers, and others have developed and applied approaches for dealing with these risks. What has changed are the additional impacts due to climate change, which are often difficult to anticipate, in particular at the regional level.

In the last decades, it has become apparent that the overexploitation and pollution of water resources poses a serious challenge to the health of communities and ecosystems worldwide. In addition, urbanisation and land-use change often entail the sealing of previously permeable soils and the extension of built infrastructure into natural floodplains. These challenges require modelling capacities in order to make sustainable long-term infrastructure decisions, and have evoked new concepts of water management among public and private actors, including by the international development community.

These concepts can help to increase climate resilience if they respond to the specific climate risk context in a region. In any case, it is important to assess specific climate vulnerabilities, projections and potential impacts of climate change, including affiliated uncertainties, and expose how the planned activities will contribute to increasing climate resilience. The following concepts respond in particular to climate change-induced water scarcity, but also involve co-benefits for sustainable development as a whole.

Water Demand Management

Drought and water scarcity increase in many regions due to climate change and variability, increasing water use, change in land cover and other issues. About two-thirds of the world population experience severe water scarcity during one month of the year or more (Mekonnen and Hoekstra, 2016). In many cases, the management or reduction of water demand can increase resilience to climate change-induced water scarcity and provide a sustainable alternative to increasing water supply, in particular if sources are already used beyond safeyield.

Water pricing can contribute to reducing water demand without threatening safe water supply of adequate quality for vulnerable ecosystems and communities in compliance with the human rights to water and sanitation. For example, this can be achieved through charging higher tariffs for large commercial customers during dry months, while keeping an affordable price for the amount of water which is necessary for adequate living. Activities to encourage efficient water use also include non-pricing approaches, such as the installation of water meters or awareness campaigns and education, including on household water-saving behaviours and devices (Tortajada et al., 2019). The use of water-efficient and drought-resistant crops can decrease water demand for agricultural irrigation, so that saved water can be used for other purposes.

Water loss reduction

It is estimated that a large share of the water pumped in supply networks does not reach customers or is not billed. For instance, Mexican cities have reported water losses of more than 40% (OECD, 2016). Hence, the detection and reduction of losses from water networks, both administrative and physical, can substantially help to improve water security. As for the installation and rehabilitation of networks, it helps to increase climate resilience specifically in light of increasing water scarcity.

➔ ***The reduction of water losses can help to increase resilience to climate change- induced water scarcity.***

Physical water losses through leakage e.g. in pipes and storage systems can be reduced through repair. Unauthorised or unbilled water use, for instance through government agencies exempt from water billing, requires political support and must consider the needs of poor communities. The reduction of water losses results in less water that needs to be pumped, also saving electricity costs and, depending on the energy used, reducing GHG emissions.

Good practice example

Peru I: Implementing Resilient Water Management

Water loss reduction in coastal cities: Peru is particularly vulnerable to the impacts of climate change. Parts of the coastal dry areas are prone to drought and desertification. Natural water storage in glaciers in the Peruvian Andes, which has contributed to water security also in coastal areas, has started to disappear. Water scarcity threatens the economic development in those areas, which at the same time must also deal with population growth and increasing water demand.

Water suppliers in the coastal cities of Tacna and Chimbote face the challenge of meeting growing water needs. Due to deficient water networks and missing water meters, the utilities are neither able to quickly detect and fix leakage nor to measure individual water use and to reduce the excessive use of water through economic incentives. As a result, a large part of the population in both cities often gets water supply for only a few hours per day. On behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), the German development bank KfW supports water utilities in Tacna and Chimbote in facilitating a sustainable and reliable water supply. The focus of the activities is the avoidance of water losses, for instance through network improvement and provision of equipment and material. The activities also include support for improving data and information on the network and water use. The network is divided into sectors in order to locate, analyse and reduce water losses. The installation of water meters at house level enables customers to monitor their own water consumption and reduce the respective costs. The programme also includes accompanying awareness campaigns. The initiative aims at enhancing climate resilience through increasing the continuity of water supply by at least two hours per day and contributing to the sustainable water supply in Tacna and Chimbote.

Peru II: How an agriculture company contributes to improving Peru's climate resilience

Virú Group ("Virú") is one of the three biggest agricultural exporters in Peru. In addition to its own cultivation, extending over 8,000 ha of farmland, Virú buys fruits and vegetables from smallholders. Its products are processed at three processing plants and distributed worldwide. It includes asparagus, artichokes, avocados, peppers, mangoes and heart of palms, as well as value-added products, such as pestos, bruschettas, and ready-to-eat meals. Its main customers are supermarket chains, including REWE, Carrefour, EDEKA and local traders.

The German development financier DEG supports expansion plans with long-term loans and assisted Virú as part of its Business Support Services (BSS) in implementing a state-of-the-art wastewater treatment plant, which enables the reuse of water and reduces the water footprint of the company. To ensure the sustainability of the water supply, Virú installed remote-controlled computer-based groundwater-level monitoring tools in all wells to track future trends in groundwater availability. The general water footprint is low, as modern drip irrigation systems are used for all production sites.

Recent studies on the relation between extreme weather events (El Niño) and the financial performance of Peruvian agricultural companies showed that the financial impact of El Niño was successfully mitigated in companies with a best-practice water management and emergency-response infrastructure, such as storage reservoirs providing irrigation water for at least seven days.

Network extension and rehabilitation

Despite the targets of the Sustainable Development Goal on Clean Water and Sanitation (SDG 6) to reach universal access by 2030, it is estimated that more than 2 billion people still lack access to safe drinking water. More than 800 million lack access even to basic water services. About 4.5 billion have no access to safe sanitation, more than half of which lack basic sanitation (UN, 2018). The lack of access to safe drinking water can significantly increase vulnerability to climate change-induced water scarcity, since communities without access often depend on water sources with significant variability in availability and quality. Availability and pricing, in turn, might be directly affected by the impacts of climate change.

Depending on the specific vulnerability context, the extension and rehabilitation of water network infrastructure can increase climate resilience and improve household income, access to education, food security and health. The necessary funding is usually provided by governments, partly assisted by the international donor community. The proper maintenance of existing infrastructure reduces the risk of deterioration and the need for costly rehabilitation efforts.

It is important to consider future climate impact scenarios during the planning and design phase.

Reuse of treated wastewater

Resilience to increasing water scarcity can also be improved through the reuse of treated wastewater as an alternative resource. Reuse for agricultural irrigation has been practiced for decades, in particular in water-scarce areas, for instance in Spain (Jódar-Abellán et al., 2019). Treated wastewater of adequate quality can also be used to recharge groundwater or surface water resources or for industrial purposes, for instance as cooling water. The direct reuse as drinking water, including through blending with other sources, is only practiced in a few cases, for instance in Singapore (Tortajada and Nambiar, 2019).

➔ ***Increasing coverage of wastewater treatment comes with opportunities for climate resilience and GHG mitigation.***

It is estimated that still over 80% of the world's wastewater, including more than 95% in some least developed countries, is discharged into the environment without any treatment, threatening marine and freshwater ecosystems, communities and contributing to GHG emissions (WWAP, 2017). As emerging and developing economies increase their coverage of wastewater treatment, the opportunity to use treated effluent or to store it as a substitute for scarce surface or groundwater is arising.

Treated wastewater can be used as a cost- and energy-efficient alternative water source for irrigation, especially compared to costly alternatives, such as the development and operation of long-distance transfer systems. Enabling conditions for wastewater reuse include an adequate institutional and regulatory framework and setting quality standards and norms for different use purposes. Potential users and their perspectives, including potential cultural taboos, must be involved in the decision-making process from the beginning. In addition, it should be noted that the reuse of treated wastewater might involve environmental and health risks, which can be contained by proper treatment and an adequate institutional and regulatory framework.

Desalination

In the case of water scarcity, increased by the impacts of climate change and variability, the generation of water through desalination processes can be a suitable alternative for improving climate resilience. Water-scarce coastal areas might consider desalination of seawater as one factor contributing to improved water security. Brackish water, for instance from aquifers, can provide an alternative source in dry areas, including in regions which are far from the coast and might otherwise consider using water which is transferred from long distances. Technologies for the desalination of saltwater and brackish water, e.g. through reverse osmosis, have become considerably cheaper and more energy-efficient in recent decades (Ghaffour et al., 2013). Due to the lower salt content, the desalination of brackish water requires less energy, and water quality is often better compared to seawater, making treatment processes less demanding.

The separation of salt generates brine as a byproduct, which has a very high salt concentration. If brine is not disposed of in an environmentally sustainable way, it can significantly threaten the health of ecosystems. Therefore, the challenge of sustainable disposal of brine needs to be addressed in the planning, design and operation phases of desalination activities. Brine can be diluted in seawater, for example through diffusors in accordance with the specific environmental and geographic conditions (Voutchkov, 2011). In landlocked areas, if conditions permit, approaches might include the sustainable disposal in evaporation ponds and natural sinks and injections in saltwater aquifers. It is important to mention that every case of desalination requires a thorough assessment of the social, environmental, marine, geographic and geological conditions, with the objective of minimising negative impacts through brine.

Even though desalination has become more efficient, it still requires a considerable amount of energy, for example for generating the necessary pressure in the reverse osmosis process. The use of fossil fuels for the necessary electricity would increase the emission of CO_2. Therefore, it is advised to assess the potential for increasing the share of renewable energy in the country's energy mix and to optimise energy efficiency when engaging in or expanding desalination practices. The respective infrastructure does not necessarily need to be built physically next to the desalination facilities for direct supply. Desalination requires continuous energy supply and would thus need a solution for energy storage. Instead, renewable energy might feed into the general electricity grid, which could also be connected to the desalination infrastructure. Only decentral desalination facilities without access to energy will need a specific new source of energy.

Resilient Rainwater Management

Changes in seasonal and geographic rainfall variability and intensity, as well as gradual trends in the total yearly amount of rain, are among the most direct impacts of climate change (*see Chapters 4 and 5*). Through an optimised rainwater management system, threats can be reduced and even turned into opportunities if rainwater is used as a resource.
For example, rain can be collected and used for groundwater recharge. Main goals of climate-resilient rainwater management include the prevention of flood damage, protection of water resources and optimisation of water use.

In cities, support for water retention areas can be combined with the creation of public parks, which are deliberately flooded in case of heavy rains. Surfaces in cities are often sealed, preventing the natural runoff of water. Permeable surfaces instead allow for water infiltration, improve natural drainage and can also have a cooling effect. Rainwater collection, diversion and storage can provide an additional source of water, especially in areas which are threatened by water scarcity. The specific elements of rainwater management depend on the location as well as the current and future climate, social and geographic features (Palazzo, 2019).

Resilient Sanitation Systems

While water is projected to be the main channel through which the impacts of climate change will be transmitted, the impacts on sanitation systems cannot be neglected. Extreme weather events such as drought, flooding, or storm surges, as well as sea level rise, put sanitation systems at risk. Yet, sanitation has received little attention in the discussion and research on the impacts of climate change. Information on what resilience means for different sanitation systems and how climate change might affect the way we manage sanitation services is sparse.

UNESCO and UN-Water (2020) emphasise that climate change is likely to slow down or undermine the achievements related to access to safely managed water and sanitation, if the design and management of systems is not made climate-resilient. Even small losses of sanitation coverage due to impacts of climate change can have disproportionate effects on public health. For instance, a whole community can be affected by contamination even though only a few latrines were flooded.

An increased occurrence of floods and heavy rainfall can be a challenge for sanitation systems, especially in cities. Flooded pit latrines or septic tanks can cause uncontrolled discharge of untreated faeces and wastewater, thus posing a public health risk. Sewage treatment plants can also be damaged due to extreme weather events. Periods of drought pose challenges to water-based sanitation systems. Water shortages can impair the functionality of sewer systems and lead to their accelerated corrosion. In addition, the concentration of pollutants in wastewater can become higher and thus exceed the capacity of receiving waters. The rise in sea level might affect sewage treatment plants, which are increasingly located in coastal, low-lying areas (of cities). Floods, storm surges and saltwater intrusion can significantly threaten the functioning of wastewater treatment plants. Increasing intensity and frequency of storms may damage or even destroy sanitary infrastructure (latrines, sewers, sewage treatment plants). Accompanying interruptions in the power supply also threaten the operation of grid-connected sanitary systems.

Sustainable and climate-resilient sanitation systems are therefore necessary in protecting public health. They can also make a significant contribution to urban resilience, as they can be a source of water, energy and nutrients. Recent research suggests applying several principles to increase the resilience of urban sanitation systems including: optimised and robust hardware to sustain shocks; flexible options and diversified risks; adaptive management to withstand disturbances; raised awareness and knowledge to minimise damage; consideration of complex system dynamics; and attention to the distributional effects on equity. While the resilience of the hardware is important, the flexibility and adaptability of operation and management of services is equally relevant, in order to address the uncertainty of climate change impacts (ISF-UTS and SNV, 2019).

6.4 Nature-based Solutions and Ecosystem-based Adaptation

As shown in *Chapters 4 and 5*, even small changes in climate can significantly change hydrological patterns at the river-basin and local scale, for instance through more intense and more frequent floods and droughts. Extreme weather phenomena severely affect ecosystems and have potentially devastating socio-economic impacts (McKinsey, 2020).

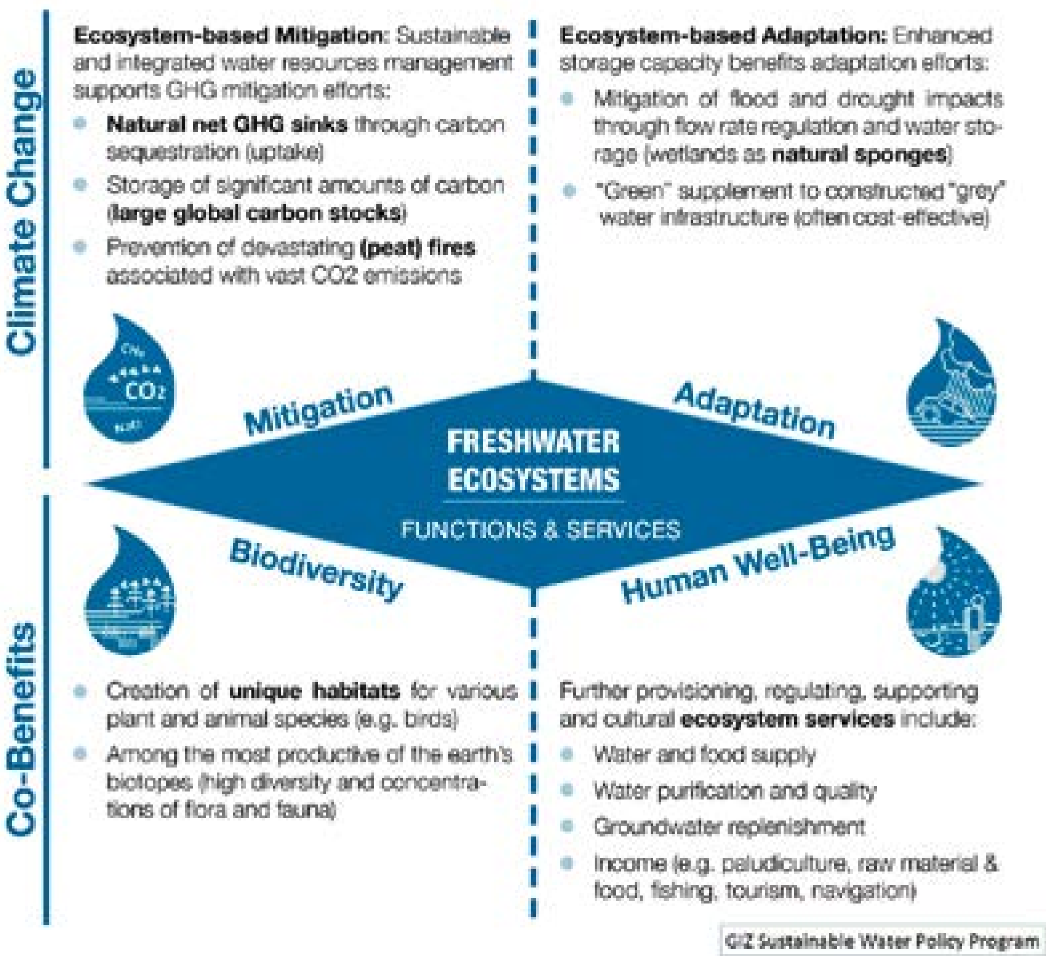
Nevertheless, if managed appropriately, ecosystems can absorb parts of the impacts of climate variability and change. For instance, forests and wetlands can catch a share of floodwater and might derive part of that water to recharge aquifers. In addition, ecosystems can also contribute to the mitigation of GHG (*see Chapter 7*), while safeguarding biodiversity and fostering human well-being (e.g. economic activities, livelihoods, etc.).

➔ ***Ecosystems can absorb part of the impacts of climate variability and change.***

Ecosystem services are goods and services provided by healthy ecosystems (*see definition box below*). Essential water-related ecosystem services include coastal flood and drought protection by mitigating adverse effects of weather variability and extremes. Other services comprise water purification as well as the reduction of erosion and sedimentation. *Figure 32 below* provides an overview of potential functions and services provided by freshwater ecosystems with a focus on wetlands. However, most of the described benefits are also applicable to lakes, rivers or spring ecosystems. The figure displays that the benefits for climate action provided by healthy water-related ecosystems usually come along with several co-benefits in different socio-economic and environmental spheres.

Ecosystems can play an essential role in promoting robust, but flexible adaptation solutions. The corresponding climate activities often also aim at protecting, sustainably managing or restoring ecosystems in order to effectively address societal challenges. Such activities can be grouped under the concept of **Nature-based Solutions (NbS)**, as described in more detail below. A strategy that builds on NbS in order to particularly address climate change impacts is called an **Ecosystem-based Adaptation (EbA)** approach (*see definition box below*).

Figure 32: Freshwater ecosystems' functions and services for climate change mitigation and adaptation, and related co-benefits. Source: GIZ



Definition of terms

Nature-based Solutions, Ecosystem Services, Ecosystem-based Adaptation, Ecosystem-based Mitigation

The term **Nature-based Solutions (NbS)** emerged around 2002 (Cohen-Shacham et al., 2016). IUCN defines NbS as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits". The defining feature of an NbS is, therefore, not whether an ecosystem used is 'natural', but whether natural processes are being proactively managed to achieve set objectives (compare Cohen-Shacham et al., 2016; Nesshöver, 2017; UNESCO WWAP, WWDR, 2018). It can be used as an umbrella concept that covers a range of approaches, including ecosystem-based approaches and green infrastructure.

Ecosystem Services are goods and services provided by healthy ecosystems, including medicinal plants, clean water and air, and protection from extreme natural events (IUCN, 2018).

Ecosystem-based Adaptation (EbA) is an issue-specific Nature-based Solution for addressing climate change impact. The term EbA was coined in 2008 and defined in 2009. The definition of EbA used in the Convention on Biological Diversity (CBD) is now the most commonly accepted (Friends of Ecosystem-based Adaptation (FEBA) 2017):
"Ecosystem-based Adaptation is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change."

Ecosystem-based Mitigation (EbM) is an issue-specific Nature-based Solution that uses "ecosystems for their carbon storage and sequestration services to aid climate change mitigation" (Doswald and Osti, 2011). Emissions reductions are achieved through creation, restoration and management of healthy ecosystems (e.g. forest restoration, wet-/peatland conservation).

EbA approaches have gained importance under the UNFCCC Paris Agreement (e.g. in Nationally Determined Contributions (NDCs), climate finance, national policies and budgeting) (FEBA, 2017). Furthermore, ecosystems' potential in terms of climate change mitigation can be included in overall mitigation strategies as approaches (*see Chapter 7*). However, in order to avoid inadequately "re-packaging" business-as-usual conservation or development activities as EbA activities, quality standards have evolved to guarantee appropriateness and coherence. Regarding the water sector, these criteria and standards can help to design and/or implement EbA measures in order to clearly demonstrate the climate change adaptation effects of a respective water management action. Furthermore, there are several other guidelines and tools for the resilient design, effective implementation and impact assessments of EbA approaches in addition to the criteria defined by FEBA (*see box on the next page*).

Tools

Selected guidebooks for resilient design, effective implementation and impact assessment of Ecosystem-based Adaptation

Several guidelines, guidebooks and sourcebooks have recently been published with support by several donors, including the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and co-produced by GIZ. Some of the most recent ones include:

Voluntary guidelines for the design and effective implementation of ecosystem-based approaches to climate change adaptation and disaster risk reduction and supplementary information (2019) (English) (Secretariat of the Convention on Biological Diversity, 2019).

Guidebook for Monitoring and Evaluating Ecosystem-based Adaptation Interventions (2020) – Practical guidebook for planners and practitioners that describes key considerations and components for each step of Monitoring and Evaluation (MandE) of EbA projects and points to additional tools and methodologies that can be used under specific circumstances (English) (GIZ, UNEP-WCMC and FEBA, 2020).

Climate Risk Assessment for EbA (2018) – A guidebook for planners and practitioners providing a standardised approach to assessing risks within social-ecological systems based on two application examples (river basin and coastal zone management) (English/Spanish) (GIZ, EURAC and UNU-EHS, 2018).

Valuing the Benefits, Costs and Impacts of EbA (2017) – A sourcebook of methods for decision-making and valuation of benefits, costs and impacts (English/Spanish) (Emerton, 2017).

Making Ecosystem-based Adaptation Effective: A Framework for Defining Qualification Criteria and Quality Standards (2017) – A practical assessment framework for designing, implementing and monitoring EbA measures that encourages practitioners and decision-makers to use them. (English) (FEBA, 2017).

Enabling Ecosystem-based Adaptation (EbA) through Integrated Water Resources Management (IWRM) (2020, forthcoming) – Based on case studies, this report for planners and practitioners showcases the potential of IWRM processes as an entry point for a wider-scale landscape approach to EbA planning and implementation (GIZ, 2020).

Nature-based Solutions for flood risk management

As shown in *Chapter 5*, the risk of more severe flooding events is projected to increase, for example in the Upper Niger, the Blue Nile and the Ganges. Here, NbS – specifically EbA – offer great potential for robust and flexible flood risk management strategies. Decision-makers should agree on an adequate combination of infrastructure-based (grey) and/or nature-based (green) adaptation options on the basis of best available information. For example, nature-based flood retention measures can store stormwater, and thus complement and reduce the need for grey infrastructure designed for urban drainage systems. River floodplains can store flood water and thereby reduce the need to build embankments (Browder et al., 2019). Climate resilient flood risk management strategies also hold great potential for complementing overall disaster risk reduction efforts (*see box on Ganges Case Study on page 97*).

Dadson et al. (2017) grouped common nature-based measures in flood risk management into three categories:

1. **Water retention in the landscape through management of infiltration and overland flow:** Increasing water retention in the landscape can be done through land-use changes (e.g. grassland conversions, wetland/peatland restoration), other forms of agricultural practices (cover crops, crop rotation) and livestock practices (restriction of grazing season), among others. Further measures include managing field drainage and creating buffer zones on farmland, such as shelter belts.
2. **Managing the hydrological connectivity and the conveyance of water in the landscape:** This can be done by the management of farmland (hillslopes, ponds and ditches), channel maintenance, modifications to drainage regimes and the placement of farm structures, such as culverts.
3. **Making space for water storage** (*see Chapter 6.5*)**:** Water can be stored in aquifers, reservoirs as well as in wetlands. Another measure is to restore floodplains through reconnecting rivers and setting back embankments, for example. Restoring river profiles and maintenance can increase space for water, reducing the need for space in other areas in case of flooding.

Experience has shown that NbS are often most effective when green infrastructure is combined with grey infrastructure approaches. Such a combination can provide cost-effective adaptation solutions with a significant risk reduction potential. The predominant type of land use, along with existing social, ecological and hydrological settings, mostly determines which combination of nature-based and infrastructure-based options performs most effectively.

Good practice example

Implementing EbA within watershed management to manage extremes in South Africa

Droughts in South Africa are becoming increasingly common. In KwaZulu-Natal the "uMngeni Ecological Infrastructure" project aims at integrated watershed planning and management. The goal is to improve the resilience of water services to climate change at a watershed scale. The "Ecological Infrastructure Partnership" is a collaboration of public and private actors who share expertise and resources to protect and enhance the state of ecological infrastructure in the uMngeni catchment. The initiative has 23 signatories and is part of the "Strategic Infrastructure Investment Project 19". The project follows the principles of EbA by using the ability of ecosystems to provide services to downstream communities in a resilient manner. It seeks to enhance governance and regulatory capacity at a catchment scale while implementing restoration measures in selected sites, thus leading to improved water services to downstream communities. The socio-economic co-benefits include improved livestock production, an increase in employment in rural areas, and the long-term protection of species-rich endemic grassland ecosystems. The project was funded by the Critical Ecosystem Partnership Fund and implemented by Wildlands Conservation Trust.
Source: GIZ, 2019.

6.5 Flexible water storage

As shown in *Chapter 5*, many river basins are expected to experience an increase in the probability and/or severity of hydrological extremes and the variability of the local climate. Water storage systems are essential for dealing with seasonal and annual water variability and can also serve as a buffer against extremes, providing answers to multiple impacts of climate change and variability through the following functions:

- Store part of the excess water during extreme precipitation and flooding;
- Gradually release stored water in times of drought;
- Balance increasingly uncertain water variability;
- Replace natural storage systems threatened by climate change, such as glaciers.

In this context, it should be noted that in some regions, such as the Andes and the Himalayas, water storage in glaciers is an essential element of the water cycle in the respective basins, including the Ganges basin (*see Chapter 5.2*) and the Upper Amazon basin (*see Chapter 5.3*).

➔ ***Water storage can provide answers to multiple impacts of climate change and variability.***

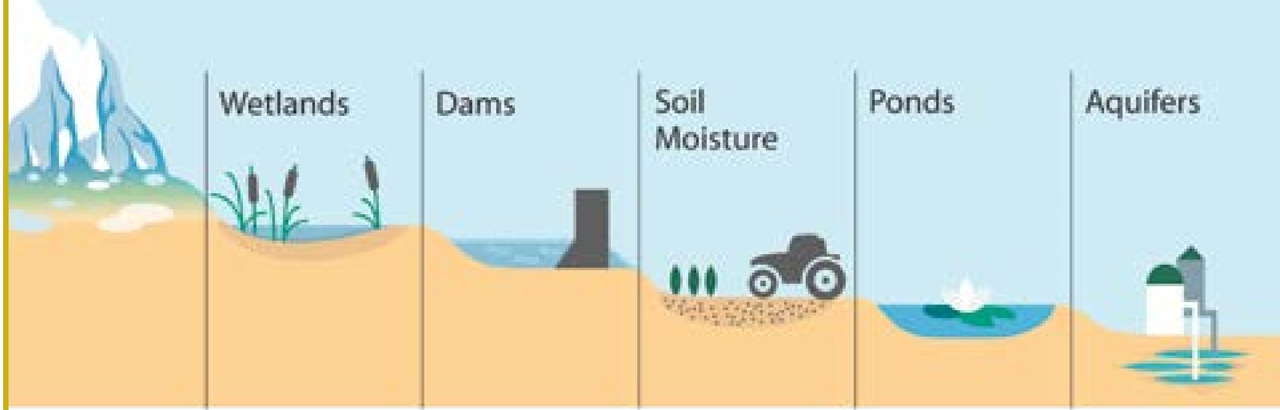
In the face of climate change, natural storage system depletion, and increased water demand, the ability to accommodate varying levels of precipitation and hydrological flows is essential. To this end, more storage systems are needed, and these should be flexibly designed and managed.

