

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. Moreover, 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

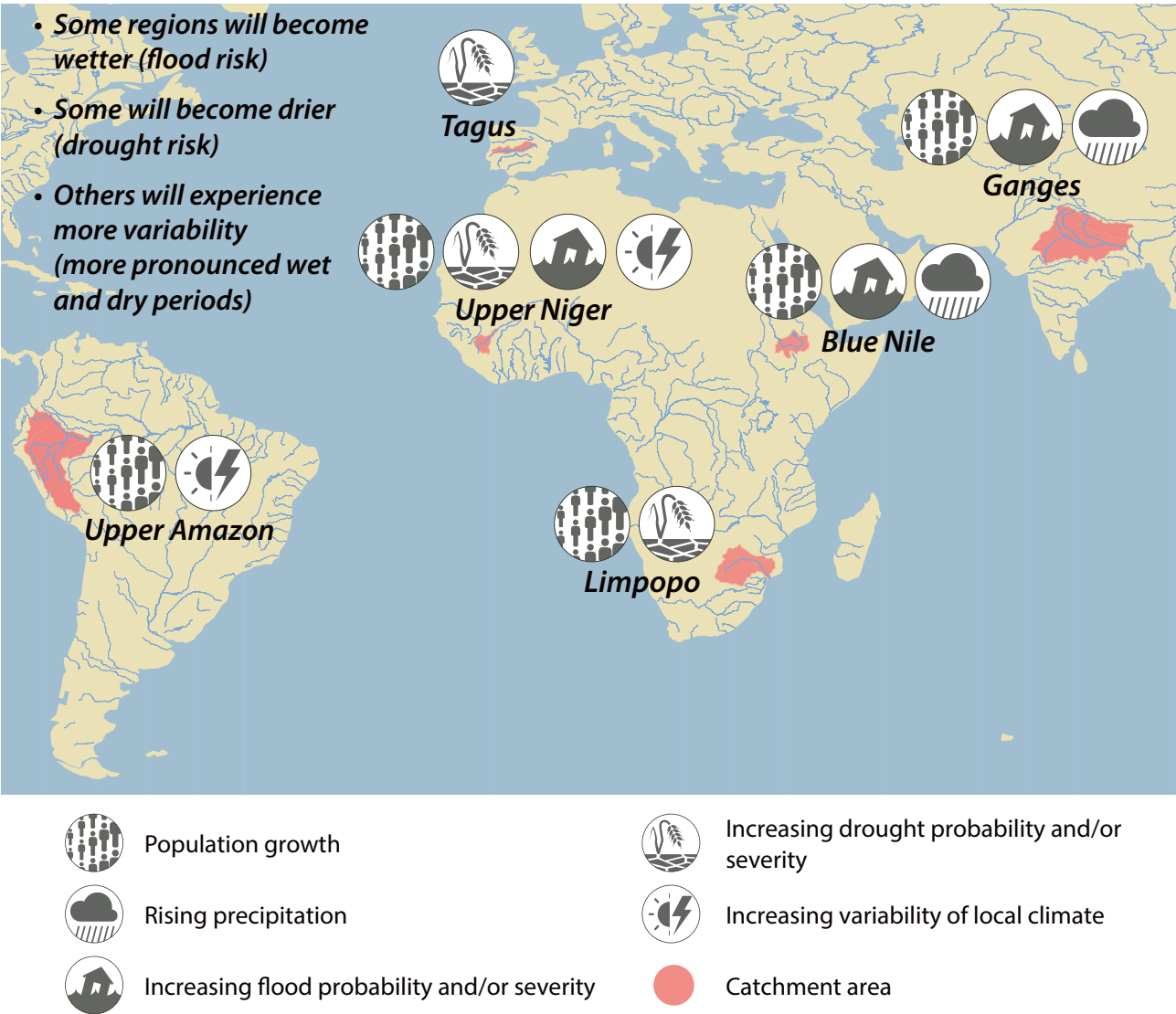


Figure 10: Location of the six case study areas together with the projected changes for the local water sectors towards the end of the twenty-first century

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 north-western 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 km². 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

