Hydrological impacts of Climate Change in Bhutan

Preparing a Climate Rationale for the Green Climate Fund

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Summary

Bhutan has an abundance of water, which is transported by the main rivers through the country. However, as communities and agricultural land are primarily found higher up in the mountains, the water flowing through the deep valleys is often out of reach for practical usage. The pronounced height difference between the rivers and the communities makes pumping of water expensive and, therefore, unsuitable. Therefore, **Bhutan is a country under water stress,** where communities face regular issues with water availability.

A **climate rationale** was prepared for the 6 Eastern Dzongkhags in Bhutan to support the Bhutan Government and the Food and Agriculture Organization (FAO) in their efforts to submit a funding proposal for the Green Climate Fund (GCF). The climate rationale is the overarching narrative supporting a proposal, which ensures that it links climate change to regional climatic features, impacts and adaptation options (GCF, 2022). The climate rationale focusses on key water related issues at the basin and watershed levels. The data used for the climate rationale is a mix of global, regional, and local datasets. The data was directly applied to setup a hydrological model supporting the hydrological impact assessments.

The climate in Bhutan is already changing. A **historical trend analysis** shows decreasing trends in annual rainfall amounts (0.4% yr^{-1}) and annual average discharge (0.5% yr^{-1}) and a significantly increasing trend in the annual average temperature (0.03°C yr^{-1}). These trends likely have accelerated over the last 10-20 years.

There are many water-related **issues linked to climate change**. In the climate rationale, we focus on the drying up of the springs and the occurrence of extreme precipitation events. A recent study by the Bhutan government shows that many springs are indeed drying up or have already disappeared. In many cases the drying up of the springs could be attributed to climate change. Also, recent unprecedented (flash)flood events in multiple regions point at a changing climate.

By combining the on-the-ground datasets and reports with the historical trend analysis using global and regional data, it can be concluded that the **reported issues are supported by multiple data sources**. Apart from a changing climate, factors like land degradation and other anthropogenic changes are considered to contribute to the problem in specific locations or regions. Nevertheless, it can be concluded that climate change is a major contributor to drying up of the springs and the occurrence of extreme events.

The analytical work for the climate change impact assessment is based on **climate projections** also supporting the latest 6th IPCC report and datasets (CMIP6). This is an update compared to earlier work conducted under the UNDP-NAP project and for the National Communications, which were based on the 5th IPPC reports and datasets (CMIP5). CMIP6 shows a more diverse pattern of changes than previous scenarios (CMIP5), that only showed an increase in precipitation amounts, both for the near and the far future. CMIP6 datasets show that both wetter and dryer conditions are possible in the near future, which is consistent with the observed trends in the current regional climate with a large temporal and spatial variability. For the far future the projections confirm earlier assessments that wetter conditions are more likely.

It is likely that climate change further impacts the water availability and specifically the **spring discharge**. In the Southern regions of the study area the spring discharge is likely to decrease, whereas in the Northern regions both a decrease and an increase in spring discharge can be expected. The spatial variability is large and the uncertainty in these projections is large, given the heterogeneity of the process contributing to the changes. Spring discharge is impacted by changing mean rainfall amounts (that can be both increasing and decreasing), changing rainfall patterns (more, or less intense rainfall), increasing temperature and potential evaporation and the physical properties of the soil.

The impact of climate change on **extreme events** is clearer. In most projections, more intense rainfall events are foreseen, leading to an increase in the frequency of (flash)floods and landslides, both for the near and the far future.

Climate change also has a large impact on **snow and glacier dynamics**. The area with permanent and frequent snow cover (>75% of the time) is projected to decrease by 40-60% of the considered region. These changes impact particularly river discharge dynamics affecting e.g. hydropower production.

Climate change also impacts **soil erosion and sediment transport**. These processes are affected by climate change in different ways. More intense rainfall increases soil erosion through enhanced splash erosion (caused by the impact of falling raindrops) and erosion from surface runoff. Increased temperature and retreat of the snow cover exposes the bare soil to erosion. It also may induce changes in vegetation cover and species, impacting the soil erosion processes.

The impact of **climate adaptation options** on spring discharge and the impact of extreme precipitation events has been quantified. Options to increase the storage capacity and to improve recharge capacity can regulate the seasonal discharge pattern, improving the water availability for local communities. It can be concluded that investing in climate adaptation improves water availability and reduces the climate risks related to (flash)floods.

Recommendations to further improve the climate rational include the usage of dynamically downscaled climate scenarios. For the government of Bhutan, it is highly recommended to improve the hydrometeorological monitoring network and hydromet services.

Contents

1 Introduction

1.1 Background

Supported by FAO, the Government of Bhutan is preparing a proposal for the Green Climate Fund to invest in climate robust agriculture in Bhutan. Through this proposal, they aim to secure funds to improve the climate resilience of the rural communities in Bhutan, focusing on the 6 Eastern Dzongkhags (regions) in Bhutan: Lhuentse, Monggar, Pema Gatshel, Trashiyangtse, Trashigang and Samdrup Jongkhar, shown in Figure 1-2.

In this study, the Climate Rationale for Bhutan is developed. Green Climate Fund (GCF) proposals require justification of the proposed adaptation solutions. For the selected investments, we evaluate current and future climate impacts within the project area and how the proposed adaptation solutions address these impacts.

According to the World Meteorological Organization (WMO) a Climate Rationale is supposed to include at least the following 4 key aspects, as shown in Figure 1-1:

- It is based on reliable, relevant, and usable climate information.
- It provides evidence for climate investments and policy decision making.
- It includes climate impact assessments on policies and projects.
- It provides quality assurance, effectiveness, and transformational value of climate action.

Following these aspects, the Bhutan Climate Rationale provides an evidence base for the link between climate risks, climate change and the proposed investments. The Climate Rationale shows the predominant role of climate change on current and/or future issues in the project area and shows how the proposed interventions reduce the climate risks.

The Climate Rationale is based on a solid scientific assessment, making use of the best available data and information. The data is used to assess the climate stressors, followed by an interpretation of the data. Adaptation options are selected and assessed on their effectiveness to reduce the climate risks. Once implemented, a monitoring and evaluation framework is required to assess the effectiveness of the adaptation and mitigation options.

The climate rationale aims at supporting the decision-making process and preparation of adaptation plans. To support a broad range of plans, the Climate Rationale contains different time horizons for different types of investments. The near-future time horizon to prepare plans and adaptation measures with a short life cycle and a far-future time horizon for investments with a longer life cycle.

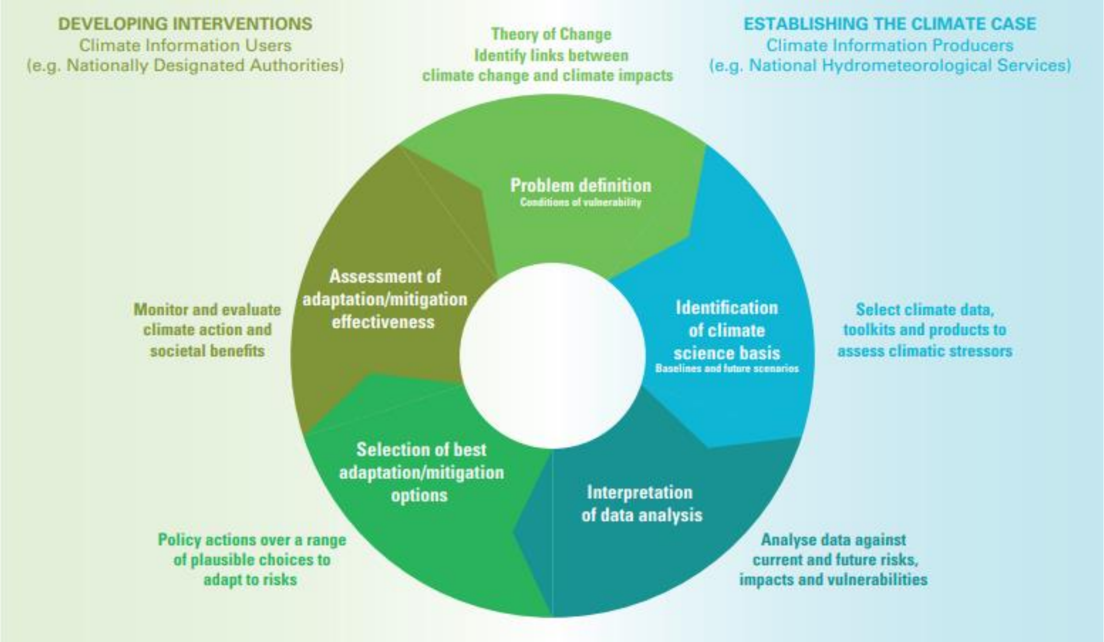

Figure 1-1 Theory of change for identifying links between climate change and climate impacts according to the WMO (source: https://unfccc.int/documents/196543).

The Climate Rationale presented in this report builds upon a previous study (Jeuken et al., 2021), the latest climate change insight and datasets (IPCC, 2021) and the best available local and regional datasets. Improved understanding of the impacts of climate change in Bhutan is realized by combining the different datasets and information sources and by running a hydrological model.

Figure 1-2 Overview of Bhutan and the administrative regions (Dzongkhags).The red line shows the study area.

In the previous project (Jeuken et al., 2021), both bottom-up consultations with local stakeholders and a top-down hydrological modelling approach were applied, following the Climate Risk-based Decision Analysis (CRIDA) framework (Mendoza et al., 2018). The bottom-up approach included local data collection and structured interviews to understand the current observed and perceived issues in the regions. The top-down approach included a climate impact assessment using regional and global climate- and hydrological modelling.

The current study builds on top of the work presented by Jeuken et al. (2021), by including more local information into the model and analysis, zooming in to the most dominant reported hydrological climate impacts and by using the latest climate scenarios from the CMIP6 experiment. By doing this, knowledge from previous studies is preserved and the climate rationale for Bhutan is strengthened.

1.2 Study area

Bhutan is a country in Central Asia and is known as one of the most natural countries in the world. Bhutan is one of the only two countries that have a negative net carbon emission. The country has an abundance of water, originating from both direct rainfall and snow and glacier melt. Most water, however, is far out of reach for practical usage for drinking water or for irrigation. The rivers transport the water through the deep valleys to India, while the rural communities in Bhutan live higher up the mountains, depending largely on rainfall and mountain springs for their water usage. This makes these communities very vulnerable for changes in the local rainfall, which could be exacerbated by climate change. A climate rationale has been compiled linking global and regional climatic changes to impacts for the local communities. This study supports this climate rationale by quantifying observed and projected climate change characteristics and their impact on water availability and the probability of extreme weather events for Bhutan.

The study area is within the river basin of the Drangmecchu River. The South-Eastern part of the project area is part of different river basins and drains directly towards India. The Drangmecchu River basin is of particular interest in the context of adaptation to climate change, as it displays a large topographical and climatic variability with steep slopes, strong precipitation and temperature gradients and very high elevation in the upstream part of the basin, which is dominated by snow and glaciers. People living in this part of Bhutan are among the most vulnerable people in Bhutan and climate impacts are likely to be large for large parts of the rural communities.

The elevation difference in Bhutan and within the project area is enormous. The lowest parts are approximately 100 m+MSL and the highest parts around 7500 m+MSL, all within a horizontal distance of ~135 km. This makes the climate and hydrology in Bhutan highly variable over the different regions and from North to South.

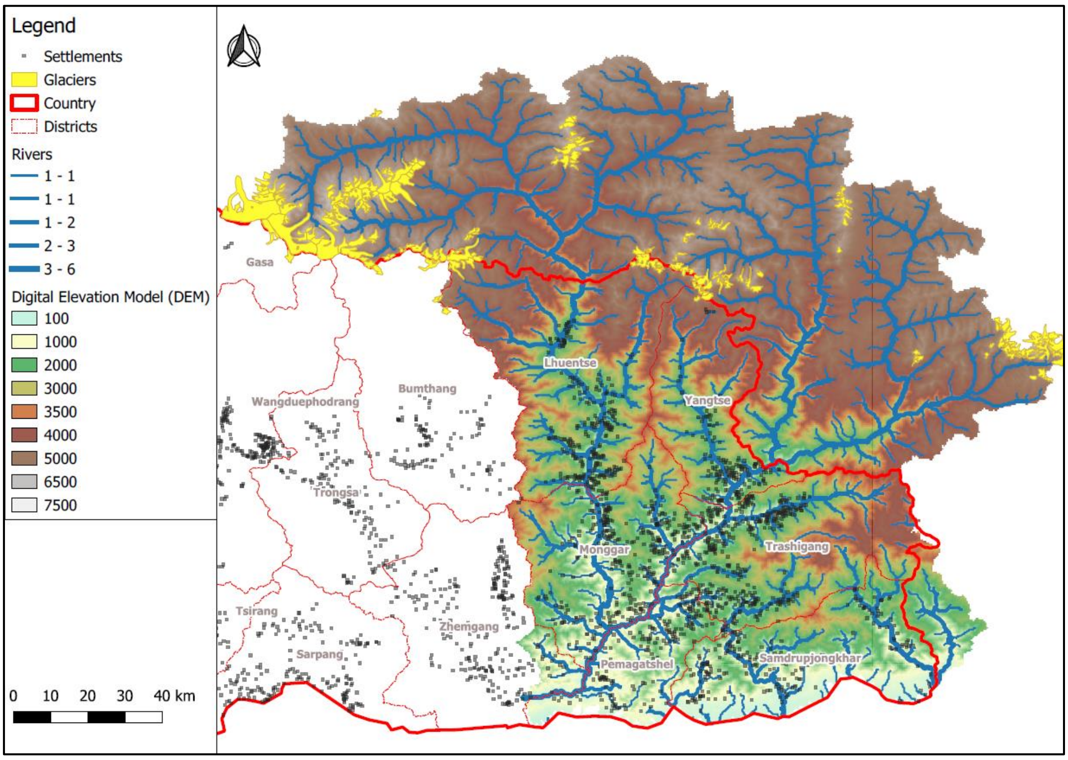

Figure 1-3 Overview of the study area. The river attribute value indicates the stream order, a typically used measure for the size of the river (where 1 indicates small upstream streams and 6 indicates the largest rivers). The coloured area shows the study area.

The Drangmecchu River originates from the Tibetan plateau in China. Around 50% of the river basin lies outside Bhutan, but most precipitation feeding the catchment falls within Bhutan. There is a strong precipitation gradient, with mean annual precipitation ranging between approximately 500 mm yr^{-1} to 5000 mm yr^{-1} between North and South. For the period 1981-2010 annual precipitation in the north, center and southern regions is approximately 1300 mm yr^{-1}, 2300 mm yr^{-1} and 4000 mm yr^{-1}, respectively. Mean annual temperature in the northern, center, and southern regions is -3°C, 6°C and 14°C respectively.

The climate in Bhutan can be categorized as a typical Monsoon climate, with a dry period in winter between November and April and a wet season in the summer months of June, July, August, and September. In most areas in the country, around 80% of the total annual precipitation falls within the four Monsoon months. In winter, the Northern parts of the basin are covered with snow and far upstream the rivers are fed by glacier melt.

1.3 Climate change

In the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) the latest developments and scientific insight on climate change are presented, based on a detailed review of numerous scientific publications (IPCC, 2021). Evidence is found that the climate is already changing, and in some cases rapidly. The temperature is rising, and precipitation patterns are changing. Climate change scenarios indicate a further increase of the temperature and corresponding changes in precipitation amounts and temporal and spatial distribution. These changes influence water availability and the occurrence of extreme rainfall and flood events. Generally, extreme rainfall events will become more frequent and more severe and water availability is likely to further reduce in many regions in the World.

IPCC published a special report on mountain areas and the cryosphere (Hock et al., 2019). The report presents observed and projected changes in snow and glacier cover, pointing to a general and rapid decline of both the snow and glacier extent in many mountain areas around the world. The changes in snow and glacier processes affect the water resources in Alpine regions and further downstream, as presented by Khanal et al., 2021 for the Hindu Kush Mountain Range. Changed timing of snow melt results in a different distribution of river discharges over the year. The melting of the glaciers causes a reduction of the water storage at high altitude, reducing a valuable source of water in times of limited precipitation. The decline in snow and glacier cover also increases potential evaporation with the land surface being exposed to solar radiation and increased heating up, further reducing the seasonal river discharges in high mountain areas.

Rainfall amounts and patterns are changing in mountain areas around the world. In many cases, more extreme rainfall events are reported already, and a further increase of the number and severity of extreme rainfall events is projected. This leads to an increase in natural hazards such as (flash)floods and landslides. Reduced annual or seasonal rainfall amounts combined with increased potential evaporation are also reported, resulting in reduced river runoff and reduced water availability.

How the climate is changing locally depends on many factors. Increased temperature changes atmospheric circulation patterns and the distribution of moisture over the earth’s surface. The dynamic mechanisms responsible for the distribution of moist air vary strongly from region to region (Gimeno et al., 2016). The main drivers at a global scale are shown in Figure 1-4 and include Atmospheric Rivers (AR) and Low-Level Jets (LLJ). Bhutan is mainly affected by Low-Level Jets bringing moist air, which are associated with the Indian Summer Monsoon.

Climate change is impacting the location and strength of Low-Level Jets. Sandeep et al. (2015) found that climate change results in a northward shift of the LLJ, changing the air flow patterns in the region. Boschi et al. (2019) presents the current pathways of moist air into the Hindu-Kush Himalaya region for the average climate conditions as well as for 3 historic extreme flood events. A northward change of the LLJ leads to moist air being transported towards the Northern Regions in Bhutan.

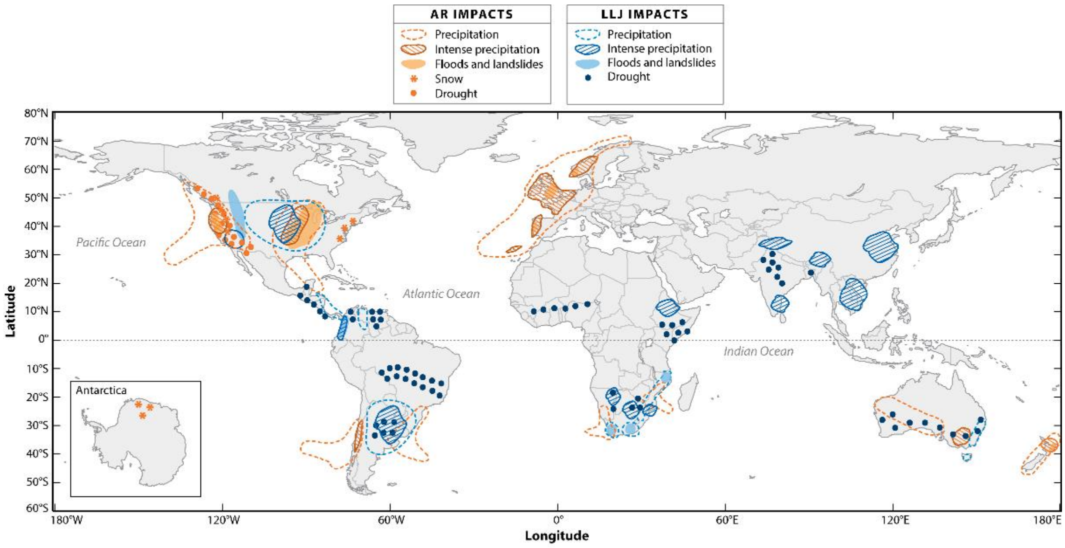

Figure 1-4 Global assessment of drivers of extreme precipitation events and linking to their main drivers (copied from Gimeno et al., 2016).

Warmer air also has a higher moisture carrying capacity, following the Clausius-Clapeyron (CC) relation. This thermodynamic law states that for each degree warmer air, the moisture carrying capacity increases by ~7%, meaning a potential increase of precipitation. With global climate predictions range between 1,5- and 6-degrees warmer climate, the atmospheric moisture content will increase by around 10-40%.

The amount of rainfall and the occurrence of extreme events depend both on the moisture content of the air and the capacity to transport moisture into the region. Both the dynamic transport and the thermodynamic processes therefore play an important role in the occurrence of extreme events. Many local factors influence these processes and lack of sufficiently dense and good quality observation data hampers development and calibration of the models. However, under controlled conditions, Siler et al. (2014) and Shi et al. (2015) conducted experiments showing that increases in heavy precipitation events in mountainous areas are associated with relative changes on the wind or lee side of mountain range, hinting at a higher percentage increase in rainfall amounts on the leeside of the mountains. This contributes to the fact that the local conditions, such as the orientation of the mountains relative to the (dominant) air flow patterns is determining how climate change affects local conditions. There are many local factors that influence such patterns to emerge, and it is well possible that due to changing atmospheric conditions or changes in the earths atmospheric flow patterns, the high-altitude rainfall actually decreases due to more stable weather conditions at higher altitude (e.g., Chow et al. (2019) and Pepin et al. (2022)).

The combination of these processes is illustrated in Figure 1-5. It is shown that under current climate conditions and air temperature, most rainfall falls in the first, lower altitude mountain ranges. Changes in moisture carrying capacity and dynamic air flow patterns alter the location and magnitude of (extreme) rainfall in mountainous regions. Climate change also alters the partition of precipitation in rainfall and snowfall, with increasing temperatures resulting in more rainfall (Figure 1-6). This impacts (flash)flood risks in mountainous areas, but also contributes to reduced water availability caused by less storage of water at higher altitudes.

Other phenomena determine extreme rainfall amounts in the Eastern Himalaya region of Bhutan, such as a monsoon break, caused by disturbances in the atmosphere or the occurrence of Westerlies. Monsoon breaks typically result in extreme rainfall amounts in North-Eastern India and Bhutan and relatively dry conditions in central India. The occurrence of Westerlies is projected to increase with increased temperature, potentially resulting in more frequent Monsoon breaks and associated extreme rainfall events in Bhutan.

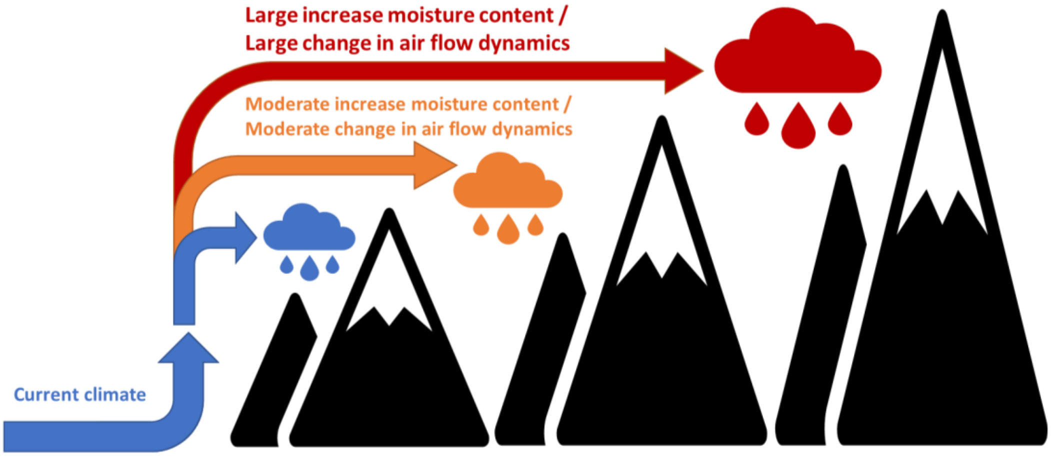

Figure 1-5 Schematic showing how climate change affects rainfall patterns in a mountainous regions such as the Hindu Kush Mountains. The high-altitude regions are exposed to different dynamical and thermodynamic changes than lower-lying regions.