In light of increasing uncertainty about future climate conditions, relying on grey infrastructure alone will not be enough. Rethinking how green NbS can best be combined with infrastructure-based grey measures is necessary to manage climate risks, while safeguarding freshwater ecosystems. There are various nature-based approaches to increasing storage capacity and thereby fostering adaptation efforts, including through the conservation of wetlands, afforestation of catchment areas, managed groundwater recharge, and improved soil moisture retention. At the same time, these measures to increase storage capacity often provide co-benefits, for instance in terms of biodiversity protection, GHG mitigation, and soil erosion control.

The **Water Storage Continuum Concept** (McCartney and Smakhtin, 2010) suggests that storage planning at river basin and regional scales should consider a portfolio of surface and sub-surface storage options, including reservoirs, wetlands, soil moisture, ponds and aquifers, with the objective of achieving the best environmental and economic outcomes in the face of the case-specific vulnerability and climate change impact scenarios. Each of these storage options has its own strengths and weaknesses, which often further depend on the biophysical and social contexts in which they are implemented. Climate change also affects different storage types in different ways: under some climate scenarios, some types might fail, while others may continue to function. *Figure 33* provides an overview of different water storage systems, their potential for increased climate resilience and related co-benefits, as well as potential disadvantages. In light of increasing climate variability, and uncertainty of future climate and socio-economic scenarios, McCartney and Smakhtin (2010) recommend combining different types of storage in a system. This will improve the overall storage system's ability to perform under various climate scenarios, as well as create flexibility in adapting storage management to changing conditions. McCartney et al. (2013) provide a tool for a rapid (first-cut) evaluation of the effectiveness of different water storage options under existing and possible future climate conditions, which is based on a set of biophysical and demographic indicators.

On a related note, also fossil and deep-lying groundwater resources can be an important source of high-quality drinking water in several regions, such as in dryland regions in Africa (e.g. in the Sahara and Kalahari regions). As such, they may serve as a temporary solution for drinking water supply and may account for shortages in surface water availability during drought events. Yet, it must be emphasised that, especially in dryland regions with little or no groundwater recharge, fossil groundwater resources are often not renewable and are therefore not a long-term solution for water supply.

Resilient water storage buffers the impacts of climate change and replaces natural storage, such as in glaciers.



	Wetlands	Dams	Soil Moisture	Ponds	Aquifers
Flood mitigation potential	Capture and slowly release floodwaters Detain floodwater pollutants	Rapid uptake and release High storage capacity	Reduce run-off and increase retention	Cost-effective and solution but limited capacity	High storage capacity but slow uptake through infiltration
Drought mitigation potential	Maintain river flows during dry periods Inundated areas recharge aquifers	Long-term predictable storage Controllable release	Extends period of water availability	Decentral low-cost solution but limited reliability	Long-term storage without evaporation losses
Other benefits	Ecosystem-based Mitigation: Carbon sink & storage Support livelihoods and high biodiversity Natural water treatment	Renewable energy generation	Support livelihoods (rainfed agriculture)	Support livelihoods (aquaculture)	Improves water quality Artificial recharge mitigates land submergence and counteracts saltwater intrusion
Disadvantages	Potentially produce CH_4 emissions	High evaporation losses Potentially high social and ecological costs Potentially produce CH_4 emissions	Use limited to plant growth	High vulnerability to pollution	Potentially high energy consumption for infiltration and pumping

Figure 33: The potential of different water storage systems for increased climate resilience (own compilation based on McCartney and Smakhtin, 2010)

Managed Aquifer Recharge as part of flexible storage concepts

Sub-surface storage options include techniques that intentionally enhance natural groundwater recharge by building infrastructure and/or modifying the landscape, collectively known as **Managed Aquifer Recharge (MAR)**. MAR, which is also applied in combination with surface water storage, is one storage approach that holds major potential for alleviating adverse impacts of both floods and droughts in a particular basin.

MAR techniques range from sophisticated infiltration wells to the relatively simple measure of decentralised stormwater infiltration. MAR has the potential to serve various purposes, including maximising water storage, replenishing depleting aquifers, improving water quality, preventing saltwater intrusion into groundwater in coastal areas, improving soil quality and providing ecological benefits, such as safeguarding groundwater-dependent plant communities or enhanced downstream river flows. In any case, a sound knowledge of the soil, aquifer and water conditions is a prerequisite for effective use of MAR.

Moreover, risks of groundwater pollution must be considered, e.g. when infiltrating stormwater. For instance, infiltration of water can mobilise potentially hazardous substances in the sub-surface. The implementation of MAR measures should, therefore, follow a careful approach, involving a thorough desk study assessment and feasibility study, as well as a first pilot MAR activity with adequate testing and monitoring. If successful, a more comprehensive MAR system with continuous monitoring of quantity and quality could be installed.

6.6 Transboundary Resilience Management

Administrative boundaries do not stop the natural flow and extension of rivers, lakes and aquifers. 310 rivers and lakes, covering 47% of the Earth's land surface (McCracken and Wolf, 2019), as well as numerous groundwater aquifers, cover two or more sovereign states. As outlined in *Chapter 5*, the climate-related challenges facing many transboundary river basins are considerable. Some countries, such as Egypt, depend almost entirely on water coming from neighbouring states. In the case of shared water resources, water management activities in one country might affect the quantity and quality of water resources in neighbouring countries.

In order to improve water-related cooperation among riparian countries, **Transboundary Water Management (TWM)** activities have been agreed upon and supported by the international community in recent decades. Many transboundary river basins, such as the Mekong, Nile and Niger basins, have established their own transboundary River Basin Organizations (RBOs). International conventions on TWM include the 1997 UN Water Convention and the 1992 Convention on Transboundary Watercourses of the UN Economic Commission for Europe (UNECE). Today, TWM has become an internationally recognised and renown concept for improving regional cooperation and preventing conflicts through water cooperation.

To address the climate change-related challenges outlined in *Chapters 4 and 5* of this report (e.g. the risk of projected increases in flooding in the Niger, Blue Nile, and Ganges basins), transboundary water cooperation should account for climate change and related uncertainties. By working together, actors at the transboundary, national, and local level can harness the potential of water governance and climate policy approaches for both climate change adaptation and mitigation, as well as water security. In doing so, they can further build on well-established examples of transboundary water cooperation and take cooperation to another level: **Transboundary Resilience Management (TRM).**

➔ ***Following a TRM approach, decision-makers can create synergies and co-benefits in river basins by integrating water and climate interventions more closely.***

The aim of TRM is to combine key elements of climate resilience with transboundary cooperation mechanisms in order to support implementation of collaborative climate action. Elements of resilience management include a mechanism for integrated climate risk and vulnerability assessments, a strategy and planning process and realistic financing options. Such a management approach may even be expanded to complement national climate plans and strategies through transboundary planning documents, including both mitigation and adaptation aspects.

While the strength, mandate and scope of transboundary RBOs varies considerably from one basin to another, they regularly have established governance functions that are critical for resilience management, including data collection and storage, knowledge generation, processes for participation of stakeholders from different levels and sectors, and for coordination of various interests. In addition, they often have established mechanisms for strategic and investment planning and dispute settlement. In order to be resilient,

Good practice example

Basin Ganges – Managed Aquifer Recharge (MAR) for flood mitigation and dry-season water supply

The Ganges is the world's most populous river basin. More than 650 million people rely on its waters and ecosystem services. Over recent decades, the Ganges has become one of the most polluted large rivers and, especially during the last few years, some lower reaches of the river have had unprecedented low water levels during the pre-monsoon season. This has caused high damage to surface drinking water supply, power generation units, irrigation systems and navigation. These low water levels are mainly caused by the overexploitation of groundwater (Mukherjee et al., 2018). Climate change is aggravating this situation, which is already perceived as a water crisis. Precipitation, and hence river flows might increase in the future, but climate change may also cause more extreme weather events (see Chapter 5.2).

A comprehensive basin-wide assessment by the World Bank (2014) found that the current capacity in the basin to manage floods and droughts is likely to be inadequate. Furthermore, while it plays a key role for adaptation and disaster risk management, large-scale infrastructure, such as dams alone, will not be enough to avert the worst of climate impacts on local communities in the basin's highly variable monsoon-driven climate. The study recommends transitioning from mere flood control to flood management. Infrastructure-based interventions need to be complemented by nature-based interventions with a more pronounced focus on regional forecasting and/or warning systems, drainage and "soft" responses, such as disaster preparedness or flood insurance.

When it comes to tackling more frequent extreme weather events and aggravating water scarcity in the future, underground water storage solutions are emerging as a potential adaptation solution for the basin. Underground Taming of Floods for Irrigation (UTFI) is a MAR-based approach to facilitate aquifer recharge and store wet-season high flows in upstream areas, in order to mitigate the risk of flooding further downstream at basin scale.

The groundwater recharge structures installed in upstream areas both offer flood protection and form water reserves for the dry season or prolonged droughts. UTFI is still at an early stage of development. The International Water Management Institute (IWMI) has investigated the potential of the concept (Pavelic et al., 2015), estimating that 68% of the area in the basin closest to the river is highly or very highly suitable for deploying the concept. The project also established a pilot in Western Uttar Pradesh, which serves both as a scientific experiment and practical demonstration. UTFI has also been applied in the Chao Phraya River Basin in Thailand (WWAP/UN-Water, 2018). While the potential to deploy UTFI across the basin is theoretically large, further research is needed to validate its technological feasibility and economic viability.

the institutional and other governance frameworks for transboundary cooperation themselves also need to provide for flexibility in adapting policies, strategies and institutional structures to changing conditions. This requires regular review processes that allow for learning and strategies that adapt accordingly. Moreover, the scope of cooperation might be extended beyond water to include other critical sectors, such as energy and agriculture. As in all climate-related initiatives, it is essential to gain ownership by the member countries' focal points to the UNFCCC, in most cases the environment ministries, but also planning and finance ministries.

Despite the water sector's long-standing experience in fostering transboundary cooperation, it is often a challenging process, as riparian states might have differing investment priorities and adaptation goals. It should be noted that transboundary water cooperation arrangements provide suitable mechanisms for increasing regional (climate) resilience. Proactive countries might also start TRM with one or more engaged neighbours, if there is no existing transboundary institutional structure. In turn, climate adaptation can also be an entry point for improved transboundary cooperation on topics that are potentially sensitive. Joint climate adaptation action on a transboundary basin level can help to establish a way of cooperation that is focused on beneficial aspects of collaboration (e.g. creating win-win scenarios for improving climate resilience) rather than on potentially controversial ones.

Transboundary Climate Risk and Vulnerability Assessments

Many countries have already conducted climate risk and vulnerability assessments at the national level. However, making use of transboundary climate risk and vulnerability assessments can complement a national perspective by identifying and planning joint adaptation activities.
The process of preparing a climate risk and vulnerability assessment is also an opportunity to raise awareness and build trust between the parties involved, as is data and information-sharing in general. In many basins, local or national efforts to adapt to present and future climate conditions are already underway. The joint assessments can be an effective means to draw attention to such efforts, evaluate them, and, if deemed successful, promote them in other parts of the basin. If conducted in a systematic, comprehensive, and inclusive fashion, such assessments can lay a solid, explicit foundation to proceed with joint adaptation planning and implementation in transboundary river basins (Fritzsche et al., 2014; UNECE and INBO, 2015).

Examples of vulnerability assessments for international river basins already exist: For instance, in 2013, the UN Environment Programme (UNEP) published a vulnerability assessment report on the Nile River Basin. The report, which was prepared in cooperation with the Nile Basin Initiative (NBI) and the Nile Basin states, makes use of satellite and other data to address questions surrounding the potential future impacts of climate change on the Nile water systems and the hotspot areas that are especially vulnerable to these changes. It also discusses possible action to manage or avert negative effects of climate change (UNEP, 2013b). Climate risk assessments have also been prepared for, among others, some of the case study basins of this report (*see Chapter 5*).

Good practice example

Climate risk assessment to inform adaption responses for water resources development in the Niger Basin

The Niger Basin Climate Risk Assessment (NBA and WB, 2014) has played an important role in building knowledge on how to enhance the resilience of water resources against climate change and variability in the Niger Basin. Undertaken as a joint initiative by the Niger Basin Authority (NBA) – the transboundary RBO – and the World Bank, its aim was to assess climate change risks for different water-using sectors, and particularly the Sustainable Development Action Plan (SDAP), which was adopted in 2008 by the Heads of State of the nine NBA member countries (Andersen et al., 2005).

The methodology of the Niger Basin Climate Risk Assessment follows a bottom-up, risk-based approach (see Chapter 6.2). As a first step, the study develops an understanding of the water resources system in the Niger Basin, planned SDAP infrastructure investments and how climate change will possibly affect them. The central question of the assessment was how future changes in precipitation would alter run-off patterns and eventually affect the performance of the SDAP infrastructure, focusing on the planned Fomi, Taoussa, and Kandadji dams and associated irrigation schemes.

As a second step, 38 climate projections derived from 15 GCMs were used to validate climate hazards and their probability of exceeding identified risk levels, and recommended relevant adaptation options in the Niger Basin. The assessment suggests that climate change impacts on runoff in the basin are moderate, mostly projecting runoff changes from -18% to +10% by 2050. According to the study, irrigated agriculture is relatively insensitive to these projected changes, if the existing Sélingué dam at the Sankarani tributary in Mali and the three planned dams mentioned above are fully replenished during the rainy season. SDAP, and in particular the planned Fomi dam in the Guinean highlands, are characterized as insurance for the protection of irrigated agriculture against the potential impacts of climate change.

However, crop water requirements might increase by 5% due to higher temperatures by 2050. Under the SDAP scenario, including the construction of the Fomi, Taoussa, and Kandadji dams, minimum river flows and associated ecosystems passing the Markala dam in the Middle Niger Basin could be severely hit by growing water abstraction due to warmer temperatures. The analysis reports a 50% probability that, once in five years, the ten-day average minimum flow at Markala dam will be less than $25m^3$ per second (the adopted minimum norm is $40m^3$). Improving irrigation efficiency would help to moderate water demand and increase climate resilience.

Since the overall sensitivity of the SDAP to the impacts of climate change is projected to be relatively low, the authors recommend focussing on managing freshwater variability in the short- to medium-term. As a co-benefit, this could also increase resilience to potentially increasing water variability. Water managers can contribute to increased resilience against climate variability and change with their long-standing experience in dealing with a climate that has been extremely variable in the Niger River Basin in recorded history, for instance through water harvesting, micro-water storage systems and ecosystem conservation.

Regional Adaptation Strategies and Planning

Transboundary approaches to adaptation strategies and plans could take different forms, ranging from regional harmonisation of adaptation plans to jointly implemented investments that are mutually beneficial, up to basin-wide adaptation plans (World Bank, 2017). Extending the strategy and planning efforts that take place at the national level (e.g. within the framework of developing NDCs and NAPs) to the bilateral or regional level could help to strengthen approaches enhancing transboundary resilience. However, in the absence of sufficient institutional and financial resources, expanding the scope of these planning processes to the regional level may overwhelm national actors' capacities.

If national actors fail to consider the cross-border consequences of adaptation interventions, climate change adaptation might strain inter-riparian relations, thereby increasing the risk of water and climate change-related conflict. This could occur, for example, if a water storage facility is constructed upstream in order to improve climate resilience without considering downstream effects, such as reduced water availability for human livelihoods and ecosystem needs (Tänzler et al., 2013).

In an international climate context, the LDC Expert Group (*see Chapter 8*), for instance, has highlighted potential ways in which regional cooperation can inform and aid the adaptation process (LEG, 2015). There are successful examples of regional cooperation, such as data collection when national capacities in this area are limited. Regional cooperation can create opportunities and synergies for an integrated planning insofar as national governments can profit from established regional expertise, data and information. Conversely, there are examples of national planning instruments that have already been used in the context of transboundary water management activities. One example is the Niger Basin Authority (*see box on Niger case study on page 63*), which used NAPs and National Adaptation Programmes of Action (NAPAs) to coordinate and prioritise planning for different adaptation activities.

Actors have requested appropriate climate finance support for river basin cooperation and specifically for RBOs (see Tänzler et al., 2013; Blumstein et al., 2016). Most recently, the World Bank analysed the current prospects of climate financing for transboundary water cooperation (World Bank, 2017). It considers transboundary RBOs to be in a unique position to ensure long-term planning and implementation of resilience-building projects (World Bank, 2017). The RBOs of Niger and Lake Chad have presented plans to encourage climate resilience investments and support the implementation of climate-related activities. In addition, at the Mekong and the Nile, RBOs have prepared strategies and project proposals to access climate finance and published transboundary adaptation. Meanwhile, some climate funding channels, such as the Adaptation Fund, have started to include transboundary activities into their portfolio.

Insights on Transboundary Resilience Management in select case study basins

RBOs that are active in the river basins introduced in *Chapter 5* or their superordinate basins have already implemented climate programmes at the basin level. Some have also conducted climate risk assessments with a varying level of detail and geographic scope. In addition, joint strategies on climate resilience have been prepared.

Nile Basin (including the Blue Nile)

With the founding of the Nile Basin Initiative in 1999, ten Nile Basin countries formed an intergovernmental partnership to institutionalise transboundary water cooperation. The basin-wide institution provides a forum for the basin states to consult each other and coordinate the sustainable management and development of the shared Nile Basin water and related resources. When it comes to addressing climate change impacts, the NBI has carried out various activities to strengthen TRM:

Climate Risk Assessment

The UNEP's Division of Early Warning and Assessment (DEWA) published a Vulnerability Assessment Report in 2013 (UNEP, 2013b). The assessment was produced in collaboration with the Nile Basin Initiative, the Nile Basin Partner States, the UNEP-DHI Centre for Water and Environment and the Global Water Partnership (GWP). One of the study's key recommendations was that policymakers should employ climate-compatible development strategies that promote economic growth, while reducing risks to the environment. In addition, the authors suggested focusing on the sustainable use of groundwater resources by investing in and building up local actors' capacity to gain a full understanding of the local and transboundary aquifers.

Joint Strategy, Planning and Coordination

There are several efforts that can be used and further developed to jointly address climate change in the basin. The NBI 10-Year Strategy for 2017-2027 chose climate change adaptation (improve basin resilience to climate change impacts) as one of its six goals.

Joint Programmes and Projects

There are already several programmes and project-related activities that can support the implementation of the strategy and strengthen transboundary resilience management. The GIZ is currently implementing a project on conserving biodiversity in the Nile Basin transboundary wetlands (2015-2020) commissioned by the German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) – this is additional to overall support of the NBI provided by GIZ, thanks to financing from the German Federal Ministry for Economic Cooperation and Development (BMZ). Meanwhile, UNDP is currently implementing a Global Environment Facility (GEF)-financed project to enhance joint management of surface and groundwater resources in selected transboundary aquifers in the Nile Basins, executed by NBI.

Ganges Basin

The Joint River Commission between India and Bangladesh was formed in 1972 to deal with potential disputes about sharing more than 50 transboundary rivers. The two countries have agreed to cooperate on the Ganges and signed a respective treaty in 1996. However, this treaty (even more so in a larger basin perspective, which includes China and Nepal) has no focus on climate change-related challenges yet. A prominent entry point for starting an assessment is "The Ganges Strategic Basin Assessment" prepared by the World Bank (World Bank, 2014) that seeks to facilitate regional cooperation in the sustainable use and management of the water resources of the Himalayan rivers. This basin assessment, however, has only a limited scope on climate change challenges and solutions.

Upper Amazon Basin

While the relevant authorities at the Upper Amazon do practice transboundary water cooperation, they do not take the institutionalised approach common to many other transboundary rivers. Nevertheless, several intergovernmental organisations play an important role in addressing climate change challenges in the region (USAID, 2018). For instance, there is the Latin American Technical Cooperation Network on National Parks, other Protected Areas and Wildlife (REDPARQUES), a network of public and private entities established in 1983 by the countries of Latin America. The REDPARQUES programme "Protected Areas, Natural Solutions against Climate Change", implemented jointly with the World Wide Fund for Nature (WWF), focuses specifically on how the protected areas of the Upper Amazon region in Colombia, Ecuador and Peru can help to build climate resilience. The programme is financed by the German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU).

Another key player is the Amazon Cooperation Treaty Organization (ACTO), an international organisation that seeks to promote sustainable development in the Amazon basin. The member parties include Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname and Venezuela. The parties signed the treaty in 1978 and created ACTO in 1995 to strengthen its implementation. By 2010, ACTO had started to include climate change considerations into its Strategic Cooperation Agenda, according to USAID (2018). In cooperation with UNEP and supported by the GEF, the member countries executed the project "Integrated and Sustainable Management of Transboundary Water Resources in the Amazon River basin, considering Climate Variability and Change (2013-2018)".

Joint Strategy, Planning and Coordination and Joint Programmes and Projects

In 2018, ACTO published "The Strategic Action Program – Regional Strategy for Integrated Water Resources Management in the Amazon Basin" (ACTO, 2018). Among the overall 19 strategic actions outlined in the programme are a) the implementation of a Regional System to Monitor Water Quality in the Rivers of the Amazon Basin, b) the development of a Programme for the Protection and Use of Groundwater for Public Supply in the region, and c) the creation of Forecast and Warning Systems for Extreme Hydroclimatic Events (droughts and floods), as well as d) the establishment of an Integrated Regional Platform for Information on Water Resources in the Amazon Basin.

Niger Basin

The Niger Basin Authority (NBA) is an intergovernmental organisation aiming to foster co-operation in managing and developing the resources of the basin of the Niger River.

Climate Risk Assessment

As discussed above, the 2014 Climate Risk Assessment (NBA and WB, 2014) assessed the climate change impacts on a basin-wide action plan. The Niger Basin Sustainable Development Action Plan (SDAP), adopted in 2008 by the Heads of State and Government of the nine member countries of the NBA, is one of the major initiatives under the authority with a strong focus on managing several hydroelectric and agricultural dams built along the river.

Joint Strategy, Planning and Coordination and Joint Programmes and Projects

In 2018, the Green Climate Fund (GCF) board approved the Programme for integrated development and adaptation to climate change in the Niger Basin, a multinational programme involving the nine basin countries Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Niger and Nigeria. The program is co-financed by the African Development Bank (AfDB), the EU Commission's Africa Investment Facility, the GEF, the Forest Investment Fund (FIP) and the various national governments with a combined investment of almost USD 210 million, including loans, grants and in-kind finance. The main objective is to improve the resilience of populations and ecosystems in the Niger Basin through sustainable management of natural resources. The programme is executed jointly by NBA and the nine participating countries, with AfDB acting as an accredited entity.

The GEF-supported project "Integrated Development for Increased Rural Climate Resilience in the Niger Basin" aims at increasing water security, climate resilience, and management of natural resources at regional, sub-basin and community levels in the Niger Basin. In doing so, it contributes to the implementation of the SDAP as well as the NBA's Strategic Plan. Also, the German Federal Ministry for Economic Cooperation and Development (BMZ) is supporting the ongoing work of the NBA with the project "Transnational water management in the River Niger Basin" (2019-2021), implemented by GIZ. The focus is directed at the sustainable development of transboundary water resources in the Niger Basin, including the improvement of flood warning processes and identification of more than 200 climate-relevant projects by NBA.

Limpopo Basin

As part of the Southern African Development Community (SADC) "Revised Protocol on Shared Watercourses" framework, the riparian states of the Limpopo river basin, namely Botswana, Mozambique, South Africa and Zimbabwe, signed the Agreement for the Establishment of the Limpopo Watercourse Commission (LIMCOM) in 2003. Its main objective is to provide recommendations on the uses of the Limpopo, its tributaries and its waters for purposes and measures of protection, preservation and management of the river.

Programmes on supporting transboundary cooperation with relevance for addressing climate change or climate change impacts exist either to support the cooperation at the Limpopo directly or via the SADC framework. For instance, the German Federal Ministry for Economic Cooperation and Development (BMZ) and the UK Department for International Development (DFID) financed activities on improving water management and protection against droughts and floods in cooperation with SADC, implemented by GIZ (2016-2019).

6.7 References

ACTO (Amazon Cooperation Treaty Organization) (2018): **The Strategic Action Program – Regional Strategy for Integrated Water Resources Management in the Amazon Basin.**
http://www.otca-oficial.info/assets/documents/20181022/d2726864fa8c9bf232eeb8fbe7ca7e11.pdf

Andersen, I., and Golitzen, K. G. (Eds.) (2005): **The Niger river basin: A vision for sustainable management.** Washington, DC: The World Bank.

Blumstein, S. , Pohl, B., and Tänzler, D. (2016): **Linking Water and Climate Diplomacy.** Berlin: adelphi.

Bouwer, L., Haasnoot, M., Obeysekara, J., Konyha, K., Hagemann, K., Vazquez, A., and Jeuken, C. (2018): **Dynamic adaptive planning for urban coastal flooding in the city of Miami, Florida.** EGU General Assembly Conference Abstracts, 20, 7942.

Browder, G., Ozment, S., Rehberger Bescos, I., Gartner, T., and Lange, G. M. (2019): **Integrating Green and Gray. Creating Next Generation Infrastructure.** Washington, DC: **The World Bank and World Resources Institute**

Brown, C., Ghile, Y., Laverty, M., and Li, K. (2012): **Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector.** Water Resources Research, 48(9), DOI: *https://doi.org/10.1029/2011WR011212*

Carstens, C., Sonnek, K. M., Räty, R., Wikman-Svahn, P., Carlsson-Kanyama, A., and Metzger, J. (2019): **Insights from Testing a Modified Dynamic Adaptive Policy Pathways Approach for Spatial Planning at the Municipal Level. Sustainability,** 11(2), 433, DOI: *https://doi.org/10.3390/su11020433*

CBD (Convention on Biological Diversity) (2010): **X/33 Biodiversity and climate change, Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at its Tenth Meeting;** UNEP/CBD/COP/DEC/x/33; 29 October 2010, Nagoya, Japan.

Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (Eds.) (2016): **Nature-based Solutions to address global societal challenges. Gland, Switzerland:** IUCN. xiii, 97.

Dadson, S. J., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., and O'Connell, E. (2017): **A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK.** Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 473 (2199), 20160706.

Doswald, N., and Osti, M. (2011): **Ecosystem-based approaches to adaptation and mitigation: good practice examples and lessons learned in Europe** (pp. 41-42). Bonn, Germany: BfN, Federal Agency for Nature Conservation.

Druce, L, U. Moslener, C. Gruening, P. Pauw, and R. Connell (2016): **Demystifying Adaptation Finance for the Private Sector.** A joint study between UNEP FI and BMZ, implemented by GIZ and conducted by the Frankfurt School UNEP Collaborating Centre for Climate and Sustainable Energy Finance, The German Development Centre (DIE) and Acclimatise.

Emerton, L. (2017): **Valuing the Benefits, Costs and Impacts of Ecosystem-based Adaptation Measures.** A sourcebook of methods for decision-making. Bonn/ Eschborn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

References

FEBA (Friends of Ecosystem-based Adaptation) (2017): **Making Ecosystem-based Adaptation Effective: A Framework for Defining Qualification Criteria and Quality Standards** (FEBA technical paper developed for UNFCCC-SBSTA 46). Bertram, M., Barrow, E., Blackwood, K., Rizvi, A.R., Reid, H., and von Scheliha-Dawid, S. (authors). GIZ, Bonn/Eschborn, Germany, IIED, London, UK, and IUCN, Gland, Switzerland.

Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M., and Kahlenborn, W. (2014): **The Vulnerability Sourcebook: Concept and Guidelines for Standardised Vulnerability Assessments.** Bonn/Eschborn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

García, L.E., Matthews, J.H., Rodriguez, D.J., Wijnen, M.,DiFrancesco, K. N., and Ray, P. (2014): **Beyond Downscaling: A Bottom-Up Approach to Climate Adaptation for Water Resources Management. AGWA Report 01.** Washington, DC: The World Bank.