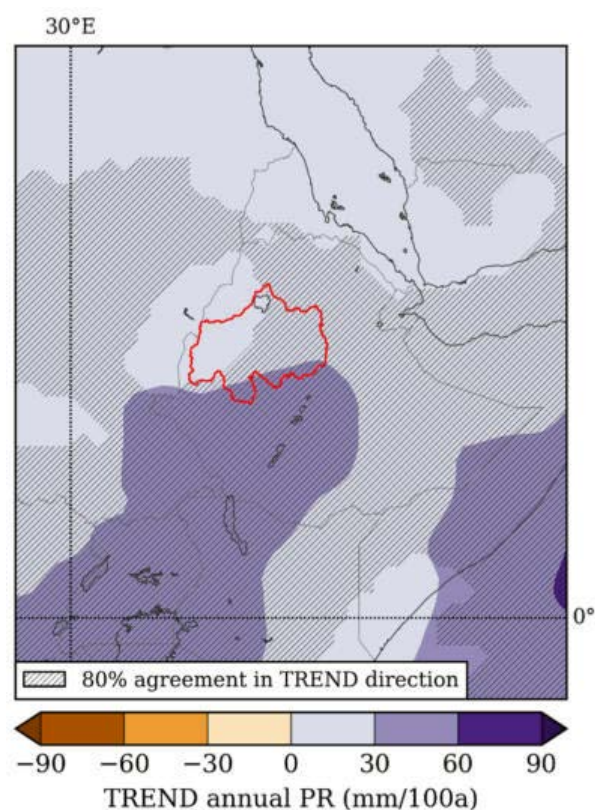


Table 2: Baseline conditions and projected changes in hydrological and climatological indices for the Blue Nile basin. Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential 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%

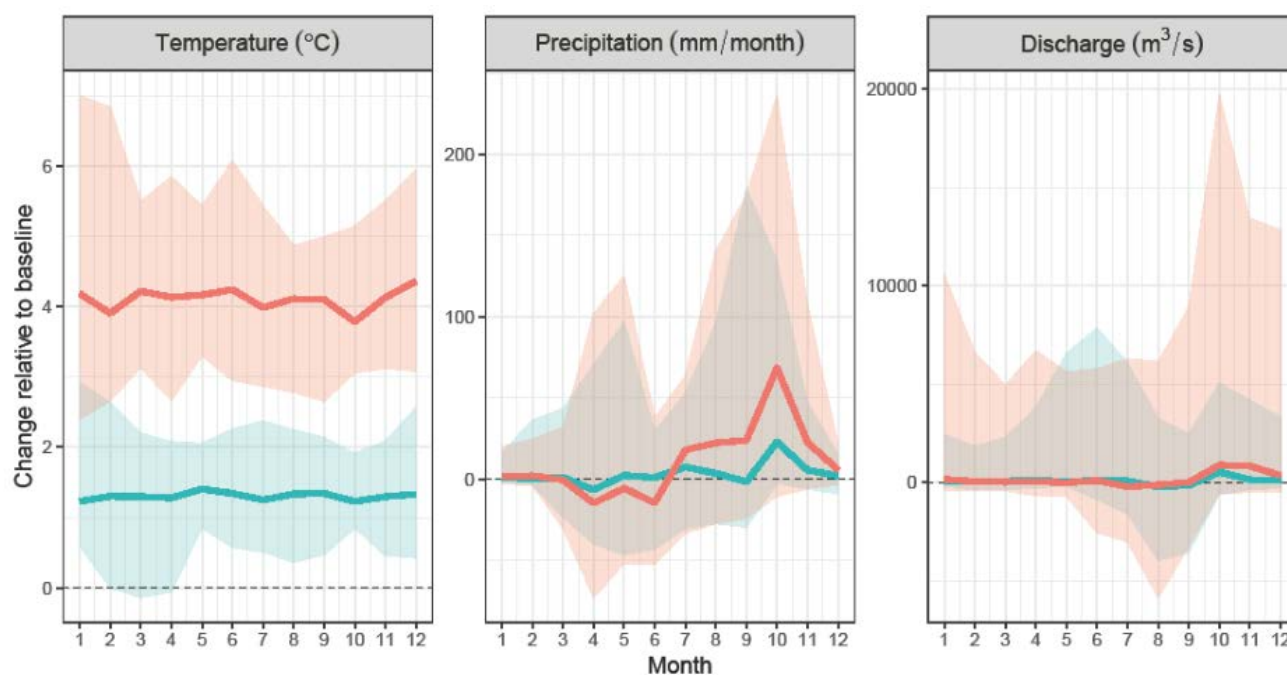
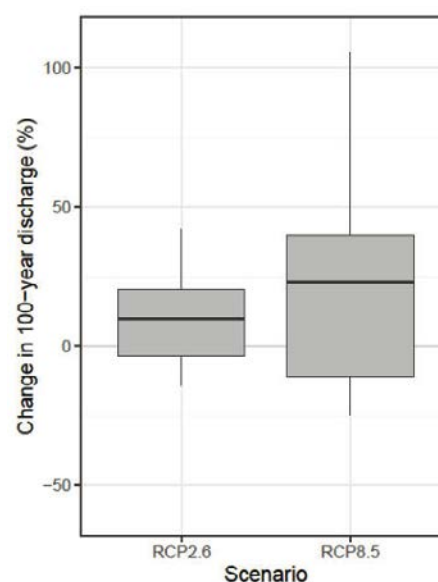