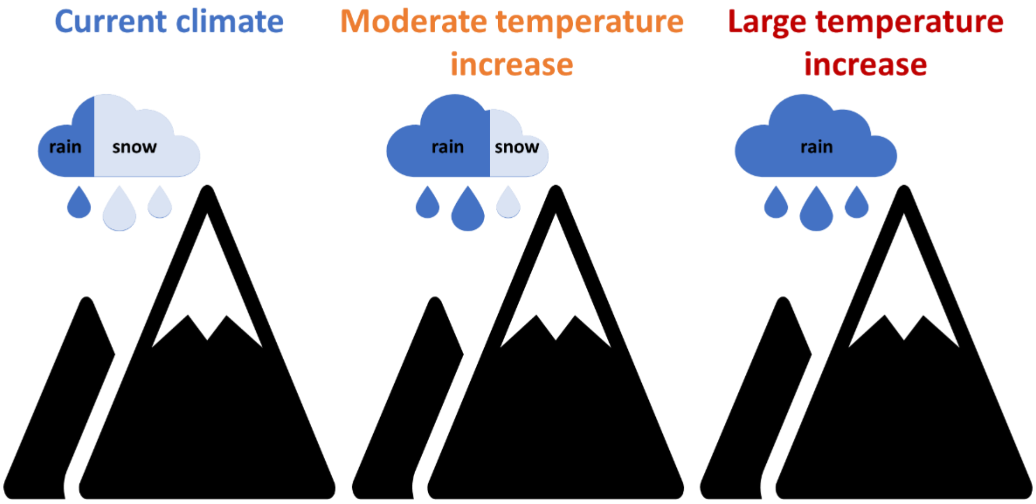

Figure 1-6 Schematic showing how climate change affects the partition of rainfall and snowfall with increasing temperature.

The changing climate is impacting many regions in the World. In mountainous regions, the impacts are large, mainly because these regions are among the most rapidly changing regions. Temperature increases at higher altitude are projected to be faster than global mean, and the fact that snow and glacier cover are rapidly reducing implies that the temporal distribution of water availability is shifting. This will make communities on the mountain slopes, as well as further downstream, vulnerable for changes in precipitation and melting patterns. A relatively stable source of water (glacier and snow melt) is being replaced by a highly variable source of water: rainfall runoff. Communities in mountain areas are also likely to experience more frequently extreme rainfall events and the accompanied hazards such as (flash)floods and landslides.

1.4 About this report

This report presents the Climate Rationale in a structured manner. The climate rationale is the overarching narrative supporting a proposal, which ensures that it links climate change to regional climatic features, impacts and adaptation options (GCF, 2022). The climate rationale includes an assessment of past and future climate trends and their impact on water resources, using the best available information.

The climate rationale describes the system at risk and identifies how climate change will affect the system in the future. Non-climatic factors which may exacerbate the impact are also considered to describe the interactions between climate change and non-climatic drivers. The climate rationale explores activities that address current or future projected climate change impacts.

Chapter 2 presents the most prominent hydrological climate impacts, as being reported by the Bhutan government as well as in previous studies (Jeuken et al., 2021). The two dominant issues, drying up of mountain springs and the occurrence of extreme rainfall events, are described in detail, as well as some other issues as increased snow and glacier melt, glacial lake outburst floods and pests and diseases.

In Chapter 3, the data that was used for the study is presented and the general approach for the analysis is presented, which includes a historical trend analysis, the analysis of climate projections, the hydrological impacts assessment and the sediment impact assessment. Next to that, the detailed approach for the two dominant climate related hydrological issues is explained in more detail.

Chapter 4 shows the results of historical trend analysis and future climate projections. The results are presented for several selected indicators, linked to the prominent hydrological impacts as described in Chapter 2. This is done by combining data from different sources, building on the work done earlier by Jeuken et al. (2021).

The next chapter (Chapter 5) quantifies the impact of climate change on the water resources, and more specifically on the two main identified hazards (drying up of the springs and extreme rainfall events and related to that, (flash)floods).

In Chapter 6, the impact of different adaptation options is evaluated. These adaptation options are designed to increase water availability and supply to cope with the springs drying up, and reduce flood impacts in Trashiyangtze, which was selected based on a previous extreme (flash) flood event.

Chapter 7 presents the rationale, guiding potential ways forward to anticipate the implications of climate change in Bhutan and specifically the 6 Easternmost Dzongkhags.

2 Description of the most prominent hydrological climate change impacts

Climate change is impacting water resources and extreme precipitation and discharge events in Bhutan. The climate rationale for Bhutan focusses on key issues in Bhutan and in the study area specifically. The key issues that are reported by the Bhutan government are: 1) Drying up of the springs; and 2) Impacts from extreme rainfall events, such as (flash) floods, landslides, and soil erosion. In the following section the issues are introduced in more depth. Also, other issues related to snow and glacier melt, glacier lake outburst floods and pests and diseases, as discussed during a field visit in May 2022 are briefly introduced here.

2.1 Drying up of the springs

In the Hindu Kush Mountains, there are many small springs and water sources. The springs are defined as locations where sub-surface water reaches the surface in the form of small streams or ponds. Combined, these springs are in many cases the source of smaller and bigger streams and rivers. The springs are used by local communities for drinking water and irrigation and provide an important, if not the most important, source of water.

Figure 2-1 Examples of springs encountered during the field visit in May, 2022.

Many small streams and springs are reported to be drying up by the local communities (WMDMAF, 2021). It is suspected that these small springs are affected by reduced rainfall amounts and by the intra-annual rainfall variability. The result is that over the years, there is less recharge to supply the springs with sufficient water.

This issue is specifically important to the smaller rural communities that live high up the mountains, far away from and high above the larger rivers. These communities depend solely on the local rainfall and the spring discharge for their daily water use. In a worst-case scenario drying up of these springs will force these communities to give up their land and move to other places that do have access to sufficient water supply. There are already reports of small rural communities having abandoned their home grounds because of a lack of water availability.

In 2021, the Watershed Management Division of the Ministry of Agriculture and Forestry in Bhutan published an extensive overview on the status of the springs in Bhutan (WMDMAF, 2021). As can be seen in Figure 2-2 already a significant number of springs in the study area had dried up or is drying up (red markers).

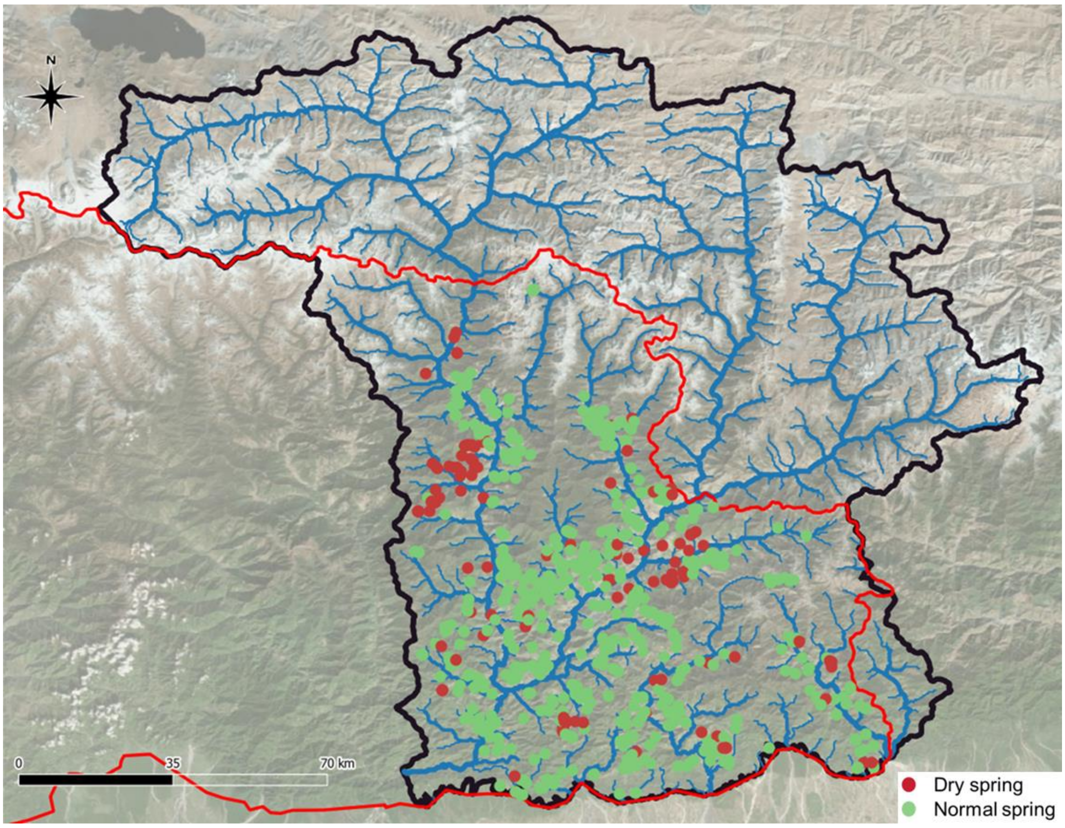

Figure 2-2 Status of springs in the study area as reported by the Watershed Management Division of the Ministry of Agriculture and Forestry.

Many reasons may explain the drying up of the springs, including climate change, landslides, earthquakes, land degradation or forest fires. The mechanisms are very different, but the impact on the local communities is similar. Since many communities are already lacking sufficient water availability, they are extremely vulnerable to (small) changes.

The main reported (WMDMAF, 2021) causes of drying up of the springs is climate change. Reduced total rainfall amounts, increased evaporation and more intense rainfall events combined with more consecutive dry days, could potentially all contribute to the drying up of the springs. Figure 2-3 illustrates the processes of how reduced (effective) rainfall amounts can lead to springs drying up.

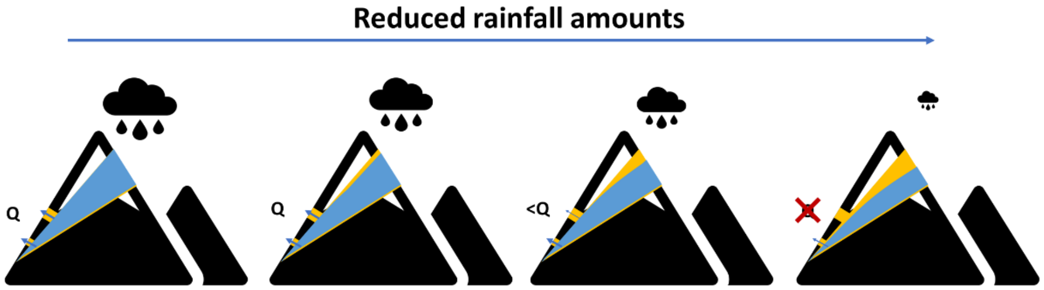

Figure 2-3 Schematic showing how reduced rainfall in the spring watershed could lead to reduced spring discharge or drying up of the springs. In the figure, the black colour indicates the impermeable bedrock, the yellow colour the porous parts / aquifer and the blue colour indicates the water table.

As said, there could also be other reasons than climate change causing springs to dry up. The springs discharge in many cases originates from subsurface flow, following a complex flow path through the subsurface and underlying rocks. In mountainous areas, such as the Hindu Kush Mountains, these flow paths also include cracks and caves in the bedrock. In areas with tectonic activity, earthquakes can alter these flow paths, or even close these flow paths. Figure 2-4 shows what happens to the water table if a flow path is closed due to tectonic movements, reducing the spring discharge due to reduced water table in the subsurface. It is often reported after big earthquakes that springs dry up or new (or old) springs start discharging water (again) (Valigi et al., 2020).

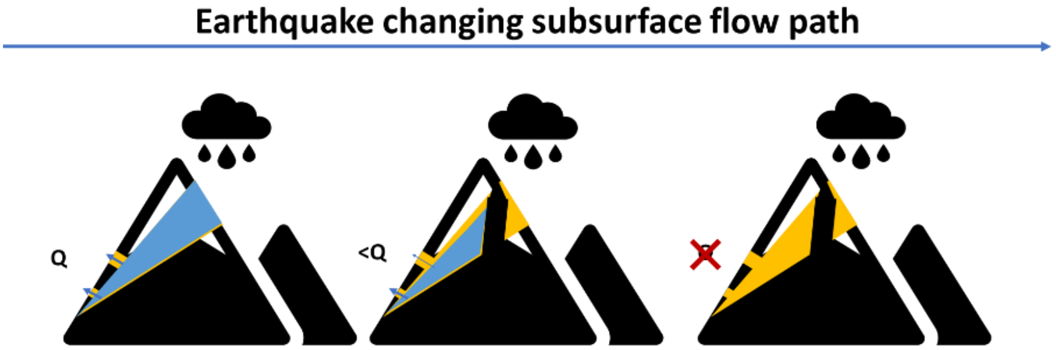

Figure 2-4 Schematic showing how an earthquake can change subsurface flow paths and how this could lead to reduced spring discharge or drying up of the springs. In the figure, the black colour indicates the impermeable bedrock, the yellow colour the porous parts / aquifer and the blue colour indicates the water table.

Also, landslides can alter spring discharge, either by (temporarily) covering parts of the recharge zone in a spring watershed, or by covering or filling up the springs itself. This is schematically shown in Figure 2-5.

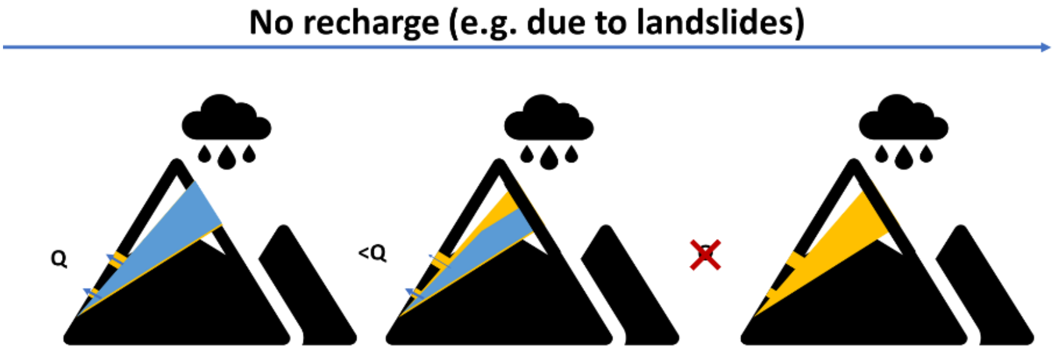

Figure 2-5 Schematic showing how a landslide can (temporarily) block the recharge zone (right side of the mountain, indicated by the black continuous line) and how this could lead to reduced spring discharge or drying up of the springs by reducing the groundwater table. In the figure, the black colour indicates the impermeable bedrock, the yellow colour the porous parts / aquifer and the blue colour indicates the water table.

Finally, land degradation by either human activities or forest fires, can reduce the effective recharge in the spring watershed. Land degradation can be in the form of for example compacting of the soil by extensive cattle grazing, covering the land with impermeable surfaces (e.g. roads or houses), or by increasing the drainage capacity of the land by digging small canals for irrigation. All these factors combined can reduce recharge to the subsurface, reducing the amount of water available to feed the springs.

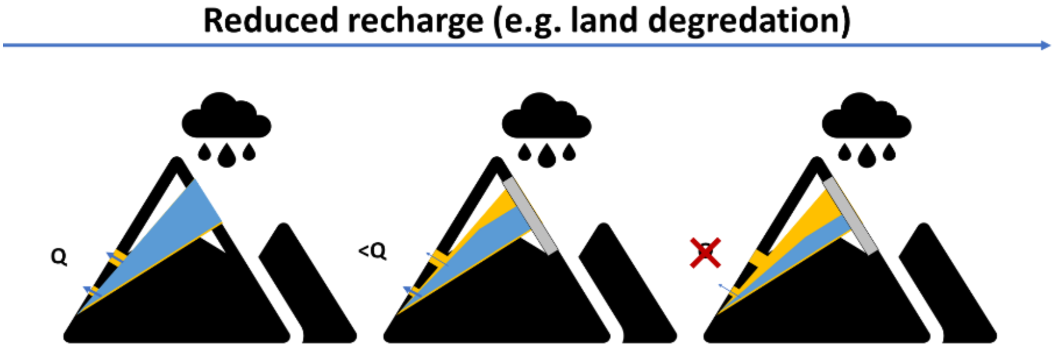

Figure 2-6 Schematic showing how for example land degradation can reduce recharge rates and how this could lead to reduced spring discharge or drying up of the springs. In the figure, the black colour indicates the impermeable bedrock, the yellow colour the porous parts / aquifer and the blue colour indicates the water table.

2.2 Impacts from extreme rainfall events

2.2.1 (flash)floods

Extreme rainfall events can trigger flash floods and create erosion. As Bhutan is a very steep country, rivers and streams often react very quickly to rainfall, leading to very short lead times for early warning. In addition, accurate weather forecasting in these mountainous regions is challenging, which leaves many people that live close to these streams vulnerable to (flash) floods. These extreme events are therefore an important issue for Bhutan.

Next to the direct thread to lives and property of people, cascading effects of extreme rainfall can be substantial. Flash floods pose a direct threat to critical infrastructure such as drinking water supply and road access. These indirect impacts have the potential to aggravate the threat to the livelihood of people living in remote areas of Bhutan.

An example of the devastating power of such an event was the flash flood in Trashiyangtze in August 2021 (Figure 2-7). Three casualties were reported during this event and the main drinking water intake for the town was destroyed. As the roads to the town were blocked by landslides, also alternative drinking water supply by trucks was hampered, leaving the town on low water supply for several days.

The event was reported to have happened on a bright and clear day with no rainfall in the town itself. The casualties and the people in town were taken by surprise as no warning was given for the event. It was probably triggered by heavy rainfall (far) upstream in the catchment. This kind of events show the importance of good information systems to be in place to warn people in advance. The lack of such a system, including a sufficiently dense hydrometeorological observation network, contributes to low climate resilience in many communities in Bhutan.

Figure 2-7 Search and rescue activities after a flash flood (source: https://kuenselonline.com/three-students-missing-in-trashiyangtse/).

Extreme events are not only related to floods, also the rainfall itself can cause issues for local communities. Agriculture is affected by intense and unforeseen rainfall events, which are being reported to be happening more frequently in recent years (Jeuken et al., 2021). During the harvesting season extreme downbursts may ruin crops put on the land to dry before bringing them in for storage and production, reducing the farmers income considerably. Currently these sudden rainfall events are difficult to predict.

Extreme rainfall events are an issue in most regions in Bhutan. The number and severity of these events is also increasing with climate change, due to the projected increasing precipitation amounts and higher intensity rainfall events. Climate change might also impact the regions that are affected by these events due to changes in air flow patterns.

2.2.2 Landslides

Landslides along the steep slopes occur regularly in Bhutan, damaging important infrastructure such as roads and water supply pipelines. Although landslides are often the result of multiple factors (such as road construction) intense rainfall contributes strongly to the occurrence of landslides. Increased rainfall intensity linked to climate change will therefore potentially also increase the risk of landslides.

Especially the road network of Bhutan is vulnerable to landslides. Traffic disruptions are already a huge problem during the wet season, as also experienced during the field work in May 2022 (see Figure 2-8). At minimal, the traffic disruptions are a hinderance for people and goods travelling from point A to B, but in many cases, landslides also pose a direct threat to lives of people travelling these roads.

Bhutan also has limited options for alternative routes, so traffic disruptions directly impact supply lines and access to hospitals and other critical infrastructure locations.

Especially during the wet season, when also flying is often not an option due to poor visibility, the options for people going around are very limited, increasing the need to be highly self-sufficient for drinking water, food, and other essentials for living.

Figure 2-8 Clearance of a landslide (left) and travel conditions after clearance (right) on the road between Sengor and Mongar during the field visit of May 2022.

2.2.3 Erosion and sediment transport

There are many factors contributing to soil erosion, including detachments of soils due to splash (erosion from rain drop impact on the exposed soil surface) or surface water flow (runoff). Soil erosion can lead to soil degradation and loss of productive land. Locally soil erosion can cause mudflows, with devastating effects. Further downstream, the huge influx of sediment poses a threat to existing infrastructure, such as hydropower and water supply inlet structures (see for example Figure 2-9). Currently, the water infrastructure is relatively limited in Bhutan, but there are extensive plans to further develop the hydropower sector in Bhutan, including the building of many new dams and reservoirs (World Bank, 2016).

Figure 2-9 Sediment mining in Bhutan (source: https://www.thethirdpole.net/en/climate/erratic-weather-spells-tough-time-ahead-for-bhutans-hydropower/)

Climate change can impact soil erosion and sediment transport in a variety of ways:

- Increased rainfall intensity increases soil erosion through more splash erosion as well as more erosion due to surface runoff.
- Increased river flows and flow velocities increase the riverbed erosion potential.
- Increasing temperature reduces the permanent snow and glacier cover, exposing the underlying soil for splash and surface runoff erosion.
- Increasing temperature and associated evapotranspiration, combined with changing or decreasing annual precipitation pattern could change the vegetation cover, resulting in a different soil holding capacity of the vegetation.

Not all changes will be in the same direction. Some changes might increase soil erosion and sediment transport (such as more intense rainfall), but other changes might also increase the stability of the soil, such as more vegetation at higher altitude.

2.3 Other issues

Bhutan faces many other issues related to climate change, mainly linked to increasing temperature. There are issues linked to snow and glacier melt and specifically to glacier lake outburst floods (GLOF), but also issues related to pests and diseases for (irrigated) agriculture.

Although also important, these issues are not included in the climate rationale, but are briefly discussed here and upcoming sections and Annexes.

2.3.1 Snow and glacier melt

Bhutan is situated in the Hindu Kush Mountains, with elevations in the country and its river basins rising to above 7000 meters above mean sea level. Large parts of the high elevated lands are regularly or permanently covered with snow and glaciers. There have been many studies on the snow and glacier stores in the Hindu Kush Mountains and their (accelerating) disappearance due to increasing temperature, especially in summer (IPCC 2021).

Recent observations, however, also report increasing glacier volumes in the Hindu-Kush region for several glaciers, such as the Yala glacier in Nepal (WGMS, 2021).
This could be related to changes in air flow patterns such as more frequent Westerlies bringing in moist air from the Mediterranean Sea.

Snow and glacier melt contribute strongly to the base flow of the rivers in Bhutan. These sources of water are crucial for maintaining for example hydropower production during dryer spring, summer, and autumn months. If these sources of water would disappear, baseflow in the rivers could potentially drop reducing the power production potential for Bhutan. Downstream, in India, reduction in base flows can impact water availability for irrigation in specific seasons.

The melting of the snow and glaciers is already going on as is shown in several studies (e.g. Nie et al., 2021, IPCC, 2021). Increasing temperature will result in enhanced snow and glacier melt in the short run and thus increasing the base flow of the rivers. The projections differ per region, but studies show that a peak in glacier melt runoff is to be expected within the coming decades. Since the glacier volumes are finite, at some point the glaciers will disappear, reducing the baseflow of the rivers depending on this source of water (Khanal et al., 2021).

Changes of precipitation patterns have an ambiguous impact on snow and glacier coverage. There are reports pointing towards the possibility of increasing glacier extents, mainly in the Western Himalaya and western slopes due to increasing precipitation amounts at higher altitudes (WGMS, 2021), mainly caused by more active Westerlies. Due to a lack of reliable on-the-ground observations it’s unknown in many cases how snow and glacier melt rate at these altitudes are balanced with potential increased influx of extra precipitation.

2.3.2 Glacier Lake Outburst Floods

Higher up in the mountains, some glaciers pose an omnipresent danger in the form of glacier lake outburst floods (GLOFs). These types of floods are not directly linked with intense rainfall, but rather with high temperatures. Also, other factors such as landslides or earthquakes can lead to the occurrence of GLOFs. GLOFs can be extremely dangerous and the magnitude of this type of floods can be very large. These floods also happen very fast, leaving little time to prepare and evacuate.

Climate change, with higher temperatures being projected especially at the higher altitudes, increases the risk of GLOFs for specific glaciers. The fast melt rate destabilizes the glaciers and the volume of the glacier lakes can quickly increase due to rapid melting. This makes it also more complex to carefully monitor the risk.