Ghaffour, N., Missimer, T., and Amy, G. (2013): **Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability.** Desalination, 309, 197-207, DOI:10.1016/j.desal.2012.10.015

GIZ and EURAC (2017): **Risk Supplement to the Vulnerability Sourcebook. Guidance on how to apply the Vulnerability Sourcebook's approach with the new IPCC AR5 concept of climate risk.** Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

GIZ, EURAC and UNU-EHS (Deutsche Gesellschaft für Internationale Zusammenarbeit /eurac research/United Nations University-Institute for Environment and Human Security) (2018): **Climate Risk Assessment for Ecosystem-based Adaptation – A guidebook for planners and practitioners.** Bonn/Eschborn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

GIZ (2019): **Emerging lessons for mainstreaming Ecosystem-based Adaptation: Strategic entry points and processes.** Authors: Lili Ilieva and Thora Amend. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn.

GIZ, UNEP-WCMC and FEBA (2020): **Guidebook for Monitoring and Evaluating Ecosystem-based Adaptation Interventions.** Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany.

GIZ (2020) (forthcoming): **Enabling Ecosystem-based Adaptation (EbA) through Integrated Water Resources Management (IWRM).** Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., Ter Maat, J. (2013): **Dynamic Adaptive Policy Pathways: A New Method for Crafting Robust Decisions for a Deeply Uncertain World. Global Environmental Change 23** (2), 485-498,DOI: *http://dx.doi.org/10.1016/j.gloenvcha.2012.12.006*

Hall, J.W., and Borgomeo, E. (2013): **Risk-based principles for defining and managing water security. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences**, 371 (2002), 20120407.

Hallegatte, S. (2009): **Strategies to adapt to an uncertain climate change. Global environmental change**, 19 (2), 240-247.

Hallegatte, S., Shah, A., Lempert, R., Brown, C., and Gill, S. (2012): **Investment decision making under deep uncertainty-application to climate change.** Washington, DC: The World Bank.

References

IPCC (Intergovernmental Panel on Climate Change) (2014): **Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change**, by Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al.(Eds). Cambridge/New York: Cambridge University Press.

ISF-UTS (Insitute for Sustainable Futures, University of Technology Sydney) and SNV (2019): **Considering climate change in urban sanitation: conceptual approaches and practical implications.** The Hague: SNV.

IUCN (International Union for Conservation of Nature and Natural Resources) (2018): **Glossary of Definitions.** *https://www.iucn.org/sites/dev/files/iucn-glossary-of-definitions_march2018_en.pdf*

Jódar-Abellán, A., López Ortiz, M., Melgarejo, J. (2019): **Wastewater Treatment and Water Reuse in Spain. Current Situation and Perspectives.** Water, 11, 1551-1574, DOI:10.3390/w11081551.

Matthews, J. H., Jeuken, A., and Mendoza, G. (2015): **Designing for Climate Confidence: Moving Beyond Uncertainty in Sustainable Water Management.** *https://alliance4water.org/resources/Designing_for_Climate_Confidence_WCCE.pdf*

McCartney, M., Rebelo, L-M., Xenarios, S., and Smakhtin, V. (2013): **Agricultural water storage in an era of climate change: assessing need and effectiveness in Africa. Colombo, Sri Lanka:** International Water Management Institute (IWMI). IWMI Research Report 152, DOI:10.5337/2013.207

McCartney, M. P., and Smakhtin, V. (2010): **Water storage in an era of climate change: Addressing the challenge of increasing rainfall variability.** Blue Paper. Colombo, Sri Lanka: International Water Management Institute (IWMI).

McCracken, M., and Wolf, L. (2019): **Updating the Register of International River Basins of the world, International Journal of Water Resources Development**, 35 (5), 732-782, DOI: 10.1080/07900627.2019.1572497

McKinsey (2020): **Climate risk and response, physical hazards and socioeconomic impacts.** *https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Sustainability/Our%20Insights/Climate%20risk%20and%20response%20Physical%20hazards%20and%20socioeconomic%20impacts/MGI-Climate-risk-and-response-Full-report-vFashx*

Mekonnen, M. M., and Hoekstra, A. Y. (2016): **Four billion people facing severe water scarcity.** Sci. Adv. 2, e1500323.

Mendoza, G., Jeuken A., Matthews, J., Stakhiv E., Kucharski, J., and Gilroy, K. (2018): **Climate Risk Informed Decision Analysis (CRIDA). Collaborative Water Resources Planning for an Uncertain Future.** Paris, France: UNESCO.

Morgan, A.J. (2018): **Water stewardship revisited: shifting the narrative from risk to value creation**, WWFGermany, Berlin. *http://d2ouvy59p0dg6k.cloudfront.net/downloads/wwf_waterstewardship_brief_web_final.pdf*

Morgan, C. L. (2011): **Vulnerability Assessments: A Review of Approaches.** Bangkok: International Union for Conservation of Nature. *https://portals.iucn.org/library/efiles/edocs/2011-068.pdf.*

Mukherjee, A., Bhanja, S.N. and Wada, Y. (2018): **Groundwater depletion causing reduction of baseflow triggering Ganges river summer drying.** Sci Rep 8, 12049. *https://doi.org/10.1038/s41598-018-30246-7*

References

Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., and Krauze, K. (2017): **The science, policy and practice of Nature-based Solutions: An interdisciplinary perspective. Science of the Total Environment**, 579, 1215-1227.

NBA (Niger Basin Authority), and World Bank (2014): **Niger River Basin Sustainable Development Action Plan. Niger River Basin Climate Risk Assessment.** *http://www.abn.ne/images/documents/PDREGDE/volume1_english_summary_report_niger_cra.pdf*

OECD (Organisation for Economic Co-operation and Development) (2016): **Water Governance in Cities, OECD Studies on Water**, OECD Publishing, Paris. *http://dx.doi.org/10.1787/9789264251090-en*

OECD (Organisation for Economic Co-operation and Development) (2019): **Purpose codes list for 2019 reporting on 2018 flows.** *https://www.oecd.org/dac/financing-sustainable-development/development-finance-standards/DAC-CRS-PPC-2019.xls*

Palazzo, E. (2019): **From water sensitive to floodable: defining adaptive urban design for water resilient cities,** Journal of Urban Design, 24 (1), 137-157, DOI: 10.1080/13574809.2018.1511972

Pavelic, P., Brindha, K., Amarnath, G., Eriyagama, N., Muthuwatta, L., Smakhtin, V., Gangopadhyay, P. K., Malik, R. P. S., Mishra, A., Sharma, B. R., Hanjra, M. A., Reddy, R. V., Mishra, V. K., Verma, C. L., and Kant, L. (2015): **Controlling Floods and Droughts through Underground Storage: From Concept to Pilot Implementation in the Ganges River Basin.** IWMI Research Report No. 165. Colombo, International Water Management Institute (IWMI), DOI: *doi.org/10.5337/2016.200.*

Petr, M., and Ray, D. (2017): **Evaluating options for robust forest adaptation to climate change.** QJ For, 111, 183-187.

Radhakrishnan, M., Nguyen, H. Q., Gersonius, B., Pathirana, A., Vinh, K. Q., Ashley, R. M., and Zevenbergen, C. (2018): **Coping capacities for improving adaptation pathways for flood protection in Can Tho, Vietnam.** Climatic change, 149(1), 29-41.

Ray, P. A., and Brown, C. M. (2015): **Confronting Climate Uncertainty in Water Resources Design: The Decision Tree Framework.** Washington, D.C.: The World Bank.

Sadoff, C., and Muller, M. (2009): **Water management, water security and climate change adaptation: early impacts and essential responses.** Stockholm: Global Water Partnership.

Schaer, C., and Kuruppu, N. D. (Eds.) (2018): **Private-sector action in adaptation: Perspectives on the role of micro, small and medium size enterprises.** UNEP DTU Partnership. *http://orbit.dtu.dk/ws/files/162053774/MSME_Adaptation_updated_WEB.pdf*

Schiermeier, Q. (2014): **Water risk as world warms.** Nature News, 505(7481), 10.

Schneider, T. (2014): **Responsibility for private sector adaptation to climate change.** Ecology and Society, 19 (2), 8.

Secretariat of the Convention on Biological Diversity (2019): **Voluntary guidelines for the design and effective implementation of ecosystem-based approaches to climate change adaptation and disaster risk reduction and supplementary information.** Technical Series No. 93. Montreal: Secretariat of the Convention on Biological Diversity.

References

Tänzler, D., Mohns, T., and Ziegenhagen, K. (2013): **Adaptation to climate change for peace and stability. Strengthening of approaches and instruments as well as promotion of processes to reduce the security risks posed by climate change in the context of climate change adaptation.** Dessau-Roßlau: Umweltbundesamt.

Termeer, C.J.A.M., Buuren, A. van, Dewulf, A., Huitema, D., Mees, H., Meijerink, S.V., and Rijswick, M. van (2017): **Governance Arrangements for Adaptation to Climate Change.** In: Storch, H. von (Ed.), Oxford Research Encyclopedia of Climate Science. USA: Oxford University Press.

Tortajada, C., González-Gómez, F., Biswas, A., and Buurman, J. (2019): **Water demand management strategies for water-scarce cities: The case of Spain. Sustainable Cities and Society**, 45, 649-656, DOI: *https://doi.org/10.1016/j.scs.2018.11.044*

Tortajada, C., Nambiar, S. (2019): **Communications on Technological Innovations: Potable Water Reuse.** Water, 11 (2), 251, DOI: *https://doi.org/10.3390/w11020251*

United Nations (2018): **Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation.** New York.

UNEP (United Nations Environment Program) (2013a): **PROVIA Guidance on Assessing Vulnerability, Impacts and Adaptation to Climate Change. Consultation Document.** Nairobi: UNEP Provia Secretariat. *www.unep.org/provia/Portals/24128/PROVIA_guidance_report_low_resolution.pdf*

UNEP (United Nations Environment Program) (2013b): A**daptation to Climate-change Induced Water Stress in the Nile Basin: A Vulnerability Assessment Report.** Division of Early Warning and Assessment (DEWA). Nairobi, Kenya: UNEP *https://na.unep.net/siouxfalls/publications/Nile_Basin.pdf*

UNECE (United Nations Economic Commission for Europe), and INBO (International Network of Basin Organizations) (2015): **Water and Climate Change Adaptation in Transboundary Basins: Lessons Learned and Good Practices.** Geneva: United Nations.

UNESCO (United Nations Educational, Scientifc and Cultural Organization)/UN-Water (2020): **United Nations World Water Development Report 2020: Water and Climate Change**, Paris, UNESCO.

USAID (United States Agency for International Development) (2018): **Climate Risk Profile: Amazon Basin.** *https://www.climatelinks.org/sites/default/files/asset/document/S.AmericaRegional_CRP_Final.pdf*

Voutchkov, N. (2011): **Overview of seawater concentrate disposal alternatives. Desalination**, 273 (1), 205-219, DOI: *https://doi.org/10.1016/j.desal.2010.10.018*

World Bank (2014): **Ganges Strategic Basin Assessment – A Discussion of Regional Opportunities and Risks.** Washington, DC: The World Bank. *http://documents.worldbank.org/curated/en/955751468000263739/pdf/103889-WP-Ganges-Strategic-Basin-Assessment-A-Discussion-of-Regional-Opportunities-and-Risks-PUBLIC.pdf*

World Bank (2017): **Climate Resilience in Africa: The role of cooperation around transboundary waters.** Washington, DC: The World Bank.

References

World Economic Forum, Marsh and McLennan, and Zurich Insurance Group (2020):
The Global Risks Report 2020. Geneva: Switzerland.

WWAP (United Nations World Water Assessment Programme) (2017):
The United Nations World Water Development Report 2017: Wastewater, The Untapped Resource. Paris: UNESCO.

WWAP (United Nations World Water Assessment Programme)/UN-Water (2018):
The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. Paris: UNESCO.

WWF (World Wide Fund For Nature), and DEG (Deutsche Investitions- und Entwicklungsgesellschaft) (2018):
Water Risk Filter, https://waterriskfilter.panda.org/

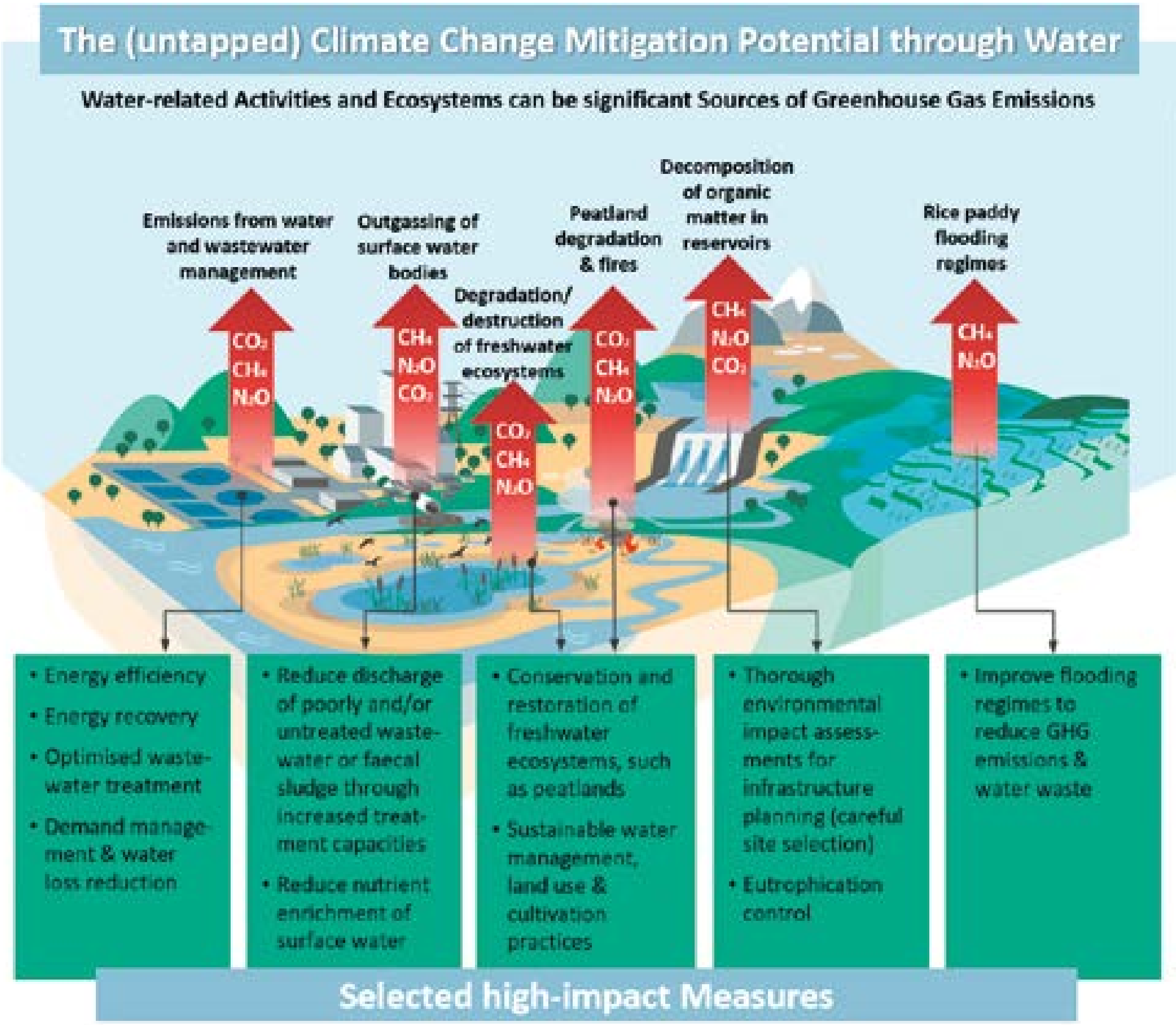
7. Mitigation of greenhouse gases through water

The relevance of water for safeguarding climate resilience is undisputed. However, the water sector itself, as well as water-related activities in other sectors, contribute to climate change by emitting different GHG – in parts highly potential ones. To consider the full mitigation potential of water-related activities, this chapter discusses GHG associated with:

- Energy-intensive processes for purifying, supplying and treating water and wastewater.
- Methane and nitrous oxide emissions from wastewater and faecal sludge management and discharge.
- Emission of GHG from surface water bodies.
- Decomposition of organic material in reservoirs.
- Degradation and destruction of wetlands, in particular peatlands; and
- Different flooding regimes for rice paddy irrigation.

Collectively, GHG emissions from these six categories might cause more than 10% of global anthropogenic GHG emissions, rendering water security a potentially vital element of global climate mitigation activities and strategies. However, this study argues that, despite its significance as a key ingredient in reducing GHG emissions, water security across sectors is widely overlooked.

Figure 34: **Water management – the potential for climate change mitigation**



Key Messages of Chapter 7

- A significant amount of energy and its respective carbon emissions (depending on the source of energy) is required to abstract, supply and treat water and wastewater. Depending on the sanitation system and its management, wastewater and faecal sludge management can cause additional emissions before, during and after treatment. User-friendly tools can help utilities in emerging and developing countries to reduce emissions and save energy costs.

- Untreated and improperly treated wastewater and (faecal) sludge as well as the (over-) use of agricultural fertiliser can contribute to global warming by facilitating the formation of highly potent GHG in surface waters, namely, methane (CH_4) and nitrous oxide (N_2O). Reducing inflows of poorly treated wastewater and faecal sludge, i.e. of organic matter and nutrients, into surface waters can significantly contribute to climate change mitigation.

- Freshwater ecosystems, such as inland wetlands, can absorb and store substantial amounts of carbon. For instance, though covering only 3% of global land surface, peatlands alone store twice as much carbon as all of the planet's forests combined – making them carbon pools of global significance. In consequence, it is especially their carbon storage function that renders healthy natural wetlands an important asset to global mitigation efforts, although they are important GHG sinks, as well.

- Safeguarding the integrity of natural wetlands through conservation and restoration/rewetting measures is a low-hanging fruit for fostering climate ambitions through Ecosystem-based Mitigation (EbM) approaches. These activities can potentially create various co-benefits in the field of biodiversity conservation and human well-being. The sustainable management of water resources is a key element in safeguarding inland wetlands' climate regulation ecosystem services.

- Rice paddies have a significant water footprint. Globally, however, they also are major GHG sources. Water sector measures aimed at rice paddies' flooding regimes bear the potential to foster both water efficiency and climate mitigation.

7.1 GHG emissions from water and wastewater management

The management of water and wastewater involves processes with a high energy demand and, depending on the source of energy used, respective emissions of GHG. In 2014, energy-intensive processes associated with abstracting, supplying and treating water and wastewater accounted for around 4% of global electricity consumption (IEA, 2016). In the US, energy consumption of water and wastewater utilities can represent 30-40% of a municipality's total energy costs (Copeland and Carter 2017). Of the electricity consumed in the water sector, around 40% was used to extract water, 25% for wastewater treatment and 20% for water distribution.

➔ ***Water and wastewater management accounts for around 4% of global electricity consumption. Energy consumption in the sector could double by 2040.***

Growing water demand, higher regulatory standards for treating wastewater and the uptake of desalination are projected to more than double energy consumption in the water sector by 2040 (IEA, 2016). This applies especially to developing countries, where large population segments still lack access to drinking water supply and sanitation services. Moreover, where water and wastewater utilities facilitate access, they often rely on inefficient pumps, leaky distribution lines and dated treatment technologies.

Data and knowledge on GHG emissions from water supply and sanitation at the global level is limited. In the US, water-related use of energy alone was responsible for almost 5% of national GHG emissions (Rothausen and Conway, 2011). Thus, energy-efficient technologies and management approaches can significantly reduce GHG emissions in the water sector.

Municipal wastewater treatment requires energy for the different treatment stages, for instance for pumps, blowers, mixers and screens. The aeration process is often the most energy- intensive part of wastewater treatment. In addition, wastewater collection and treatment processes entail the release of significant amounts of methane (CH_4) and nitrous oxide (N_2O). Although this emission amount is lower than CO_2, its adverse effects on climate are much stronger. The IPCC has estimated the global warming potential of CH_4 at 28-34 times the effect of CO_2 over a timespan of 100 years. Concerning N_2O, global warming potential is

Definition of terms

The Carbon cycle is used to describe the flow of carbon in various forms, e.g. as CO_2, carbon in biomass and carbon dissolved in the ocean as carbonate and bicarbonate through the atmosphere, hydrosphere, terrestrial and marine biosphere and lithosphere.

Adapted from IPCC (2018) p. 544

Carbon sequestration is the uptake (e.g. the addition of a substance of concern to a reservoir) of carbon-containing substances, in particular CO_2, in terrestrial or marine reservoirs. Biological sequestration includes direct removal of CO_2 from the atmosphere through land-use change (LUC), afforestation, reforestation, revegetation, carbon storage in landfills and practices that enhance soil carbon in agriculture (cropland management, grazing land management). In parts of academic literature, but not in this report, (carbon) sequestration is used to refer to Carbon Dioxide Capture and Storage (CCS).

Adapted from IPCC (2018) p. 544, 560

Carbon Dioxide Removal refers to anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

IPCC (2018) p. 544

Mitigation (of climate change) describes a human intervention to reduce the sources or enhance the sinks of GHG.

Adapted from IPCC (2018) p. 554

Pools are reservoirs in the earth system in which elements, such as carbon, reside in various chemical forms for a period of time.

Adapted from IPCC (2014) p. 216

Sink denotes a reservoir (natural or human, in soil, ocean and plants) in which a GHG, an aerosol or a precursor of a GHG is stored. Note that UNFCCC Article 1.8 refers to a sink as any process, activity or mechanism which removes a GHG, an aerosol or a precursor of a GHG from the atmosphere.

Adapted from Ramsar Convention Secretariat (2018) p. 2

Stock is the total carbon stored in an ecosystem, regardless of the time it took to build up this stock.

Adapted from Ramsar Convention Secretariat (2018) p. 2

indicated at 265-298 times the effect of CO_2 for the same timespan (IPCC, 2013).

Moreover, in the absence of oxygen, CH_4 can be released in sewers, in particular in case of long detention times of wastewater (Foley et al., 2010). Another possible source of CH_4 are onsite sanitation systems. Here, long detention times of faecal sludge, for instance, can also increase CH_4 formation. During treatment, CH_4 can be released during anaerobic digestion (if biogas is not or incompletely flared or collected). Depending on the specific treatment and conditions, a share of CH_4 might also remain dissolved in already treated wastewater, thus, gases potentially escape at a later stage. Furthermore, CH_4 emissions can arise during activated sludge management, sludge storage and through leaking biogas. N_2O can be released through the removal of biological nitrogen during wastewater treatment. Uncontrolled sludge disposal is also a source of CH_4 and N_2O (*see Chapter 7.2*).

In the absence of wastewater collection and treatment services, communities often rely on onsite sanitation systems, such as septic tanks or pit latrines. In this case, GHG emissions depend on the individual use of the system, e.g. poor flush latrines vs. dry latrines, the quality and efficiency of faecal sludge management and the type of faecal sludge treatment.

The registration of emissions from wastewater and faecal sludge was included by the IPCC task force on National Greenhouse Gas Inventories in its 2006 guidelines and 2019 refinement in a specific sub-section of the waste sector (IPCC, 2019). Emissions resulting from the influx of untreated or poorly treated wastewater and faecal sludge into surface waters are addressed in *Chapter 7.2*.

Trends and regional differences in GHG emissions from water supply and treatment

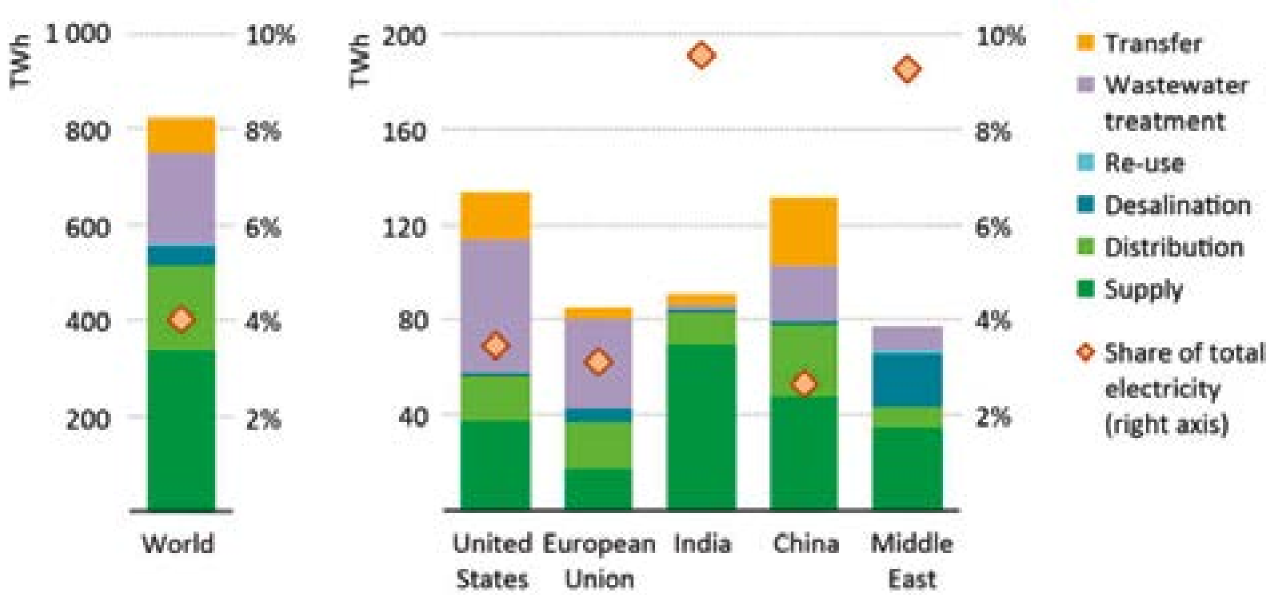
Global electricity consumption in the water sector is projected to increase by 2.3% per year, until it reaches a total of 1470 TWh in 2040 (IEA, 2016). However, the amount of energy used in the water sector varies widely across regions, depending on climate conditions, topography, existing infrastructure and other factors. Furthermore, when displaying water sector energy trends and comparing its energy use in different regions, it is important to be aware of different reference values, such as total energy consumption, as well as the share of electricity and energy consumption based on fossil fuels.

In developed countries, by far the greatest share of water-related energy consumption is used for wastewater treatment and end-use (Rothausen and Conway, 2011). The comparative lack of wastewater treatment plants in developing countries suggests that less CO_2, CH_4 and N_2O is emitted from energy-intensive and often fossil fuel-based wastewater treatment processes. However, this does not necessarily mean that GHG emissions caused by wastewater treatment processes are generally lower in developing countries, since CH_4 and N_2O not only emerge from wastewater treatment, but also, and in a much more uncontrolled way, from wastewater and faecal sludge, which is discharged into the environment without any kind of treatment (*see Chapter 7.2*). In addition, the extraction of groundwater for irrigation can account for high GHG emissions, in particular in more arid regions and countries in which rain-fed agriculture cannot be performed throughout the year. For instance, groundwater depletion and pumping for irrigation, often using diesel pumps, accounts for 2-7% of India's total annual CO_2 emissions (Mishra et al., 2018).