Figure 12: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

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

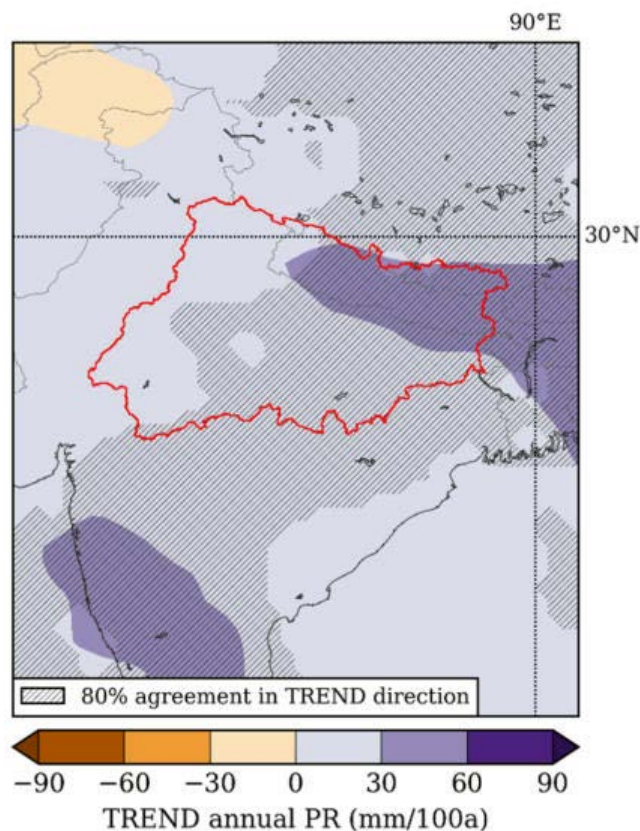


Table 3: Baseline conditions and projected changes in hydrological and climatological indices for the Ganges basin. Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential 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%

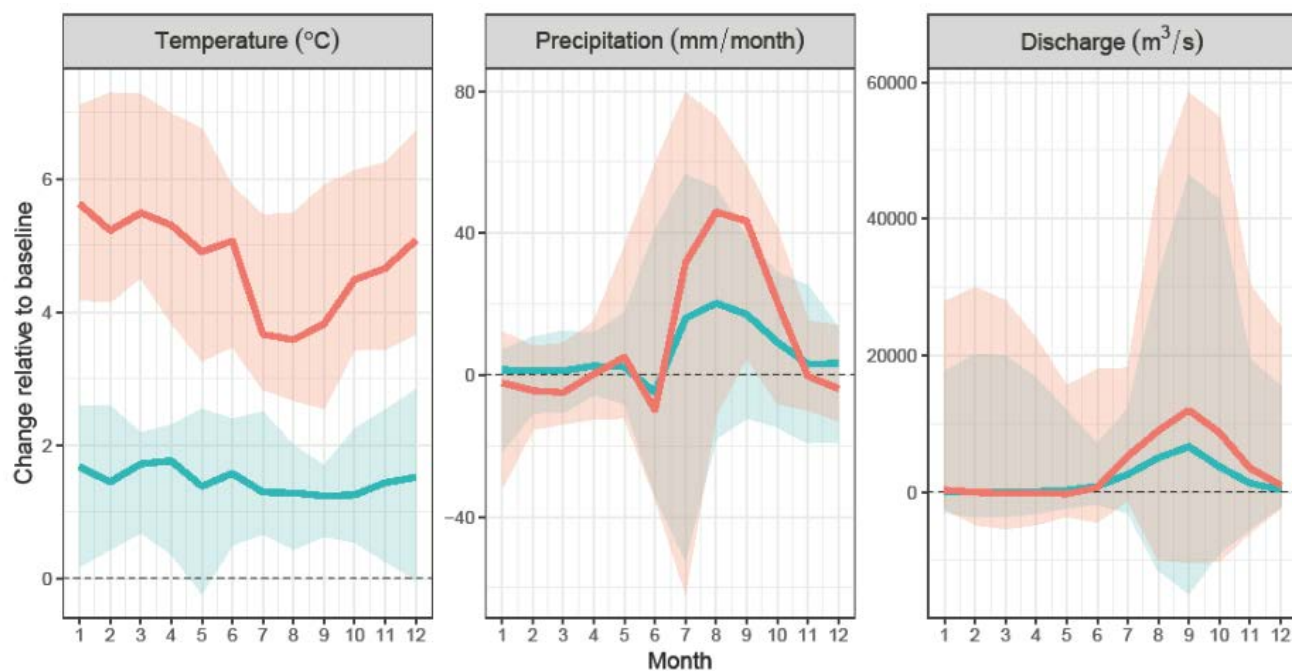
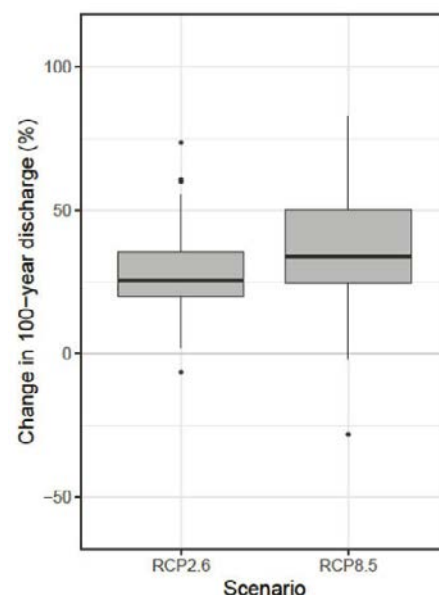