In 2022, the heatwave in India and Pakistan was suggested to lead to a high number of GLOFs (see for example Figure 2-10). Also, in Bhutan there are several glaciers marked as potential risk for GLOFs. In the study area, the number of glaciers at risk however is low.

According to the ICIMOD inventory on potentially dangerous glacial lakes (Mool, 2001a,b), only one potentially dangerous lake was within the project area, the Kuri Glacial Lake. Given the fast melting rate of the glaciers in recent years potentially the number of dangerous lakes will increase in the future.

Figure 2-10 Bridge collapse in Pakistan after a glacier lake outburst flood (GLOF) in the summer of 2022. (source: https://www.onenewspage.com/video/20220508/14658895/Pakistan-bridge-swept-away-by-glacier-lake-outburst.htm).

2.3.3 Pests and diseases

An issue of different order is the presence of new pests and diseases, especially related to agriculture. Higher temperatures trigger new species to survive at higher altitude, causing a threat to the original species living there. An example of a pest being introduced into higher altitudes in Bhutan is the Armyworm, which causes substantial damages to crops, such as rice, maize, wheat, and buckwheat. Also, other pests and diseases, such as many mosquito-borne diseases are making their way up to the higher altitudes of Bhutan.

The fact that Armyworms are now found at higher altitude in Bhutan is most likely linked to the increasing temperatures (Tenzin et al., 2019 and Naveenkumar, 2018). Further increase of the temperatures may result in pests and diseases moving further into Bhutan, making farmers and the communities depending on their production more vulnerable.

Figure 2-11 Visit to the Agricultural Research and Development Centre in Wengkar, Bhutan.

3 Data and methods

The climate rationale is prepared from different perspectives, considering different levels to describe the issues and climate impacts. The levels that are considered in the climate rationale include the national frameworks and government policies, the basin level, watershed level and finally the community or farm level.

The national framework links the climate rationale to government policies and frameworks. It also links to current developments and plans and ambitions for the country and the impact of climate change on these plans.

At the basin level, the climate rationale focusses on how the main water system and rivers are affected by climate change. Adaptation options include improved governance, policy, and capacity building. Improved information for water resources planning and early warning are also part of the adaptation options at the basin level.

For the watershed level, the focus is on improved water availability and supply through potential adaptation options, including nature-based solutions[1] and resilient infrastructure.

Finally, at the community or farm level, the focus is on reduced water demand and use. Typically, adaptation at this level focusses on community level adaptation options that enhance the resilience, such as rainwater harvesting and efficient irrigation techniques.

In the climate rationale for Bhutan, the focus is at the watershed level, focusing on the smaller stream and springs. However, also the basin level and community level are included.

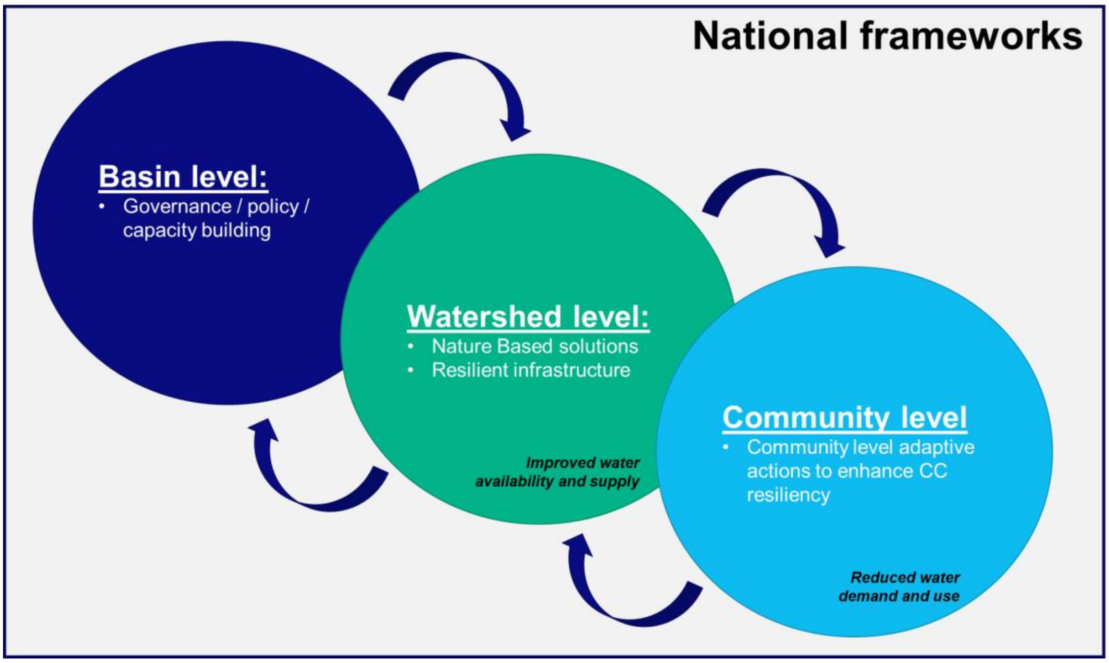

Figure 3-1 The different perspectives for presenting a climate rationale for Bhutan, linking the national frameworks, basin level, watershed level and community level.

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[1] Nature based solutions are typically applied at the small scale (e.g. watershed level) but do have an impact on the basin level as well.

3.1 Data

The climate rationale is based on different datasets, comprising of global, regional, and local datasets. Combined, these datasets best represent the most prominent hydrological climate change impacts and their origin from hydrometeorological perspective.

For the rainfall data, many global data sources are available. In this study we used the global ERA5 (Hersbach et al., 2018) and w5e5 (Lange et al., 2021) datasets, as well as the regional IMDAA (Ashrit et al., 2020) dataset and station data from the local hydromet service (NCHM). These datasets were selected based on the data availability over a longer period (minimal 30 years), and for the IMDAA dataset because of the local relevance and the focus on important Monsoon characteristics over the Indian subcontinent. The local hydromet station data was used as a first order validation of the global datasets as shown in Figure 3-2, although during the field visit in May 2022 it was concluded that the elevation of the stations makes the representability of the data insufficient to be used in this study, as shown for two station in Figure 3-3. The stations are in many cases located at the bottom of the valley where it was observed to be much dryer compared to higher altitudes. The highest station in the study area is located at 1930 meters above MSL, which represents less than 20% of the total area in the study area in which more than 80% of the land is above 1930 meters above MSL.

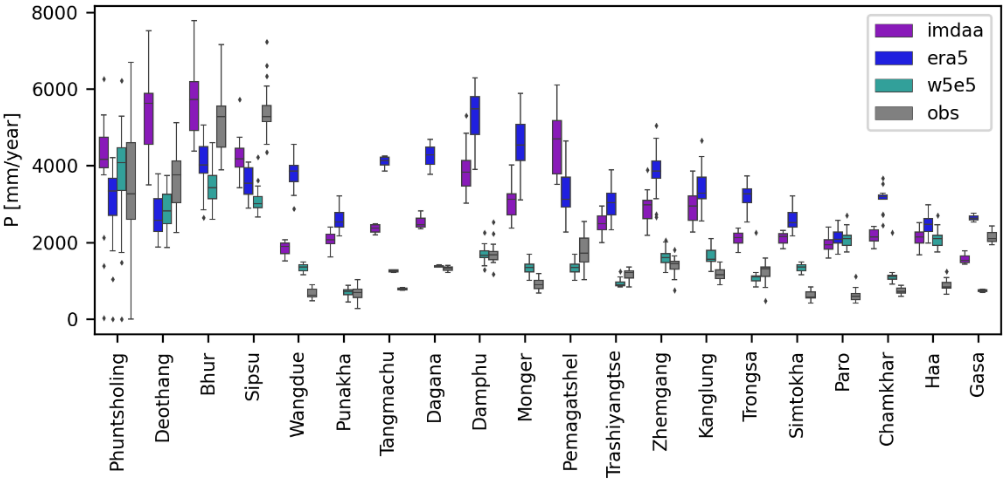
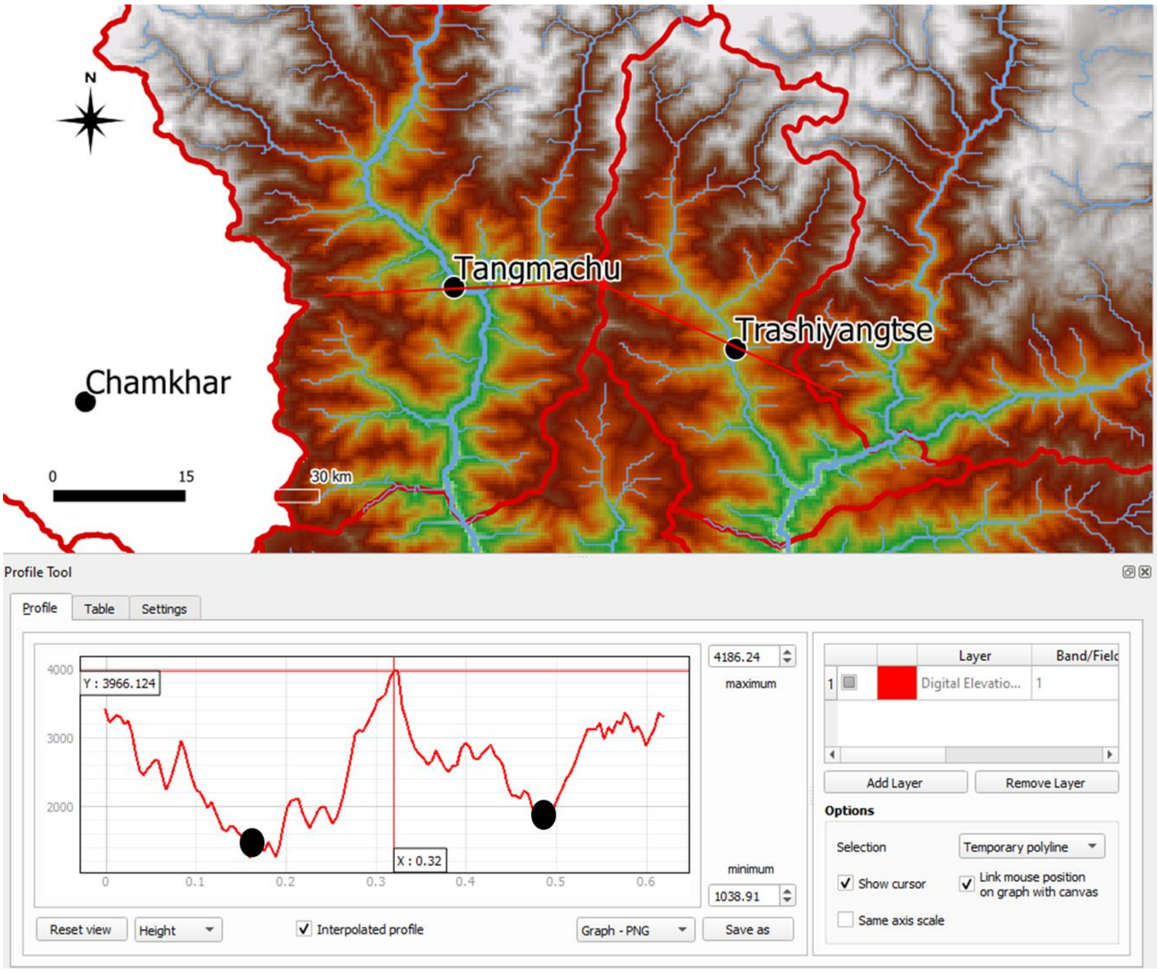


Figure 3-2 Comparison of different datasets for selected meteorological stations within Bhutan.

For the temperature, the ERA5 dataset is used. A lapse rate correction, using the higher resolution elevation profile, was done to correct the ERA5 dataset for the orographic effects. A lapse rate correction factor of 6.5°C per 1000 meters is used.

The potential evaporation is calculated using the Pennman Monteith formula (Monteith, 1965) to also consider the high humidity at higher altitude that was observed during the field visit in May 2022.



4186.24 maximum

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Figure 3-3 Elevation profile in part of the study area (in red) and the location and altitude of two meteorological stations (black dots).

The discharge data was obtained from the National Centre for Hydrology and Meteorology (NCHM). There are only 5 gauging station within the study area, as is shown in Figure 3-4. The discharge data is primarily used to calibrate and validate the hydrological model but was also used to select best historical rainfall dataset. For this purpose, the Budyko framework was used to determine feasible runoff coefficients, given the different rainfall inputs, and observed discharge. Feasible in this case means that not more water can flow out of the catchment than could come in via precipitation, or given the climate conditions in Bhutan, not much less than 50% of the rainfall should flow out of the catchment. For each dataset (IMDAA, ERA5 and w5e5) and for all hydrological stations, the position within the Budyko curve can be determined and plotted as shown in Figure 3-5.

The w5e5 dataset indicates that there must be another source of water apart from the rainfall. The volume of water flowing out of the catchment is (much) higher than the volume of rainfall entering the catchment. This indicates that the w5e5 dataset underestimates the rainfall. This could probably be explained by the fact that this dataset is bias corrected using the observation station data, which was concluded not to be representing the real conditions in Bhutan as these stations are located in the much more arid valley bottoms, compared to the very humid and wet higher altitude zones.

The ERA5 dataset shows the opposite. For the ERA5 dataset it seems that there is too much water (or rainfall) coming into the system compared to the outflow.

This means that the catchment is leaking water in some way, for example to deeper groundwater or through diversions. As both mechanisms are deemed not to be realistic, the ERA5 dataset was concluded to overestimate the rainfall.

Finally, the IMDAA dataset seems to best fit in the feasible domain, showing more realistic behavior, although also for the IMDAA dataset some basins (e.g. basin 22) over- or underestimates the rainfall. Because of the good fit in the Budyko framework, the IMDAA dataset is used as the historical rainfall dataset in the rest of this study.

For the climate projections, the NASA NEX-GDDP-CMIP6 datasets are used (Thrasher et al., 2012). These statistically downscaled climate scenarios are based on the latest global climate models used in the CMIP6 experiment. The purpose of this dataset is to provide a set of global, high resolution, bias-corrected climate change projections that can be used to evaluate climate change impacts on processes that are sensitive to finer-scale climate gradients and the effects of local topography on climate conditions.

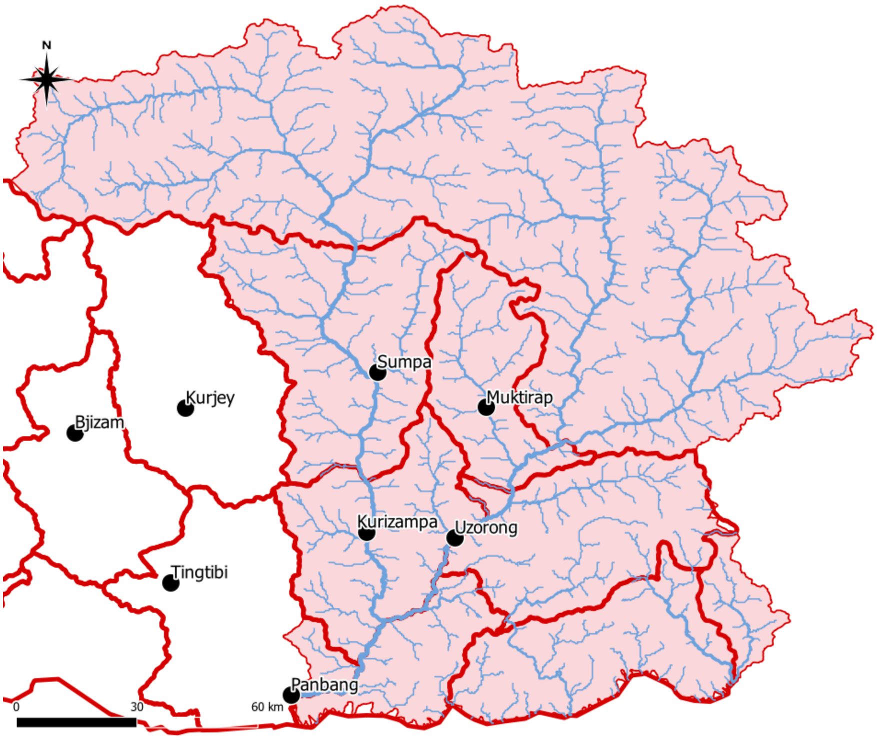

Figure 3-4 Overview of the hydrological stations within the study area (red shaded area).

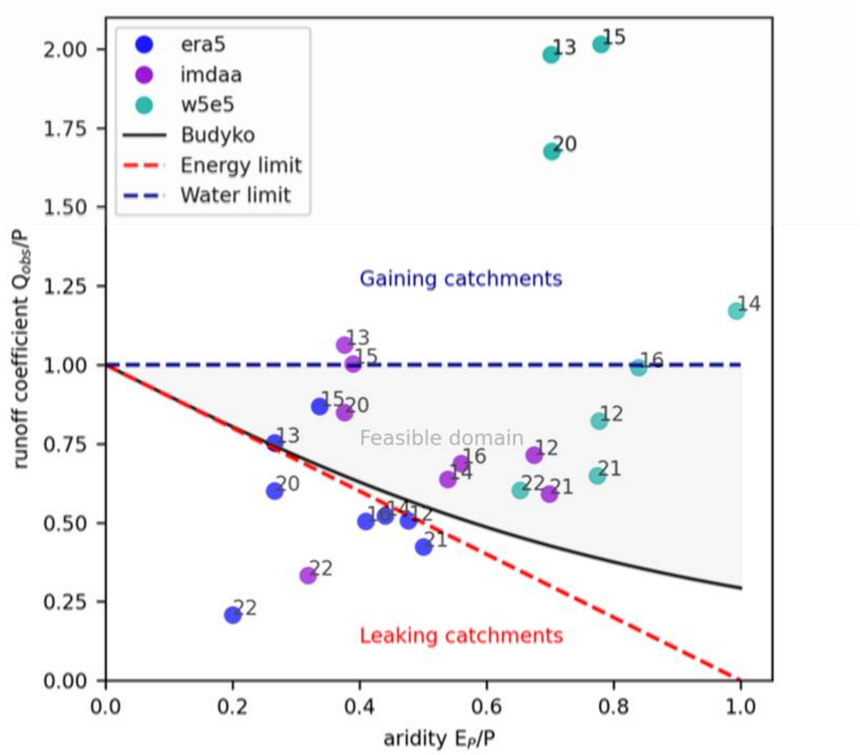

Figure 3-5 Analysis of the runoff coefficient and aridity index river basins using the Budyko framework for 3 different gridded datasets: The ERA5 dataset, the IMDAA dataset and the W5E5 dataset. The feasible domain is marked grey and lies between the leaking catchment divide (red dotted line) and the gaining catchments divide (blue dotted line). Under normal conditions it is expected that the points fall within the feasible domain.

For the setup of the hydrological model, mostly global datasets are used. The complete list of datasets used in the model is presented in Table 3-1. The method for setting up the model is described in Eilander et al. (2022) and the online documentation for the HydroMT toolbox can be found here: https://deltares.github.io/hydromt_wflow/latest/. The upscaling of the global datasets to the model resolution for the soil properties is done using Pedo Transfer Functions as described in Imhoff et al. (2020). The upscaling of the hydrographic datasets is done through the methods described in Eilander et al. (2021).

Table 3-1 Used datasets for the initial Wflow model setup. More information and direct link to the datasets can be found here: https://deltares.github.io/hydromt/latest/user_guide/data_existing_cat.html

Dataset	Component	Data type	Reference
merit_hydro_v1.0	Hydrography	RasterDataset	Yamazaki et al. (2019)
merit_hydro_ihu	Hydrography	GeoDataFrame	Eilander et al. (2021)
rivers_lin2019_v1	Hydrography	GeoDataFrame	Lin et al. (2019)
hydro_lakes	Lakes & reservoirs	GeoDataFrame	Messager et al. (2016)
hydro_reservoirs	Lakes & reservoirs	GeoDataFrame	Lehner et al. (2011)
modis_lai	Landuse	RasterDataset	Myneni et al (2015)
globcover	Landuse	RasterDataset	
soilgrids_v1.0	Soil	RasterDataset	Hengl et al. (2017)
chelsea	Meteo	RasterDataset	Karger et al. (2017)
era5_daily	Meteo	RasterDataset	Hersbach et al. (2019)
koppen_geiger	Meteo	RasterDataset	Kottek et al. (2006)

3.2 General approach

The general approach for compiling the first component in the climate rationale consists of 4 steps:

1. Historical trend analysis.
2. Analysis of climate projections.
3. Hydrological impact assessment.
4. Sediment impact assessment.

The steps are described in detail in the next sections.

3.2.1 Historical trend analysis

The first step in the climate rationale is to analyze the historical trends in the hydrometeorological data. By analyzing the historical rainfall, temperature and discharge observations, signals of already ongoing (climate) change can be detected. This is done by analyzing the anomalies in the annual averages of the observations. For each year the average rainfall, temperature or discharge is compared to the long-term average to determine a long-term trend in the data.

As part of the historical trend analysis, a data validation assessment is done. Since there are limited amounts of hydrometeorological data available in Bhutan, also global and regional datasets are considered for use in the historical trend analysis. The data assessed is focused on the meteorological datasets. The datasets are compared and assessed in terms of total rainfall volumes. The Budyko framework (Budyko, 1974, Bouaziz et al., 2018) is used to compare available meteorological datasets using observed streamflow data.

3.2.2 Analysis of Climate projections

The next step in the climate rationale is to look at the climate change projections. There are many different climate models and experiments available that can be used as input for this analysis. An assessment of the available climate projection data was made, and for reasons of comparison and continuity it was decided to continue working with the same models as were being used in Bhutan for the National Adaptation Program (NAP) and the National Communications. The climate models were part of the NASA-NEX GDDP dataset (hereafter referred to as NASA). For the previous work for the national communications and for the UNDP-NAP project, the NASA dataset are based on the CMIP5 experiments. For climate datasets based on the CMIP5 experiments, also CORDEX and CORDEX-CORE datasets are available.

Since the UNDP-NAP project and the National Communications were last updated, the IPCC 6th assessment was finished and the CMIP6 experiments were published. These experiments comprise the latest developments in science in the field of climate projections. Also, for the CMIP6 experiments, the statistically downscaled NASA dataset was already available, including the same set of climate models (updated using the latest available knowledge and data) as those that were used in UNDP-NAP and the National Communications. For comparability and recognizability with previous assessments it was decided to use the CMIP6-NASA dataset as input for this study, as is schematically shown in Figure 3-6.To compare the datasets, only some high-level statistics are calculated, comparing the area and time average change in precipitation and temperature. The comparison helps to better understand the difference between the datasets and position this study in relation to the UNDP-NAP project and the National Communications.

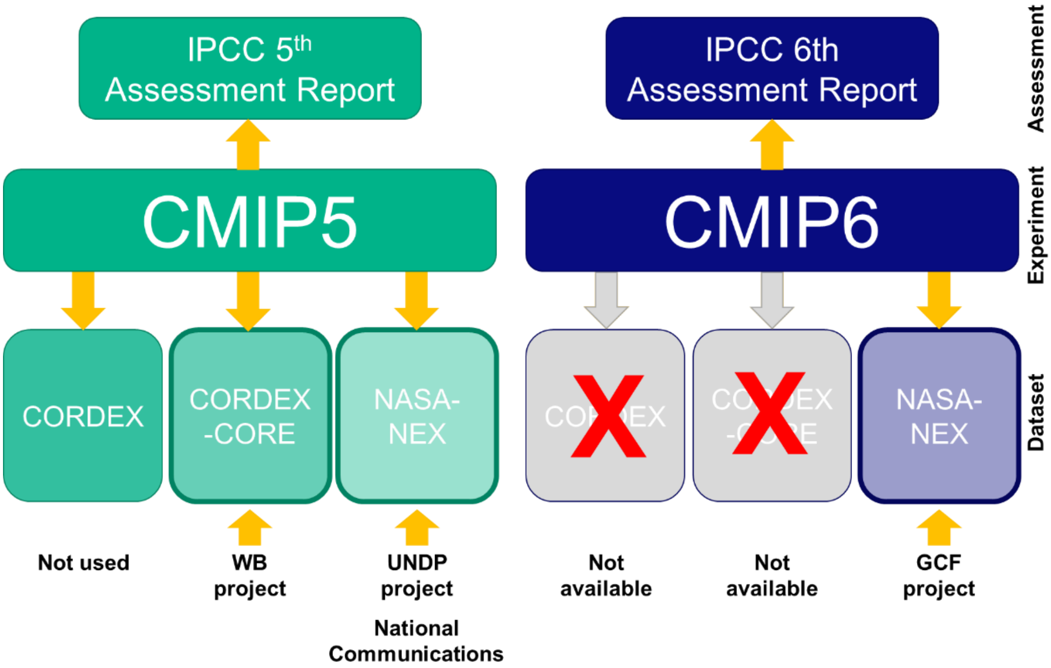

Figure 3-6 Schematic overview of available and considered climate datasets for the Climate Rationale.