Alternative water resources, such as desalination, can also be associated with high energy use. Roughly 0.7% of global water needs are met by water from desalination and water reuse (*see Chapter 6.3* for climate resilience and environmental aspects of these approaches). However, these processes account for almost a quarter of total energy consumption by the water sector (IEA, 2016). It is projected that desalination will account for the largest increase in electric energy consumption, as production of freshwater from seawater desalination might increase nine-fold and brackish water desalination five-fold. Today, desalination accounts for about 5% of global water sector electricity consumption. In 2040, it is estimated that desalination will account for more than 20% of water-related global electricity demand by the water sector (IEA, 2016).

In terms of regional distribution, desalination technologies are mainly prevalent in North Africa and the Middle East (*Figure 35*). In 2016, desalination accounted for just 3% of the Middle East's water supply, but 5% of its total energy consumption. Moreover, the production of desalinated seawater is projected to increase almost fourteen-fold in the Middle East by 2040 (IEA, 2018).

Figure 35: Electricity consumption in the water sector by process and region, 2014, Source: IEA, 2016.



One challenge concerning the quantification of GHG emissions is the limited availability of comprehensive assessments on the water sector's energy profile. In parts, that can result in major shortcomings in terms of demonstrating the water sector's mitigation potential in the field of supply and treatment, as well as promoting informed water decision-making on water-climate policies. In addition, existing studies deploy different methodologies and delineate water sector boundaries in different ways.

Strategies to reduce GHG emissions in water, wastewater and faecal sludge management

The decarbonisation of energy-intensive processes in the water sector has gained currency over recent decades. Energy-related measures have taken on an increasing role in new strategies for designing and managing water systems (Hering et al., 2013). Solutions are versatile, ranging from the promotion of energy-efficient technologies to onsite renewable energy production. For instance, the GHG-saving potential of water treatment processes can be quite high, since sewage and sludge treatment offers the possibility of producing low-GHG fertiliser from recovered nutrients or renewable energy from organic matter (Wang et al., 2018).

The International Energy Agency (IEA) estimates that if economically available energy efficiency and energy recovery potentials in the water sector are utilised, the sector could reduce its energy consumption by 15% in 2040. Therefore, wastewater treatment, desalination and water supply offer the largest potential for savings (IEA, 2016).

➔ ***Water and wastewater utilities can substantially contribute to national GHG mitigation targets.***

However, most of this energy reduction potential is being squandered (Li et al., 2015). For instance, only a few water and wastewater utilities in Europe and the US have become energy-neutral by deploying energy-optimising measures (Rothausen and Conway, 2011). Wastewater treatment processes hold additional potential for reducing GHG emissions. Through analysing, monitoring, reporting and reducing these emissions, water and wastewater utilities can contribute a substantial share to national GHG mitigation targets. Some measures aimed at mitigating GHG emissions associated with energy consumption as well as wastewater and faecal sludge management are listed below:

- **Energy efficiency:** Addressing unnecessary water consumption and water losses are sustainable and cost-efficient ways to prevent GHG emissions, since the energy associated with the treatment and supply of water can simply be reduced. Water losses in distribution networks can be high, even in some water-scarce countries. For instance, an estimated 48% of water is lost in India, including through leakage, theft or inaccurate metering (IEA, 2016). Active leakage control, including sounding techniques, is an efficient way to find unreported leaks. Pressure management, on the other hand, is a cost-effective water loss strategy, reducing the number of bursts and leaks.

- **Reuse:** The reuse of water from wastewater and faecal sludge treatment for purposes with less strict water quality requirements than for potable water also holds significant water and energy-saving potential (Grant et al., 2012). Moreover, water-use efficiency can enhance water security and climate resilience, while significantly reducing processing costs. Energy efficiency in water, wastewater and faecal sludge management can further be increased by deploying adequate technologies and management processes. The optimisation of pumping systems might include updating or replacing pumps, but also improving control, operation and data acquisition. Energy demand during wastewater treatment can be reduced through the installation of efficient aerators and diffusers, as well as optimised aeration control.

- **Renewable energy:** There is significant potential to reduce GHG emissions by deploying renewable energy during water, wastewater and faecal sludge management. For instance, the organic matter in wastewater and faecal sludge contains more energy than is needed to treat it (Li et al., 2015). Treating sludge in anaerobic digesters allows treatment plants to capture biogas, which can be further processed into biofuels, heat and electricity. Using anaerobic treatment approaches, a plant can cover 50-75% of its own energy consumption. Additional modifications, such as technologies that turn biogas into biomethane, can further optimise the energy performance of treatment plants (McCarty et al., 2011). Apart from gaining energy through treatment processes, the extended use of renewable energy, such as solar and wind power, can further lower the carbon footprint of water and wastewater utilities.

- **Optimised wastewater treatment:** The mere extension of wastewater and faecal sludge treatment coverage reduces emissions from untreated wastewater in surface water, as further discussed in *Chapter 7.2*. Anaerobic wastewater treatment can improve energy conservation and reduce GHG, if the methane produced during the process is not released into the environment. Nature-based Solutions, such as constructed wetlands, also have the potential to substitute energy-intensive treatment technologies. Besides the use of biogas for generating energy, approaches to avoid CH_4 emissions include biogas flaring and avoiding biogas leakage (Paolini et al., 2018).

The benefits of tapping into the mitigation potential of the water sector stretch beyond saving GHG emissions. Lowering energy consumption can substantially **reduce operational costs of water and wastewater utilities**, which can be as high as 40% in developing countries (Liu et al., 2012). If well-planned and, depending on local conditions, inclusive of energy-pricing systems, investments into energy efficiency can pay off within a few years (Ballard et al., 2018).

However, an extensive implementation of the aforementioned measures to address GHG emissions bears inherent challenges. For instance, traditional wastewater treatment infrastructures were not developed to pursue multiple purposes in parallel, such as the removal of pollutants, energy recovery and nutrient recycling (Wang et al. 2018). In addition, several solutions to foster energy efficiency in the water sector have been designed for and in developed countries. Individual needs and (economic) realities in low-income countries might require customised, different or new solutions to reduce energy consumption in water supply and treatment (Larsen et al., 2016).

Adverse impacts of renewable energies on water-related ecosystems

Global demand for electricity is expected to grow by roughly 70% by 2035 (WWAP, 2014). Renewable energies play a growing role in energy production. However, while it involves much lower CO_2 emissions, renewable energy production also entails adverse environmental impacts. These have also come to affect water security and water-related ecosystems through pollution or high levels of water use. It is strongly recommended to account for and mitigate these impacts.

Hydropower accounts for 16% of global electricity production and is, therefore, the largest source of renewable energy (WWAP, 2014). Dams built to generate hydro-electricity and store water resources bring multiple benefits, like flood protection, reliable water supply and energy security. But they also have negative consequences for river ecosystems and the people that depend on them (Vörösmarty, 2010). The negative externalities of dams, such as loss of biodiversity, declining fisheries and relocation of local communities, might exceed the benefits of job creation and energy supply (Ziv et al., 2012; Winemiller et al., 2016). Moreover, water is lost through evaporation and seepage from reservoirs (Gerbens-Leenes et al., 2009). Reservoirs can also emit large quantities of CH_4, corresponding to 1.3% of global CO_2-equivalent emissions (Deemer et al., 2016).

Wind and solar power do not require large quantities of water resources for energy production. The water footprint of these two energy forms is among the smallest per produced kWh, compared to other renewable energies (Mekonnen et al., 2015). However, wind and solar power have less visible negative impacts on water security and water-related ecosystems. Advanced lithium batteries, which have high-energy storage capacity to balance out the supply-demand gap, require large amounts of chemical-containing water to extract the ore (Izquierdo et al., 2015). Without proper treatment and disposal, the wastewater pollutes ecosystems and can precipitate water conflicts among local water users.

Biofuel often has a large water footprint, especially when crops are cultivated in semi-arid and arid areas (Gerbens-Leenes et al., 2009). The cultivation of energy crops, such as corn, sugar cane or palm oil, and the cooling processes in power plants to burn biofuels, require a lot of water (Raptis et al., 2016). In addition, ecosystems, like wetlands or forests, have been drained or converted to expand the production of bioenergy. By causing the loss of these natural carbon pools, in particular peatlands (see Chapter 7.3), the industry is responsible for significant GHG emissions. Moreover, the rise of energy crops has starkly increased competition for arable land, thereby indirectly causing land use change (including the loss of wetlands, for example).

The cultivation of energy crops also necessitates large quantities of **fertiliser and manure**. Washed out by the rain or carried away by winds, significant amounts of nutrients enter wetlands, lakes and rivers. Once there, they cause high levels of eutrophication, which is a main threat to freshwater ecosystems and biodiversity. Furthermore, the enrichment of nutrients in an ecosystem can have a positive correlation with the increased emission of GHG. Converting forests or other natural environments to cultivate energy crops often fosters soil erosion. Consequently, sedimentation can pollute rivers, wetlands and lakes (Croitoru and Sarraf, 2010).

Good practice example

Helping countries towards a climate-smart water sector: Water and Wastewater Companies for Climate Mitigation (WaCCliM)

In order to reach the goal of the 2015 Paris Agreement to limit global warming to well below 2°C, all sectors need to contribute and increase their GHG mitigation ambitions. As exposed in this chapter, the urban water sector is a notable source of emissions. These will most likely increase due to growing water demand and increasing service coverage, in particular in emerging and developing countries. Since 2014, the project **Water and Wastewater Companies for Climate Mitigation (WaCCliM)**, financed by the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety of Germany (BMU) and implemented by GIZ and the International Water Association (IWA), has been working with selected countries and utilities to prove that in the urban water sector, climate mitigation action can be achieved, alongside and in harmony with climate-resilient sustainable development.

WaCCliM's experience has shown that the flow of water into, through and out of cities connects NDC and SDG commitments of developing and emerging countries. The project has introduced a roadmap of systematic steps and measures towards low-carbon water and wastewater utilities that can also plan for climate risks and improve their services. Helping utilities on this path is the project's **Energy Performance and Carbon Emissions Assessment and Monitoring Tool (ECAM)**, which any utility can use to assess its GHG emissions and pinpoint opportunities to use less energy – or even generate its own energy. ECAM also functions as an important tool providing data for Measurement, Reporting and Verification (MRV) systems for the sector and helps to monitor compliance with NDCs. ECAM has been used beyond the project: The Zambian water programme Climate-friendly sanitation in peri-urban areas of Lusaka, financed by the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by GIZ, developed an additional module for faecal sludge management for ECAM and calculated a baseline of GHG emissions for the whole urban water cycle of Lusaka.

WaCCliM has piloted mitigation solutions, ranging from energy-efficient pumps to technologies for generating power with biodigesters, with utilities in Jordan, Mexico, Peru and Thailand. Prioritized measures in these pilot utilities have led to an annual mitigation equivalent to more than 10,000 tons carbon dioxide – or planting about 50,000 trees per year. The water and wastewater utilities using WaCCliM tools to pioneer GHG benchmarking and climate-smart planning are becoming national sector leaders, and they are providing evidence for an increased consideration of water as a sector for combined mitigation and adaptation action in the next round of NDCs. The WaCCliM vision on climate-smart urban water systems has to be achieved on a local, national and global scale. So, while WaCCliM works with national and international partners to enable local action, it does this with a larger transformation in mind. The toolbox of both mitigation and adaptation planning measures will be available to utilities everywhere on the **knowledge platform Climate Smart Water:** www.climatesmartwater.org

7.2 GHG emissions from organic matter and nutrient inputs into surface waters

Alongside the energy consumption of water supply and treatment processes, there are other major sources of GHG emissions related to water sector procedures as well as on environmental standards and their enforcement. Surface water bodies, such as artificial reservoirs, rivers, canals, open drains, lakes or wetlands, naturally produce considerable amounts of GHG (Bastviken et al., 2011). For instance, GHG formation in surface waters stimulated by the influx of poorly treated or untreated wastewater and faecal sludge can become a major cause for increased GHG emissions, since such influx comes along with the enrichment of nutrients and organic matter. Globally, over 80% of the wastewater is not collected or improperly treated. Particularly in developing countries, the release of untreated wastewater remains an ordinary practice, due to a lack of infrastructure, technical and institutional capacity, and financing (WWAP, 2017).

The enrichment process of water bodies with dissolved nutrients is also called eutrophication. Higher amounts of nutrients, such as nitrogen (N) and phosphorus (P), as well as organic matter added to water systems, also reinforce the production of CH_4 and N_2O. An increased formation of these gases in receiving waters, associated with unmitigated nutrient and organic carbon influx, correlates with the amount of GHG being emitted eventually. In addition, from a climate mitigation perspective, CH_4 and N_2O are distinctly problematic, due to their high global warming potential. Furthermore, the resultant emissions are generally higher in countries with warmer climates, because higher temperatures potentially stimulate the microbial transformation processes linked to GHG production. Also, higher temperatures decrease gas solubility further exacerbating gasification rates.

Agricultural run-off can also carry significant amounts of P and N into water systems, both from inorganic fertiliser and livestock manure. While the mass of fertiliser applied was relatively lower in most developing countries during the 20th century, it is set to grow strongly in the future. Therefore, it is likely that such trend results in an overall nutrient surplus. In Africa, for instance, the quantities of N and P that are applied to land but are not taken up by crops or are removed during harvests will increase significantly by 49% (N) and 236% (P) between 2000 and 2050 (Bouwman et al., 2013).

Reservoirs, lakes and other lentic waters are major sources of GHG as well. Eutrophication of lentic waters under scenarios of future nutrient loading to surface waters show that enhanced eutrophication of lakes and reservoirs will significantly increase CH_4 emissions from these systems (+30-90%) over the next century. Thereby, changes in CH_4 emissions could have an atmospheric impact equivalent to 18-33% of that from current fossil fuel CO_2 emissions (Beaulieu et al., 2019). In addition, the distinct conditions of reservoirs created by dams – characterised by fluctuating water tables and a high occurrence of organic material – produce considerably more CH_4 than natural lakes or other surface waters. Dam reservoirs, therefore, contribute approximately 1.3% of anthropogenic GHG emissions (Deemer et al., 2016).

➔ ***A growing scientific consensus links nutrient influx into surface water bodies and GHG emissions from them – primarily CH_4 and N_2O.***

Finally, there is now emerging scientific consensus on the link and positive correlation between excessive nutrient loadings into receiving surface water bodies and GHG emissions from them – primarily CH_4 and N_2O (Beaulieu et al., 2019; Deemer et al., 2016; DelSontro et al. 2018; Fernandez et al., 2019; Murray et al., 2019; Prairie et al., 2018; Sanches et al., 2019). In consequence of this consensus, enhanced wastewater treatment and sanitation efforts not only contribute to improved water quality, but also potentially lower degrees of CH_4 and N_2O emissions.

Challenges to estimate actual GHG fluxes from surface waters

The emission of GHG from surface waters, such as CH_4 and N_2O, does not automatically equal the amount of gases being formed in them. Consequently, the amount of gases being transferred from the liquid phase – hence, the actual GHG emission – is often hard to estimate without complex direct measurements within a certain study area. In this connection, the broad absence of real-time gas emission flux data form surface waters constitutes one of the major challenges, when estimating their actual adverse climate impact. Not least because of above challenges concerning the quantification of emissions (using consistent or institutionally accepted protocols) and a resulting lack of sufficient data, global estimates on total GHG emissions from surface waters are not available until now.

➔ ***Severe organic pollution already affects one seventh of all river stretches in Africa, Asia and Latin America.***

However, given the low wastewater treatment rates in many developing countries, it is likely that untreated wastewater has a significant climate impact (Bogner et al., 2007). This assumption can be substantiated through studies showing that severe organic pollution already affects one-seventh of all river stretches in Africa, Asia, and Latin America, and that figure has been steadily increasing (UNEP, 2016). Furthermore, an absence of global estimates does not mean that GHG emission from surface are not being quantified at all. GHG emissions can be estimated for a certain region by using an emission factor approach, as described by the IPCC and the EPA (IPCC, 2006; USEPA, 2019). However, this approach needs to make use of several assumptions and simplifications. For instance, N_2O emissions from surface water bodies are described by a point emission factor, which suggests that 0.5% of the total nitrogen loading is emitted as N_2O, without accounting for regional specifics or nitrogenous substrate differences (ibid.). Furthermore, there is no corresponding measure for CH_4 emissions introduced up to now.

Strategies to reduce GHG production in and emission from surface waters

There are different solutions to prevent lakes, reservoirs and other surface waters from becoming even greater sources of GHG. These solutions seek to lower the quantities of nutrient and organic matter that enter water systems by different means:

- **Control of GHG from insufficiently treated wastewater and faecal sludge:** A low wastewater collection and treatment coverage as well as the absence of formalised faecal sludge management for decentralised sanitation in the majority of urban poor settlements in several developing countries renders this field of action a top climate priority. Thereby, a reduction of CH_4 and N_2O emissions from surface waters can be achieved by enhancing proper wastewater and faecal sludge management. This explicitly includes the appropriate processing and disposal of sludge, as in the foreseeable future the majority of the global urban population will depend on decentralised sanitation systems, since only 41% of the global population is connected to centralized sanitation systems in 2017 (WHO, UNICEF, 2019; *see Chapter 7.1*).

- **Watershed management to reduce nutrient and organic matter inputs:** To lower the GHG emissions associated with the nutrient enrichment of water bodies, watershed management strategies with a focus on nutrient reduction need to be put in place (e.g. management practices including the reduction of nutrient-laden soils through excessive fertiliser use, vegetated filter strips and proper handling of animal manures).

- **Reservoirs created by dams:** With the current support for hydropower in many countries, strategic and careful site selection of new reservoirs will be important (e.g. upstream of nutrient pollution sources). Furthermore, improving the design and management of existing ones is another measure that can help to reduce GHG emissions (Deemer et al., 2016). GHG fluxes from reservoirs strongly depend on various environmental conditions, such as soil characteristics or prior vegetation cover. In consequence, the use of other renewable energy sources than hydropower might be advisable from a climate mitigation angle in some cases.

- **Indirect positive mitigation effects through nutrient recovery:** Fertiliser production (mostly fossil-fuelled) accounts for a significant amount of global GHG emissions. Fossil fuel consumption could be reduced by using wastewater N and P for fertiliser directly through recovering those nutrients. However, it often remains a challenge to fully capture the nutrient recovery potential in an energy- and cost-efficient manner (McCarty et al., 2011), in particular concerning conventional wastewater, which usually has a lower share of N and P compared to more concentrated fluids. Still, an expected increase of nutrient demand might create further economic incentives for nutrient recovery in the future (Cordell et al., 2009). Another forward looking process is to produce bio-char or “terra preta” from faecal sludge and to create a carbon sink, when adding this bio-char to agricultural land, where it can increase the fertility of soils (Biederman et al., 2013; Woldetsadik et al., 2017).

7.3 GHG emissions from peatlands

Wetlands constitute the largest carbon stocks among terrestrial ecosystems. Their conservation depends on water security together with environmental protection, resources management and land use. Peatlands – one type of wetlands – are important as global carbon pools. Measures using wetlands for climate change mitigation involve a) avoiding the destruction of natural wetlands through conservation efforts, including the safeguarding of their carbon sink function and the prevention of significant GHG emissions coming along with their degradation; and b) restoring already degraded wetlands to recover their ability to remove and store CO_2. This grants wetlands a particularly powerful role among **Ecosystem-based Mitigation (EbM)** measures as few other systems can address both elements of climate change mitigation – reducing the sources and enhance the sinks of GHG. However, the potential to store carbon varies by wetland type, which range from floodplain swamps and alpine mires to seagrass meadows and mangroves. Common to all of them is that their plant communities remove CO_2 from the atmosphere through photosynthesis and build it into their biomass. When wetland plants die, dead plant material (carbon-rich organic matter) sinks to the wetland's ground. There it cannot fully decompose due to a lack of oxygen (*see Figure 36 on the next page*). In this way, wetlands accumulate more and more carbon over time, eventually, forming thick organic layers respectively carbon pools. The associated uptake process of carbon from the atmosphere in terrestrial reservoirs is called **carbon sequestration.**

➔ ***Peatlands store twice as much carbon than all global forests.***

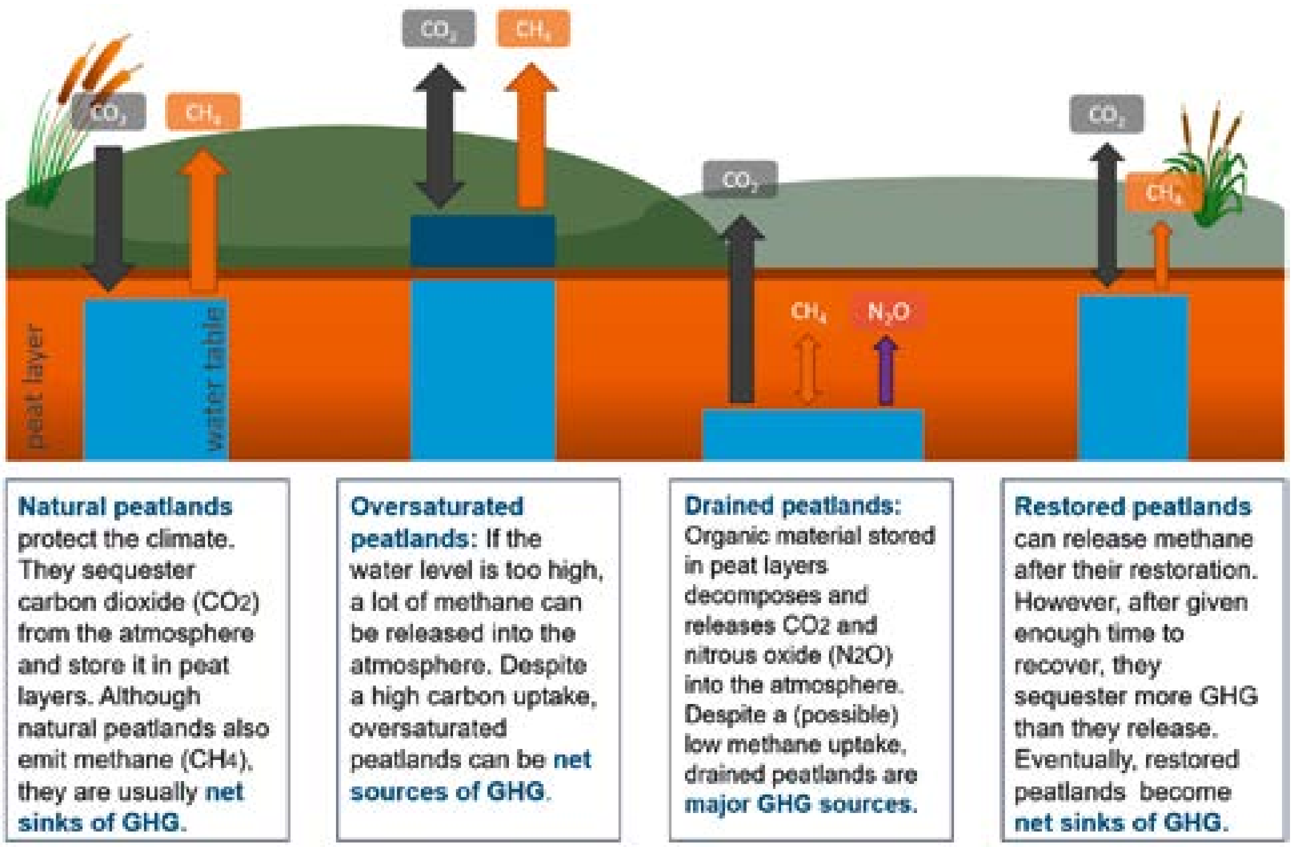
Although only covering 3% of the earth's land surface, peatlands contain nearly one-third of the land-based carbon. This equates to double the amount of carbon locked in the biomass of global forests (Crump, 2017). Peatlands form thick layers of peat, sometimes over thousands of years, allowing them to store more carbon than any other wetland type. A slow formation process of these peat layers – thus a slow creation of carbon pools – makes it imperative to avoid the loss of peatlands in the first place. Furthermore, the amount of carbon stored in peatlands depends on different factors, such as the water table and the vegetation cover. In general, tropical peatlands – almost exclusively located in developing countries – store much more carbon per area unit than those in boreal climates (*see Table 8*). For the sake of completeness, it needs to be noted that also other types of wetlands store high amounts of carbon, such as forested inland wetlands, salt marshes and mangroves. Even though peatlands constitute bigger carbon stocks on a global scale, other types of wetlands can have higher carbon sequestration rates rendering them promising subjects of interests for advanced climate action as well.

Climate	Total peatland	CL[a]	GL[a]	FL[a]	N/A[a]	Degrading peatland	Actual emissions[b]	Peat C	Degrading Peat C
	Area (Mha)						$Gt\ CO_2$ eq.	Gt C	
Tropical	58.7	8.5	11.3	34.6	4.3	24.2	1.48 (0.04–2.79)	119.2	49.1
Temperate	18.5	3.5	5.0	8.9	1.3	10.6	0.16 (0.10–0.21)	21.9	12.5
Boreal	360.9	6.8	85.6	249.5	19	15.5	0.26 (0.16–0.36)	427.0	18.3
Polar	25.0	0.1	14.9	9.7	0.4	0.7	0.01 (0–0.02)	29.6	0.8
Oceanic	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0 (0–0)	<0.1	<0.1
Total	**463.2**					**50.9**	**1.91 (0.31–3.38)**	**597.8**	**80.8**

a) Peatland area according to land use classes (CL), grassland (GL) and forest land (FL). N/A means that no distinct land use type could be identified
b) Annual mean values for CO_2, CH_4, N_2O, and DOC; values in parentheses show the lower and upper range of emissions

Table 8: Area and emission overview of global peatlands (adopted from Leifeld and Menichetti, 2018)

Figure 36: The key role of water for optimising the climate-regulating function of peatlands (Adopted from Umweltbundesamt, 2019)



The GHG footprint of wetlands, in particular in connection to methane emission has been subject to discussions. Wetlands are the largest contributor to natural CH_4 emissions (more than 75%) (Zhu et al., 2016). Therefore, some have argued that draining natural wetlands could be an effective strategy to reduce CH_4 emissions (Muller, 2019). However, this doesn't reflect the whole picture of GHG fluxes: While CH_4 emissions tend to decline after the drainage of a wetland, the subsequent release of CO_2 and the loss of potential prospective sequestration services eventually turn drained wetlands into net sources of GHG emissions (Petrescu et al., 2015). Indeed, almost all wetlands are net carbon sinks, when carbon sequestration and CH_4 emissions are examined over an appropriate time period that also accounts for the decay of CH_4 in the atmosphere (IPCC, 2014; Joosten et al., 2016, Mitsch et al. 2011). In this connection, peatlands have a particularly high mitigation potential, since they cause less than a quarter of all CH_4 emissions emitted by wetlands, while being carbon pools of global significance (Turetsky et al., 2014).

Geographical distribution of peatlands and (potential) GHG emission hotspots

Around 75% of the current GHG gas emissions from degrading peatlands is caused in the tropics; those from boreal peatlands are trivial in comparison (*see Table 8 on the previous page*). Actual emissions from tropical peatlands mainly stem from Southeast Asia as *Figure 37* shows. Yet, *Figure 38* also shows that peatlands in Africa and Amazonia – that are still mostly in an intact natural condition – are likely to emerge as future emission hotspots unless adequate safeguards and conservation efforts are established. However, when estimating future potential emissions from peatlands and the resultant global warming potential, it is critical to acknowledge that the known extent and size of global peatland carbon stocks are still highly uncertain (Leifeld and Menichetti, 2018). In 2011, scientists discovered the largest peatland in the Amazonas, the Pastaza-Marañon Foreland Basin in Peru (Lähteenoja and Page, 2011; Draper et al., 2014), and a few years later the largest tropical peatland, the Cuvette Central in Africa's Congo Basin (Dargie et al., 2017).

