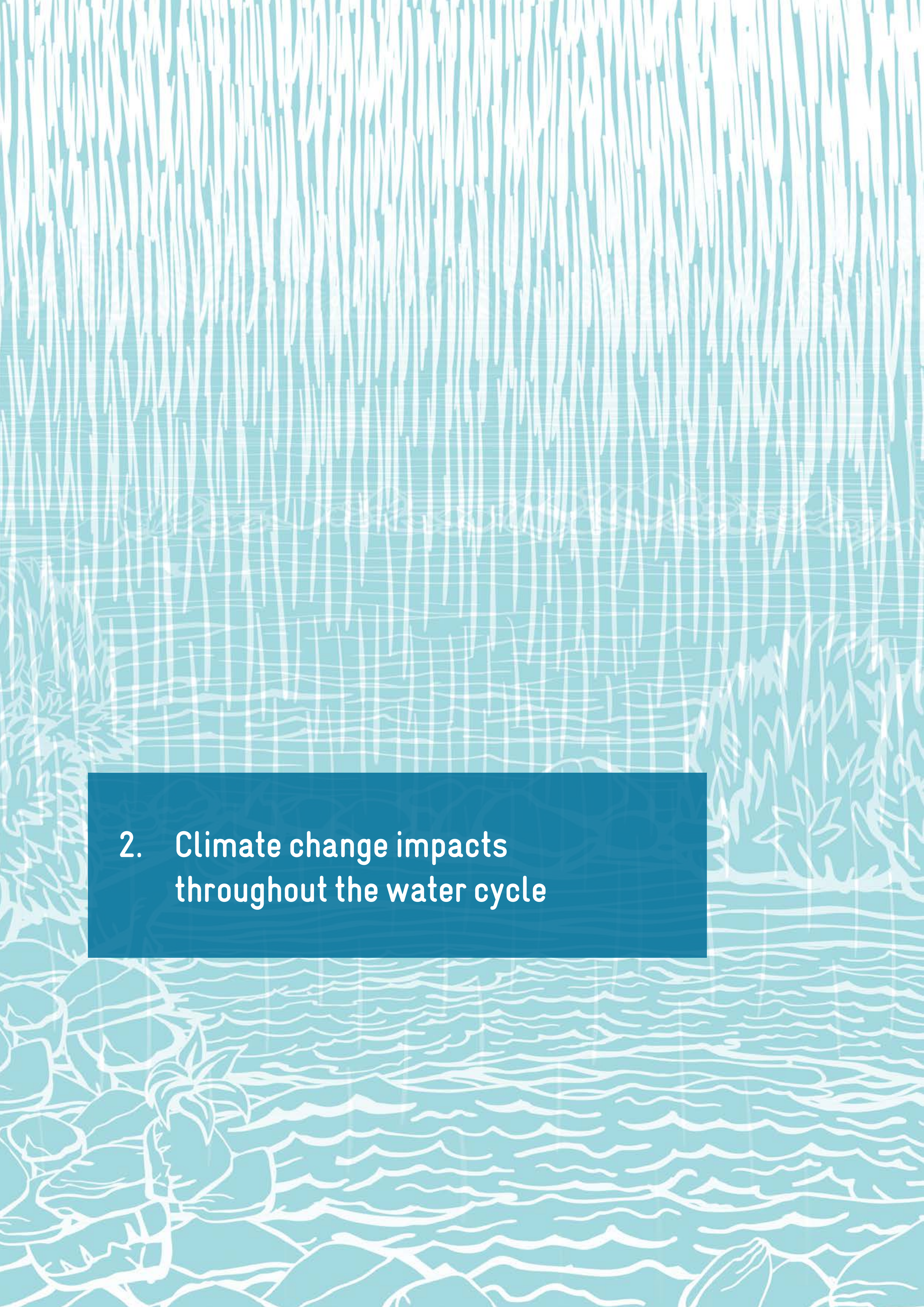

2. Climate change impacts throughout the water cycle

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).