Climate change has different effects in different hydro-climatic zones. Especially the large elevation differences in Bhutan make it difficult to draw simple conclusions that are valid for the whole region about how the climate is changing. Therefore, the climate change analysis focusses on three distinct zones as shown in Figure 3-7: 1)

The lower altitude zone 2) the medium altitude zone; and 3) the high altitude zone[2]. By looking at how climate change is affecting key variables such as temperature and precipitation within each zone specifically, climate zone specific conclusions can be drawn.

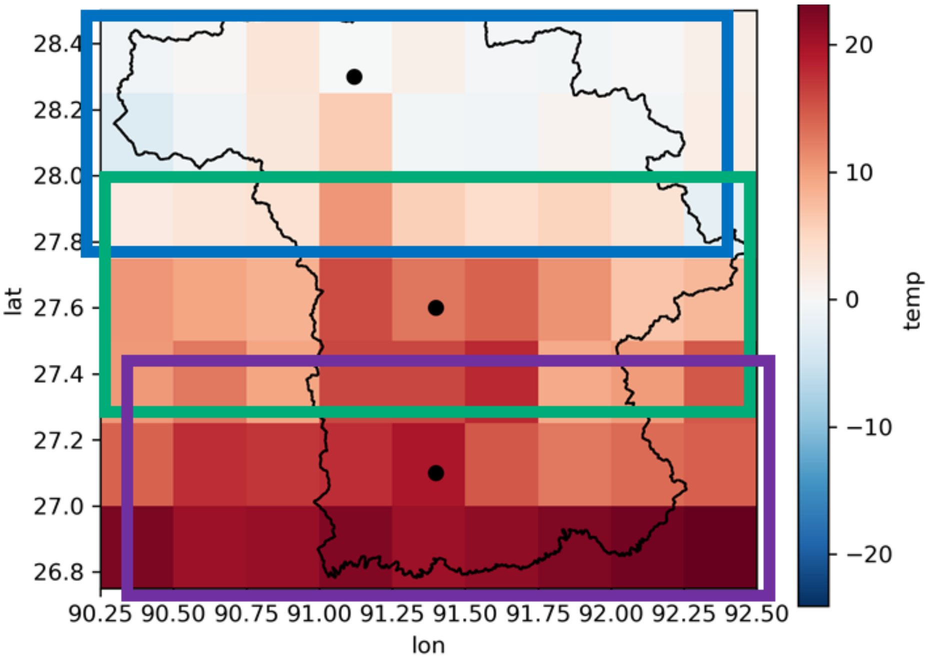

Figure 3-7 Definition of low (purple box), medium (green box) and high (blue box) elevation zones in Bhutan used for the analyses of model projections.

For investing in the agricultural sector, such as rainwater harvesting tanks and small-scale water infrastructure, the changes in the near future are more relevant than the far future. The typical life cycle for these investments is between 10 – 30 years[3]. Therefore, the analysis is focussing on the near-future changes, meaning the period between 2020 and 2050. To also present a further outlook, the results will also be shown for the far future, which comprises the period 2070 – 2100.

Since most climate models are very coarse and the bias for the historical period is relatively large, the climate signal is introduced as a delta-change on top of the historical observation dataset (Navarro-Racines (2020) and Hawkins (2013)). The same method was also applied in the previous study under the UNDP NAP project. For this delta-change method, the relative changes in the mean monthly precipitation, or the absolute changes in the mean monthly temperature are calculated and applied on the historical dataset. There are advantages and disadvantages to this approach.

The advantage is that the absolute values for precipitation and temperature are very much in line with the observed values. This makes it possible to better compare results between the historical climate and future climate. As the delta change method imposes the climate change signal on the historical observed data, it is possible to evaluate how a specific year would be affected by the impact of climate change. The delta change method allows to better recognize specific historical wet or dry years in the transformed time series representative of future conditions.

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[2] This division in sub-regions is a simplified manner to analyse the impact of altitude on the climate change signal. Other factors, such as the orientation of the mountains, in combinations with the air flow patterns, is also an important factor for explaining spatial variability in the climate change signal.

[3] Based on a personal communication with the FAO team during the field visit in May 2022.

The disadvantage of the delta-change method is the fact that no big changes in the weather patterns can be simulated. For example, changes in the persistence of weather patterns leading to dry conditions are not represented with this method.

It was concluded that the advantages of the delta-change method are larger than the disadvantages. However, it is important to keep these differences in mind when exploring and using the results of the climate impact assessment, for example when drawing conclusions on long, persistent drought conditions.

For the use in the different detailed assessments, a reduced set of scenarios is used. This set of scenarios includes the reference run (current climate) and a wet and a dry scenario for the near future. The selection of the wet and the dry scenario considers several indicators, including total precipitations amounts, mean annual streamflow, annual maximum and 7-days minimum streamflow. Figure 3-8 illustrates that model MRI-ESM2-0 with SSP 126 is a relatively wet scenario for the near future, considering both the cumulative streamflow and the maximum annual streamflow for the station of Pangbang on the Drangmecchu river. In contrast, model MRI-ESM2-0 for scenario SSP 585 has relatively low mean annual streamflow in comparison to historical conditions and low annual minimum 7-days streamflow in comparison to historical conditions on average for all the spring locations included in the model, as shown in Figure 3-9. This scenario was selected to represent a relatively dry scenario for the near future.

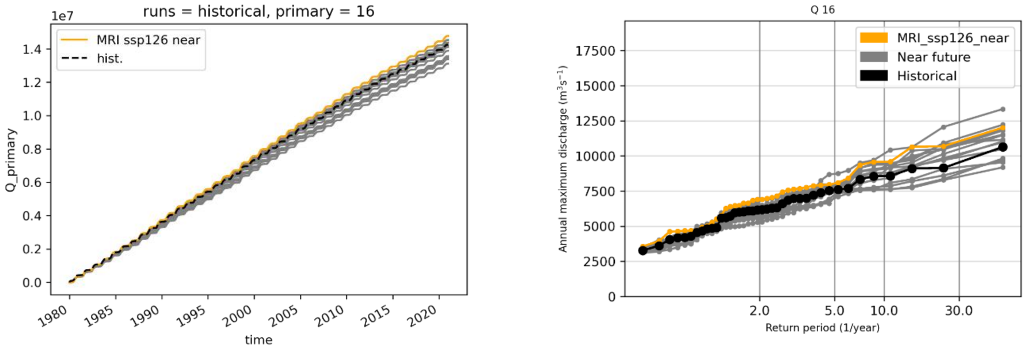

Figure 3-8 Selection of the wet scenario, based on the cumulative runoff (left) and statistics of annual maximum runoff (right) for the station of Pangbang on the Drangmecchu river. The black line shows the historical scenario, the grey lines show all near future scenarios and the orange line shows the selected wet scenario.

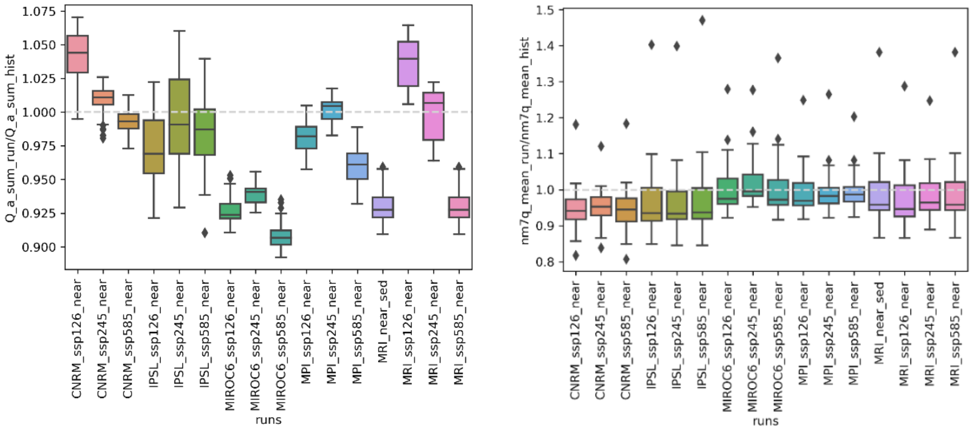

Figure 3-9 Selection of the dry scenario, based on the ratio of mean annual streamflow and annual minimum 7-days streamflow for each scenario as compared to historical conditions. The width of the boxplots indicates the variability across all the springs included in the model.

3.2.3 Hydrological impact assessment

To assess the impact of climate change on the hydrology, a hydrological model is used. For the climate rationale for Bhutan the wflow_sbm model is used (van Verseveld et al., 2022). Wflow_sbm is a spatially distributed, physics-based hydrological model that simulates the rainfall-runoff process. All relevant hydrological processes are included, such as snow and glacier processes, rainfall interception, soil water balance and evaporation processes, vertical and lateral sub-surface flow, and overland and river flow. A schematic overview of the wflow_sbm concept is shown in Figure 3-10.

The wflow_sbm model is well suited for the climate rationale, as it provides sufficient level of detail to asses small scale processes such as recharge and runoff in small (spring) watersheds and is coarse enough to also assess the hydrological impacts at the basin scale, including for example impacts of snow and glacier melt on the river discharge. The wflow_sbm model also includes a soil erosion and sediment transport module which is fully coupled with the hydrological model (Boisgontier et al., 2020).

Furthermore, wflow_sbm is fully open-source and freely available, making it very accessible for experts in Bhutan. And since wflow_sbm is fully grid-based, it links very well to the many available (global) spatial datasets. Since many areas in Bhutan lack sufficient data on for example soil properties, landuse, elevation and meteorological inputs, these global datasets are valuable first estimates to use in the modelling. Based on the modelling results and analysis, this approach also supports the tailoring of the data collection process to the data that is most relevant for improving the hydrological impact assessment for the region of interest. Wflow_sbm is also widely used around the world for Early Warning Systems.

For the climate rationale the model has been setup using global data at first. The model has been refined using locally collected data. Specifically, the locations of springs and small water sources have been added as model output locations, allowing to investigate the hydrological climate impacts at specific springs. It must be noted that although the model is grid-based, not all springs could be added to the model individually because of the resolution of the model. In some cases, multiple springs would be in the same model grid cell and therefore had to be merged. The model was setup at a resolution of approximately 0,5x0,5 km^2.

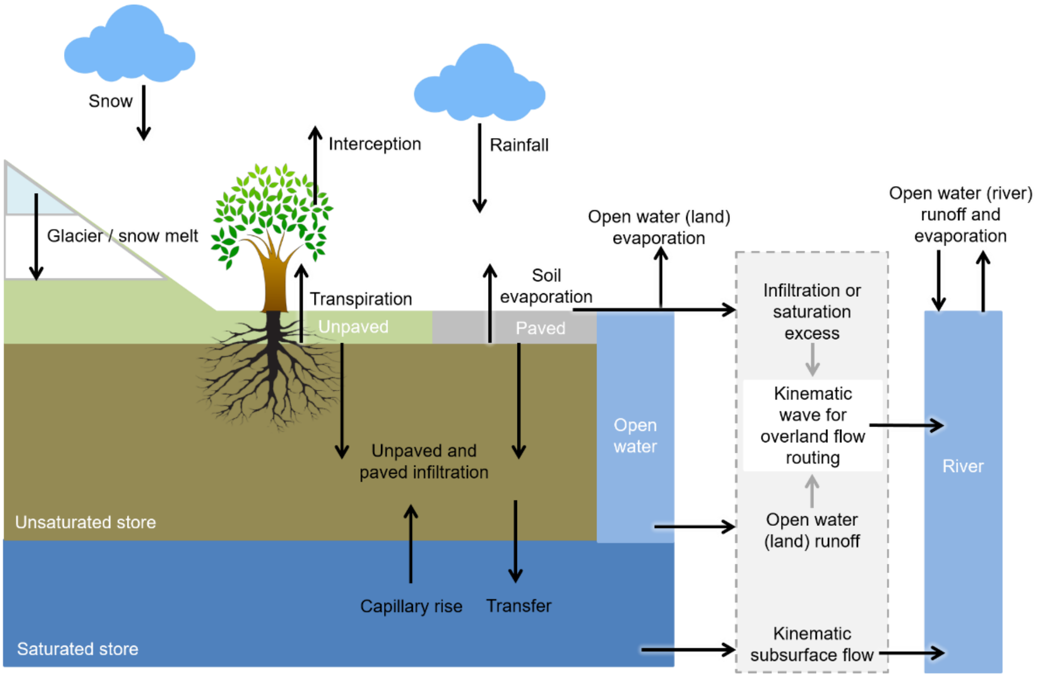

Figure 3-10 Schematic overview of the wflow_sbm model concept (Van Verseveld et al., 2022).

The model was evaluated using observed streamflow data at 5 gauging stations within the basin. No in-depth calibration was done, but the model performance was evaluated. The quality of the model is considered to be of sufficient quality to be used for the preparation of the climate rationale. This is demonstrated in Figure 3-11 and Figure 3-12. Here the model performance is demonstrated for two stations, Pangbang and Kurizampa, by comparing simulated and observed discharge and derived statistics (annual average runoff and mean monthly runoff).

When comparing the daily streamflow (top row) it is shown that the model simulates well the hydrological response to rainfall. The model does seem to underestimate the flows in the months March, April, and May. This might be the effect of snow melt occurring later in the model compared to reality.

When comparing the annual average discharge (bottom-left) the model performance shows some more deviations from the observations, although the general trends seem to be matching relatively well for the Kurizampa station. For the Pangbang station, the observation timeseries is too short (only 9 years) to draw firm conclusions.

The discharge regime (or mean-monthly discharge) shows a relatively good match between simulated and observed flows. Again, for both Pangbang and Kurizampa the underestimation of the March, April and May flows is clearly visible.

The differences between observed and simulated discharges, however, are relatively small and the seasonal and annual patterns match quite well. For the purpose of a climate impact assessment, looking at relative changes between different simulations, these differences are deemed small enough to not impact the conclusions from the climate runs.

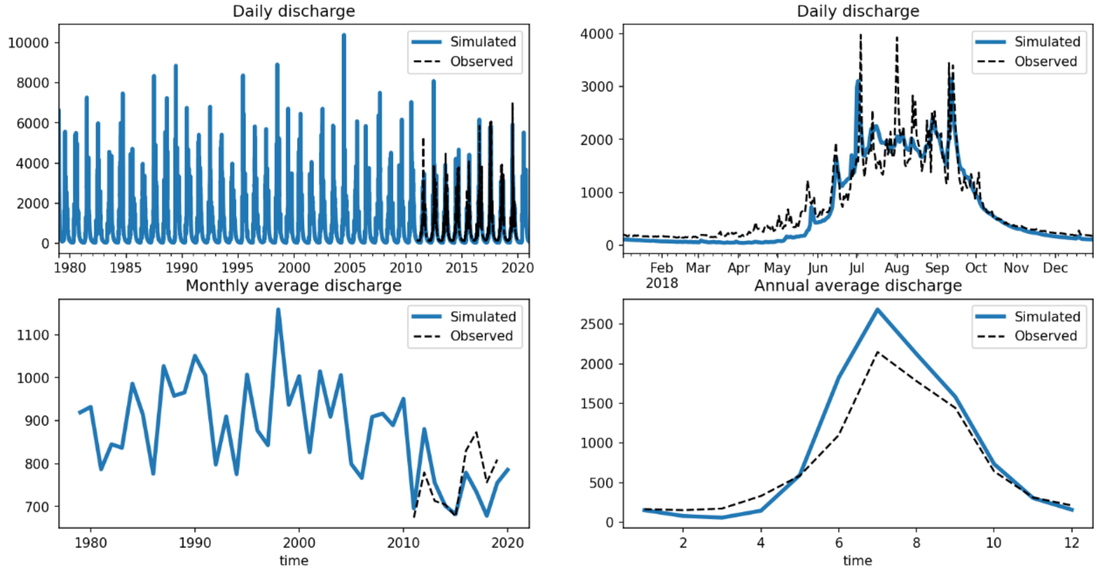

Figure 3-11 Comparison of the Wflow_sbm model (blue lines) with observations (black dotted lines), for the daily timeseries over the whole period (top left), daily timeseries for a specific year (top right), the annual average discharge (bottom left) and the mean monthly discharge regime (bottom-right) for the Pangbang hydrological gauging station.

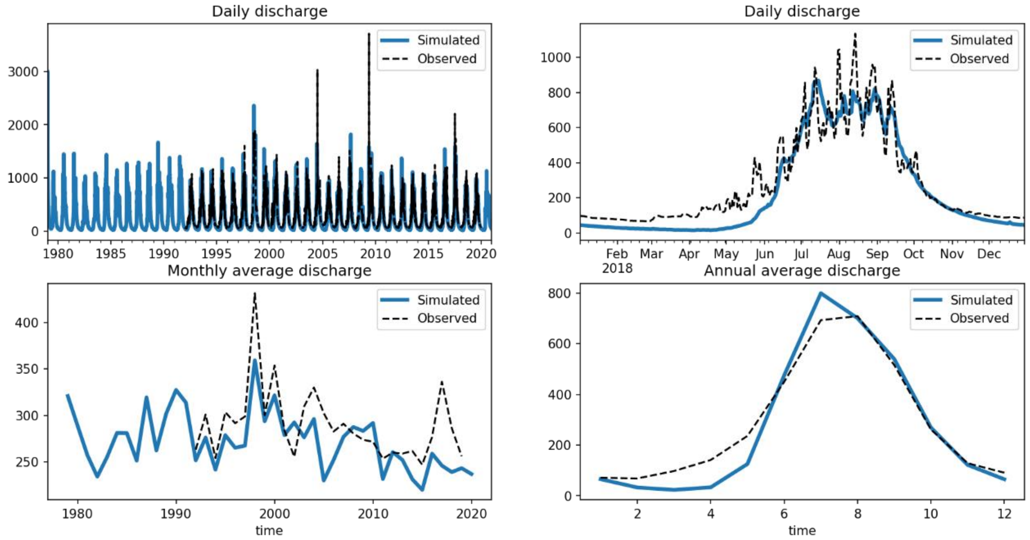

Figure 3-12 Comparison of the Wflow_sbm model (blue lines) with observations (black dotted lines), for the daily timeseries over the whole period (top left), daily timeseries for a specific year (top right), the annual average discharge (bottom left) and the mean monthly discharge regime (bottom-right) for the Kurizampa hydrological gauging station.

Since the model also simulated the snow and glacier processes, an assessment of the quality of the model for snowpack simulation was done. In Figure 3-13 the percentage of time that there is snow in a certain region in the model is compared to the observed percentage of time that there is snow cover. For the observations, the MODIS 0.05° dataset is used (Hall et al., 2006). As can be seen, the simulated and observed snowpack show generally the same pattern, although the model seems to slightly overestimate the amount of time there is snow. This could be caused by a bias in the observations (e.g. caused by blockage from clouds (Tran et al., 2018)) or by the fact that the model was not specifically calibrated for the snow module[4]. For the conclusions of the climate rationale, in which the relative changes are more important than the absolute values, the snow module in the wflow_sbm model are deemed sufficiently accurate, since it seems to well represent the spatial patterns of snow accumulation.

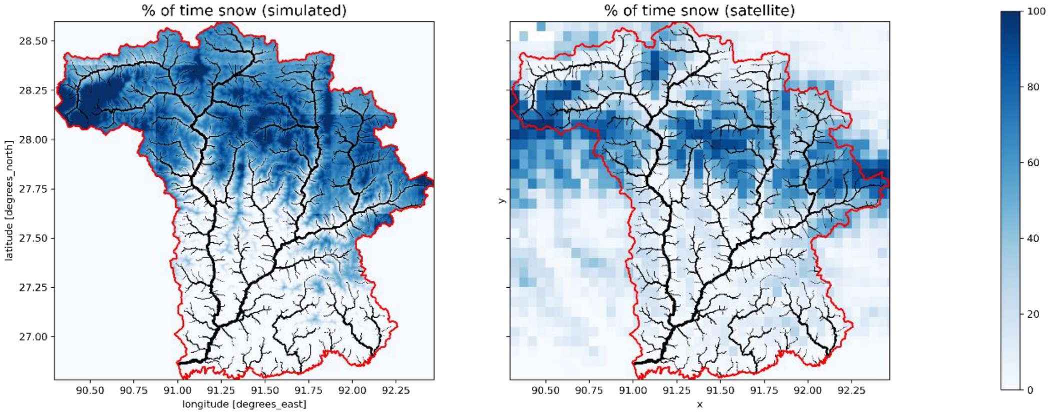

Figure 3-13 Percentage of time with snow in the basin as simulated on the left and observed (MODIS satellite) on the right.

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[4] The Wflow_sbm model includes a snow module. This works on a simple degree-day factor approach using a threshold temperature that determines the divide between snow accumulation and melt. The threshold temperature is a sensitive parameter than can be obtained after detailed calibration of the model.

For the climate rationale, the NASA-NEX-GDDP climate projections are used as input for the hydrological model following a delta-change approach as described in 3.2.2. In this way the hydrological impact of climate change on the hydrology can be quantified. For the analysis, the hydrological outputs are used to calculate decision support indicators (DSI) that reflect the relation between climate change and the issues as described in Chapter 1. For each issue, specific DSIs are calculated. In Table 3-2 an overview of the selected decision support indicators is presented.

Table 3-2 Overview of selected Decision Support Indicators (DSI)

Issue	Parameter	Decision Support Indicator (DSI)
Drying up of springs	Mean annual precipitation	% change
	Number of consecutive dry days	Statistics of the annual maximum values
	Average recharge per spring watershed	Statistics of the annual minimum values
	Spring discharge	Statistics of the annual minimum values
Extreme events	Extreme rainfall above 30 mm/day	Number of days per year
	Discharge per location of interest	Statistics of the annual maximum values
	Soil erodibility	Mean soil erodibility over the study area
	Suspended sediment concentration	Mean annual suspended sediment concentration
Snow and glaciers	Basin average snow coverage	Percentage of time with snow coverage

3.2.4 Sediment impact assessment

Apart from hydrological impacts, also impacts on soil erosion and sediment transport are assessed. There is a link between soil erosion and intense rainfall and thus potentially with climate change. To assess this impact, a soil erosion and sediment transport model is used which is forced by the hydrological model. Relevant variables (including river flow, overland flow, interception evaporation) which are simulated as outputs of the hydrological model are used as input for the sediment model. The wflow_sediment model is described in detail in Boisgontier and Van Gils (2020.

The soil erosion and sediment transport models are setup using the same global datasets as were used for the hydrological assessments described above. No data was available for calibration or validation of the sediment model. Therefore, the model is setup using the standard parameter values that are derived from land cover and soil property datasets[5].

For determining the impact of climate change on soil erosion and sediment transport, only a small set of scenarios is run: a reference, a dry scenario and a wet scenario as described in Section 3.2.2.