Figure 37: Global peatland distribution and annual actual emissions from peatland degradation: The colored area shows the worldwide distribution of peatlands and the GHG emissions currently released from them. The different legend colors indicate the amount of GHG emissions per hectare (Source: Leinfeld and Menichetti 2018).

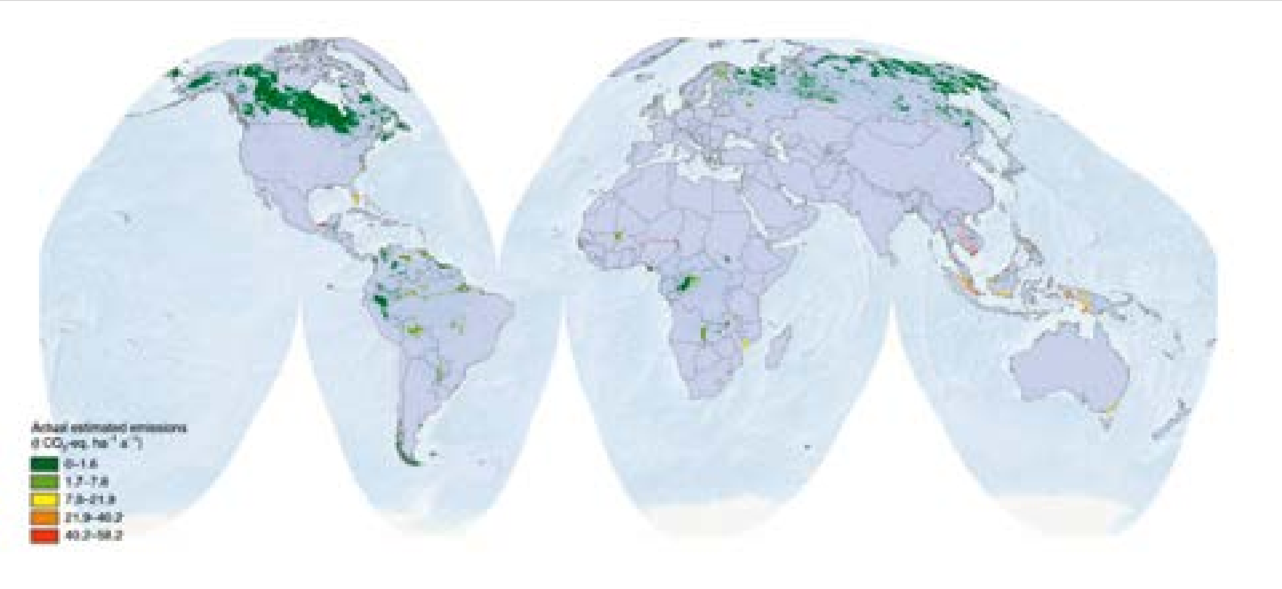
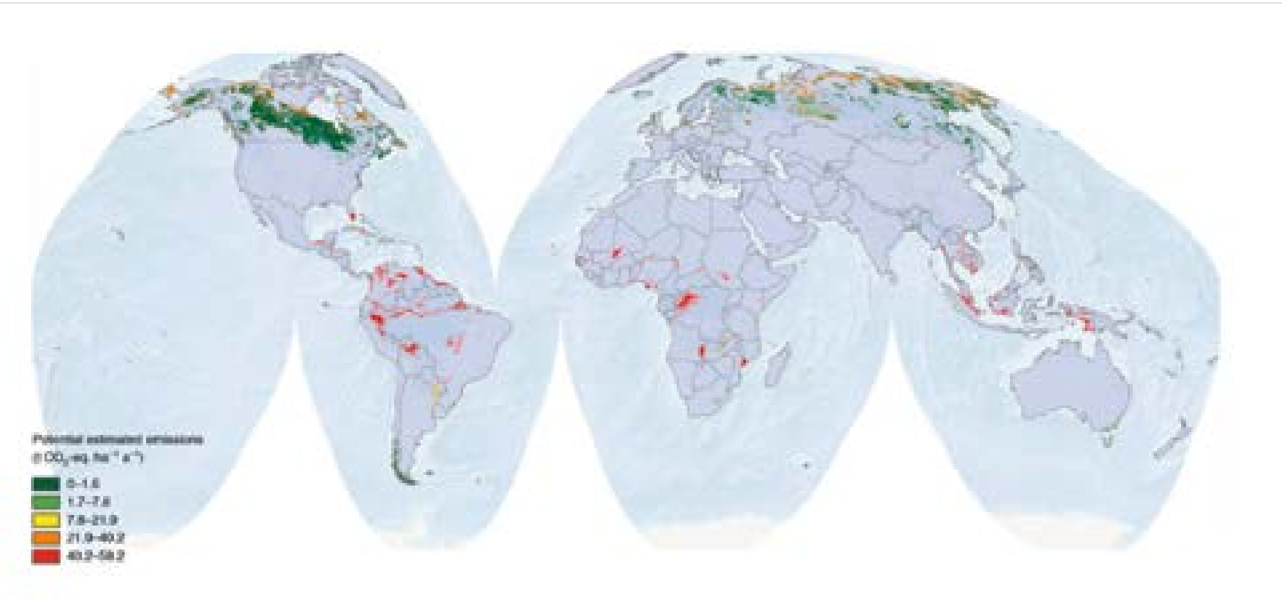


Figure 38: Global peatland distribution and annual potential emissions from peatland degradation: The colored area shows the worldwide distribution of peatlands and the potential annual GHG emissions per hectare if those peatlands would be drained. The map shows that peatlands across the tropics would become emission hotspots while emissions from boreal areas would also increase (Source: Leinfeld and Menichetti 2018).



➔ ***Comprehensive global mapping efforts of wetlands are urgently required.***

Recent discoveries of the large peatlands, as mentioned above, have far-reaching implications for global peatland conservation and restoration. First, they illustrate that tropical peatlands may be much larger than estimated and are undervalued in current global assessments (Leinfeld and Menichetti, 2018). Their extent and volume may be three times greater than in previous estimates (Gumbricht et al., 2017). Comprehensive global mappings of wetlands – in particular peatlands – are urgently required to foster mitigation and conservation efforts through informing decision-making and reducing uncertainties. This can help to prevent the further degradation of (unknown) peatlands, including their vast carbon stocks (*see boxes below* on peatland mapping initiatives and the Nile basin peatland assessment). Second, these discoveries have revealed that the carbon pools contained by African and South American peatlands may be as large as or even larger than those in Southeast Asia. The African Cuvette Centrale peatlands alone are estimated to contribute as much as 29% to the global peat stock. As a result, the Democratic Republic of Congo and the Republic of Central Africa, over whose territories the Cuvette Central spreads, were upgraded to the second and third most important countries in the tropics for peat areas and carbon stocks (Dargie et al., 2017). This not only underpins the essential role peatlands play in climate mitigation, it also implies that much of the future peatland conservation efforts need to go beyond Southeast Asia by accounting also for potential future emission hotspots in Africa and Latin America.

Initiatives involved in mapping global peatlands

The latest discovery of the Cuvette Centrale is just one example highlighting the poorly investigated extent and condition of peatlands around the world. There are several initiatives underway to improve the data availability on peatlands. One is the 🌐 Global Peatland Database (GPD). Started in the 1990s by the International Mire Conservation Group, it collects and integrates data on the location, extent, and ecological status of peatlands and organic soils worldwide and for 268 individual countries and regions. The database contains analogue and Geographic Information System (GIS) maps, reports, observations, pictures, and is supported by the Peatland and Nature Conservation International Library (PeNCIL). The GPD regularly produces comprehensive analyses including worldwide overviews on peatland status and resultant emissions. Its spatial information on peatlands is used to inform peatland conservation in areas of climate change mitigation and adaptation, biodiversity conservation and restoration, and sustainable land use planning.

The 🌐 Global Peatland Initiative is another effort by leading experts and institutions that collaborate to improve the conservation, restoration, and sustainable management of peatlands. One of the outputs of the Global Peatlands Initiative will be an assessment that seeks to discern the status of peatlands worldwide and their importance in the global carbon cycle. It will also examine the monetary value of peatlands for national economies. The Global Peatlands Initiative has carried out a peer-reviewed rapid response assessment for peatlands (Crump, 2017) based on existing data and studies. This rapid assessment looks at the location and extent of peatlands, key threats affecting them, existing conservation policies and their effectiveness, and it suggests future interventions.

Good practice example

Nile Basin Peatlands: Assessment of soil carbon, CO_2 emissions, and mitigation potential

The total peatland area in the Nile Basin is estimated to be 30,445 km^2. That is approximately a fifth of the largest peatland complex in the tropics, the Cuvette Central in the Congo Basin, and comparable to the largest described peatland complex in Amazonia with 35,600 km^2 (Draper et al., 2014). About 40% of the total peatland area estimated for the entire Nile Basin is found in the Nile Equatorial Lakes (NEL) countries (Uganda, Tanzania, Rwanda, Burundi, Kenya). Unfortunately, land-use change in the Nile Basin continues to accelerate and an increasing area of peatlands is being impacted directly (burning and clearing for agriculture, peat extraction for energy) or indirectly (drainage for infrastructure, surrounding plantations causing groundwater drawdown). Other threats to peatlands in the Nile Basin include changing rainfall patterns and fire hazards. The consequences are increased CO_2 emissions through the loss of carbon stocks and productive land.

Recently, the Nile Basin Initiative (NBI) with support from GIZ, on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under the International Climate Initiative (ICI), commissioned the study: "Assessment of Carbon (CO_2) Emissions Avoidance Potential from the Nile Basin Peatlands". The objective of the study was to contribute to the discussion on CO_2 emissions' mitigation potential in the Nile Basin, by calculating the current carbon stocks in the Nile region. The study estimated the peat soil carbon stocks in the Nile Basin to be between 4.2 and 10 Gt of organic carbon (GtC). Within these parameters, the country with the highest carbon stock is South Sudan (1.5–3.59 GtC), followed by Uganda (1.3–3.1 GtC). Peat carbon stock losses and mitigation potential within the NEL region were explored with a model assuming that in 2015 25% of all peatlands were drained and that from 2015 until 2050 the drained area will increase annually by 1 %. Resulting losses of about 0.2 GtC over the period 2015-2050 can be regarded as CO_2 emission reduction potential, if no new drainage will be implemented and all drained peatlands are rewetted by 2025. The potential emission reduction would account for 678 Mt CO2 in total, or 19.4 Mt CO_2 per year. Calculations based on more differentiated estimations of initial drained area per country (in 2015) suggests an even higher emission reduction potential of 885.5 Mt CO_2 for the NEL region.

In order to prevent further peat loss in the region, NBI and GIZ are working together to deliver a sustainable peatland management for the region. The strategy features further research needed for a sustainable management, including mapping and monitoring efforts that are necessary to estimate the impact of land use and land-use change on peatlands' GHG emissions as well as the loss of ecosystem services.

Approaches to exploit the climate mitigation potential of peatlands

The ability of peatlands to absorb and store potential GHG emissions depends on the constant availability of water (among other factors, such as peat-forming plants). Consequently, the creation of oxygen-free conditions is an indispensable prerequisite for peat formation and conservation. In consequence, the mismanagement of water resources can disrupt the hydrology and ecological functioning of peatlands and, thus, weaken or nullify their climate change mitigation effects (Page et al., 2009). Water management institutions, such as river basin organisations, can be prime actors tasked with regulating the hydrology of peatlands. They have a great deal of influence when it comes to controlling threats in and around peatlands and cultivating and restoring them in a sustainable manner. Moreover, water-sector specialists, water managers, and freshwater conservationists can contribute critical expertise and know-how (such as in hydrological modelling) to inform a sustainable water management – also in face of expected global expansions of agricultural activity, transport infrastructures, and mining as major drivers for peatland deforestation and drainage (Roucoux et al., 2017, Dargie et al., 2019).

There are also **economic incentives** to protect wetlands. A study by Griscom et al. (2017) sought to quantify the mitigation potential of natural climate solutions, including wetlands. The authors suggest that EbM options can collectively meet 37% of cost-effective CO_2 mitigation needed by 2030 to keep global warming below 2°C. To this end, restoration and conservation of wetlands (including coastal wetlands) can offer a share of 14% of suitable EbM opportunities. Furthermore, in terms of low-cost EbM options (defined by Griscom et al. at or below USD 10 per tonne of CO_2-equivalents per year), measures aimed at wetlands can constitute a share of 19%. However, Griscom et al. also highlight that avoiding the loss of wetlands tends to be less expensive than wetland restoration. Furthermore, they stress that the prevention of loss is an urgent concern in developing countries. In addition, the **economic value of wetlands' ecosystem services** is usually higher than that gained from cultivating them in a not sustainable manner. Moreover, economic profits from intensive economic use of wetlands are often not shared with the society as a whole (Ramsar Convention on Wetlands, 2018). A recent study estimates that wetlands deliver 43.5% of the monetary value of all global inland and coastal biomes. Thereby, peatlands alone represent one-fourth of the total financial value provided by freshwater ecosystems (Davidson et al., 2019).

In this connection, discoveries such as the Cuvette Centrale peatlands further underpin the EbM potential of wetlands, while constituting promising opportunities of conserving them through sustainable water management and land use. Despite a growing acknowledgement of peatlands' importance for climate action, they still remain largely undervalued by governments. In addition, although peatland emissions are included in the IPCC guidelines for National Greenhouse Gas Inventories (Volume 4, Chapter 7 on wetlands; IPCC, 2006) and mitigation measures to reduce them are eligible for national accounting under the UN Framework Convention on Climate Change, they rarely make an appearance in national GHG emission inventories (Moomaw et al., 2018; Roucoux et al., 2018).

Co-benefits of wetland conservation and restoration

Peatlands and other wetlands come with various additional advantages beyond their climate-regulating functions. Compared to forests and grasslands, they do not only hold higher carbon stocks per area unit, but also provide more hydrologic ecosystem services. This efficiency in terms of ecosystem services per area unit is a great asset as many other EbM options demand more land to achieve comparable outputs. Thus, land use competition, e.g. with agricultural activities, is potentially lower (Leifeld and Menichetti, 2018). Furthermore, inland wetlands, such as peatlands, provide several ecosystem services, including water storage, treatment, or flood control. In consequence, EbM through wetlands usually comes along with various **co-benefits** beyond mitigation in the fields of climate adaptation, the protection and conservation of biodiversity as well as human well-being (*Figure 32 on page 90*) (Griscom et al., 2017). The conservation of tropical peatlands is not only accompanied by benefits for climate action, but by distinctly positive effects on biodiversity (Posa et al., 2011).

Unsustainable water resources management can pose considerable threats to peatlands. As displayed above, constant water availability forms the lifeline for natural peatlands. For example, planned dams and water transfers in both the Pastaza-Marañon and the Cuvette Central basin threaten floodwater-dependent downstream peatlands. Their hydrological connectivity with the landscape means that perturbations taking place upstream or closely around a peatland can negatively affect the whole system (Page et al., 2009). The principles of **Integrated Water Resources Management (IWRM)** on the policy, legislation and implementation levels can help to minimize damage from unsustainable developments. The IWRM framework considers natural conditions of freshwater and other ecosystems in decision-making. Thereby it pursues a basin-wide approach, which is one key to ensure that peatlands and other wetlands are managed along their hydrological boundaries. Another important approach

Good practice example

Indonesia: Peatland Management and Rehabilitation (PROPEAT)

Large-scale drainage areas and the conversion of peat and wetlands in Indonesia began in the late 1960s. These were established to promote the success of agriculture, where lands were converted to shrimp ponds. In the heart of North Kalimantan, the peatland and mangrove ecosystem are an integrated landscape in Delta Kayan-Sembakung. Over 20 years, the Delta has suffered from the conversion practices. The delta covers more than 580,000 ha area and provides the community with enormous natural resources and abundant environment services. Today 170,000 ha of Delta has been converted to shrimp ponds and leaving less than 30% of intact mangrove forest.

Since 2019, the **Peatland Management and Rehabilitation project (PROPEAT)**, financed by the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by GIZ, has been working with the Ministry of Environment and Forestry of Indonesia and the Provincial Government of North Kalimantan to improve the management of peatland ecosystems in North Kalimantan. As of 2020, PROPEAT collaborated with local universities to conduct a baseline study on aquatic and terrestrial biodiversity as well as socio-economic issues. Results of this study will be used as basis for the government to formulate a policy on peatland management at the provincial level. Furthermore, the PROPEAT project conducted carbon assessments in three districts to assess the carbon stock of peatland and mangrove areas. These assessments will be further used for the provincial action plan on GHG, thus, also the mitigation contributions by peatlands will be considered.

In parallel to the above study, PROPEAT promotes the policy of peat and wetland rehabilitation and management through integrative planning processes. The project currently facilitates discussions with stakeholders to develop strategic planning in the Kayan Sembakung Delta, which is the core of the peatland and mangrove ecosystem in North Kalimantan. This strategic planning process will further be integrated in the long-term provincial management plan. In the long run, the project aims to improve current practices of peatland and mangrove management, thereby, it also aims to use findings from applied research and documentation of field experience for dissemination at the local, national and international level.

to protect wetlands and their carbon-pool function is to ensure that river flows sustaining wetland hydrology are not threatened through water resource developments (*see box below on Environmental Flows*).

If eligible, another possibility for safeguarding the integrity of wetlands can be to declare them as **Ramsar Sites** – wetlands of international importance. Pursuing such declaration requires signatories of the Ramsar Convention to conduct initial ecological inventories and develop management plans for wetlands. Both are vital elements to inform and guide a sustainable wetlands management and avoid disturbance of their hydrology. While not offering formal protection in itself, a declaration as a Ramsar Site can still constitute a first step to further promote the creation of legislation aimed at wetland protection (Roucoux et al., 2014; Darpie et al., 2019).

Tools

Environmental flows as a key tool for wetland protection and restoration

Environment flows are defined as "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Arthington et al., 2018). When implemented, they can be part of reducing the degradation and loss of wetlands, protect, and restore their ecological integrity as well as halt the loss of biodiversity. While so far mainly applied for rivers, there are examples where the implementation of environmental flows has proven to maintain or improve biodiversity outcomes and ecosystem services of wetlands (Yang et al., 2016).

Successful implementation of environmental flows for wetlands can be attained through, among others, careful water-infrastructure planning and development; adequate releases of water from dams; or sustainable water allocation planning. All of these interventions need to be grounded in research that investigates the relationships between flow conditions, wetland ecology, and possible human interactions, so called environmental flow assessments. Within the context of climate change, **environmental flow assessments**, taking into account the effects of climate change, can also provide a better understanding on dynamics around water availability and allocation needs within river basin systems (Barchiesi et al., 2018).

Different tools have emerged to assess and implement environmental flows. The Environmental Flow Calculators, developed by the International Water Management Institute (IWMI), is a software solution to make rapid and desktop-based e-flow assessments.

Restoration: Rewetting of degraded peatlands

Strategies for the restoration of wetlands depend on the type of wetland, its hydrological characteristics, and the causes of degradation. For instance, if swamps connected to a river are degrading due to dam-based alteration of flows, water managers would need to restore environmental flows. If a wetland is drying up because of an overexploited groundwater source, it may be necessary to curtail water licences or tackle illegal pumping. In general, the prime method of restoring peatlands is their rewetting, for instance, through enhancing water inflow, soil saturation and stabilizing the groundwater level (*see Figure 36 on page 122*). Suitable measures in this regard could be the installation of ditch blockages or the sealing off cracks in the peat body, both measures aim to raise a peatlands' water table again until its peat layers are completely waterlogged again (Lunt et al., 2010). Once an oxygen-free environment and the native vegetation are restored, peatlands tend to stop releasing CO_2 emissions and start to sequester them again (Ramsar Convention Secretariat, 2018). While rewetting can raise CH_4 emissions initially, a neutral GHG emission balance is commonly achieved after a few years (IPCC, 2014; Joosten et al., 2016).

Wetland restoration can be a challenging task, especially for peatlands. The complex relationship between the hydrology and ecology of many wetland types demands that restoration measures are grounded in scientific knowledge and thorough assessments executed by sufficiently skilled water/natural resources managers. To develop restoration measures, comprehensive modelling exercises are often needed to simulate the water table for optimal ecological functioning. From a water perspective, the success of peatland restoration relies on maintaining a sufficiently stable water table over a long time period. Setting the water table correctly is not only a challenge for sustainable water management, but also key to re-establish the mitigation benefits of peatlands. This also includes the prevention of massive GHG emission through peat fires in drained peatlands (Page et al., 2009).

Sustainable cultivation of intact and degraded peatlands

Most forms of practiced peatland cultivation follow an initial drainage combined with a large-scale clearance of vegetation. This renders them unsustainable in most cases. However, economic or agricultural practices in wetlands have been developed that do not require their drainage. **Paludiculture** is one prominent example of sustainable wetland cultivation (Evers et al., 2017). Paludiculture commonly encompasses measures such as reed mowing or the manufacturing of economic goods. Generated incomes can provide local communities and governments with incentives to conserve or restore peatlands and other wetlands, as well as preventing their degradation (*see box about the Upper Amazon on the next page*).

Besides protecting wetlands' carbon pools, paludiculture constitutes further co-benefits for biodiversity, local energy supply, and climate adaptation (Wichtmann et al., 2016). However, paludiculture also faces challenges. For instance, it is hard to reach the same level of agricultural productivity through paludiculture if compared to environmentally adverse agro-industrial activities, such as extensive palm oil production. Still, only 1% of global agriculture is undertaken on peatlands (Leifeld and Menichetti, 2018). Therefore, multiple benefits provided by their ecosystem services make a strong case for a sustainably management and cultivation. The political framework can contribute to protecting ecosystems, for instance through economic incentives favouring sustainable peatland cultivation.

Good practice example

Upper Amazon – Peatland protection for climate change mitigation and adaptation by coupling climate finance, biodiversity conservation, and indigenous land use management

The project "Building the Resilience of Wetlands in the Province of Datem del Marañón, Peru" aims to improve the livelihoods of indigenous communities and making them more resilient against climate change impacts, for instance, by providing alternative income opportunities to curb deforestation and protect the carbon stocks of the peatlands. The project, which combines adaptation and mitigation elements, is financed by the Green Climate Fund with a budget of USD 9.1 million and executed by the Peruvian Trust Fund for National Parks and Protected Areas (PROFONANPE).

The project area is in the western middle portion of the Amazon Basin, in the Province of Datem del Marañón, Loreto Region, Peru. It is part of the Pastaza-Maranon Foreland Basin (PMFB), which is the largest peatland in the Amazon presenting 2.7% of the global tropical carbon stock. The Amazon peatlands in Peru remain almost entirely intact. Yet, they face an increasing number of threats from oil extraction, agriculture, illegal logging, and palm oil cultivation (Draper et al., 2014).

The project seeks to avoid deforestation of an estimated 4,861 ha of palm swamp and terra firma forests over a 10-year period and enhance the resilience and conservation of 343,000 ha of peatlands and forests. It does so by helping government departments to better facilitate land-use planning and management of the region's wetlands. The bulk of the funds will eventually be allocated to support indigenous communities to set up sustainable businesses. These resolve around sustainably harvesting peatland products, such as salted fish, the pulp of local palm trees, or natural substances for medicinal use.

The communities are supported through capacity building in business plan development, marketing and management, or equipment and supplies. The project provides a compelling case for an initiative that links climate action through community-based support of indigenous people, while combining these activities with biodiversity conservation and a better protection of tropical peatlands. Furthermore, it is the first project of its kind financed by the Green Climate Fund (Roucoux et al., 2017).

7.4 GHG emission from the cultivation of rice

Rice paddies are the largest artificial wetland type measured by their extent and constitute another source of GHG emissions. Consequently, they also come along with mitigation potential for the agricultural sector. Rice cultivation accounts for at least 2.5% of the global GHG emissions due to CH_4 and N_2O emissions that form under anaerobic conditions in flooded rice paddies. The value may be even higher given that most studies have rather underestimated N_2O emissions (Kritee et al., 2018). CH_4 emissions related to rice cultivation are expected to even double by 2100 due to global warming (van Groeningen et al., 2013). Interventions that seek to exploit this mitigation potential need to consider that rice is a food staple for almost half of the world's population.

Furthermore, an increased productivity is required to meet the growing demand for rice, especially in Sub-Sahara Africa. Rice consumes 3000-5000 litre of water per kilogram, more water than most other crops. If cultivated through irrigation, such high water demand can affect the overall water distribution and threaten supply to domestic users and ecosystems, possibly affecting water sector responsibilities. Already today, water scarcity threatens rice production in many countries. Successfully tackling inter-sectoral challenges through an independent user allocation requires an integrated water resources strategy that also accounts for conflicting user interests (Godfray et al., 2010). The water sector is a key player in terms of contributing knowledge about and solutions for producing the same amount of rice with less water, while reducing GHG emissions. This is illustrated in more detail below.

Different aspects of rice cultivation can result in GHG emissions, however, more than 90% of the emissions are associated with the flooding of paddy fields. The remainder stems from fertiliser application and water pumping. About 90% of rice is still produced and consumed in Asia, mainly in China, Indonesia, and India. However, other cultivation regions are on the rise, such as sub-Saharan Africa (Carlson et al., 2016). GHG emissions mainly correlate with chosen type of flooding regime used throughout the cultivation (*see box for different flooding strategies*). Continuous flooding, as often practiced in Vietnam, results in much larger CH_4 emissions than Mid-season Drainage (MSD), the dominant flooding practice in China. Consequently, China produces one-third of the global rice yet contributes only 23% of the rice-related CH_4. Vietnam, in turn, produces only 5% of the global rice production but 10% of the related global emissions (ibid.). Recent studies have shown that GHG emissions from rice cultivation can be reduced by up to 90% through the use of more suitable flooding techniques such as MSD. Compared to Alternate Wetting and Drying (AWD), MSD involves only one instead of several rounds of drainage, eventually reducing GHG formation. At the same time, sustainable techniques can help to achieve higher yields, increase nitrogen-use efficiencies and reduce water use (Wu et al., 2018; Kritee et al., 2018).

Different forms of intermittent flooding regimes have emerged to replace continuous flooding in some areas. AWD, for instance, is a response to water scarcity in many rice cultivating regions. This regime can save up to 30% of needed irrigation water, depending on local conditions.

Another main benefit of AWD is that it has proven to reduce CH_4 emissions by as much as 80% (Sander et al., 2016). However, there is growing evidence that N_2O emissions from intermittent flooding may be higher than those of permanent flooding regimes (Kritee et al., 2018). In order to fully account for GHG emissions from rice cultivation, actual N_2O emission need to remain a subject of further investigation in the future, mainly led by the agriculture sector.

Different flooding regimes used in rice cultivation:

Permanent flooding: The rice field is constantly flooded during the entire growing season.

Alternate Wetting and Drying (AWD): Water levels during intermittent flooding are typically allowed to fall to 15 cm below the soil surface before starting another round of irrigation. AWD is typically characterised by several drainage events.

Mid-season Drainage (MSD): The rice paddy is drained only one time for around seven days. Intermittent flooding causes one single aeration event for an extended period.

➔ *Water institutions can help to reduce GHG emissions and water demand.*

The agricultural sector has been a leading voice in terms of research and dissemination of water-efficiency technologies that can reduce water demand from rice cultivation. However, water institutions – such as ministries for irrigation and water management – are among the main partners of the agricultural sector in designing policies and instruments that would promote water-saving measures on the ground, and these institutions are also heavily involved in their implementation. Water institutions might further develop and promote appropriate flooding regimes, policies and other instruments for enhancing water-efficiency, while reducing GHG emissions and improving climate resilience of rice cultivation (ibid.). At a local level, water user associations are important actors with a strong influence on cultivation practices of farmers. In this connection, new flooding regimes could be promoted through education, awareness-raising, capacity building or incentives (Sithirith, 2017). In order to reduce the climate impact of rice cultivation, water institutions could support the co-management of different GHG emissions, water resources, and crop yields. The urgency to act upon this triple challenge facing rice cultivation requires more integrated assessments considering water use, N_2O and CH_4 emissions, and rice yields for different rice production systems on a global scale. Such holistic assessments are necessary to identify flooding regimes most promising to minimise both water use and GHG emissions in an integrated manner, while maintaining yields.