Figure 15: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

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.



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

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).

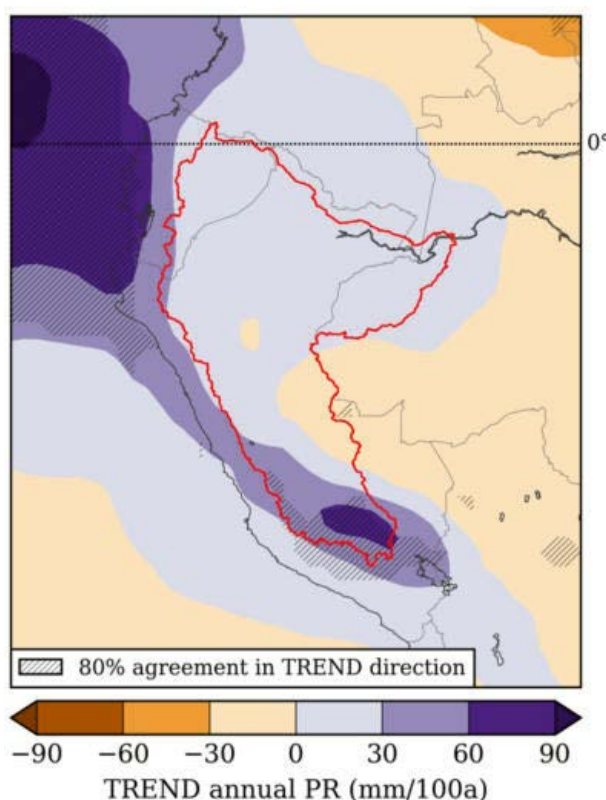


Table 4: Baseline conditions and projected changes in hydrological and climatological indices for the Upper Amazon basin. Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential 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%