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[5] https://github.com/Deltares/hydromt_wflow/blob/main/hydromt_wflow/data/lulc/vito_mapping.csv

3.3 Detailed approach for assessment of drying up of the springs

To improve the robustness of the assessment of the causal link between climate change and spring dry-up, modelling results are combined with a qualitative survey of alternative potential causes of drying up of the springs (such as earthquakes or land degradation).

The main storyline for linking the drying up of the springs to climate change is to investigate the general patterns across an ensemble of springs. For an individual spring there might be specific reasons for drying up, but as shown by WMDMAF (2021), there are several zones where many of the springs are drying up at the same time. It is deemed unlikely that for all these springs at the same time something specific (landslide, earthquake, etc.) is happening. A change at the larger system scale is deemed more likely.

For the link with land degradation and drying up of the springs, a literature study accompanied with a qualitative data assessment using FAOs Earth Map is conducted. The literature research focusses on publications on land cover changes and land degradation specifically in Bhutan. In Earth Map an indicator specifically looking into land degradation is used, the Land Productivity Dynamics (LPD, Garcia et al., 2021). A screenshot of EarthMap is shown in Figure 3-14.

The link between spring discharge and earthquakes is based on the report of WMDMAF (2021) and additional literature review. Also, for landslides the WMDMAF (2021) report is the starting point. Furthermore, an assessment of the road network combined with the spring locations is done to assess the potential impact of road construction and potentially landslides on the spring discharge.

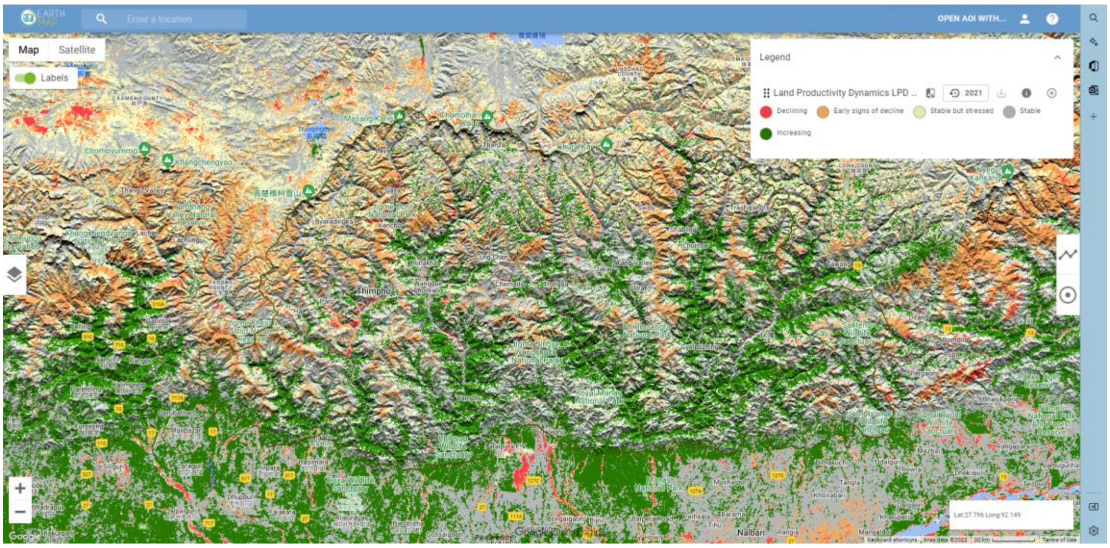

Figure 3-14 Screenshot from EarthMap showing the Land Productivity Dynamics indicator for Bhutan.

The final step in the climate rationale is to look at the adaptation options. There are basically two types of interventions that are considered:

1 Increase the water storage capacity, for example by implementing rainwater harvesting at community level
2 Increase spring water availability by increasing the groundwater recharge in the watershed, for example through nature-based solutions. These measures may include payment for ecosystem services, soil enhancement measures, agroforestry, terracing or forest restoration, which further contribute to the continued conservation effort and sustainable forest management in Bhutan.

Both options are implemented in the model differently.

Figure 3-15 Example of a water storage tank linked to the roofs to store rainwater in Bhutan.

The increased storage capacity is typically applied at the very local scale, beyond the level of detail of the model. Therefore, a simple water balance model is setup that simulates the filling and emptying of the rainwater harvesting systems for the area of Kengkhar, which is one of the villages that was visited during the fieldwork of May 2022, using the rainfall inputs from the historical and future climate projections.

Furthermore, we use the hydrological wflow_sbm model to quantify the impact of nature-based solutions which aim to increase the groundwater recharge and therefore the spring discharge. Several soil or land use related model parameters can be changed in the hydrological wflow_sbm model to represent the implemented measures. Reducing the slope of the land is an option to slow down the lateral surface runoff. Another option is to increase the surface roughness, which will also slow down the. surface runoff. While both these changes slow down the surface runoff, they do not directly impact the groundwater recharge. Alternatively, the saturated hydraulic conductivity parameter can be increased to increase the groundwater recharge by increasing the rate of water movement through the soil in vertical and horizontal directions. This last option is implemented in the model to represent nature-based solutions aimed to increase the groundwater recharge. This is discussed in more details in Chapter 6.

The selection of the best options to simulate these nature-based solutions is both based on the selected adaptation options as well as on the suitability of the model and the data to mimic these processes best.

Figure 3-16 Examples of methods to improve recharge capacity in a spring watershed. The examples show different methods: To slow down the surface runoff (top row) or capture the surface runoff water in small ponds for infiltration (bottom row).

3.4 Detailed approach to assess the impact for extreme rainfall events

For assessing the potential of adaptation measures for extreme (flash) flood events a detailed study is done on Trashiyangtze. This was one of the locations that was reported to have recently experienced fatal floods from a small stream running through town. To assess the impact of climate change and potential adaptation options, a hydrodynamic flood model is developed. This model can be used to assess water levels and potentially the flood area for given extreme event scenarios, as well as to test adaptation options such as in-stream check dams. Screenshots of the current model schematization are shown in Figure 3-17 and Figure 3-18. The software used to prepare the model is the Delft3D-1D2D Suite[6].

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[6] https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/

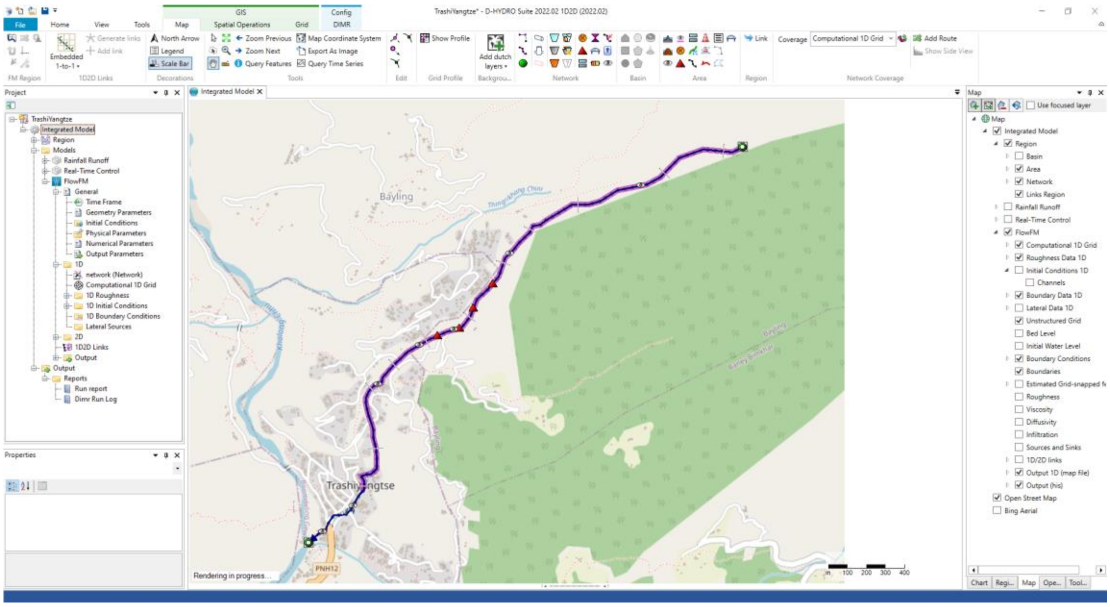

Figure 3-17 Screenshot of the hydrodynamic model schematization for a small stream in Trashiyangtze using Delft3D-FM. The figure shows the top view of the model, with in blue highlighted the river that is modelled to simulate flood events.

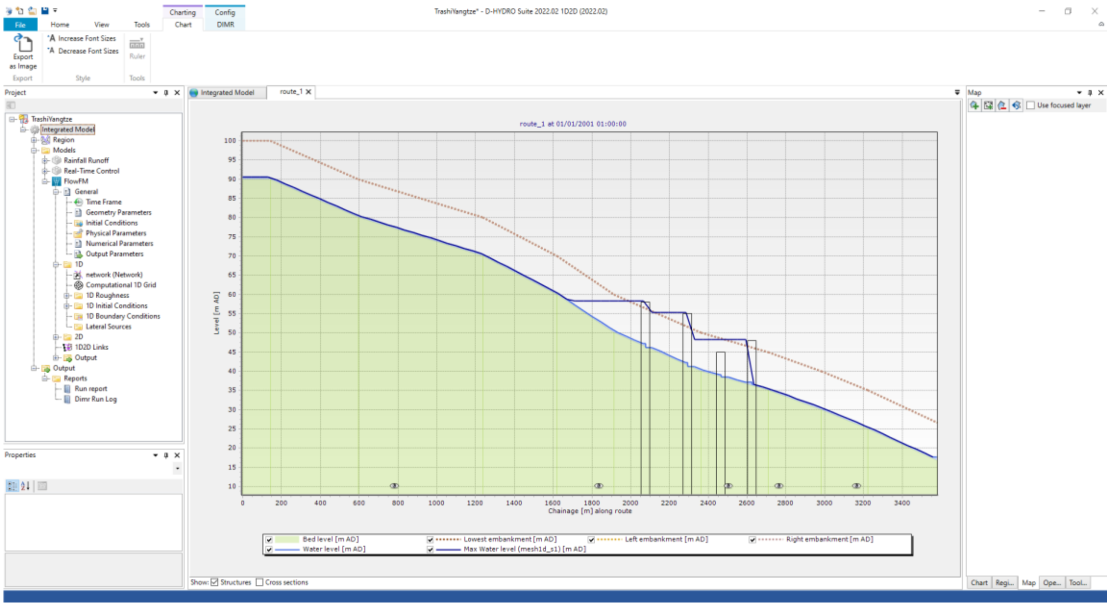

Figure 3-18 Longitudinal profile of the hydrodynamic model for a small stream in Trashiyangtze using Delft3D-FM. The figure presents the longitudinal profile of the river (green), the water table (blue) and some check-dams (black rectangles) that can be implemented as adaptation options.

The current model is setup using global and dummy data. Some first rough estimates of cross-section profiles were prepared during a field visit in May 2022 (see Figure 3-19), but more detailed data collection is required to further improve the model and its usability for assessing climate impacts for extreme events in Trashiyangtze.

Figure 3-19 Field inspection of the river profile upstream of Trashiyangtze.

The model is used to simulate current flood impacts, as well as to test different adaptation options. Adaptation options include the building of check dams along the stream, to reduce the flood peak further downstream.

4 Climate trends and projections

4.1 Historical trend analysis

Global studies on historical climate trends have shown increasing temperatures around the world. A commonly used method to present these trends is the warming stripes representation in which each year is reduced to a single tripe of a “bar code” and the color indicates warmer or colder than average. An example of such a representation of the warming climate over Bhutan is shown in Figure 4-1, based on global re-analysis data.

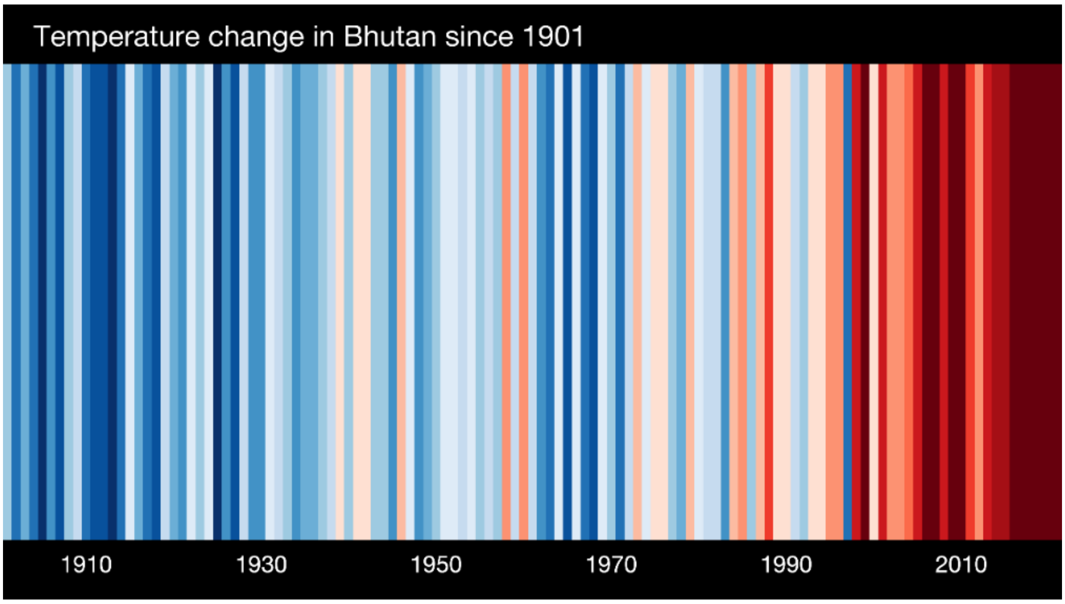

Figure 4-1 The warming stripes for Bhutan (https://showyourstripes.info/l/asia/bhutan)

In Figure 4-2 the annual anomalies in the observed annual average temperature in the ERA5 dataset over the Drangmecchu basin are shown also in a spatially more detailed manner. Each subplot represents a year in a 40-year timeframe, starting at 1980 at the top left and ending in 2020 on the bottom right.

As can be seen, there is a clear pattern of warmer years towards the end of the 40-year period. Especially the last 10 years seem to be (much) warmer compared to the long-term average. The patterns in the simple warming strip example and the more detailed example for the Drangmecchu basin

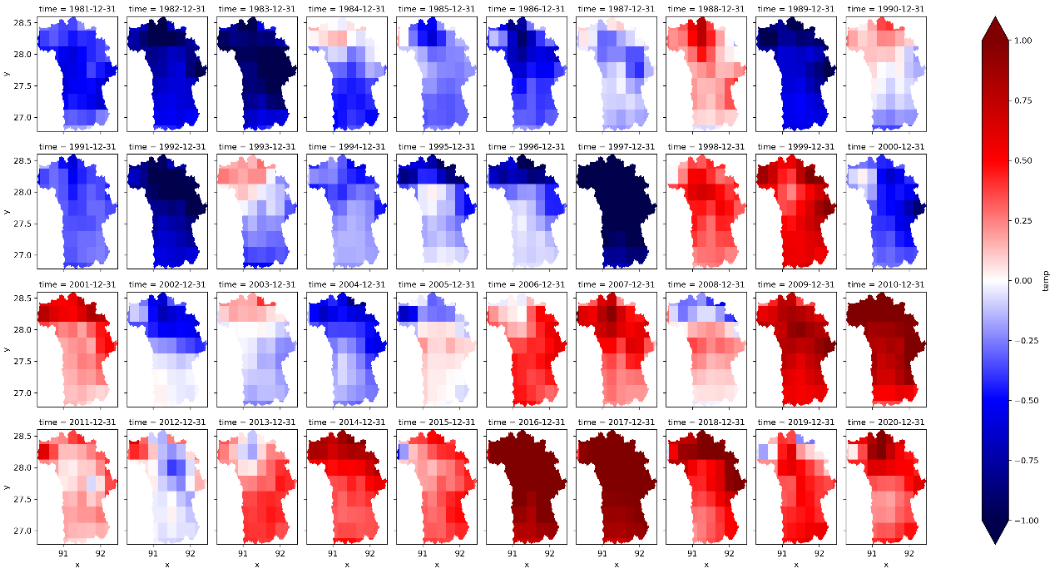

Figure 4-2 Anomalies in the annual average temperature (°C) for each year in the 40-year ERA5 dataset. Red means this year is warmer compared to the long-term average, blue means colder than the long-term average.

In Figure 4-3 the same analysis is shown for precipitation. For the first 30 years, there is no clear pattern observed, with wetter and dryer years following each other. For the last 10 years (i.e. the last row in the figure) consistently drier years are shown compared to the 40-year average of the dataset.

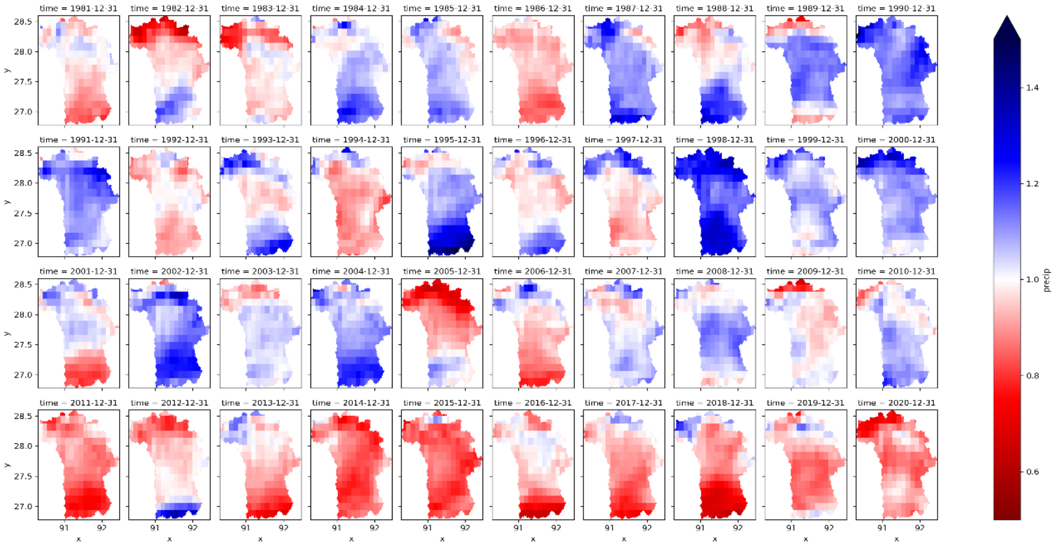

Figure 4-3 Anomalies in the annual average precipitation [-] for each year in the 40-year IMDAA dataset. Red means this year is dryer compared to the long-term average, blue means wetter than the long-term average.

A trend of the spatial mean values as shown in Figure 4-2 and Figure 4-3 is calculated and shown in Figure 4-4 both for temperature and precipitation. For temperature there is a positive trend with an average of 0.03 °C/year, which means an increase in temperature of 3 °C over 100 years. For the rainfall the trend depends on the selection of the time interval, showing a decrease of rainfall of around 0.4%/year over 1980-2020. The trends for both temperature and precipitation are significant, given the very low p-values (<0,005)

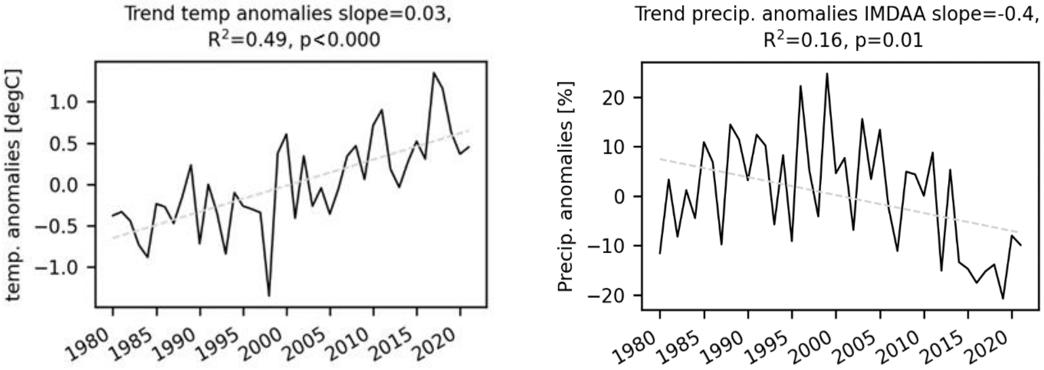

Figure 4-4 Basin average trend in the annual average temperature anomalies (left figure) and annual average precipitation anomalies (right).

Next to the climate data, also the trend in the observed discharge data for two stations, Kurizumpa and Uzrong is calculated. If indeed rainfall is going down and temperature is going up, resulting in higher evapotranspiration, a negative trend in the discharge is expected. Indeed, for both stations a negative trend in the discharge is visible with a similar slope as was observed in the temperature and precipitation anomalies. However, it should be noted that the trend in the streamflow is not significant as indicated by the p-value being larger than 0.05, which contrasts with the significant trends for precipitation and temperature.

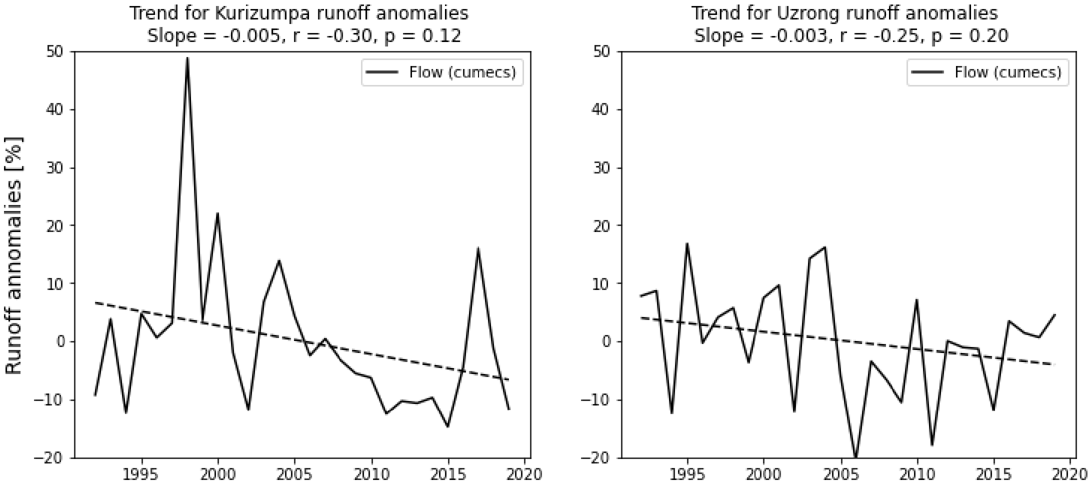

Figure 4-5 Trend in the annual average runoff anomalies at Kurizumpa (left figure) and Uzrong (right).

The increase in temperature and potential evaporation in combination with a decrease in precipitation results in a decrease in modeled streamflow with a trend of around -0,5% per year averaged over all the spring locations, as is shown in Figure 4-6. Especially for the last 10-20 years the simulated spring discharge changes sign since the late ‘90s. Also for the main hydrological gauging stations the trend shows a decrease, albeit less strong compared to the spring discharges (see Figure 4-7).