7.5 References

Arthington, A. H., Bhaduri, A., Bunn, S. E., Jackson, S. E., Tharme, R. E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A. C., Kendy, E., McClain, M. E., LeRoy Poff, N., Richter, B. D. and Ward, S. (2018): **The Brisbane declaration and global action agenda on environmental flows.** Frontiers in Environmental Science, 6. DOI: 10.3389/fenvs.2018.00045.

Ballard, S., Porro, J., and Trommsdorff, C. (2018): **The Roadmap to a Low-Carbon Urban Water Utility. An International Guide to the WaCCliM Approach.** London, United Kingdom: IWA Publishing.

Barchiesi, S., Davies, P. E., Kulindwa, K.A.A., Lei, G., and Martinez Ríos del Río, L. (2018): **Implementing environmental flows with benefits for society and different wetland ecosystems in river systems.** Ramsar Policy Brief No. 4. Gland, Switzerland: Ramsar Convention Secretariat.

Bastviken, D., Tranvik, L. J., Downing, J. A., Crill, P. M., and Enrich-Prast, A. (2011): **Freshwater methane emissions offset the continental carbon sink.** Science, 331 (6013), 50. DOI: 10.1126/science.1196808

Beaulieu, J. J., DelSontro, T., and Downing, J. A. (2019): **Eutrophication will increase methane emissions from lakes and impoundments during the 21st century.** Nature communications, 10 (1), 1375. DOI: 10.1038/s41467-019-09100-5

Biederman, L. A., and Harpole, W. S. (2013): **Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis.** Bioenergy. GCB Bioengergy, 5, 202–214. DOI: 10.1111/gcbb.12037

Bogner, J., Abdelrafie Ahmed, M., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Mareckova, K., pipatti, R., and Zhang, T. (2007): **Waste Management. In: Climate Change: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change** by Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A. (Eds.). Cambridge/New York: Cambridge University Press.

Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, J., Rufino, M. C., and Stehfest, E. (2013): **Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period.** Proceedings of the National Academy of Sciences, 110 (52), 20882-20887. DOI: 10.1073/pnas.1012878108

Carlson, K. M., Gerber, J. S., Mueller, N. D., Herrero, M., MacDonald, G. K., Brauman, K. A., Havlik, P., O'Connell, C. S., Johnson, J. A., Saatchi, and S. West, P. C. (2016): **Greenhouse gas emissions intensity of global croplands.** Nature Climate Change, 7 (1), 63. DOI: 10.1038/NCLIMATE3158

Copeland, C., and Carter, N. T. (2017): **Energy-Water Nexus: The Water Sector's Energy Use. Library of Congress.** CRS Report for Congress, R43200. Congressional Research Service.

Cordell, D., Drangert, J. O., and White, S. (2009): **The story of phosphorus: global food security and food for thought.** Global environmental change, 19 (2), 292-305. DOI: 10.1016/j.gloenvcha.2008.10.009

Croitoru, L., and Sarraf, M. (Eds.). (2010): **The cost of environmental degradation: case studies from the Middle East and North Africa.** Washington, DC: The World Bank.

References

Crump, J. (Ed.) (2017): **Smoke on Water – Countering Global Threats From Peatland Loss and Degradation. A UNEP Rapid Response Assessment.** United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal, *www.grida.no*

Dargie, G. C., Lewis, S. L., Lawson, I. T., Mitchard, E. T., Page, S. E., Bocko, Y. E., and Ifo, S. A. (2017): **Age, extent and carbon storage of the central Congo Basin peatland complex.** Nature, 542 (7639), 86. DOI: 10.1038/nature21048

Davidson, N. (2018): **Wetland losses and the status of wetland-dependent species.** In: Finlayson, M. C., Milton, g. R., Prentice, r. C., and Davidson, N. C.(Eds.), The wetland book II: Distribution, description, and conservation (pp. 369-381). Dordrecht, Netherlands: Springer. DOI: 10.1007/978-94-007-4001-3_197

Davidson, N. C., van Dam, A. A., Finlayson, and C. M. and McInnes, R. J. (2019): **Worth of wetlands: revised global monetary values of coastal and inland wetland ecosystem services.** Marine and Freshwater Research, 70(8), 1189-1194. DOI: 10.1071/MF18391

Deemer, B. R., Harrison, J. A., Li, S., Beaulieu, J. J., DelSontro, T., Barros, N., Bezerra-Neto, J. F., Powers, S. M., dos Santos, M. A., and Vonk, J. A. (2016): **Greenhouse gas emissions from reservoir water surfaces: a new global synthesis.** BioScience, 66 (11), 949-964. DOI: 10.1093/biosci/biw117

DelSontro, T., Beaulieu, J., and Downing, J. (2018): **Greenhouse gas emissions from lakes and impoundments: Upscaling in the face of global change.** Limnology and Oceanography Letters, 3 (3), 64-75. DOI: 10.1002/lol2.10073

Draper, F. C., Roucoux, K. H., Lawson, I. T., Mitchard, E. T. A., Honorio Coronado, E. N., Lähteenoja, O., Torres Montenegro, L., Valderrama Sandoval, E., Zarate, R, and Baker, T. R. (2014): **The distribution and amount of carbon in the largest peatland complex in Amazonia.** Environmental Research Letters, 9 (12), 124017. DOI:10.1088/1748-9326/9/12/124017

Evers, S., Yule, C. M., Padfield, R., O'reilly, P., and Varkkey, H. (2017): **Keep wetlands wet: the myth of sustainable development of tropical peatlands–implications for policies and management.** Global change biology, 23 (2), 534-549. DOI: 10.1111/gcb.13422

Fernandez, J., Townsend-Small, A., Zastepa, A., Watson S., and Brandes, J. (2019): **Large increases in emissions of methane and nitrous oxide from eutrophication in Lake Erie,** bioRxiv. DOI: 10.1101/648154.

Foley, J., de Haas, D., Yuan, Z. and Lant, P. (2010): **Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants.** Water Research, 44 (3), 831-844. DOI: 10.1016/j.watres.2009.10.033

Gallego-Sala, A. V., Charman, D. J., Brewer, S., Page, S. E., Prentice, I. C., Friedlingstein, P. …, and Blyakharchuk, T. (2018): **Latitudinal limits to the predicted increase of the peatland carbon sink with warming.** Nature climate change, 8 (10), 907-914. DOI: 10.1038/s41558-018-0271-1

Gerbens-Leenes, W., Hoekstra, A. Y., and van der Meer, T. H. (2009): **The water footprint of bioenergy.** Proceedings of the National Academy of Sciences, 106 (25), 10219-10223. DOI: 10.1073/pnas.0812619106

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., and Toulmin, C. (2010): **Food security: the challenge of feeding 9 billion people.** Science, 327 (5967), 812-818. DOI: 10.1126/science.1185383

References

Grant, S. B., Saphores, J. D., Feldman, D. L., Hamilton, A. J., Fletcher, T. D., Cook, P. L., Stewardson, M., Sanders, B. F., Levin, L. A., Ambrose, R. F., Deletic, A., Brown, R., Jiang, S. C., Rosso, D., Cooper, W. J., and Marusic, I. (2012): **Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability.** Science, 337 (6095), 681-686. DOI: 10.1126/science.1216852

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrero, M., Kiesecker, J. Landis, E., Laestadius, L., Leavitt, S. M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F. E., Sanderman, J., Silvius, M., Wollenberg, E., and Fargione, J. (2017): **Natural climate solutions.** Proceedings of the National Academy of Sciences, 114 (44), 11645-11650. DOI: 10.1073/pnas.1710465114

Gumbricht, T., Roman-Cuesta, R. M., Verchot, L., Herold, M., Wittmann, F., Householder, E., Herold, N., and Murdiyarso, D. (2017): **An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor.** Global Change Biology, 23 (9), 3581-3599. DOI: 10.1111/gcb.13689

Hering, J. G., Waite, T. D., Luthy, R. G., Drewes, J. E., and Sedlak, D. L. (2013): **A changing framework for urban water systems.** Water Science and Technology, 47, 10721-10726. DOI: 10.1021/es400709

IEA (International Energy Agency) (2016): **Water Energy Nexus.** Excerpt from the World Energy Outlook 2016.

IEA (International Energy Agency) (2018). **Outlook for Producer Economies,** Paris: IEA. *https://www.iea.org/reports/outlook-for-producer-economies*

IPCC (Intergovernmental Panel on Climate Change) (2006): **IPCC Guidelines for National Greenhouse Gas Inventories.** Geneva, Swizerland: IPCC.

IPCC (Intergovernmental Panel on Climate Change) (2013): **Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change** by Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.). Cambridge/New York: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change) (2014): **2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands** by Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T.G. (Eds). Switzerland: IPCC.

IPCC (Intergovernmental Panel on Climate Change) (2018): **Annex I: Glossary** by Matthews, J.B.R. (Ed.). In: **Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty** by Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds.). Switzerland: IPCC.

IPCC (Intergovernmental Panel on Climate Change) (2019): **2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories** by Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., and Federici, S. (Eds). Switzerland: IPCC.

References

Izquierdo, A. E., Grau, H. R., Carilla, J., and Casagranda, E. (2015): **Side effects of green technologies: the potential environmental costs of Lithium mining on high elevation Andean wetlands in the context of climate change.** Global Land Project: GLP News, 12, 53-56.

Joosten H. (2015): **Peatlands, climate change mitigation and biodiversity conservation. An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots.** Nordic Council of Ministers.

Joosten, H., Couwenberg, J., and Von Unger, M. (2016). **International carbon policies as a new driver for peatland restoration.** In: Bonn, A., Allott, T., Evans, M., Joosten, H., and Stoneman, R. (Eds.): **Peatland restoration and ecosystem services: Science, policy and practice,** pp. 291-313. Cambridge: Cambridge University Press/ British Ecological Society

Kritee, K., Rudek, J., Hamburg, S. P., Adhya, T. K., Loecke, T., and Ahuja, R. (2018): **Reply to Yan and Akiyama: Nitrous oxide emissions from rice and their mitigation potential depend on the nature of intermittent flooding.** Proceedings of the National Academy of Sciences, 115 (48), 11206-11207. DOI: 10.1073/pnas.1816677115

Lähteenoja, O, Page, S. (2011): **High diversity of tropical peatland ecosystem types in the Pastaza-Maraón basin, Peruvian Amazonia.** Journal of Geophysical Research, 16, G02025. DOI: 10.1029/2010JG001508

Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B., and Maurer, M. (2016): **Emerging solutions to the water challenges of an urbanizing world.** Science, 352 (6288), 928-933. DOI: 10.1126/science.aad8641

Leifeld, J., and Menichetti, L. (2018): **The underappreciated potential of peatlands in global climate change mitigation strategies.** Nature communications, 9, 1071. DOI: 10.1038/s41467-018-03406-6

Li, W. W., Yu, H. Q., and Rittmann, B. E. (2015): **Reuse water pollutants.** Nature News, 528 (7580), 29. DOI: 10.1038/528029a

Liu, F., Ouedraogo, A., Manghee, S., and Danilenko, A. (2012): **A primer on energy efficiency for municipal water and wastewater utilities.** Washington DC: The World Bank.

Lunt, P., Allot, T., Anderson, P., Buckler, M., Coupar, A., Jones, P., Labadz, J., and Worrall, P. (2010): **Peatland restoration.** Scientific Review commissioned by IUCN UK Peatland Programme Commission of Inquiry into Peatland Restoration, Edinburgh, UK.

McCarty, P. L., Bae, J., and Kim, J. (2011): **Domestic wastewater treatment as a net energy producer – Can this be achieved?** Environmental Science and Technology, 45 (17), 7100-7106. DOI: 10.1021/es2014264

Mekonnen, M. M., Gerbens-Leenes, P. W., and Hoekstra, A. Y. (2015): **The consumptive water footprint of electricity and heat: a global assessment.** Environmental Science: Water Research and Technology, 1 (3), 285-297. DOI: 10.1039/C5EW00026B

Mishra, V., Asoka, A., Vatta, K., and Lamm, U. (2018): **Groundwater Depletion and Associated CO_2 Emissions in India. Earth's Future,** 6. DOI: 10.1029/2018EF000939

References

Mitsch, W. J.; Bernal, B., Nahlik, A. M., Mander, Ü., Zhang, L., Anderson, C. J., Jørgensen, S. E., and Brix, H. (2011): **Wetlands, carbon, and climate change.** Landscape Ecology, 28 (4), 583-597. DOI 10.1007/s10980-012-9758-8

Moomaw, W. R., Chmura, G. L., Davies, G. T., Finlayson, C. M., Middleton, B. A., Natali, S. M., Perry, J. E., Roulet, N. and Sutton-Grier, A. E. (2018): **Wetlands in a changing climate: science, policy and management.** Wetlands, 38 (2), 183-205. DOI: 10.1007/s13157-018-1023-8

Muller, M. (2019): **Dams have the power to slow climate change.** Nature, 566 (7744), 315-317. DOI: 10.1038/d41586-019-00616-w

Murray, R., Erler, D., Rosentreter, J., Wells, N., and Eyre, B. (2019): **Seasonal and spatial controls on N_2O concentrations and emissions in low-nitrogen estuaries: Evidence from three tropical systems.** Marine Chemistry, 221. DOI: 10.1016/j.marchem.2020.103779

OECD (Organisation for Economic Co-operation and Development) (2019): **Purpose codes list for 2019 reporting on 2018 flows.** *https://www.oecd.org/dac/financing-sustainable-development/development-finance-standards/DAC-CRS-PPC-2019.xls*

Page, S., Hosciło, A., Wösten, H., Jauhiainen, J., Silvius, M., Rieley, J., Ritzema, H., Tansey, K., Graham, L. L. B., Vasander, H., and Limin, S. (2009): **Restoration ecology of lowland tropical peatlands in Southeast Asia: current knowledge and future research directions. Ecosystems,** 12 (6), 888-905. DOI: 10.1007/s10021-008-9216-2

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L, Naja, N., and Cecinato, A. (2018): **Environmental impact of biogas: A short review of current knowledge,** Journal of Environmental Science and Health, Part A, 53 (10), 899-906, DOI: 10.1080/10934529.2018.1459076

Petrescu, A. M. R.; A. Lohila, J. P. Tuovinen, D. D. Baldocchi, A. R. Desai, N. T. Roulet, T. Vesala, A. J. Dolman, W. C. Oechel,B. Marcolla, T. Friborg, J. Rinne, J. H. Matthes, L. Merbold, A. Meijide, G. Kiely, M. Sottocornola, T. Sachs, D. Zona, A. Varlagin, D. Y. F. Lai, D., E. Veenendaal, F-J., W. Parmentier, U. Skiba, M. Lund, A. Hensen, J. van Huissteden, L. B. Flanagan, N. J. Shurpali, T. Grünwald, E. R. Humphreys, M. Jackowicz-Korczyński, M.A. Aurela, T. Laurila, C. Grüning, C. A. R. Corradi, C.A. P. Schrier-Uijl, T. R. Christensen, M. P. Tamstorf, M. Mastepanov, P. J. Martikainen, S. B. Verma, C. Bernhofer and A. Cescatti (2015): **The uncertain climate footprint of wetlands under human pressure.** In: Proceedings of the National Academy of Sciences 112 (15), 4594–4599. DOI: 10.1073/pnas.1416267112

Posa, M. R. C., Wijedasa, L. S., and Corlett, R. T. (2011): **Biodiversity and conservation of tropical peat swamp forests.** BioScience, 61 (1), 49-57. DOI: 10.1525/bio.2011.61.1.10

Prairie, Y., Alm, J., Beaulieu, J., Barros, N., Battin, T., Cole, J., Giorgio, P., DelSontro, T., Guérin, F., Harby, A., Harrison, J., Mercier-Blais, S., Serça, D., Sobek, S., and Vachon, D. (2018): **Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See?** Ecosystems, 21, 1058-1071 DOI: 10.1007/s10021-017-0198-9

Ramsar Convention on Wetlands (2018): **Global Wetland Outlook: State of the World's Wetlands and their Services to People.** Gland, Switzerland: Ramsar Convention Secretariat.

Ramsar Convention Secretariat (2018): **Wetland Restoration for Climate Change Resilience.** Ramsar Briefing Note 10. *https://www.ramsar.org/sites/default/files/documents/library/bn10_restoration_climate_change_e.pdf*

Raptis, C. E., van Vliet, M. T., and Pfister, S. (2016): **Global thermal pollution of rivers from thermoelectric power plants.** Environmental Research Letters, 11 (10), 104011. DOI: 10.1088/1748-9326/11/10/104011

Rothausen, S. G., and Conway, D. (2011): **Greenhouse-gas emissions from energy use in the water sector.** Nature Climate Change, 1 (4), 210-219. DOI: 10.1038/nclimate1147

Roucoux, K. H. Lawson, I. T., Baker, T. R., Del Castillo Torres, D., Draper, F. C., Lähteenoja, O., Gilmore, M. P., Honorio Conorado, E. N., Kelly, T. J., Mitchard, E. T. A., and Vriesendorp, C. F. (2017): **Threats to intact tropical peatlands and opportunities for their conservation.** Conservation Biology, 31 (6), 1283-1292 DOI: 10.1111/cobi.12925.

Sanches, L., Guenet, B., Marinho, C., Barros, N., and De Assis Esteves, F. (2019): **Global regulation of methane emission from natural lakes.** Scientific Reports, 9, 255, DOI: 10.1038/s41598-018-36519-5

Sander, B-O., Wassmann, R., and Siopongco, J., (2016): **Mitigating Greenhouse Gas Emissions from Rice Production through Water-Saving Techniques: Potential, Adoption and Empirical Evidence.** In: Hoanh, C., Smakhtin, V., Johnston, R. (Eds.), CAP International 2016. Climate Change and Agricultural Water Management in Developing Countries. CABI Climate Change Series. Wallingford, United Kingdon: CABI.

Sithirith, M. (2017): **Water governance in Cambodia: From centralized water governance to farmer water user community.** Resources, 6 (3), 44. DOI: 10.3390/resources6030044

Turetsky, M. R., Kotowska, A., Bubier, J., Dise, N. B., Crill, P., Hornibrook, E. R., Minkkinen, K., Moore, T. R., Myers-Smith, I. H., Nykanen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E., Waddington, J. M., White, J. R., Wickland, K. P., and Wilmking, M. (2014): **A synthesis of methane emissions from 71 northern, temperate, and sub-tropical wetlands.** Global change biology, 20 (7), 2183-2197. DOI: 10.1111/gcb.12580

Umweltbundesamt (2019): **Factsheet Moore.** Deutsche Emissionshandelsstelle (DEHSt) im Umweltbundesamt. *https://www.dehst.de/SharedDocs/downloads/DE/publikationen/Factsheet_Moore.pdf?__blob=publicationFile&v=6*

UNEP (United Nations Environment Programme) (2016): **A Snapshot of the World's Water Quality: Towards a global assessment.** United Nations Environment Programme, Nairobi, Kenya. 162pp.

USEPA (United States Environmental Protection Agency) (2019): **Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019,** EPA 430-R-19-001. Washington, D.C, USA: United States Environmental Protection Agency.

Van Groenigen, K. J., Van Kessel, C., and Hungate, B. A. (2013): **Increased greenhouse-gas intensity of rice production under future atmospheric conditions.** Nature Climate Change, 3 (3), 288-291. DOI: 10.1038/nclimate1712

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., and Davies, P. M. (2010): **Global threats to human water security and river biodiversity.** Nature, 467 (7315), 555-561. DOI: 10.1038/nature09440

Wang, X., Daigger, G., Lee, D. J., Liu, J., Ren, N. Q., Qu, J., Liu, G., and Butler, D. (2018): **Evolving wastewater infrastructure paradigm to enhance harmony with nature.** Science advances, 4 (8), eaaq0210. DOI: 10.1126/sciadv.aaq0210

References

WHO, UNICEF (2019): **Joint Monitoring Programme: Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities.**

Wichtmann, W., Schröder, C., and Joosten, H. (Eds.). (2016): **Paludiculture – productive use of wet peatlands, climate protection – biodiversity – regional economic benefits.** Stuttgart, Germany: Schweizerbart Science Publishers.

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., ... , and Stiassny, M. L. J. (2016): **Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong.** Science, 351 (6269), 128-129. DOI: 10.1126/science.aac7082

Woldetsadik, D., Drechsel, P., Marschner, B., Itanna, F., and Gebrekidan, H. (2017): **Effect of biochar derived from faecal matter on yield and nutrient content of lettuce (Lactuca sativa) in two contrasting soils.** Environmental Systems Research 6 (2), 1-12. DOI: 10.1186/s40068-017-0082-9

Wu, X., Wang, W., Xie, X., Yin, C., Hou, H., Yan, W., and Wang, G. (2018): **Net global warming potential and greenhouse gas intensity as affected by different water management strategies in Chinese double rice-cropping systems.** Scientific reports, 8 (1), 779-788. DOI: 10.1038/s41598-017-19110-2

WWAP (United Nations World Water Assessment Programme). (2014): **The United Nations World Water Development Report 2014: Water and Energy.** Paris: UNESCO.

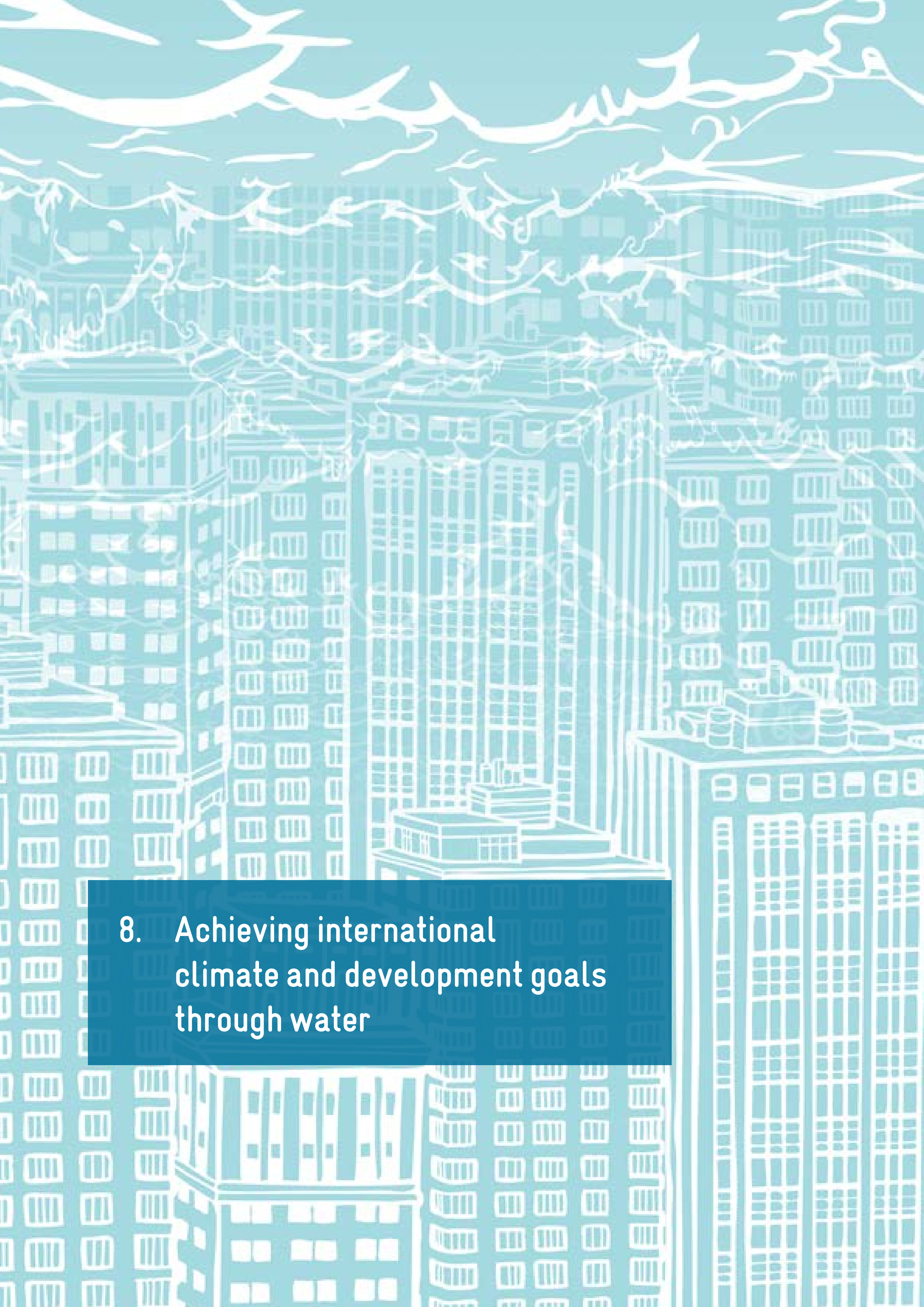
WWAP (United Nations World Water Assessment Programme). (2017): **The United Nations World Water Development Report 2017: Wastewater, The Untapped Resource.** Paris: UNESCO.

Yang, W., Sun, T., and Yang, Z. (2016): **Does the implementation of environmental flows improve wetland ecosystem services and biodiversity? A literature review.** Restoration Ecology, 24 (6), 731-742. DOI: 10.1111/rec.12435

Zhang, Z.; Zimmermann, N. E., Stenke, A., Li, X., Hodson, E. L., Zhu, G., Huang, C., and B. Poulter (2017): **Emerging role of wetland methane emissions in driving 21st century climate change.** In: Proceedings of the National Academy of Sciences, 114 (36), 9647–9652. DOI: 10.1073/pnas.1618765114

Zhu, Q., Peng, C., Liu, J., Jiang, H., Fang, X., Chen, H., Niu, Z., Gong, P., Lin, G., Wang, M., Wang, H., Yang, Y., Chang, J., Ge, Y., Xiang, W., Deng, X., He, .. (2016): **Climate-driven increase of natural wetland methane emissions offset by human-induced wetland reduction in China over the past three decades.** Scientific Reports 6, 38020. DOI: 10.1038/srep38020

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., and Levin, S. A. (2012): **Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin.** Proceedings of the National Academy of Sciences, 109 (15), 5609-5614. DOI: 10.1073/pnas.1201423109



8. Achieving international climate and development goals through water

This chapter discusses how major international climate change, sustainable development and disaster risk reduction (DRR) policy processes, as well as corresponding institutional frameworks, have been dealing with water-related challenges introduced in the previous chapters. By elaborating on selected international policy processes and frameworks, including major global agendas, and linking them to the water sector, the chapter offers approaches for the water community to address future challenges.

The chapter focuses on institutions and processes relating to the international climate change architecture that have originated within the context of the UNFCCC, and identifies promising entry points for dealing with water challenges. An integrated perspective involving the 2030 Agenda framework to implement the Sustainable Development Goals (SDGs) and the Sendai Framework on Disaster Risk Reduction can pave the way for resilient and low-carbon economies through sustainable water security.