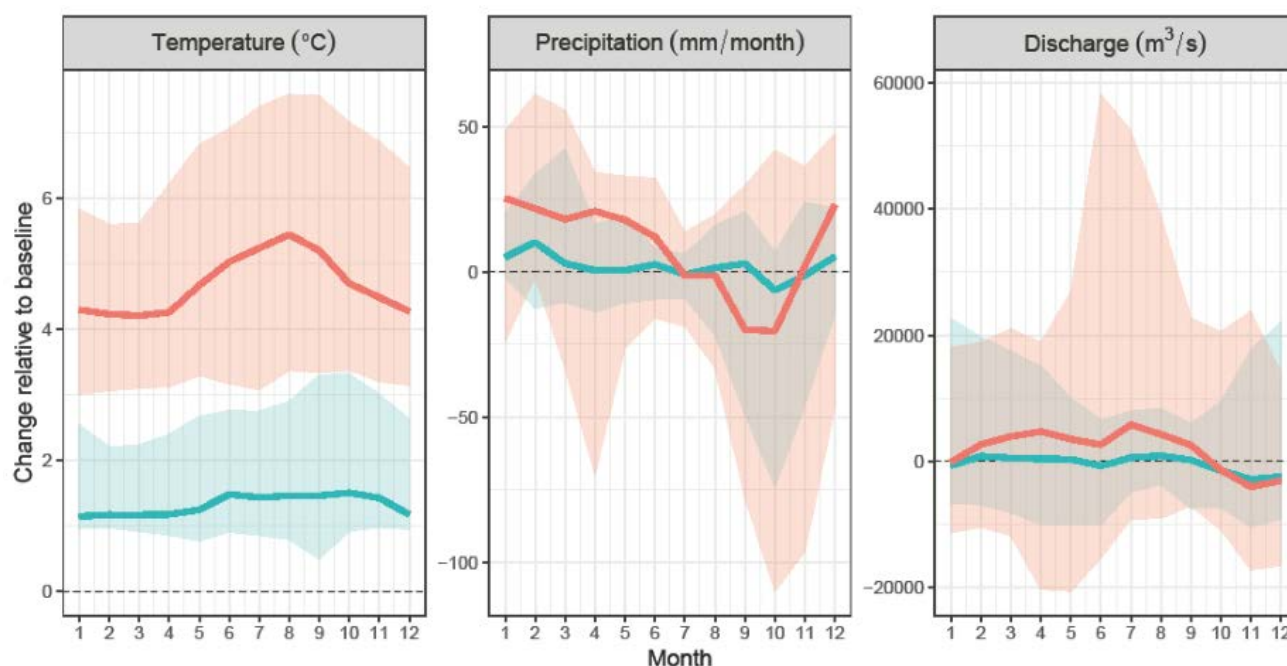
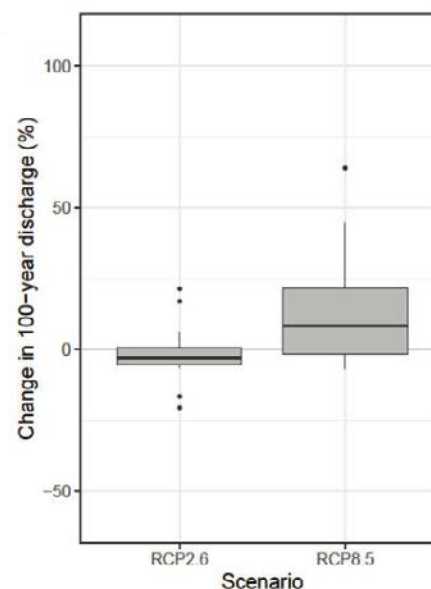


Figure 18: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

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 hydro-graphic 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 km²). 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%