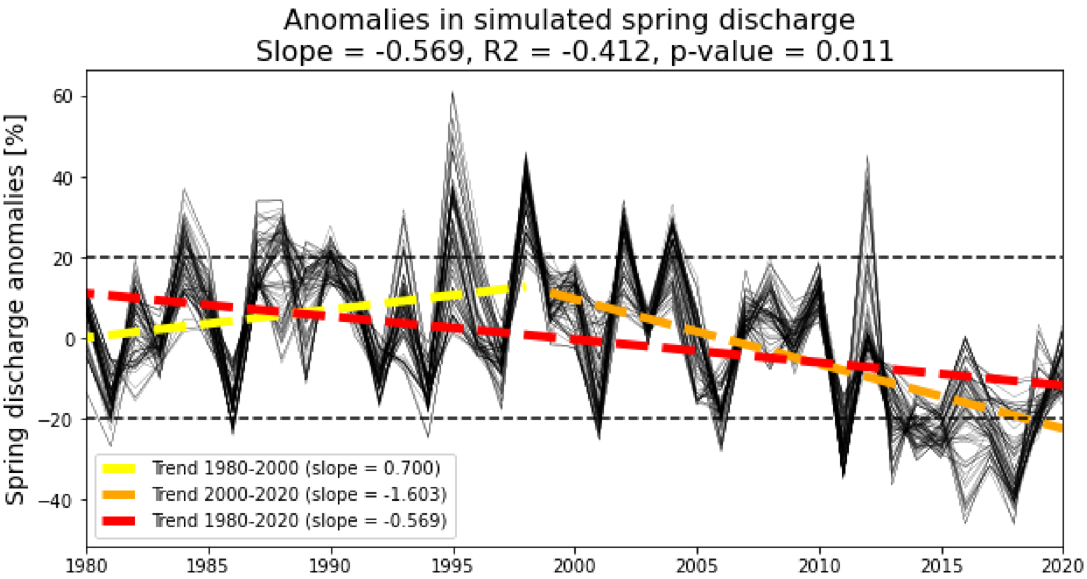

Figure 4-6 Trends in anomalies in the simulated spring discharge.

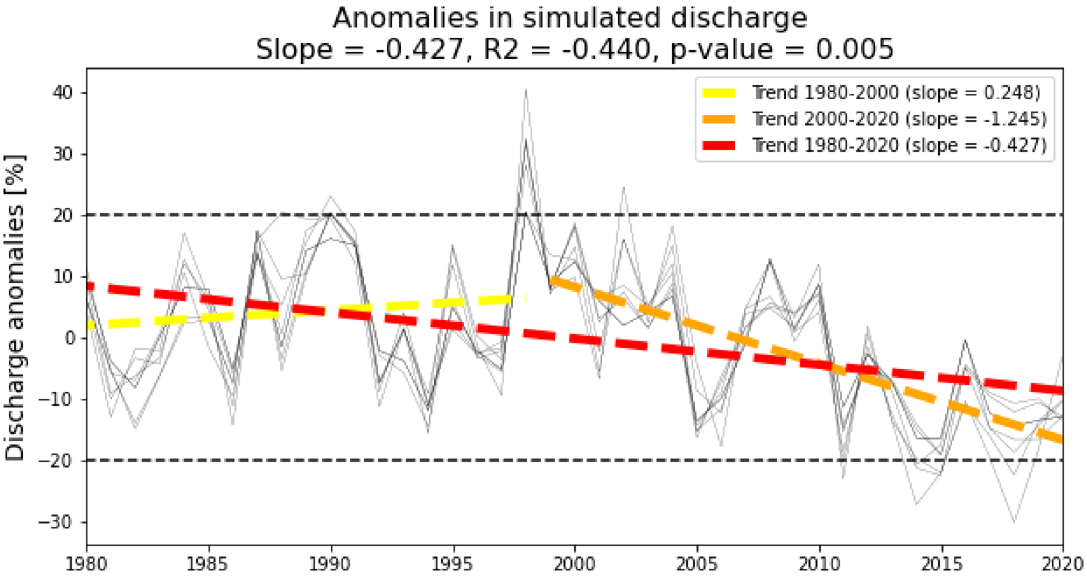

Figure 4-7 Trends in anomalies in the simulated discharge at the main hydrological gauging stations.

4.2 Future climate projections

The NASA-NEX-GDDP dataset (referred to as NASA) based on CMIP6 data projects an increase in mean annual temperature for all climate models and SSPs for the near and the far future ranging from +1°C to approximately +6°C on average over the study area (Figure 4-8). Mean annual precipitation is projected to increase for the far future by up to 25%. However, both an increase and a decrease in precipitation are projected for the near future (Figure 4-8). This contrasts with the CMIP5 projections, in which all scenarios projected an increase in mean annual precipitation for the near and the far future (Figure 4-8). Moreover, CMIP5 projects a structurally higher precipitation increase per degree warming (~10% $°C^{-1}$) with a lower confidence level (more spread between models and scenarios) compared to CMIP6 which displays a lower increase in precipitation per degree warming (~3% $°C^{-1}$) with a higher confidence level.

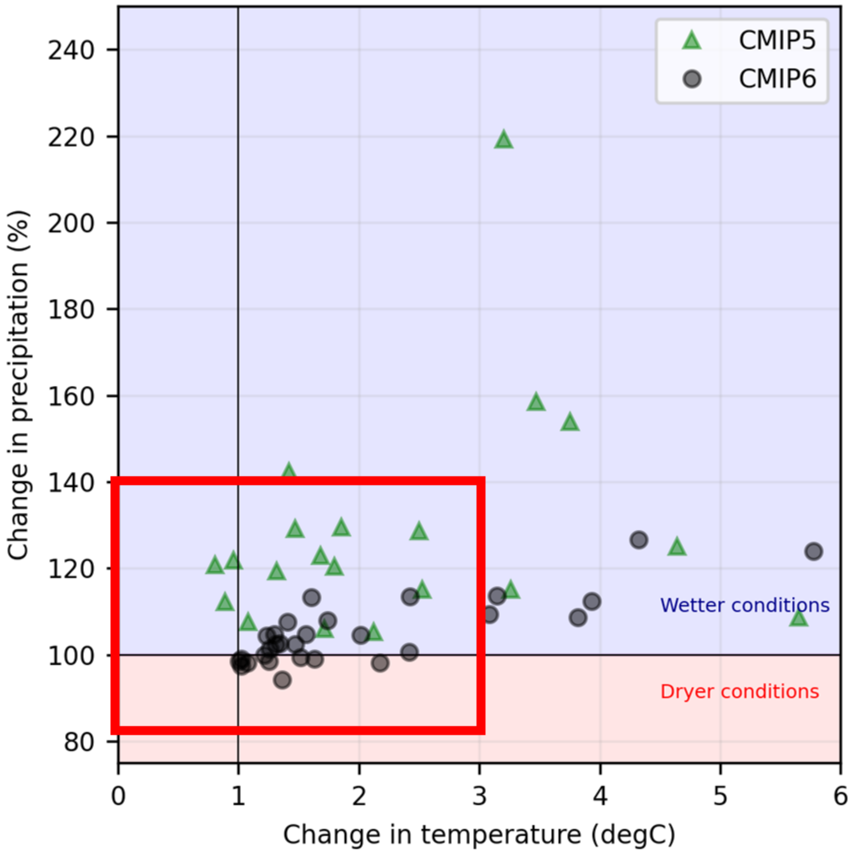

Figure 4-8 Comparison of CMIP5 and CMIP6 datasets in terms of average change in temperature and precipitation over the basin.

The disagreement on the change in mean annual precipitation amongst models and scenarios (SSPs), and the spatial variability of change is shown in Figure 4-9 for the near future. Depending on the selected model and scenario, the mean annual precipitation increases or decreases. Overall, the increase in precipitation is higher in the Northern part of the basin.

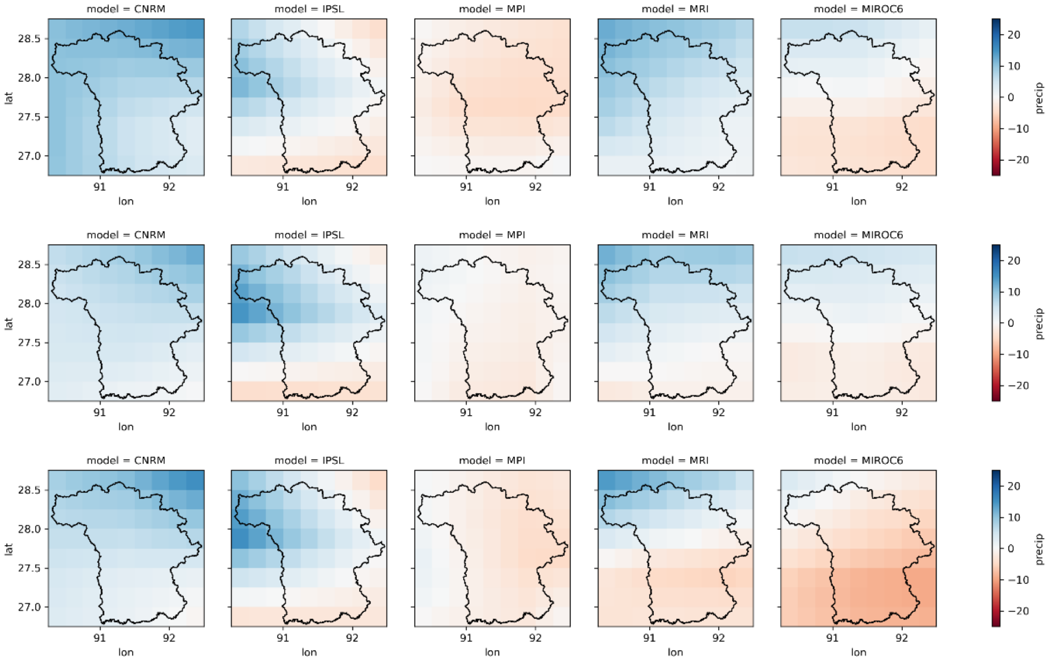

Figure 4-9 Percentage change in precipitation for the near future for the different GCMs, where the first row is ssp126, the second row is ssp245 and the third row is ssp585. Blue colors indicate a projected increase in precipitation, whereas red colors indicate a projected decrease in precipitation.

In Figure 4-10, the change in precipitation and temperature compared to the long-term historical mean is shown for the near and the far future periods for the three SSPs. As explained in Sect. 3.2.2, the change in climate is evaluated for three regions to represent high-altitude areas in the North, mid-altitude areas in the center and lower altitude areas in the South.

Mean annual historical temperature based on ERA5 in the northern, center, and southern regions is -3°C, 6°C and 14°C respectively. An increase in temperature is projected by all models for the near and the far future, ranging from approximately 1°C for the low emission scenarios (SSP126), till a staggering 7°C increase for the high emission scenarios (SSP585) for the far future (period 2071-2100). The increase in temperature over the northern, center, and southern regions is not the same. The temperature at higher altitude is projected to increase more, compared to the lower altitude regions, which is likely to influence snow patterns substantially (Figure 4-10). Conversely, disappearance of snow/glaciers will likely be an explanation of the strong altitude effect of regional warming.

Historical annual precipitation in the north, center and southern regions is approximately 1300 mm yr^{-1}, 2300 mm yr^{-1} and 4000 mm yr^{-1}, respectively for the period 1981-2010 based on the Indian Monsoon Data Assimilation and Analysis (IMDAA) dataset (Rani et al., 2021). For the future climate projections, the different climate models, and scenarios (SSPs) project a moderate increase in precipitation per degree warming (~3% °C^{-1}).

For the near future, the climate models show a large inter-annual variability (approximately ranging between -15% and +15%) but a weak climate signal, as shown in Figure 4-10. The decreasing trend of precipitation over the last 40 years (-16%), which was shown in the trend analysis of Sect. 3.2.1, already causes problems at the watershed scale (e.g. reports of springs drying up). Therefore, climate adaptations are needed to cope with up to -15% less rainfall every few years before the increasing trend begins in the mid-century.

It is interesting to note that the observed trend of decreasing precipitation in the historical data record over the past ten years is not reflected in the climate projections for the near or the far future.
The changes in precipitation over the different elevation zones are not the same. Precipitation at higher altitude is projected to increase more (4% ± 15%, median and standard deviation for SSP245 in the near future), compared to the lower altitude zones (-2% ± 13% for SSP245 in the near future), as shown in Figure 4-10. For the far future, the climate signal is more pronounced with projections mainly showing increasing precipitation amounts.

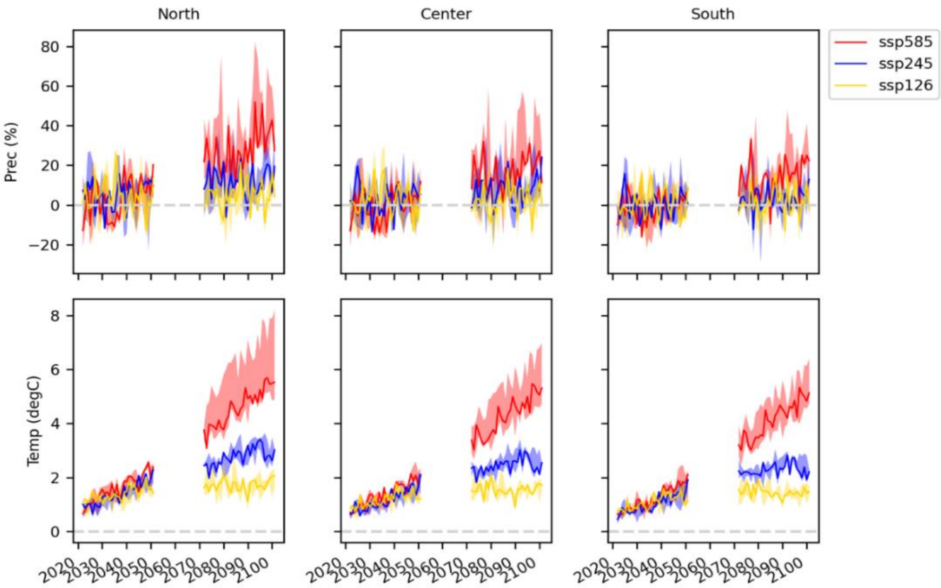

Figure 4-10 Change in median annual precipitation (top panel) and median annual temperature (bottom panel) for three representative areas in north (left column), center (mid column) and south (right column) for three SSP scenarios. The thick lines represent the 5 GCM's median and the shaded area is the min-max uncertainty band across the 5 GCM's. Results are split for the near and far future. When the plotted data is above the horizontal grey dotted line, it indicates higher precipitation and temperature than the long-term historic mean.

The data shown in Figure 4-11 is summarized in Figure 4-11, which shows that the mean annual precipitation increases by 9.5%, 7.7% and 4.9% per degree increase in temperature for the northern, center and southern regions respectively.

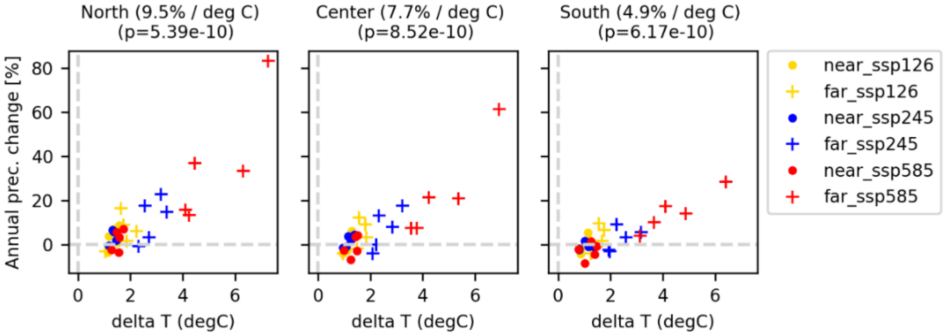

Figure 4-11 Change in annual precipitation [%] as a function of regional temperature change (deg C) for three representative areas in the North, Centre and South. Each dot represents a model. The colours and symbols show the difference in future horizon and SSP. The slope of the linear regression through the points indicates the percentage change precipitation per degree C increase in temperature and the corresponding p-value is also indicated for each region.

For the near future, an increase in temperature is projected, and therefore also an increase in potential evaporation, while no strong climate change signal is projected for precipitation (Figure 4-11). In terms of streamflow, we therefore expect to have, both, scenarios which project an increase and a decrease. These changes in meteorological variables are expected to substantially decrease the average snow accumulation over the study area. Detailed results of the hydrological impact assessment are provided in Sect. 5.

In addition to mean annual changes in temperature and precipitation, several other climate indicators have been evaluated to describe specific aspects of future climatic changes with respect to historical conditions. The indicators include changes in seasonality of precipitation amounts, number of days with temperature below 0°C and above 20°C, length of consecutive dry days and the frequency of very heavy precipitation events (above 30 mm d^{-1}). Each of them is described in more detail below.

4.2.1 Seasonality

The comparison of mean monthly precipitation for the historical and projected near and far future reveals similarity in precipitation seasonality (Figure 4-12), although the amounts of precipitation per month may differ considerably for the far future and the most extreme scenarios. Therefore, seasonality, in terms of mean monthly precipitation patterns, does not change substantially, but the absolute values of precipitation do change for the most severe scenario for the far future. However, changes in the seasonality in terms of the start of the rainy season or the start of the growing season have not been evaluated in detail.

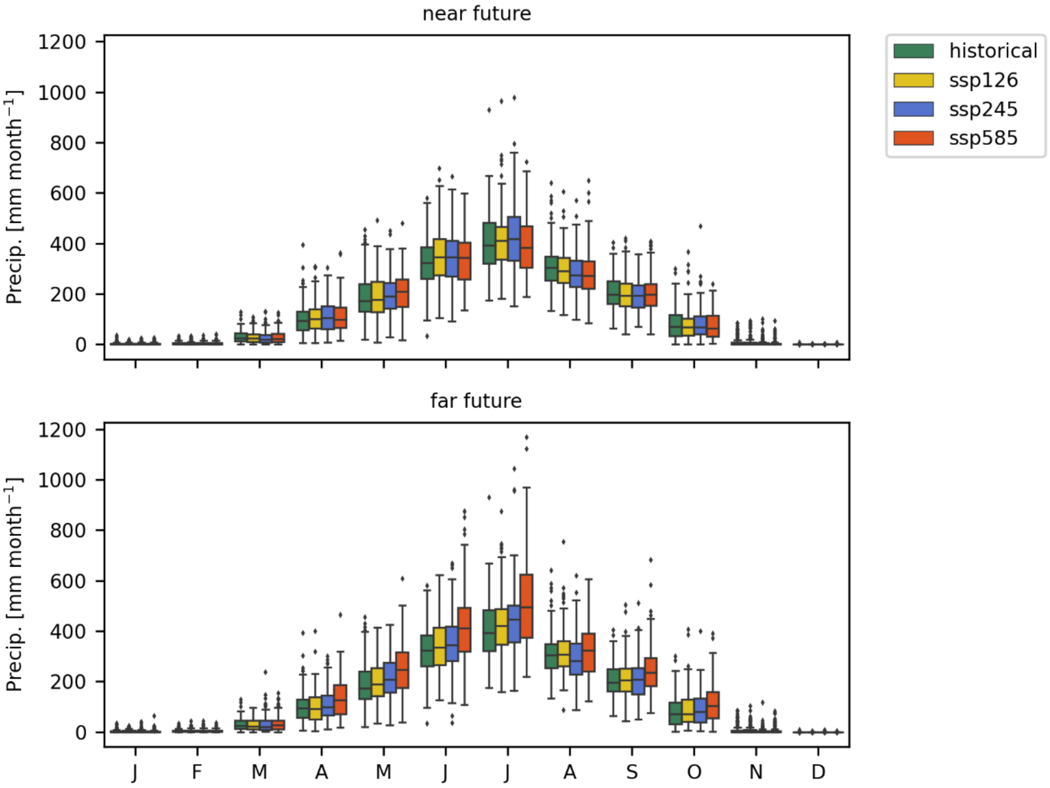

*Figure 4-12 Mean monthly precipitation (mm month^{-1}) for the historical period and future projections for each SSP scenario across the 5 GCM's. The height of the boxplot indicates the variability in the GCM projections (30 years of monthly values * 5 GCMs).*

4.2.2 The annual number of days with temperature below 0°C and above 20°C

The seasonal pattern of streamflow is likely to be affected by the changing number of days with temperature below 0°C, due to changes in snow processes.

As can be seen in Figure 4-13, the number of days with temperature below 0°C substantially decreases especially in the northern region, where it is projected to decrease by 15% ± 10% (median and std) under SSP245 in the near future and drastically decrease in the far future for the most severe scenario SSP585.

With increasing number of days with temperature below freezing point, it is expected that precipitation will not as much accumulate as snow but rather runoff directly, likely increasing the baseflow of the main rivers during the winter months. This is further discussed in the results of the hydrological impact assessment in Sect. 5.

In contrast, the number of days with temperature above 20°C is projected to increase in the Southern region in the near future under SSP245 (13% ± 10%) and more substantially in the far future (36% ± 11%). An increase in number of days with temperature above 20°C in the southern region may affect spring water availability through increased potential evaporation.

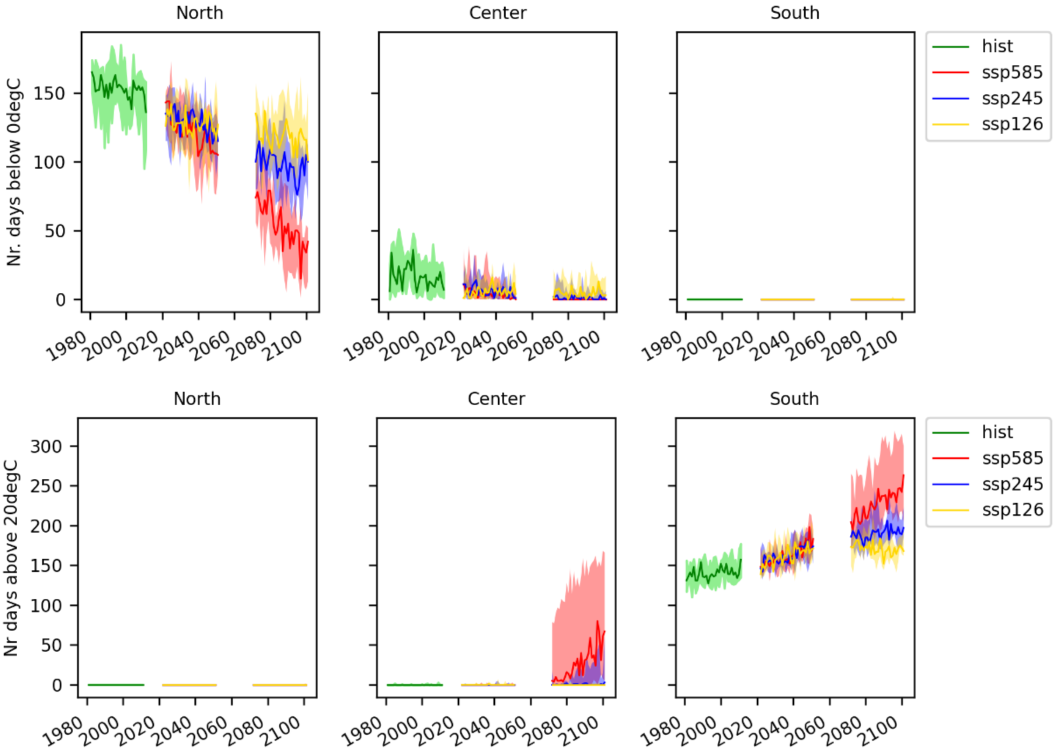

Figure 4-13 Annual number of days with temperatures below 0°C and above 20°C for the three geographic regions and across climate scenarios for the near and far future. The thick line represents the median and the shaded area is the min-max range across the 30 years and 5 GCMs.

4.2.3 The annual maximum length of consecutive dry days

The annual maximum number of consecutive dry days is projected to increase in the future, especially in the northern and center regions (Figure 4-14). However, the uncertainty across climate models is large, especially for the center and southern regions.

The maximum number of consecutive dry days is projected to change by 7% ± 20%, 8% ± 28%, -2% ± 30% (median and std) for the northern, center, and southern regions, respectively, for SSP245 in the near future.

For the far future and SSP245, projected changes are 6% ± 19%, 11% ± 28%, 6% ± 28% (median and std) for the northern, center, and southern regions, respectively, which are not substantial differences between regions.
Furthermore, Figure 4-15 shows that there is no significant relation between the increase in the annual maximum length of consecutive dry days and the increase in temperature. The changes in the length of consecutive dry days shown in Figure 4-14 are therefore a reflection of the strong climate variability rather than the climate change signal.