Key Messages of Chapter 8

- Water can play a significant part in achieving climate objectives – not only as part of the adaptation agenda, but also to support equally important mitigation objectives.
- The Paris Agreement of 2015 and its "Rulebook", which was adopted in 2018 at the 24th Conference of the Parties (COP 24) to the UNFCCC in Katowice, are the main reference frameworks that need to be considered, when formulating water-related climate priorities.
- Strategy and planning processes to implement the Paris Agreement on a national level are key areas in which water-related activities play a prominent role. This is especially relevant in the context of Long-term Strategies, Nationally Determined Contributions (NDCs) and the National Adaptation Plans (NAPs).
- The next round of NDC ambition raising (update), to be completed in 2020, can demonstrate a more comprehensive recognition of the water sector's potential for climate change mitigation and adaptation. The role of water for mitigation of GHG in particular requires a more prominent acknowledgment.
- Due to the significant overlaps between water- and climate-related SDGs, the implementation processes of the 2030 Agenda and the Paris Agreement can benefit from stronger integration of the two subject areas.
- DRR and its application, disaster risk management, need to be considered when addressing climate change adaptation priorities in the water sector. By using synergies, water-related activities offer important entry points. To this end, different initiatives that can be systematically strengthened are already underway, such as the Global Initiative on Disaster Risk Management (GIDRM).

8.1 UNFCCC, Paris Agreement and water

Water significantly contributes to the objectives of the cross sectorial international climate policy framework. The references to water in the key documents are mainly indirect – as the following list of key elements indicates:

Article 4 of the 1992 UNFCCC related to commitments of Parties to the Convention emphasises the need to cooperate and implement adaptation actions to address climate change impacts. The particular focus of Article 4 concerns the needs of developing countries. Article 4, paragraph 1(e) of the Convention commits Parties "to develop and elaborate appropriate and integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification, as well as floods."

During the 2010 UNFCCC Conference of the Parties (COP 16) in Cancun, Parties agreed to establish the **Cancun Adaptation Framework**. Its objective is to enhance action on adaptation, including through international cooperation and coherent consideration of matters relating to adaptation under the Convention. Apart from information-sharing, paragraph 14(a) of the Cancun Agreements makes specific reference to water resources, freshwater, marine ecosystems and coastal zones in a footnote, referring to "planning, prioritizing and implementing adaptation actions, including projects and programmes".

In addition, the **Nairobi Work Programme** has provided useful guidance on climate change and freshwater resources. Examples are the synthesis of adaptation actions undertaken by Nairobi Work Programme partner organizations (2011), as well as the synopsis of the Nairobi Work Programme, which focuses on water resources, climate change impacts and adaptation planning processes. The overview of good practices and lessons learnt presented in the Nairobi Work Programme can inform important steps towards a stronger integration of climate change adaptation and resilient water management.

More recently, the **Subsidiary Body for Scientific and Technological Advice (SBSTA)**, one of the two Subsidiary Bodies under the UNFCCC responsible for guiding the implementation process at the technical level, requested that decision-makers prioritise select thematic areas, many of which are water-related, such as dealing with extreme events like flash floods and heavy precipitation as well as droughts, water scarcity, coastal areas and mega deltas (SBSTA, 2019). Thus, in this context, water-related activities remain a focus.

➔ ***The text of the Paris Agreement makes no direct reference to water. Still, there are several entry points for water-related issues.***

The **Paris Agreement** itself, adopted in December 2015, makes no direct reference to water. However, with additional guidance for implementation as adopted at COP 24 in Katowice in 2018 (often referred to as "**rulebook**"), there are references related to different parts of the Paris Agreement. These mainly concern the provision of information on implementation, for instance as part of **Article 13** (modalities, procedures and guidelines for the **transparency framework**):

- Information related to climate change impacts and adaptation under **Article 7** of the Paris Agreement: adaptation strategies, policies, plans, goals and actions to integrate adaptation into national policies and strategies. Each Party should provide the following information, as appropriate on plans, strategies, policies, priorities (e.g. priority sectors, priority regions or integrated plans for coastal management, water and agriculture).

- Information on financial support provided and mobilized under **Article 9** of the Paris Agreement (sectors including water and sanitation).

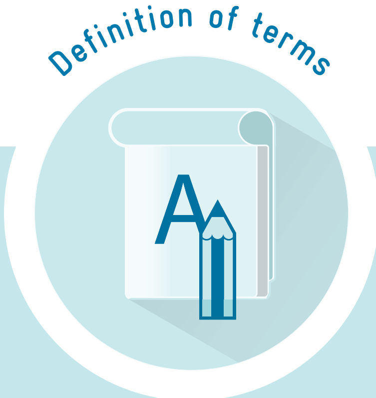
As one result of the COP in Katowice and the adopted Rulebook, **adaptation communications** have received increased attention. The Rulebook contains guidelines for countries on how to communicate and report on adaptation measures. Every five years, a global review is carried out in order to jointly analyse whether adaptation efforts are adequate and whether they consider how to deal with the impacts of climate change in a more effective manner.

In addition, the call in the Paris Agreement to develop **long-term strategies** can be relevant in particular concerning climate change mitigation through water. In accordance with Article 4, paragraph 19, of the Paris Agreement, all Parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies, keeping in mind the common but differentiated responsibilities and respective capabilities of Parties in light of different national circumstances. As of June 2020, however, only sixteen countries and the EU have submitted long-term strategies to the UNFCCC, and water plays a minor role as an entry point for GHG reduction efforts.

The importance of climate policy planning processes has increased since the adoption of the Paris Agreement. Ever since, long-term strategies (main focus on long-term mitigation) and NDCs (regular updates on short- to medium-term priorities and planned contributions to climate change mitigation and adaptation) have become important drivers for policy planning processes.

➔ *Climate change challenges can only be solved through ending siloed sector-thinking, while promoting cooperation across different line ministries.*

In many cases, one big barrier to effective adaptation planning and action is the lack of coordination in both directions – horizontal and vertical, including inter-ministerial coordination in some countries. Roles and responsibilities related to the formulation and implementation of climate action may be unclear: For instance, climate change policies are usually under the remit of the ministry of environment. Not all sector-related questions, including water – also with respect to DRR strategies and management – might be appropriately covered, if responsibilities are scattered among ministries. It might be beneficial to promote and improve the inter-ministerial and inter-sectorial coordination in order to comprehensively address climate goals. With respect to the implementation of the Paris Agreement, various relevant policy planning processes relate to water issues to different degrees.



Key climate policy planning processes

Long-term Strategies

All Parties should strive to formulate and communicate long-term low GHG emission and climate resilient development strategies, being mindful of Article 2, i.e. taking into account their common but differentiated responsibilities and respective capabilities, in light of different national circumstances.

Article 4, paragraph 19 of The Paris Agreement

Nationally Determined Contributions (NDCs)

Nationally Determined Contributions (NDCs) are a written explanation of national efforts taken by each country to reduce emissions and adapt to the impacts of climate change. The Paris Agreement requires the preparation, maintenance, and communication of NDCs. Starting in 2020, every five years, governments will take stock of the implementation and the collective progress towards achieving the purpose of the Agreement and its long-term goals. The NDCs will be updated by the countries and their ambition raised to be in line with the objectives of the Paris Agreement.

Adapted from UNFCCC n.d.: Nationally Determined Contributions (NDCs).

National Adaptation Plans (NAPs)

Developed under the Cancun Adaptation Framework, National Adaptation Plans (NAPs) are nation-specific means to identify medium- and long-term adaptation needs. They outline ways to develop and implement strategies and programmes to address the identified needs.

UNFCCC n.d.: National Adaptation Plans

The following sections show how selected climate policy processes have been dealing with water issues and what can be learnt by the water sector. So far, the mitigation potential through water (*see Chapter 7*) has not been extensively considered. Nevertheless, water's relevance for strengthening climate adaptation and resilience has gained strong attention in the NDC and also the NAP process.

Long-term Strategies and Low Emission Development Strategies

In order to take advantage of the water sector's potential to support climate change mitigation, it is necessary to integrate objectives and measures in relevant strategic documents.

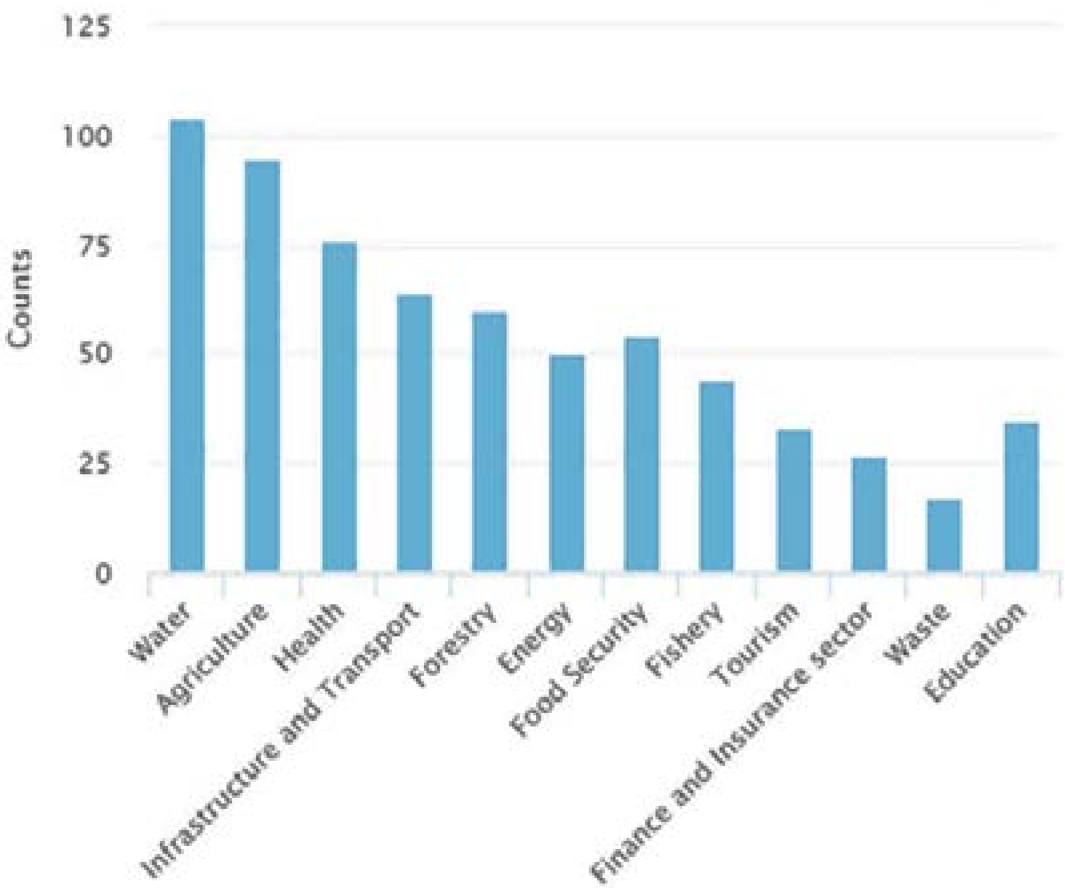
However, neither the process of designing and implementing Low Emission Development Strategies (LEDS), which started back in 2008, nor the long-term low GHG emission development strategies, as requested through the Paris Agreement, have been prominently highlighting activities in or of this sector.

LEDS as a concept was first used by UNFCCC in 2008 and then also included in the Copenhagen Accord of 2009, which recognized LEDS as indispensable to sustainable development. Further operationalized in the years after the Copenhagen climate conference, the LEDS concept today has a great deal of overlap with the request by the Paris Agreement to formulate and communicate long-term low GHG emission development strategies. These should recognize common but differentiated responsibilities and respective capacities of the countries. There is significant scope to involve ministries or agencies representing the water sector during the participatory process envisaged by UNFCCC, in addition to the other sectors prominently covered in the longterm strategies submitted so far (e.g. energy, transport, housing, agriculture).

Nationally Determined Contributions

The Paris Agreement requires all Parties to put forward their best efforts to reduce emissions and outline their reduction targets through Nationally Determined

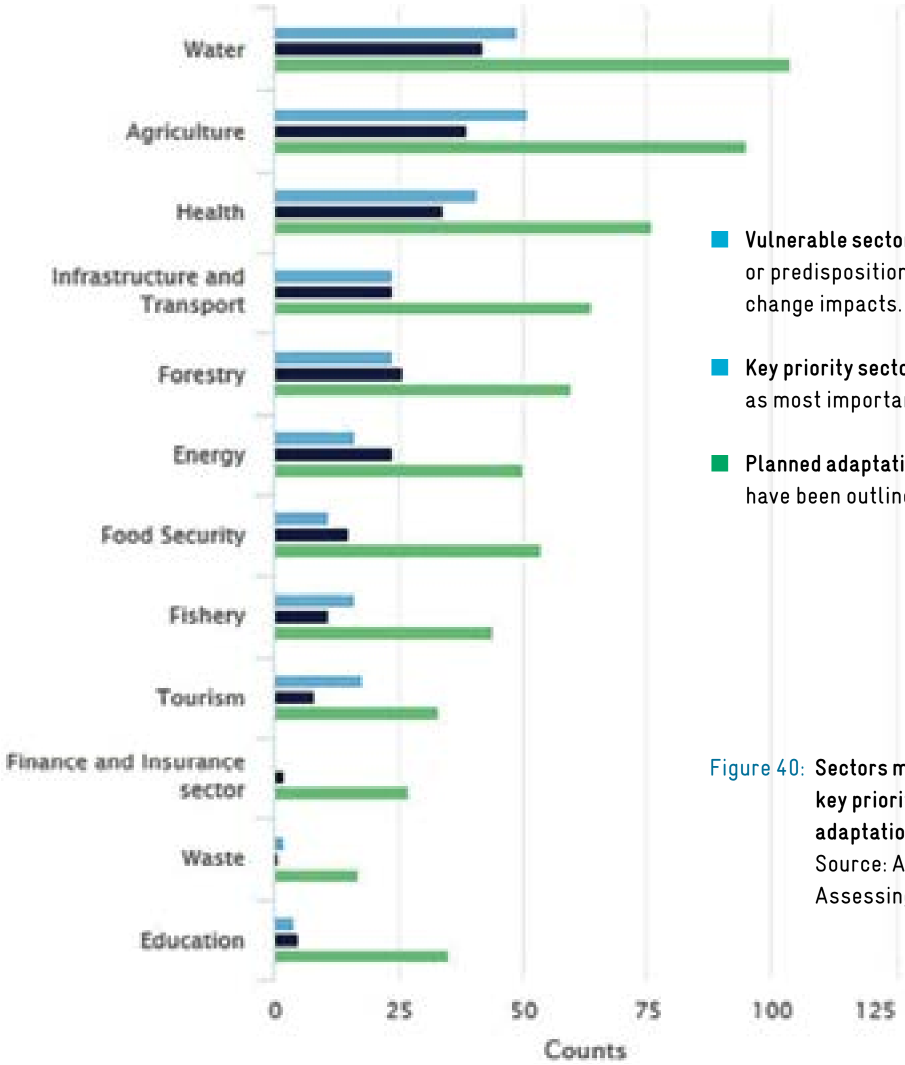
Figure 39: Number of NDCs with sectoral adaptation plans components for twelve different sectors. Source: Adaptation Community (no year): Tool for Assessing Adaptation in the NDCs (TAAN)



Contributions (NDCs). Furthermore, Parties should strengthen their climate efforts in the future by updating their NDCs every five years before submitting them to the UNFCCC.

The next round of NDC updates, in which Parties are called to raise their ambitions compared to previous NDCs, is scheduled for 2020. Thus, the role of water can still be strengthened substantially within NDCs. In general, emission targets set by current NDCs are insufficient to comply with the Paris Agreement. Consequently, policymakers will most likely face additional pressure to further explore GHG reduction potential within all sectors – including water – as well as to integrate sectors through cross-sectoral decarbonisation efforts. Sectorial NDC guidelines, such as Timboe et al. (2019) and *Chapters 6 and 7* of the present report, help water and climate actors to identify and include potential water-related issues.

In current NDCs of the Parties, water is prominently addressed with regard to adaptation. As a result of the Paris Agreement Rulebook, as well as the outcomes of COP 24, decision-makers agreed to provide further guidance and support in communicating adaptation needs and experiences; thus, more concrete priorities and activities can be expected for updated NDCs. With respect to specific adaptation references in the NDC documents, tools like the "Tool for Assessing Adaptation in the NDCs" (TAAN) database, hosted by GIZ via the knowledge platform *adaptation-community.net*, or overview studies, such as the Global Water Partnership (GWP) NDC assessment (2018), offer information needed to provide a general status quo assessment on the relevance of water for the NDC process. According to the TAAN database, water is the sector most frequently mentioned in the NDC adaptation components. More than a hundred NDCs already include a reference to a sectoral plan on water (*see Figure 39*).



- **Vulnerable sectors:** Sectors that have the propensity or predisposition to be adversely affected by climate change impacts.
- **Key priority sectors:** Sectors that have been highlighted as most important.
- **Planned adaptation actions in sector:** Actions that have been outlined to take place in a specific sector.

Figure 40: **Sectors mentioned in NDCs as vulnerable sectors; key priority sectors; and sectors with planned adaptation actions.**
Source: Adaptation Community (no year): Tool for Assessing Adaptation in the NDCs (TAAN)

Within the original NDCs, water is frequently considered as a vulnerable sector (*see Figure 40 on previous page*). It is identified as "vulnerable" in 49 NDCs, and considered a priority sector for implementing new adaptation measures in 42 NDCs. Such a prominence of water within current NDCs, however, raises further questions regarding the actual implementation of water-related adaptation activities. For instance, how can perceived or actual vulnerabilities outlined in NDCs be translated into concrete adaptation measures? Furthermore, keeping in mind that NDCs were initially designed for mitigation concerns – addressing mid- to long-term emission
targets, rather than stating actual plans, strategies or roadmaps for adaptation measures – challenges associated with implementing concrete adaptation measures become even more apparent. Consequently, the degree to which Parties will focus on adaptation components within their next NDCs remains to be seen. Eventually, the success of the NDC process – as one country-owned part within the international climate architecture – essentially depends on political support and determination.

In order to fully exhaust the water sector's potential within the NDC process, the periodic ambition-raising (update) process could address some of the contemporary flaws with respect to water. For instance, there are still gaps in adequately reflecting the close relationship between water issues and DRR concerns. Furthermore, the water sector's mitigation potential does not seem to be fully exhausted – creating an untapped GHG reduction potential within upcoming NDCs (*see Chapter 7*).

National Adaptation Plans

Another country-owned key planning element of the international climate architecture is the NAP process. It was established in 2010 as part of the Cancun Adaptation Framework – not least to complement existing short-term NAPAs, which represented the main planning approach to guiding adaptation options by Least Developed Countries (LDCs). In prioritising adaptation options, countries are advised to pay attention to specific criteria, such as potential co-benefits, conflict prevention and integrating adaptation and development planning (LDC Expert Group 2012). The core principles, defined in 2012 (*see box below*), mirror the country-owned, voluntary, participatory and transparent nature of this process.

Consequently, the NAP process is an integral part of the assessment of overall climate change vulnerabilities and, more generally, risks at different levels. NAPs can thus be decidedly useful for developing countries in assessing measures to counter climate change impacts (LDC Expert Group 2012a). As of June 2020, 20 countries have officially submitted a NAP document under UNFCCC.[1] However, several additional countries have started their NAP processes.

1 see www4.unfccc.int/sites/NAPC/Pages/national-adaptation-plans.aspx for current status

The core principles of the NAP process include:

- continuous planning process at the national level with iterative updates and outputs.
- country-owned, country-driven.
- not prescriptive, but flexible and based on country needs .
- building on and not duplicating existing adaptation efforts.
- participatory and transparent.
- enhancing coherence of adaptation and development planning.
- supported by comprehensive monitoring and review.
- considering vulnerable groups, communities, and ecosystems.
- guided by best available science.
- taking into consideration traditional and indigenous knowledge.
- gender-sensitivity.

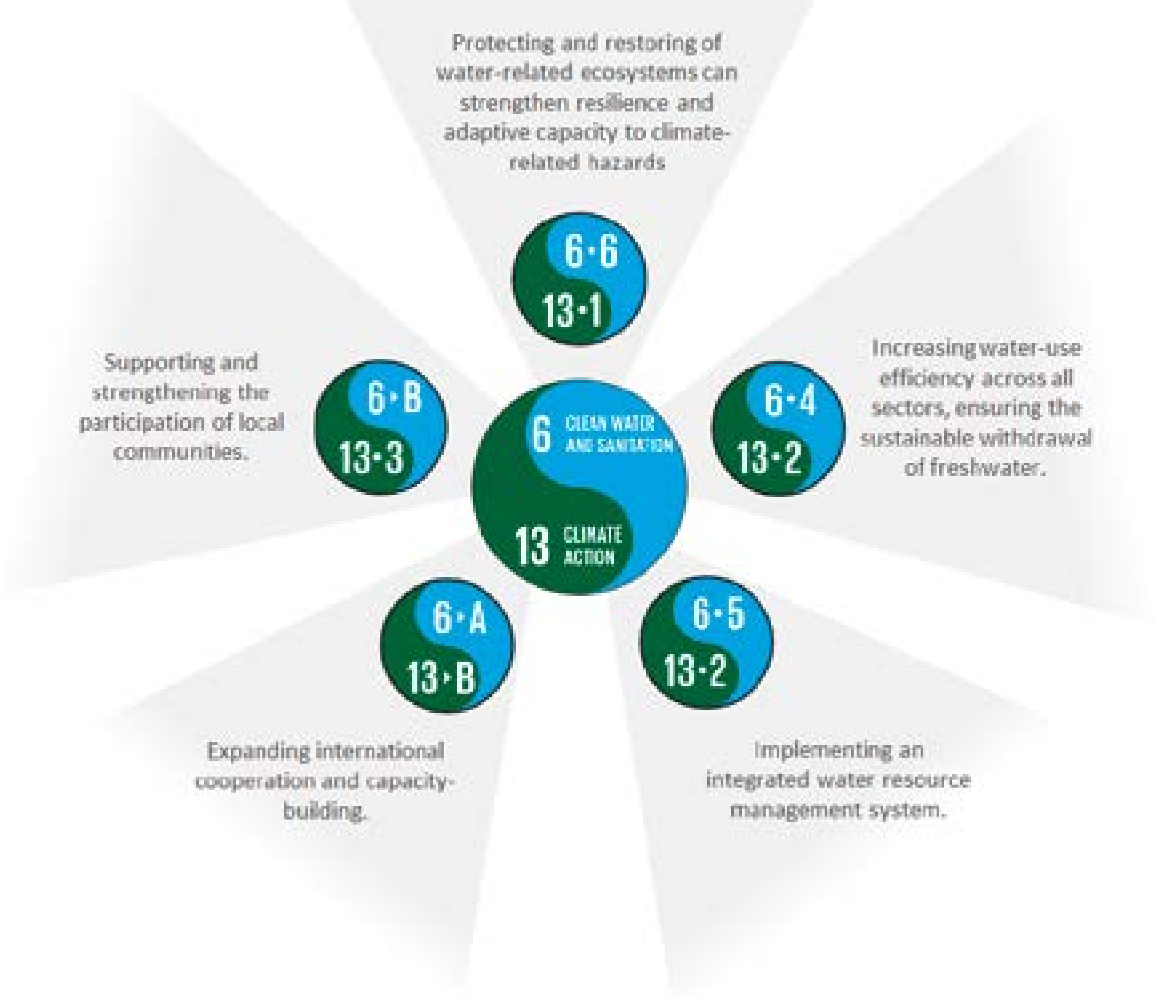
Source: Based on LDC Expert Group, 2012a

Potential entry points for the water sector in support of the NAP process can be identified (GWP, 2018):

- The identification and selection of potential adaptation options must be supported by appropriate data and information, and it requires adequate analytical capacities. At the same time, the stakeholders involved in this process are asking for easy-to-apply screening tools in addition to more sophisticated vulnerability and risk assessments (*see Chapter 6.2*).
- An effective and strong process of stakeholder engagement can help to create broad ownership of the NAP process (and the selected adaptation actions) by different stakeholder groups, especially sectors such as water. In addition, inter-ministerial and inter-sectoral coordination and cooperation is needed to ensure successful implementation. Water-related adaptation activities – as well as other sectoral adaptation activities – need to be aligned with the overall NAP implementation strategy. Continuous capacity-building can further help to improve the ownership and engagement of stakeholders.
- A due reflection on budget needs and how additional resources can be mobilised will be a key aspect of further implementation. Similar to the NDC implementation process, a financing and investment strategy and/or action plan is essential to identify and attract potential sources of funding. Such an approach can also consider innovative financing options, such as climate-related risk-transfer mechanisms.

Overall, throughout the NAP process, the perspective of water sector stakeholders can be integrated at several stages. To this end, water priorities can be communicated through the representation of relevant stakeholders at national climate change coordination entities and/or through cooperation among ministries responsible for water and climate change issues. Analysing and summarising sector assessments on risk and opportunities related to climate change and consulting with civil society and the private sector, can be helpful first steps for an effective engagement of water stakeholders.

Figure 41: **Overall relationship between SDG 6 and 13.**



8.2 Sustainable Development Goals

Climate change impacts pose substantial threats not only to water-related SDG targets, but also to the achievement of development targets as a whole. However, some of these threats are particularly critical with regard to SDG 6 on clean water and sanitation and its targets. Efforts to implement SDG 13 on climate action and SDG 6 can mutually reinforce each other, thereby creating a set of valuable synergies (UN Water, 2016).

Potential areas for the creation of synergies between the implementation of SDG 6 on water and SDG 13 on climate action can be identified (*see Figure 41 on previous page*), including increased water efficiency across sectors (SDG target 6.4). By combating climate change and its impacts (SDG 13), water scarcity can be limited (6.4), water quality improved (6.3) and water-related ecosystems and their services protected and restored (6.6).

Implementing approaches for IWRM (6.5) can support both targets on climate awareness-raising (13.3) and maistreaming climate and ecosystem values across development processes (13.2). By supporting and strengthening the participation of local communities in improving water and sanitation management (6.B), communities can also improve education, awareness-raising and capacity on climate change mitigation and adaptation (13.3). Finally, expanding international cooperation and capacity-building in developing countries in water- and sanitation-related activities (6.A) can help promote climate change-related planning and management in vulnerable countries and communities (13.B).

Beyond SDG 6 and in relation to climate change, water is explicitly mentioned in SDG 3 (good health and well-being), specifically on health impacts from waterborne diseases (3.3) and contaminated water (3.9) and SDG 11 (sustainable cities and communities), specifically target 11.5 on disasters. With regard to ecosystems, SDG 15 (life on land), which addresses terrestrial ecosystems, reveals some important links to climate action and water security issues (Bhaduri et al., 2016). For instance, target 15.1 promotes the conservation, restoration as well as the sustainable use of terrestrial and inland freshwater ecosystems and their services – with likely positive impacts on water and climate action. Conversely, the adherence to Integrated Water Resources Management principles (6.5) can support SDG 15 and 13 targets, including through mainstreaming climate and ecosystem values across development processes.

Selected sector specific interlinkages

With respect to specific sectors, measures related to buildings, industry, transport, agriculture, forests, oceans and coal replacement that can help to implement both SDGs 6 and 13 have been identified. Beyond behavioural changes, key entry points for synergies between water and climate-related SDGs are the implementation of energy efficiency measures and related alternative low-carbon policies. This applies especially to the building, industry and transport sectors. With regard to the agricultural and forest-related spectrum of synergies, another set of activities, such as sustainable manure management and avoiding deforestation and promoting sustainable forest management, offers promising co-benefits. However, some areas also show potential trade-offs where cross-sector cooperation is needed to avoid negative side effects, e.g. with respect to the role of new nuclear energy or carbon capture and sequestration.