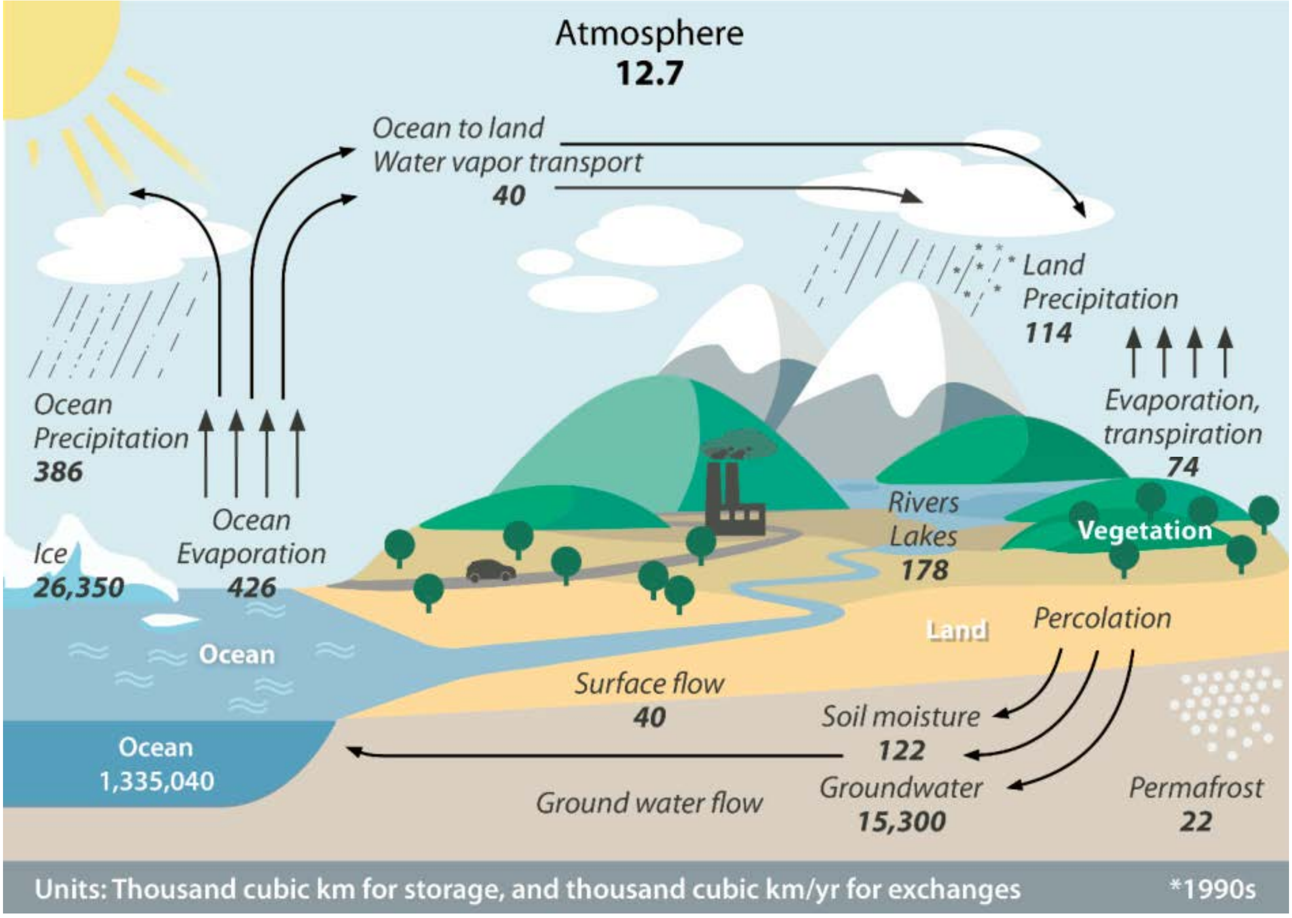

Figure 1: The global water/ hydrological cycle with estimates of the current global water budget and its annual flow using observations from 2002-2008 (units: 1000 km^3 for storage and 1000 km^3/yr for exchanges (Royal Meteorological Society, data based on Trenberth et al., 2011)).

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.

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