The large climate variability in the length of consecutive dry days may impact the lowest flows of springs and impact adaptation measures related to local water storage at the community level. This is further elaborated in Sect. 5.

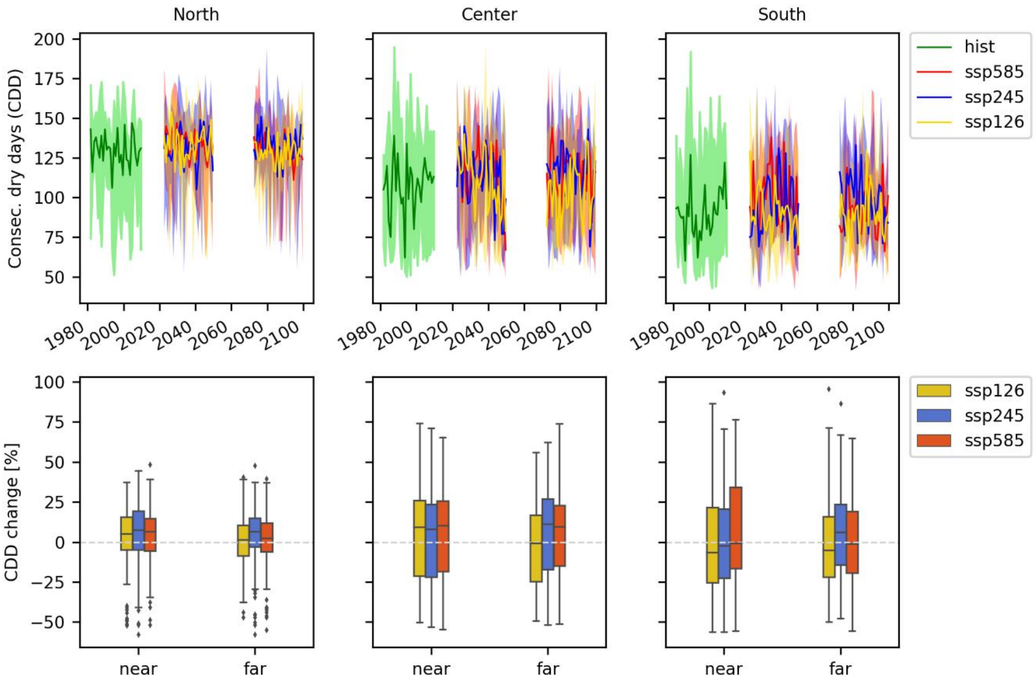

*Figure 4-14 Top: Annual maximum number of consecutive dry days for historic conditions and projected near and far future conditions for the different scenarios across GCMs for the North, Center and South areas. The line represents the median and the shaded area is the min-max range across the 5 GCMs for the 30 years. Bottom: Percentage change in the annual maximum number of consecutive dry days for the North, Center and South areas for the near and far future. The width of the boxplot represents 30 years for each of the 5 GCMs (30*5 years).*

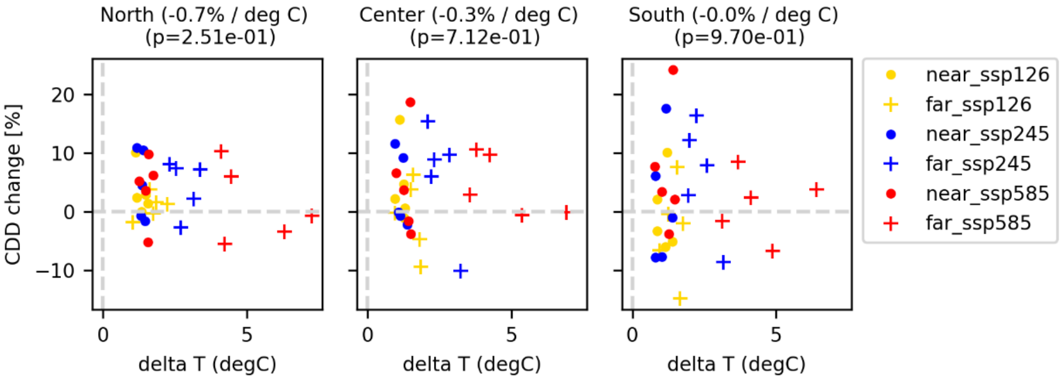

Figure 4-15 Change in annual maximum length of consecutive dry days [%] as a function of regional temperature change (deg C) for three representative areas in the North, Center and South. Each dot represents a model. The colors and symbols show the difference in future horizon and SSP. The slope of the linear regression through the points indicates the percentage change in CDD per degree C increase in temperature and the corresponding p-value is also indicated for each region. As the p-values are higher than 0.05 for each of the regions, we can conclude that there is no significant trend in the change of the annual maximum length of consecutive dry days as a function of regional temperature change.

4.2.4 The frequency of very heavy precipitation events (above 30 mm d^{-1})

The annual number of days with very heavy precipitation of above 30 mm d^{-1} is projected to increase in the near future mainly in the central region. However, also here, the variability across GCMs is large (Figure 4-16).

The number of days with precipitation above 30 mm d^{-1} is projected to change by -9% ± 97%, 15% ± 62%, 2% ± 43% (median and std) for the northern, center and southern regions, respectively, for SSP245 in the near future.

For the far future and SSP245, projected changes are 37% ± 119%, 26% ± 78%, 14% ± 44% (median and std) for the northern, center and southern regions, respectively.

Figure 4-17 shows that the number of very heavy precipitation events increases by 53.5%, 36.6% and 22.5% per degree increase in temperature for the northern, center and southern regions respectively.
The higher frequency of very heavy precipitation events is likely to increase erodibility of the soil and increase sedimentation loads in the rivers. Moreover, more frequent intense precipitation events are likely to also increase the risk of flash floods and landslides.

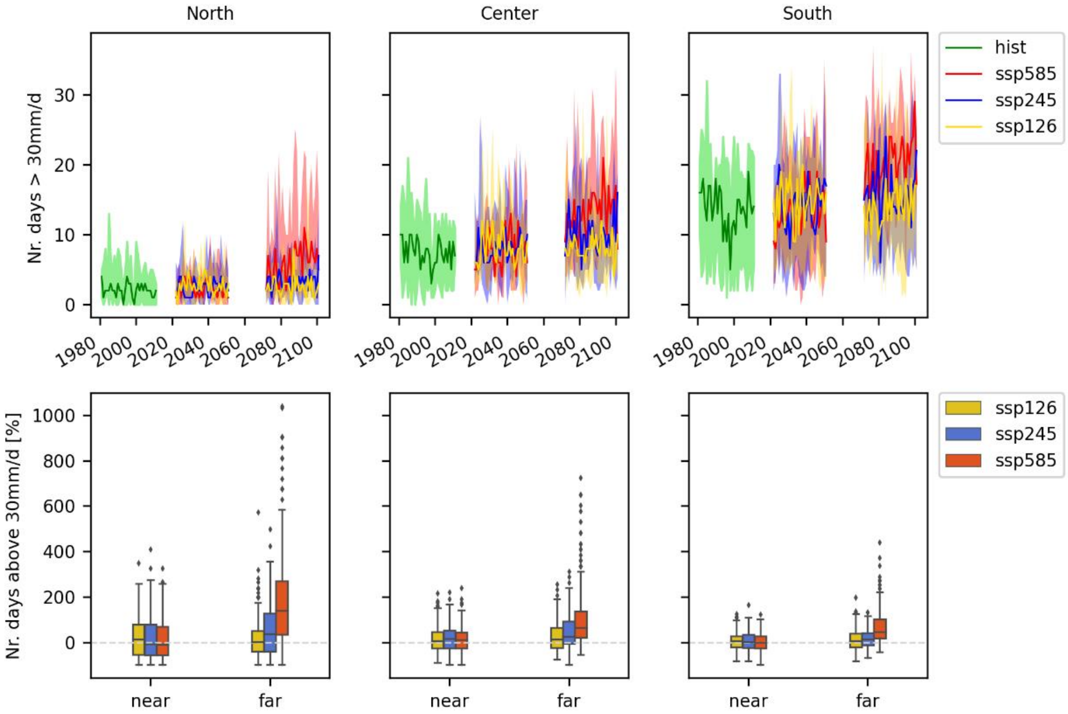

Figure 4-16 Top: Annual number of days with very heavy precipitation (>30 mm d^{-1}*) for historic conditions and projected near and far future conditions for the different scenarios across GCMs for the North, Center and South areas. The line represents the median and the shaded area is the min-max range across the 5 GCMs for the 30 years. Bottom: Percentage change in the annual number of days with very heavy precipitation for the North, Center and South areas for the near and far future. The width of the boxplot represents 30 years for each of the 5 GCMs (30*5 years).*

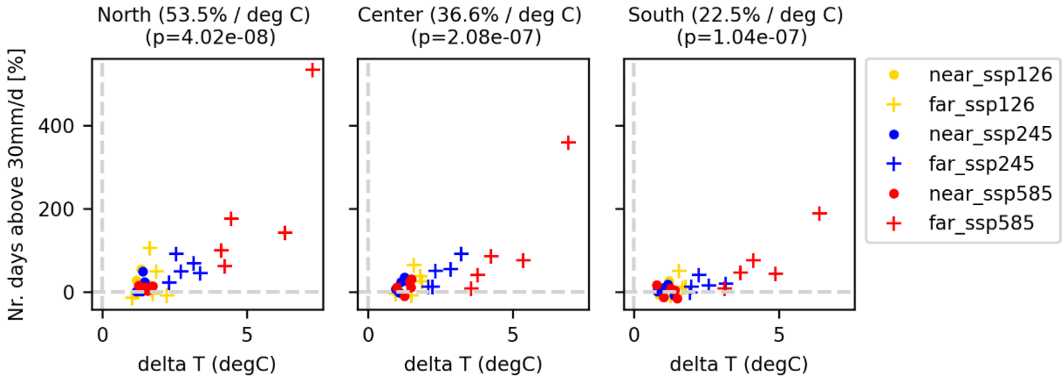

Figure 4-17 Change in annual number of days with very heavy precipitation events [%] as a function of regional temperature change (deg C) for three representative areas in the North, Center and South. Each dot represents a model. The colors and symbols show the difference in future horizon and SSP. The slope of the linear regression through the points indicates the percentage change in very precipitation events per degree C increase in temperature and the corresponding p-value is also indicated for each region.

The climate projections are subsequently used as input to run the hydrological model, which allows us to evaluate their impact on the water resources. These results are discussed in the next chapter.

5 Hydrological impact assessment

5.1 Drying up of springs

First the detailed report of the Bhutan government on Spring Water Resources Mapping is used as input for the analysis. This extensive data collection effort provides lots of information on the status of the springs, country wide and per Dzongkhag (see Figure 5-1). At this moment, around 25% of the springs is reported to be drying up or already dried up. The report also provides indications on the reason for drying up of the springs. For 36,5% of the springs, climate change is being indicated as being the major reason for the springs drying up (see Figure 5-3). This makes climate change the biggest contribution, followed by land degradation (28%, and see Figure 5-2) and anthropogenic changes (7,3%).

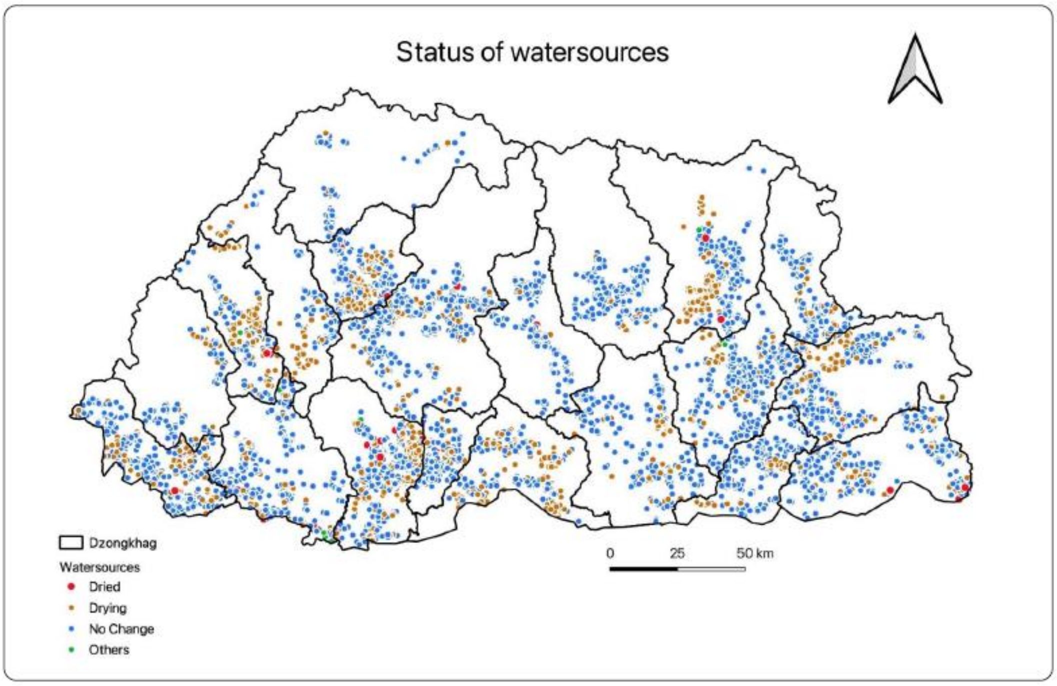

Figure 5-1 Status of the springs in Bhutan (source: WMDMAF, 2021).

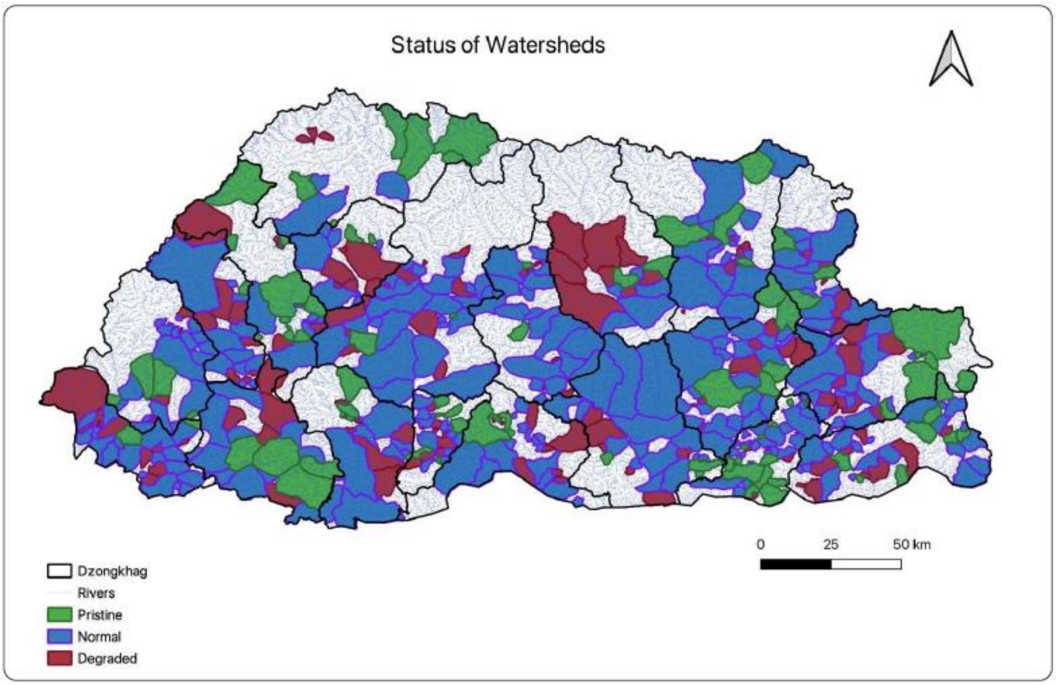

Figure 5-2 Status of the spring watersheds in Bhutan, mapped over the period 2017-2018 (source: WMDMAF, 2021).

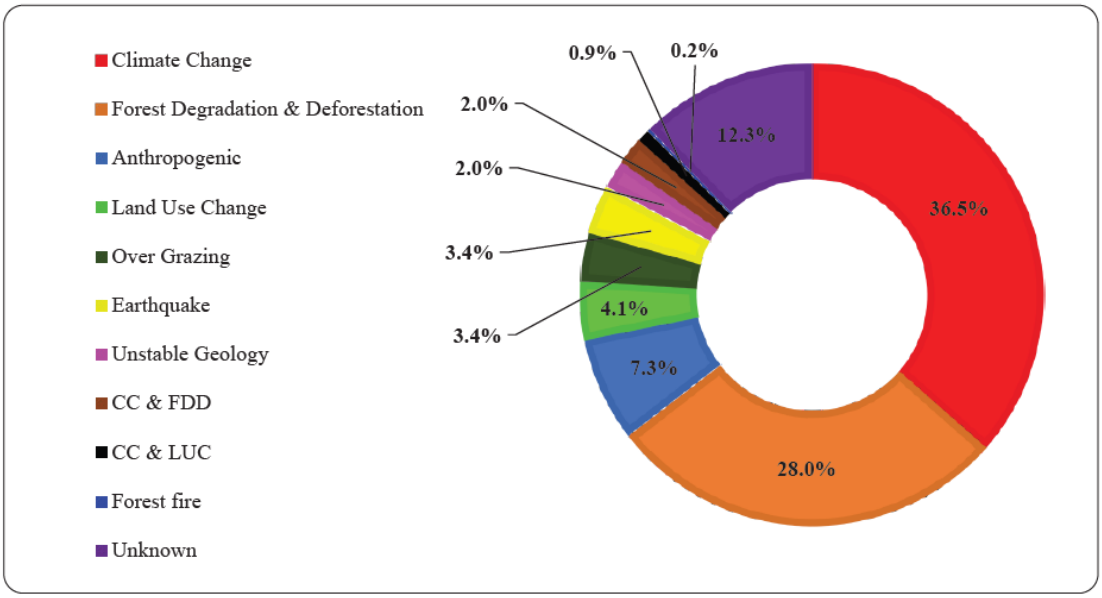

Figure 5-3 Overview of causes linked to the drying up of the springs in Bhutan (source: WMDMAF, 2021).

As mentioned before, instead of looking at individual springs, the assessment is done over larger areas. By looking at these larger zones the total water balance is shown to change (i.e. there is less water coming out of this zone). The main fluxes in the water balance are the influx of water through rainfall, the outflux of water through evapotranspiration and the outflux of water through the spring discharge. Climate influences directly two of these fluxes (rainfall and evapotranspiration), depending on the rainfall sign either reducing or increasing the outflow flux. The result is that the discharge at many springs is reduced and will further reduce with climate change. This is shown in Figure 5-4, where it is shown that most climate scenarios project a further decrease of the low flows at the spring locations.

It is relevant to state that climate change does have a strong spatially varying signature, and the mean climate change signal is obscured by considerable (spatially varying) internal variability. How this impacts every spring individually depends strongly on the climate signal and the corresponding spatial variability.

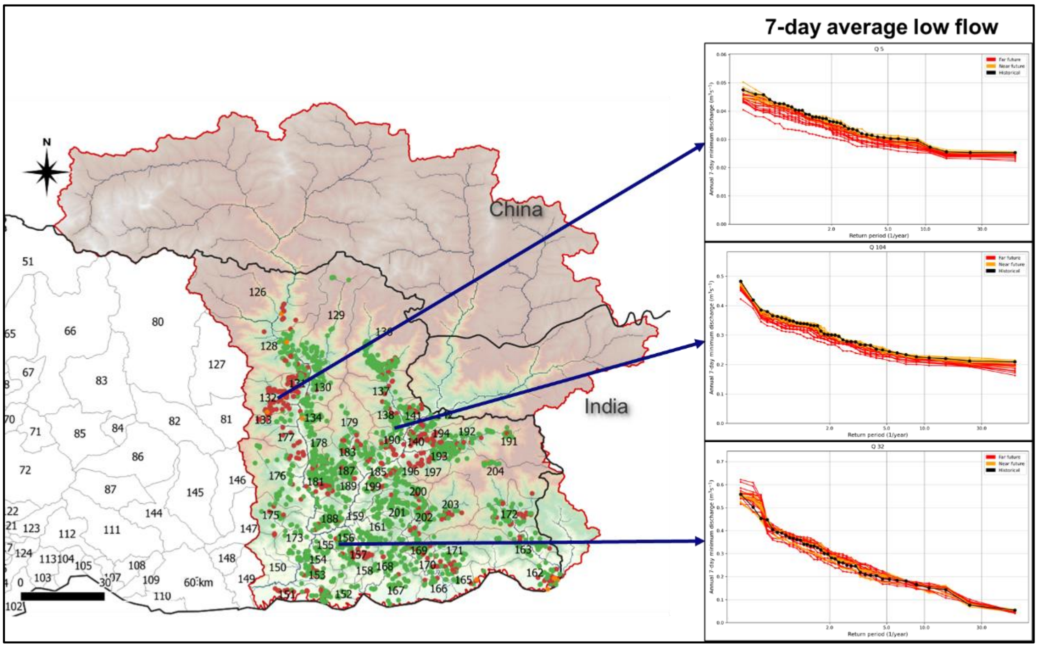

Figure 5-4 Observed and project 7-day average low flow for selected springs across Bhutan.

One indicator that can be linked to the drying up of springs is the actual recharge into the soil. In Figure 5-5 maps of simulated change in mean recharge compared to the historical simulation for a dry and a wet scenario are shown. These figures show that in general, the dry scenario shows (much) lower recharge compared to the historical simulation, whereas the wet scenario shows more recharge. When looking in detail, however, it can also be observed that the changes are not uniform. There are regions, or recharge zones, that show a decrease in recharge even in the wet scenario, or vice versa. This could be explained by the fact that the actual recharge depends on many factors, such as the amount of rainfall, the rainfall intensity, the amount of evaporation and the physical characteristics of the land. From the results presented in Figure 5-5 it can be concluded that there is a strong consensus that climate change is impacting recharge and most probably in the way that is reduced recharge over larger areas. Local increase of recharge due to climate change, however, might also be possible, which is most probably directly linked to the increased rainfall amounts that are being projected.

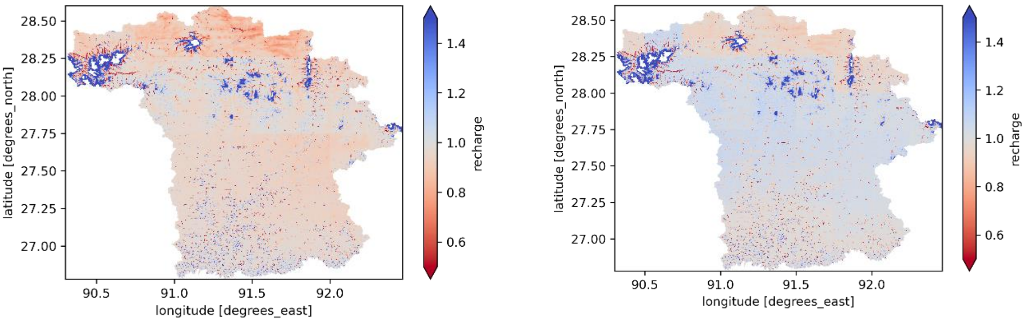

Figure 5-5 Changes in simulated recharge over Bhutan for a relatively dry scenario (left) and a relatively wet scenario (right)

As the report of the WMDMAF already points out, earthquakes are considered only a minor contribution to the springs drying up in Bhutan. Changes in spring discharge for only 2% of the springs are directly linked to earthquakes. No other reports or evidence was found that contradict this research. However, there are concerns that a future high magnitude earthquake might happen (Stevens at al., 2020), which in turn might further impact the spring discharge in the study area.

5.2 Extreme rainfall events

The impact of extreme rainfall events on (flash)floods, landslides and soil erosion and sediment transport is evaluated in the sections below.