INDUSTRY

(+) Reduced energy demand will reduce water consumption

(+/-) Low-carbon fuels can lead to a reduction in water demand and waste water, as long as the low-carbon fuel comes from a less water intensive alternative to higher carbon fuels

(+/-) CCU/S can contribute to localised water stress.

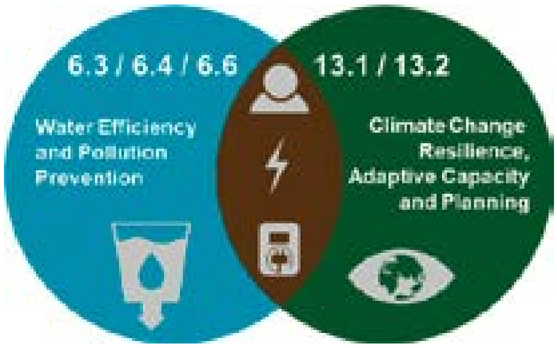
Increased Energy Efficiency | Low-carbon Fuel | Decarbonisation and CCU/S

Accelerating energy efficiency improvements: Accelerating energy efficiency and behavioural changes in the industry sector is likely to serve climate and water purposes alike. Lower demand for energy is often accompanied by reduced water consumption and an overall reduction of water withdrawal for industrial processes.

Low-carbon fuel switch: A switch to low-carbon fuels can have positive as well as negative effects on water efficiency and pollution prevention. It can lead to a reduction in water demand and wastewater – but also to increased water use, if the switch leads to a larger dependency on biofuels. But the effects on climate change are likely to be positive, due to reduced carbon emissions. In other words, in a region threatened by increasing water scarcity, low-carbon fuels will have positive consequences overall, if a less water-intensive alternative to higher-carbon fuels can be used. The specific context needs to be considered during the planning stage of industrial processes.

Decarbonisation via Carbon Capture and Sequestration and Carbon Capture and Utilisation (CCS/CCU): The IPCC also sheds light on the use of potential carbon capture sequestration or usage practices. From a water scarcity perspective, CCU/S can be both positive and negative. It can contribute to water stress, but in principle, it can also be configured in a way that it contributes to increased water efficiency compared to a system without carbon capture. From a climate perspective, CCU/S will most likely have positive effects in terms of mitigating emissions, though the efficiency and impacts of this approach are still subject to discussion.

BUILDINGS



- (+) Reduced residential energy demand might reduce water consumption
- (+/-) Low-carbon fuels can lead to a reduction in water demand and waste water, as long as the low-carbon fuel comes from a less water intensive alternative to higher carbon fuels
- (+) Improved access to energy can support clean water and sanitation technologies.

Behavioural response: Behavioural changes in the residential sector are likely to affect both water efficiency and climate change resilience in a positive way, due to the effects of reduced energy demand and reduced water demand (in case of climate change-induced water scarcity).

Accelerating energy efficiency improvement: Efficiency changes in the residential sector might have benefits for both water efficiency and climate change resilience. Using low-carbon fuels might lead to a reduction in water demand, though, so far, there is little evidence of this.

Improved access and fuel switch to modern, low-carbon energy: Using low-carbon fuels in the residential sector is likely to reduce water demand. However, water use can actually be higher in some cases – it depends on which low-carbon fuel is used. Improved access to energy, which can be supported by subsidies for renewable energies, can support clean water and sanitation technologies.

TRANSPORT

- (+) Efficiency measures leading to reduced demand will reduce water consumption
- (+/-) Low-carbon fuels can lead to a reduction in water demand, as long as the low-carbon fuel comes from a less water intensive alternative to higher carbon fuels
- (+/-) Transport electrification can have mixed outcomes, depending on the water intensity of power generation.

Behavioral Response | Increased Energy Efficiency | Low-carbon Fuel

Behavioural response: Behavioural changes in the transport sector are likely to benefit water efficiency and pollution prevention because of reduced water consumption and waste water. GHG are likely to be reduced, too, because of reduced transport energy supply.

Accelerating energy efficiency improvement: Efficiency measures in the transport sector are likely to be positive from both a water and climate perspective, thanks to reduced transport energy demand and reduced water consumption as a result of greater efficiency.

Improved access and fuel switch to low-carbon energy: Low-carbon fuels in the transport sector can be positive and negative from a water perspective. The switch can lead to reduced water demand, but can also increase water use compared to existing conditions depending on the low-carbon fuel used.

AGRICULTURE AND LIVESTOCK

- (+) Reduced food waste avoids direct water demand
- (+) Healthy diets can incorporate supply chains that are less water intensive
- (+/-) Soil carbon sequestration can alter the capacity of soils to store more water
- (+) Livestock efficiency is expected to reduce water demand, in addition to waste water flows.

Behavioral Response | Decarbonisation and CCU/S | Agricultural Management

The WEF Nexus approach (*see Chapter 6.1*) offers tools and concepts to enhance cooperation among water, agriculture and energy stakeholders in order to enhance overall resilience and efficiency.

Behavioural response: Activities to ensure sustainable healthy diets and reduce food waste can yield major positive synergies. Behavioural changes in the agriculture and livestock sector are likely to benefit the areas of water efficiency and climate change resilience. Reducing food waste also helps reduce water demand for crops and food processing, as well as prevent water being used for energy supply.

Land-based GHG reduction and soil carbon sequestration: Soil carbon sequestration can affect water efficiency in a positive and negative way. The capacity of soils to store water can change as a result of sequestration efforts which can also impact the hydrological cycle. Many current agricultural practices have played a role in destroying the carbon sink and water storage functions of soils.

GHG reduction from improved livestock production and manure management systems: Livestock efficiency measures are likely to reduce water demand. But they could also cause increased water demand and water stress if agricultural intensification is mismanaged

FORESTS

- (+) Co-benefits from responsible sourcing if the strategy incorporates water metrics
- (+) Forest certification programmes and sustainable forest management provides freshwater supplies
- (+/-) Forest management alters the water cycle in an unclear way, but it does provide sustainable and regulated provision for water purification
- (+) Tree belts can remediate dryland salinity. Watershed scale reforestation can result in the restoration of water quality.

Behavioural response: (responsible sourcing): Responsible sourcing of forest products refers to the commitment to use wood (e.g. for its products and packaging) that is sourced from certified or verified responsibly managed forests or recycled content. Related activities can benefit water efficiency and pollution prevention and climate change resilience, if the strategy incorporates water-related indicators and metrics.

Reduced Deforestation, REDD+: Forest management can have a positive effect from both a water and climate perspective. Changes in forest management and the hydrological cycle can be positive or negative, while conserving ecosystem services is likely to help countries maintain their watershed integrity and also benefit climate change resilience. It is not always clear how forest management alters the water cycle, but it often provides for sustainable, regulated water purification. Afforestation and Reforestation can remediate dryland salinity. Watershed scale reforestation can help restore water quality.

8.3 Disaster Risk Reduction

In addition to the strong linkages between climate and water SDGs , there are also important interlinkages with the Disaster Risk Reduction (DRR) agenda. Both, the 2015 Sendai Framework for DRR and the Paris Agreement, recognise the linkages between climate change and disasters (see e.g. AGWA, 2018). In practice, however, the two policy communities and their respective implementing bodies still have the potential to improve coherence, particularly with regard to implementation.

In particular, the need to promote resilient water management as a key to climate change adaptation as well as DRR underlines this point. Water can be a bridge between both policy communities.

Figure 42: Interlinkages between SDG 6, 13 and DRR. Source: Own compilation based on SDGs targets and IPCC 2018

SDG context

A starting point for examining the interrelations between climate, water and DRR are, again, the SDGs. SDG target 13.1 is most directly linked to water, aiming to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries. There are also major linkages to DRR and climate in SDG 6, e.g. the importance of expanding sustainable water management for reducing vulnerabilities to hazards. Ecosystem management also plays a major role here (*see Figure 42 above*).

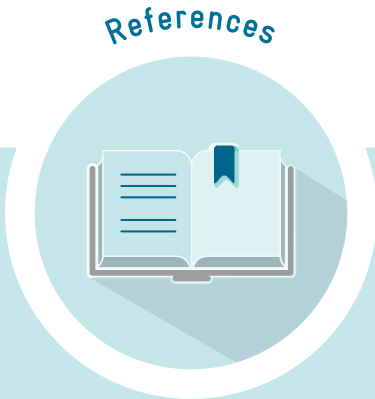
Initiatives to foster integration between DRR and CCA

Several efforts to contribute to a better integration of the different policy agendas of DRR and climate change adaptation already exist.

a) **Global Initiative on Disaster Risk Management (GIDRM)**: The GIDRM, originally launched in 2013, started its second phase in February 2018. It supports national and international activities to strengthen the coherence of the Sendai Framework, the Paris Agreement, the 2030 Agenda for Sustainable Development and the New Urban Agenda. It is directed at governmental as well as non-governmental actors, and has a focus on planning, implementing and reporting on disaster risk management. The Initiative aims to deliver good practices in different regions, such as Latin America and the Caribbean and in the Asia Pacific Region. These practices may eventually also be presented as regional recommendations to platforms such as the Global Platform for Disaster Risk Reduction. GIDRM is commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by GIZ.

b) **Climate Resilient Infrastructure Development Facility (CRIDF)**: The CRIDF aims to provide long-term solutions to water issues that affect poor communities in Southern Africa, and it puts a strong emphasis on enabling organisations to build their own water infrastructure. Funded by DFID (UK), it works with twelve different countries in Southern Africa that share water resources. With its facility approach, CRIDF seeks to facilitate access to finance for projects in the region and provides advice on how to best select and manage the projects. It also advises partners on resilient ways to select, manage and implement their projects with regard to infrastructure. One of the core ideas is to share successful cases from other regions that are convincing to local partners, thereby contributing to the diffusion of good practices.

c) **Technical Expert Meetings on Adaptation (TEM-A)**: Furthermore, in the framework of the climate change negotiations, there have been considerations on the interconnectedness of climate change, sustainable development and disaster risk reduction. In 2017, the second technical expert meetings on adaptation (TEM-A) focused on the prospects of increasing collaboration between the three agendas – with a special focus on country-level implementation. As one potential entry point, participants identified NAPs that can support using the linkages to further integrate sustainable development and DRR considerations into the adaptation process (TEP-A, 2017).



8.4 References

Adaptation Community (without year): **Tool for Assessing Adaptation in the NDCs (TAAN).** *https://www.adaptationcommunity.net/nap-ndc/tool-assessing-adaptation-ndcs-taan/taan/#*

AGWA (Alliance for Global Water Adaptation) (2018): **Mastering disaster in a changing climate: Reducing disaster risk through resilient water management.** *http://www.globalwaterforum.org/2018/12/02/mastering-disaster-in-a-changing-climate-reducing-disaster-risk-through-resilient-water-management/*

Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., Bunn, C., Shrivastava, P., Lawford, R., Foster, S., Kremer, H., Renaud, F., Bruns, A., and Rodriguez Osuna, V. (2016): **Achieving Sustainable Development Goals from a Water Perspective.** In: Environmental Science 4: 64, pp.1-13.

GWP (Global Water Partnership) (2018): **Preparing to Adapt: The Untold Story of Water in Climate Change Adaptation Processes.** *https://www.gwp.org/en/About/more/news/2018/preparing-to-adapt-the-untold-story-of-water/*

IPCC (Intergovernmental Panel on Climate Change) (2018): **Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.** *https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf*

LDC Expert Group (2012): **Synthesis report on the progress made in the implementation of the least developed countries work programme, including the updating and implementation of national adaptation programmes of action, and in accessing funds from the Least Developed Countries.** Note by the secretariat. Report FCCC/SBI/2012/INF.13.

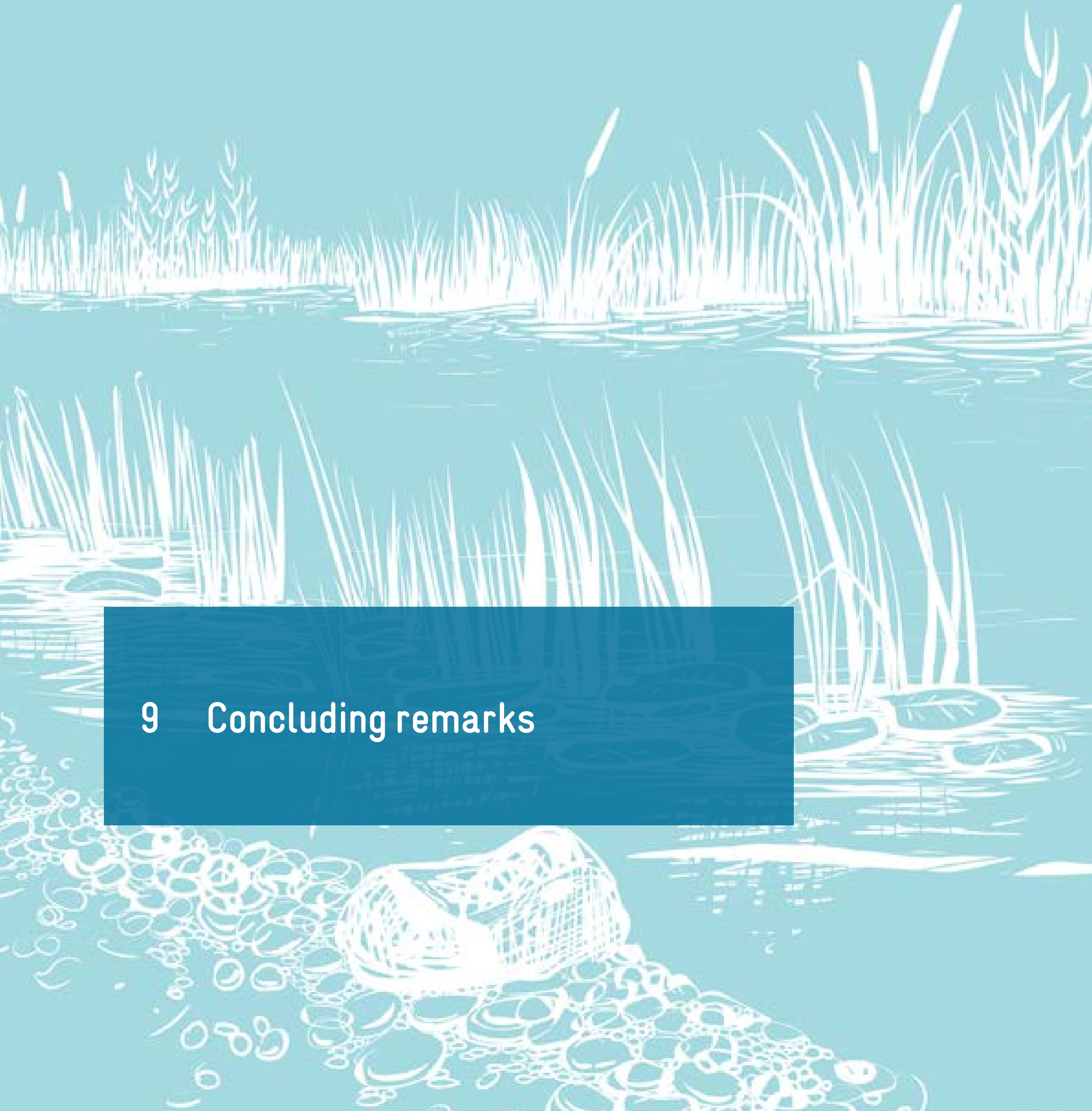
LDC Expert Group (2012a): **National Adaptation Plans. Technical guidelines for the national adaptation plan process.** UNFCCC.

SBSTA (Subsidiary Body for Scientific and Technological Advice) (2019): **Report of the Subsidiary Body for Scientific and Technological Advice** on its fiftieth session, held in Bonn from 17 to 27 June 2019. *https://unfccc.int/sites/default/files/resource/sbsta2019_02E.pdf*

TEP-A (Technical Examination Process on Adaptation) (2017): **Integrating climate change adaptation with the Sustainable Development Goals and the Sendai Framework on Disaster Risk Reduction.** *https://unfccc.int/topics/adaptation-and-resilience/workstreams/technical-examination-process-on-adaptation-tep-a*

Timboe, I., Pharr, K., and Matthews, J. H. (2019): **Watering the NDCs: National Climate Planning for 2020 – How water-aware climate policies can strengthen climate change mitigation and adaptation goals.** Corvallis, Oregon: Alliance for Global Water Adaptation (AGWA). *https://www.wateringthendcs.org/*

UN Water (2016): **UN-Water Annual Report 2016.** *https://www.unwater.org/publications/un-water-annual-report-2016/*



9 Concluding remarks

This report confirms the fundamental role of water for climate resilience. This comes with the responsibility to carefully assess the specific context of climate vulnerability as well as potential climate change impacts with the objective to identify the right actions.

Impacts of climate change on water are often uncertain, which challenges the design of appropriate adaptation actions. Water, climate and other actors have developed approaches for dealing with the new normal involving multiple uncertainties and risks. These concepts will most likely be further refined and adapted in the future, calling for a fruitful cooperation of climate and sector experts. In the long term, climate projections and impact scenarios will substantially benefit from an improved coverage of hydrometeorological monitoring networks and the transparent sharing of the respective data and information.

But there are also clear climate trends at the international and river basin levels. Impacts can be severe: Even small changes in climate can cause substantial shifts in hydrological flows and water availability, emphasizing once more the need for hydrological expertise and research. At the global level, climate change might substantially drive absolute water scarcity. Even in areas with growing annual precipitation trends, higher temperatures causing more evapotranspiration can increase overall water scarcity. However, having too much water also remains an issue.

The challenges of climate change require water actors to develop adequate solutions and reconsider traditional approaches. Remarkably, if climate aspects are well considered, renowned and established water practices can substantially improve climate resilience, while often also contributing to sustainable development, environmental protection and mitigating GHG emissions. In the case of increasing water scarcity due to climate change, these concepts might include for instance water demand management, the reuse of treated wastewater and groundwater protection.

The report also shows the strategic relevance of water storage for climate resilience. As natural storage, for instance in the form of glaciers is threatened by climate change, the protection and extension of natural and artificial storage systems buffer the climate change effects of droughts, floods and increasing water variability. Furthermore, lessons learnt from transboundary cooperation, which has proven to be a key success factor for sustainable water resources management at the regional level, can help to improve climate resilience across countries.

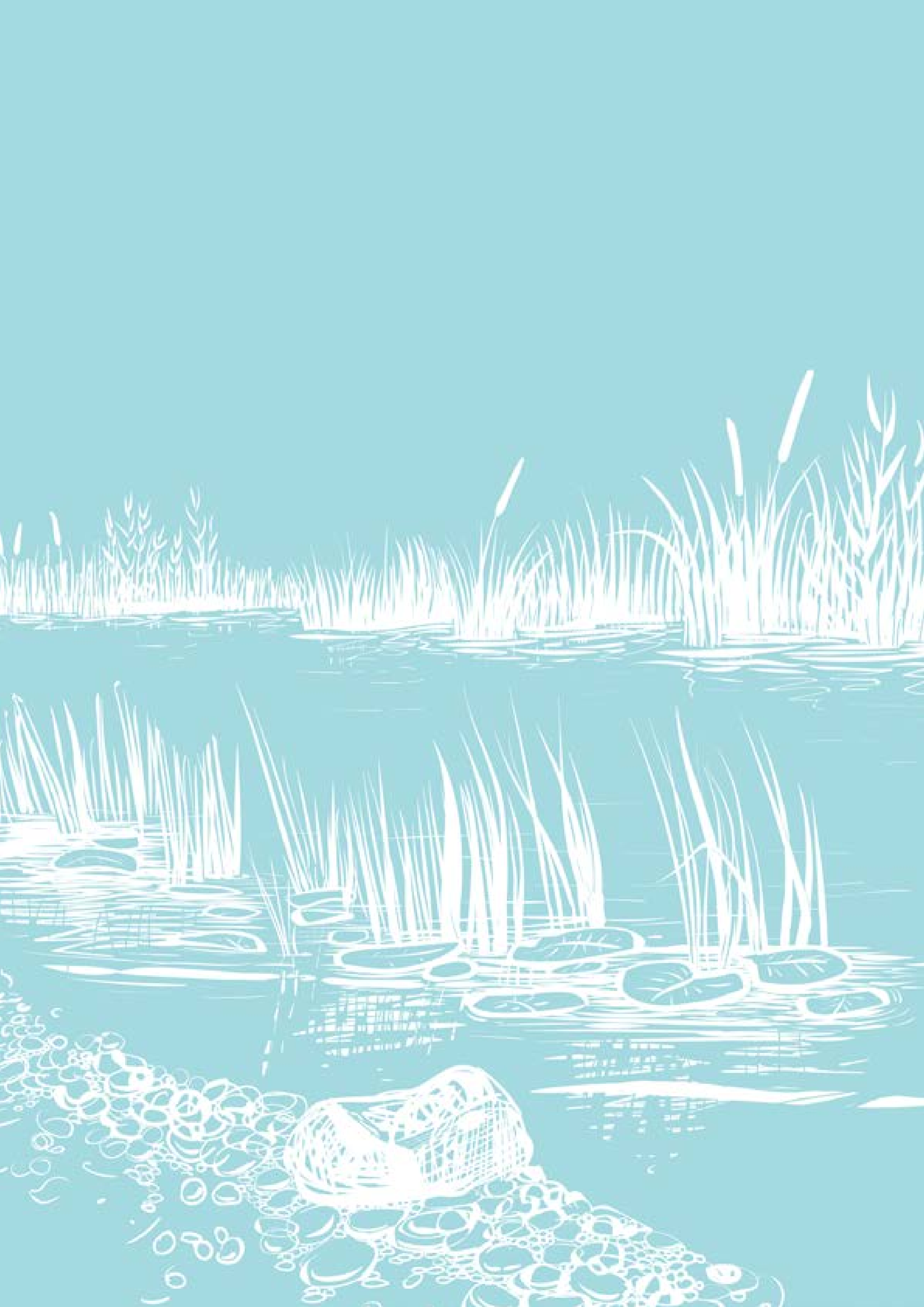
Water actors have contributed to mitigating GHG emissions most notably in urban water and wastewater management, still with substantial scaling up potential. In the last years, development agencies have generated experience, methodologies and tools to assist water and wastewater utilities in emerging and developing countries with mitigation activities.

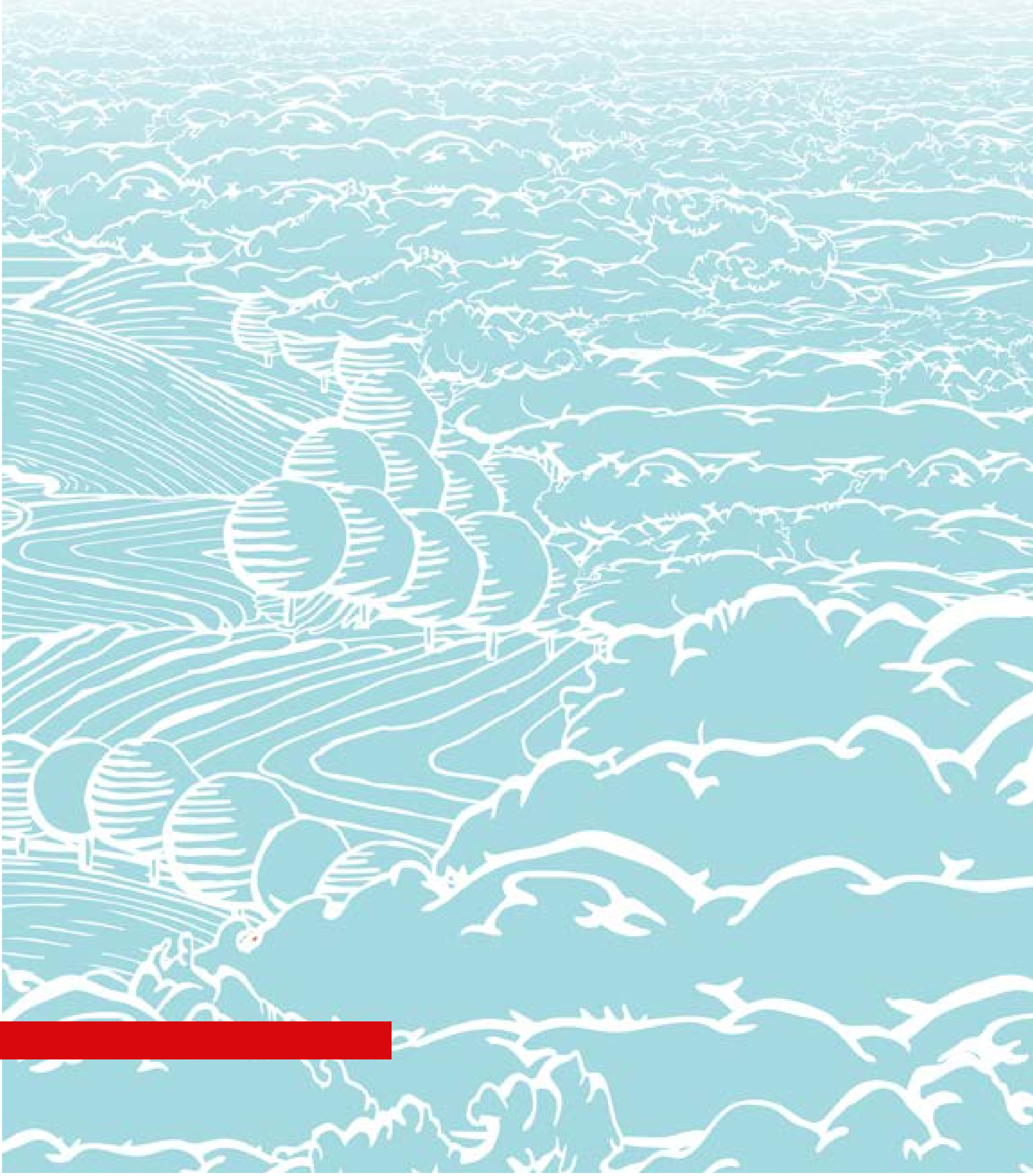
In addition, the report highlights how the protection of water resources and water- related ecosystems contributes to mitigate GHG emissions. The example of peatland conservation through consistent water supply impressively reveals the urgency for clean and continuous water supply, not only for domestic, agricultural and industrial needs, but also for saving our environement and its biodiversity and storing CO_2. Sector actors will need to further highlight these indispensable contributions through water.

Water action is strongly prioritized in national strategies on climate resilience. The evolvement and update of planning instruments offers the potential to include effective, concrete and coordinated climate action beyond sector boundaries. Concerning GHG mitigation, water is addressed to a much lesser extent. As countries raise ambitions to limit climate change to well below 2°C, all sectors need to contribute. If the whole potential of water supply and sanitation, water resources management, protection of water-related ecosystems and management of water in other sectors is considered, the contribution through water can be remarkable.

Whenever possible, activities should aim at both: reducing climate vulnerability and mitigating GHG emissions. Most of the activities suggested in this report can also contribute to protecting ecosystems and/or sustainable development. Just as an example, water demand management might contribute to transforming societies towards resilience while at the same time using less energy for water treatment and supply and retaining part of the freshwater for the survival of ecosystems. In that way, activities can contribute to advance climate and sustainability agendas altogether.

Water experts, planners, practitioners and decision-makers can react to the climate crisis with a wide range of established and new approaches. Cooperation across sectors will be a critical success factor, as climate actions are often prioritized by overarching entities and focal points. Water alone will not be able to save our climate and prepare the planet for what is coming. Yet, with the options available, water actors are more than ready to commit and contribute.





Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15

Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66

E info@giz.de
I www.giz.de

On behalf of

Federal Ministry
for Economic Cooperation
and Development