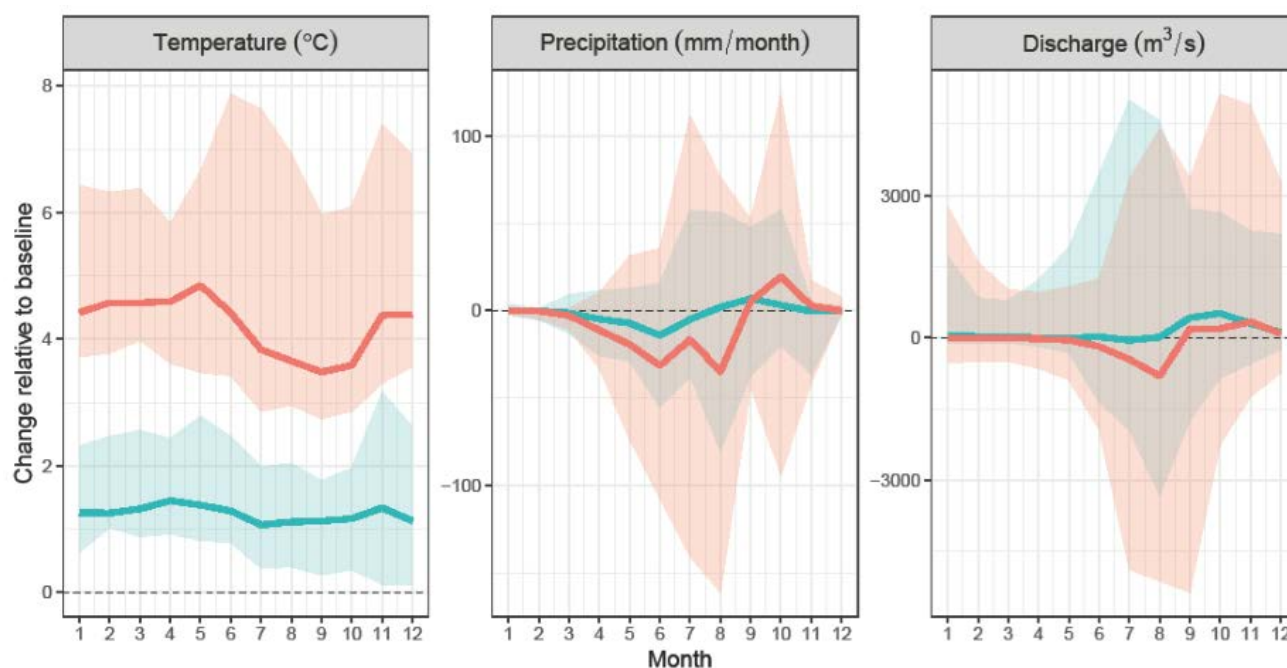
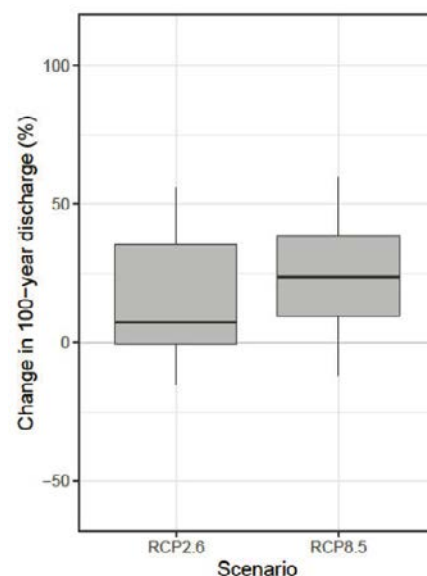


Figure 21: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

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 km². 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

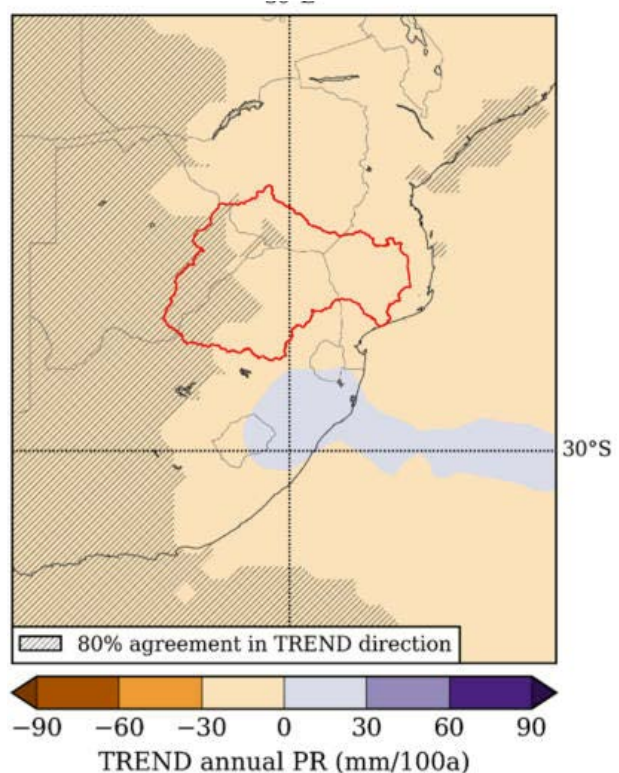


Table 6: Baseline conditions and projected changes in hydrological and climatological indices for the Limpopo basin. Baseline values: Temperature, precipitation, and river discharge are observed, actual evapotranspiration is inferred from the water balance (precipitation minus discharge), and potential 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%

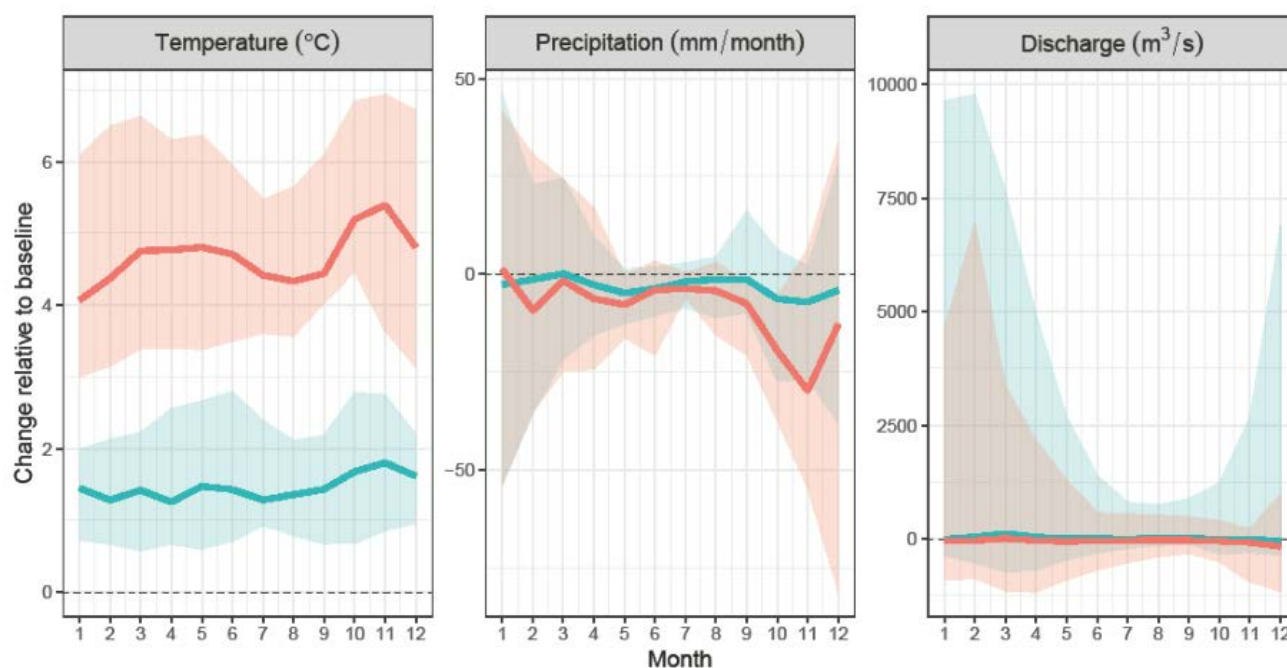
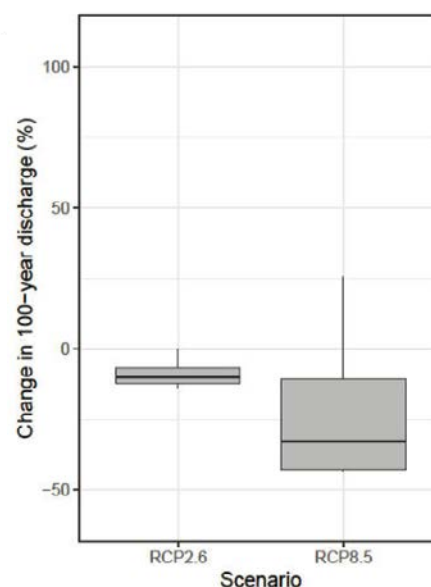


Figure 24: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

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 km². 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

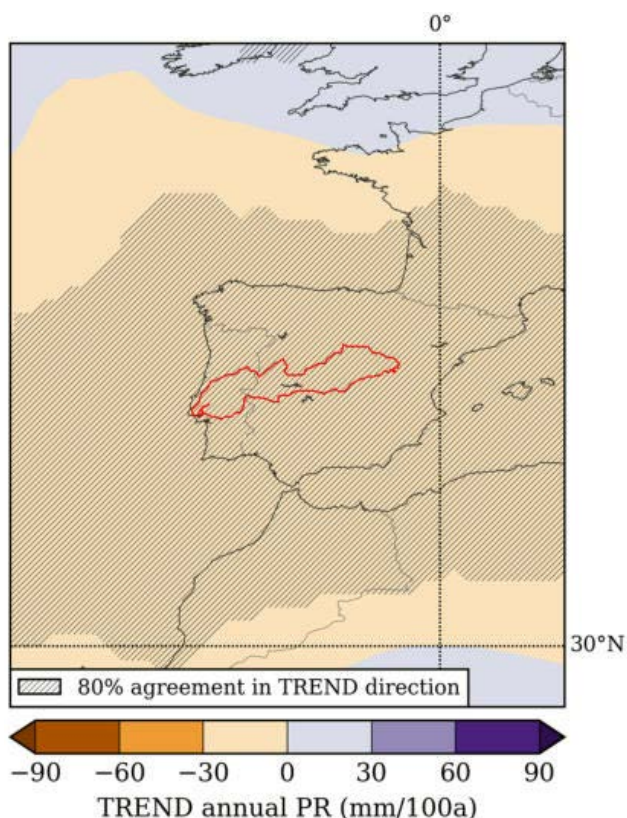


Table 7: Baseline conditions and projected changes in hydrological and climatological indices for the Tagus basin.

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%

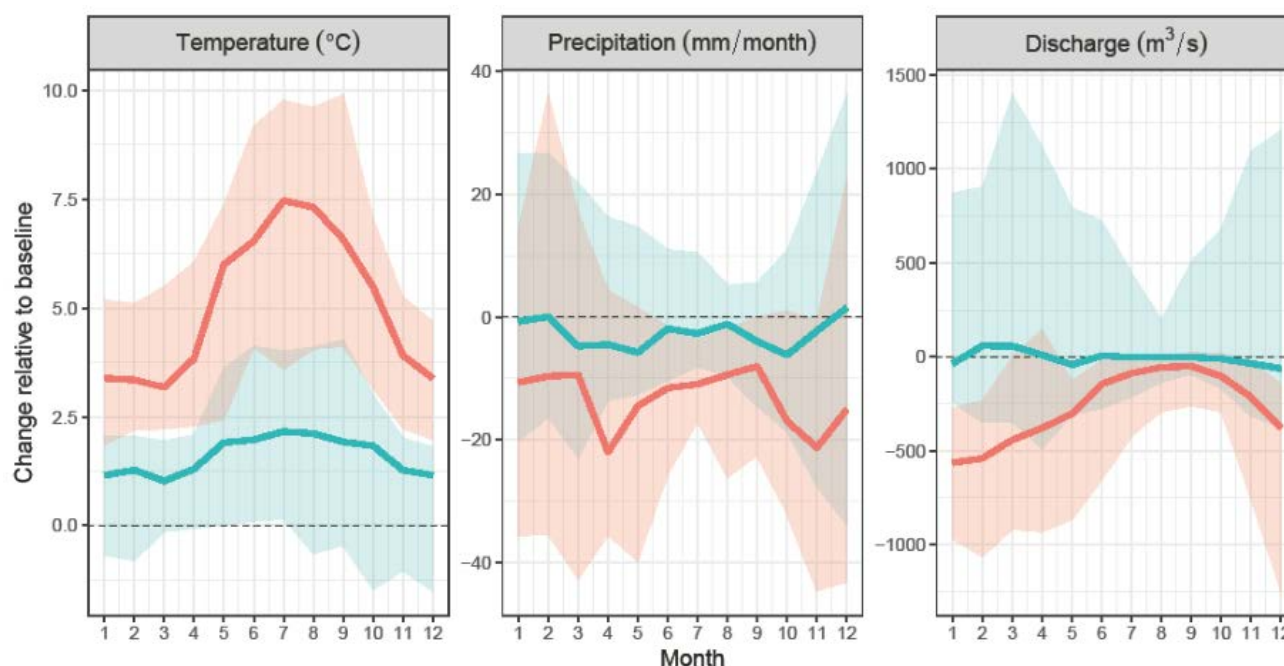
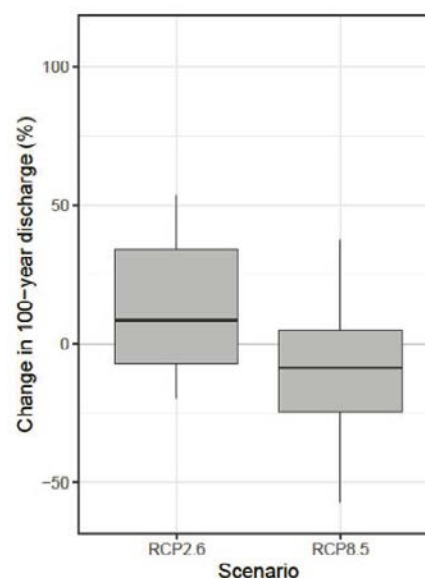


Figure 27: (above) Monthly projected changes in hydro-climatological conditions for the period 2071-2099, relative to the period 1971-2000. Data derived from the CMIP5 (temperature and precipitation) and the ISIMIP data set.

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>