5.2.1 (flash)floods and landslides

The potential impact of extreme rainfall events on the occurrence of (flash)floods or landslides is assessed through the return periods of extreme runoff events in the hydrological model relative to the return periods in the historical climate run.

In Figure 5-6 the statistics of extreme events for 3 primary hydrological gauging stations are presented. The current climate (black lines) in all cases is positioned in the lower part of the plume of the scenarios. When looking at the results vertically, this indicates that most climate scenarios indicate extremer events for similar return periods compared to the historical climate. When looking horizontally, it can be concluded that similar extreme events become (much) more frequent in many climate scenarios. For example, in station Q15, a once per 20-year event could become a once per 5-year event already in the near future, or even a once per 2-year event in the far future. The spread in the scenarios is still large, but the scenarios do hint on a higher likelihood for more extreme events.

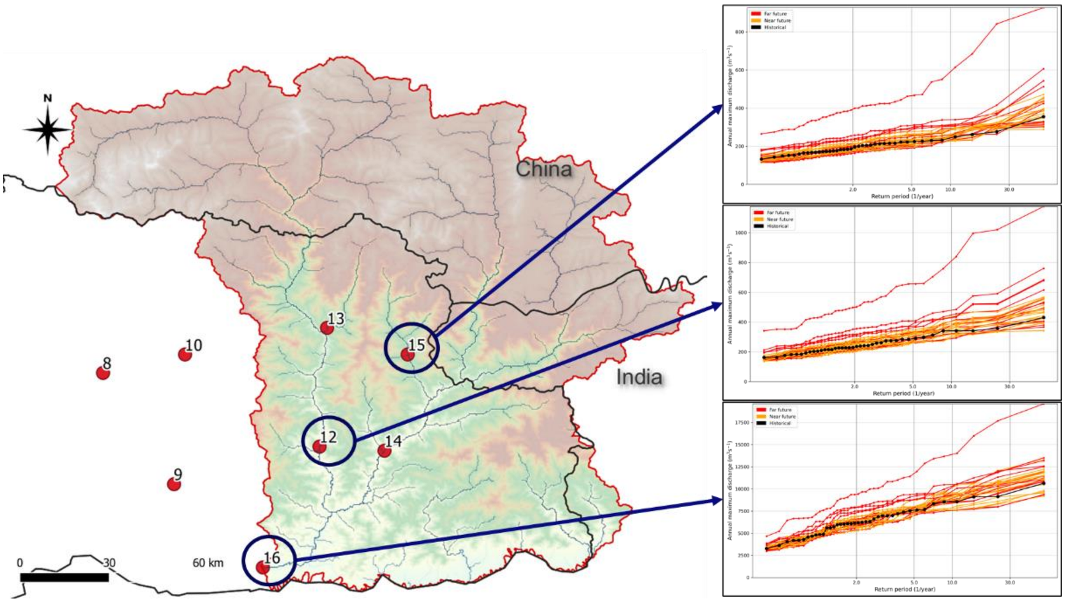

Figure 5-6 Statistics of extreme runoff events for 3 hydrological gauging stations for the current climate (black lines), near-future scenarios (yellow lines) and the far-future scenario (red line).

5.2.2 Soil erosion and sediment transport

The wflow_sediment model is run for two scenarios: one for drier and one for wetter conditions for the near future, as described in Section 3.2.2. The wflow_sediment model uses the results from the hydrological model to deduce soil erosion and delivery to the river system in the so-called soil loss part of the model (Boisgontier et al., 2020).

It then follows the fate and transport of the incoming sediments in the stream network in the so-called river part of the model.
In the dry climate scenario, mean annual precipitation and streamflow are lower than for historical conditions and this results in an overall decrease of soil over the study area, as shown in Figure 5-7. This is likely related to less intense precipitation events and lower erosion caused by overland flow.

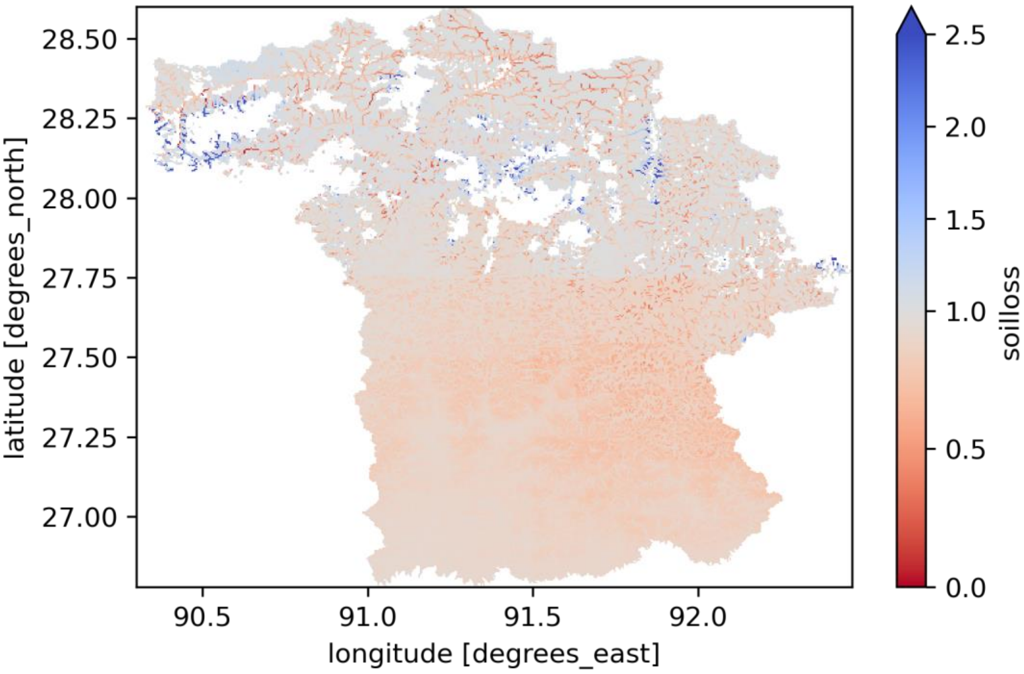

Figure 5-7 Decrease of soil erodibility in the dry scenario compared to the historical scenario (ratio of soil erodibility of the dry over the historical scenario)

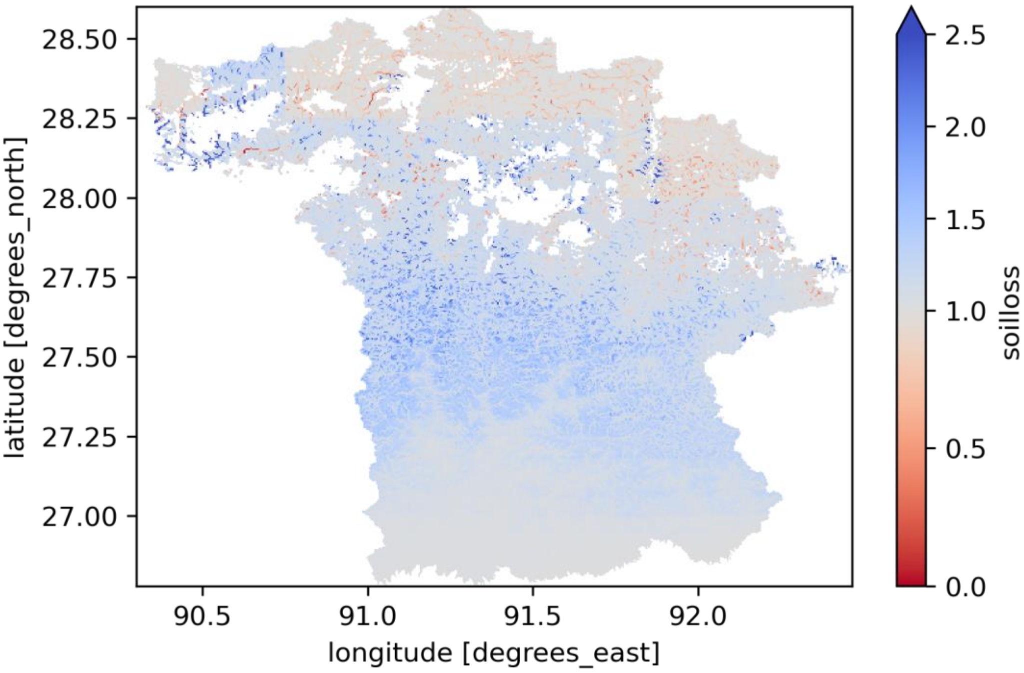

Figure 5-8 Increase of soil erodibility in the wet scenario compared to the historical scenario (ratio of soil erodibility of the wet over the historical scenario)

Once the erodibility of the soil and delivery to the river system is estimated in the soil loss part of the sediment model, it is possible to estimate the transport of sediments through the river network. The resulting estimated suspended sediment concentration at the location of Sumpakurichhu is shown in Figure 5-9 for the daily timeseries and in Figure 5-10 for the seasonal patterns and annual change factors compared to the historic simulation. In the wet scenario, the estimated sediment load increases by 14% in the month of August compared to historical conditions, while it is slightly lower than historical conditions for the dry scenario. The mean annual sediment concentration is about 7% higher in the wet scenario compared to historical conditions and is 5% lower in the dry scenario, as shown in Figure 5-10. It should be noted that no local data was available to validate the sediment model and therefore these results should only be considered to evaluate relative changes between scenarios.

It can be concluded that more heavy rainfall leads to a (non-linear) increase in sediment delivery to the river system. Together with discharge dynamics the delivery determines the sediment concentration (where river bed and bank erosion processes play a role as well), which can be inspected from the model output shown in Figure 5-10.

The increased erodibility and suspended sediment concentration for the wet scenario may have a negative impact downstream, for example for hydropower production, where high sediment concentrations cause damage to the turbines and sedimentation of the reservoirs reduces the active storage capacity. At the community level, the increased erodibility due to more and higher intensity rainfall may negatively impact farmers by degrading their agricultural land.

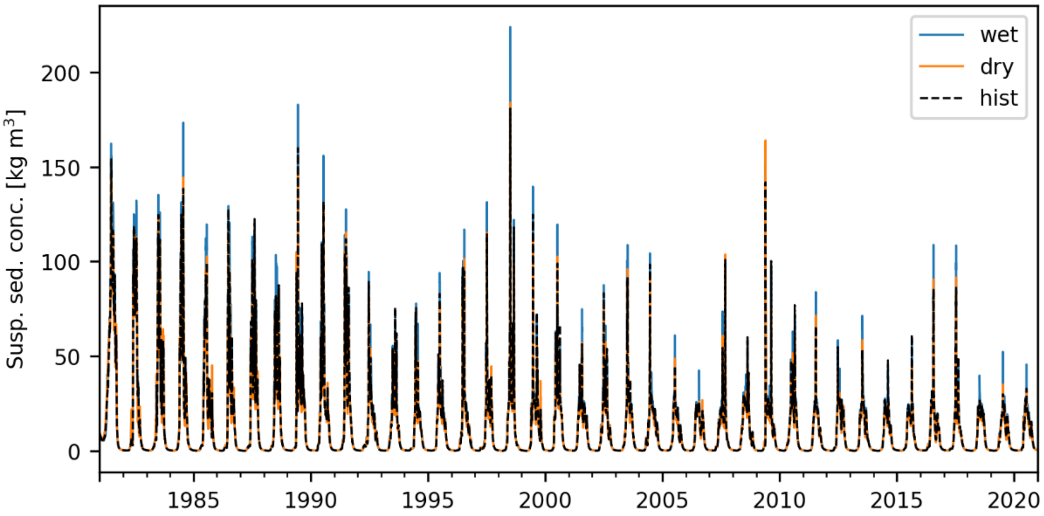

Figure 5-9 Modelled time series of suspended solid concentration for the period 1981-2020 for the historical, wet and dry scenario. It should be noted that no local data was available to evaluate the sediment model and therefore these results should be considered only in terms of relative changes.

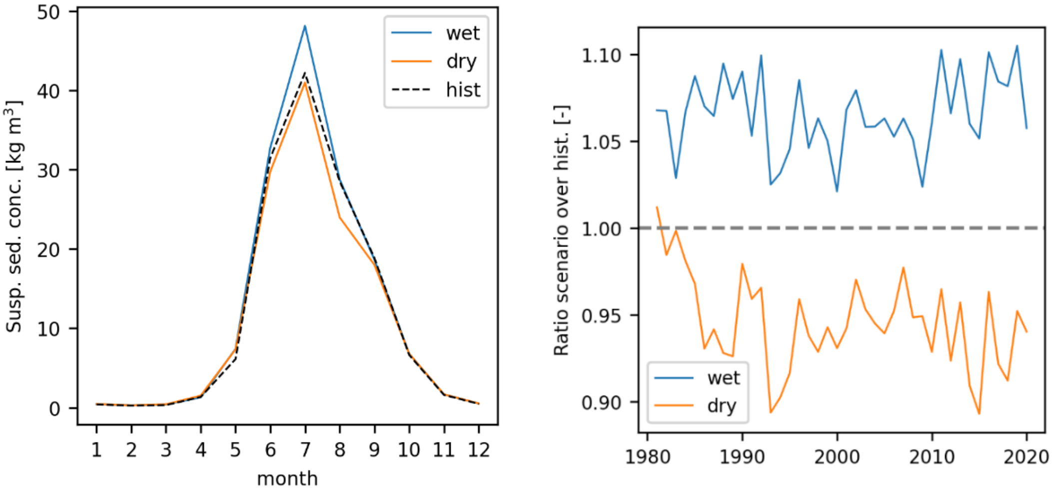

Figure 5-10 Left: Estimated mean monthly concentration of suspended sediments for the historical, dry and wet scenarios at the station of Sumpakurichhu. Right: relative difference between mean annual suspended sediment concentration in the wet and the dry scenarios compared to the historical scenario.

5.3 Snow and glaciers

The impact on snow and glacier extent has been analyzed in detail by looking at the simulation results for three different model runs: The reference model run representing the current climate, a moderate climate scenario for the near future and an extreme scenario for the near future. The model simulates both snowpack thickness and extent. In this case, the extent was used as an indicator for how the snow dynamics are changing.

In the left panel of Figure 5-11 the relative mean annual snow cover extent compared to the historical simulation has been plotted for different areas in the basin. These areas are determined based on their percentage of time with snow cover in the historical simulation. For example, the 95% coverage means that this area is covered 95% of the time with snow in the historical simulation. As can be seen in the figure, the changes are largest for the areas covered by snow more than 75% of the time. For these regions, the snow cover extent reduces considerably and even up to 60% reduction compared to the historical simulation.

In the right panel of Figure 5-11, the change in the average altitude at which the snow coverage is reached for each simulation is shown. The figure shows that the altitude at which the area is covered with for example 75% of the time shifts upwards, from around 5300 meters above MSL up to 5500 above MSL. The difference between the moderate and extreme scenarios is small for snow coverage up to 75%. Above 75% snow coverage, the altitude threshold rises even further in the extreme scenario.

The scenarios used in this analysis are all based on near future projections. The temperature increase in these scenarios is relatively modest compared to the projections for the far future, as was shown in Section 4.2. The impact of the far future scenarios is likely to be even higher.

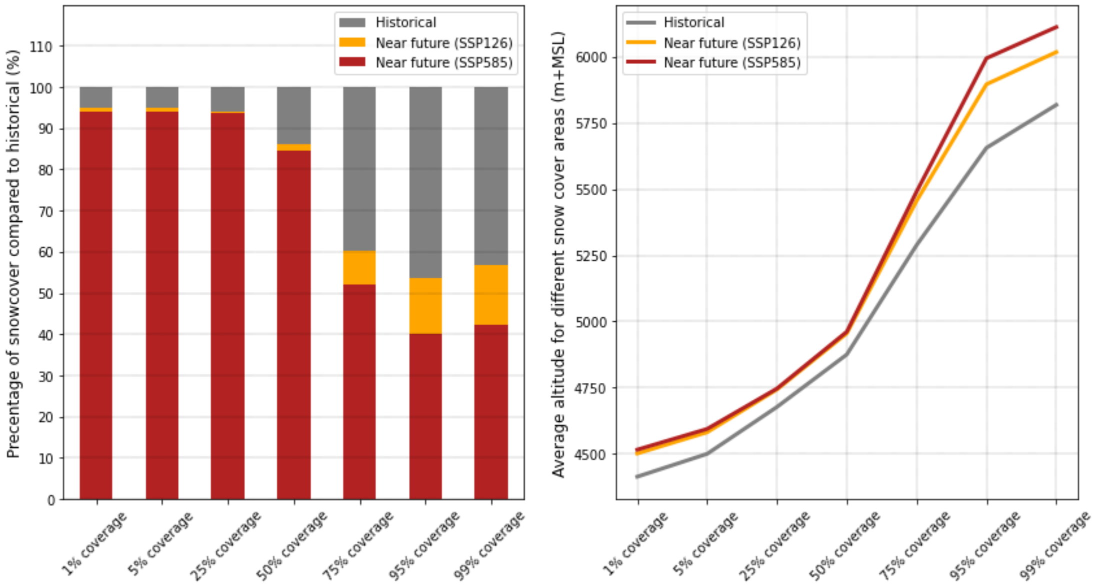

Figure 5-11 Change in snow cover area compared to historical simulations (y-axis) for different percentages of time per year of snow cover (x-axis) for two climate projections (left panel) and the change in the average altitude (y-axis) at which the percentage of time of snow coverage is reached.

In Figure 5-12 the difference in snow cover extent between the different scenarios is shown spatially for the contour of the 75% (top) and 95% (bottom) snow coverage. The figure shows a decline in the average snow area and in some cases the snow will become much more seasonal, instead of being permanent snow cover in the current climate.

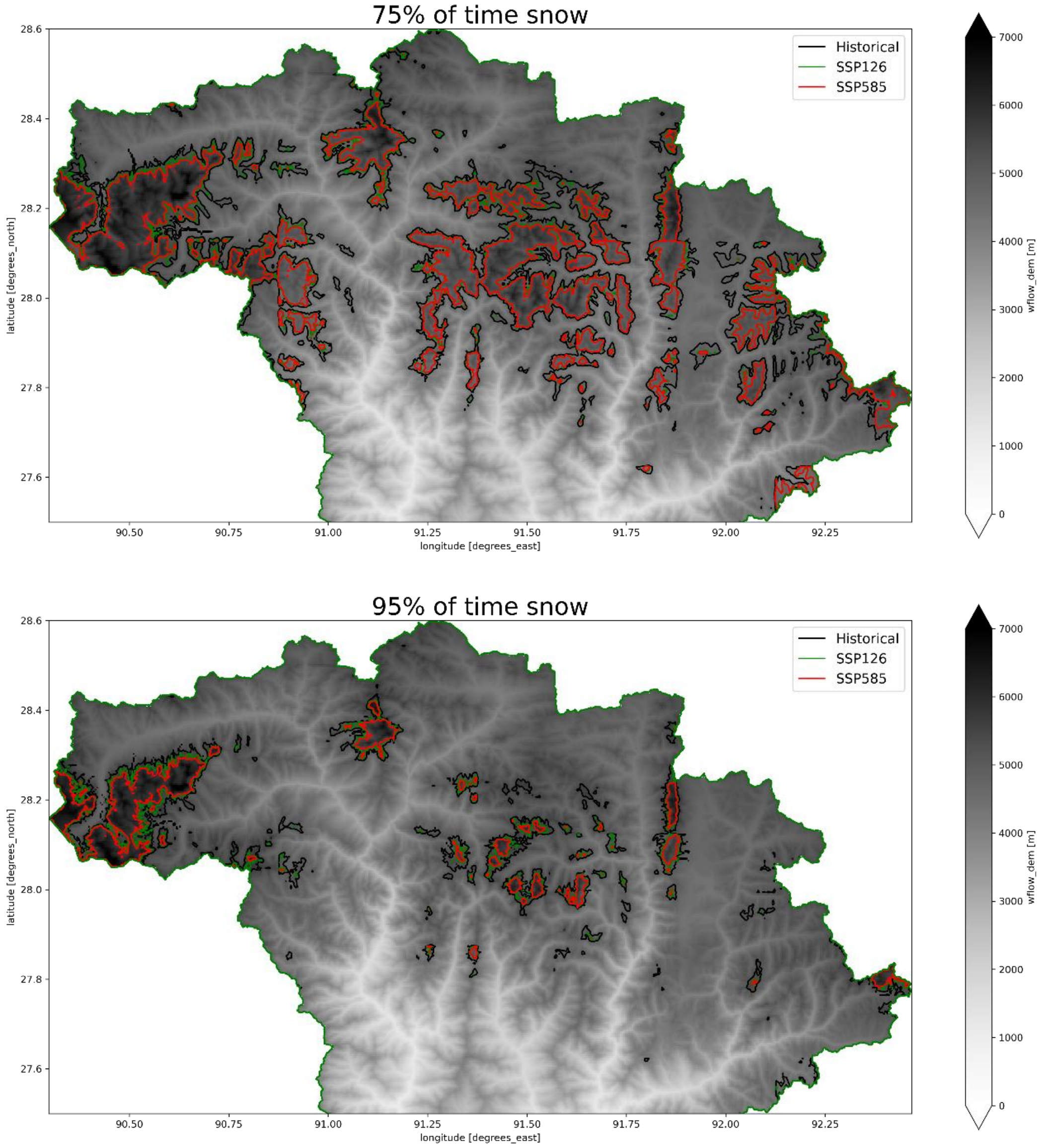

Figure 5-12 Comparison of the contours of the 75% and 95% of time snow cover areas for the current climate (black lines), moderate climate scenario (green lines) and the high-end scenario (red lines). The areas covered with the red contours is (much) smaller compared to the black and green contours, meaning that the area that is covered in 75% and 95% for the time decreases.

6 Climate change adaptation options

The Green Climate Fund application proposes to implement climate change adaptation measures at the watershed and community level to improve the availability and supply of water for local communities. We evaluate two different types of adaptation measures, consisting of (1) small scale rainwater harvesting, and (2) natural water retention measures to improve infiltration and groundwater recharge.

Small scale rainwater harvesting is realized by measures that can typically be implemented in small communities living high up in the mountains without springs in the close vicinity, such as the villages of Kengkhar and Jurmey in the Monggar Dzongkhag.

Natural water retention measures are defined by the European Commission (2014) as *multi-functional measures that aim to protect water resources and address water-related challenges by restoring or maintaining ecosystems as well as natural features and characteristics of water bodies using natural means and processes. The focus of applying natural water retention measures is to enhance the retention capacity of aquifers, soil, and aquatic and water dependent ecosystems with a view to improve their status.* The application of natural water retention measures reduces the vulnerability to floods and droughts and contributes to climate change adaptation.

6.1 Improved water availability and supply

6.1.1 Small scale rainwater harvesting

We developed a simple reservoir model to evaluate the impact of the rainwater harvesting system on climate trends in water availability for a small community. The model retains a fraction of rainfall in a buffer reservoir that otherwise would have infiltrated in the soil, and releases this water depending on the volume stored. The following assumptions were made:

- The number of houses per village is 10 and the average number of people per household is 4 persons.
- Each house currently has a storage tank of 3 m^3. Scenarios for improved storage are doubling of the number of tanks to 2 tanks per house or replacing the small storage tanks with large storage tanks of 10 m^3 each.
- The connected roof area to the storage tank to collect rainwater is assumed to be 60 m^2 per tank.
- The average water consumption per person per day is assumed to 20 liters.
- Based on these assumptions, the total daily water demand per village is calculated to be 0,8 m^3/day.
- The minimum target volume for the reservoir is set at 30% of its maximum storage. This constrain implies that when the reservoir volume is below 30% of its full content, the fraction of demand being released is reduced by the curve shown in Figure 6-1.
- Daily precipitation time series driving the reservoir model are retrieved for the village of Kengkhar for the historical, and near future dry and the wet climate change scenarios. As the tank is a closed system, there is no evaporation from the tank.

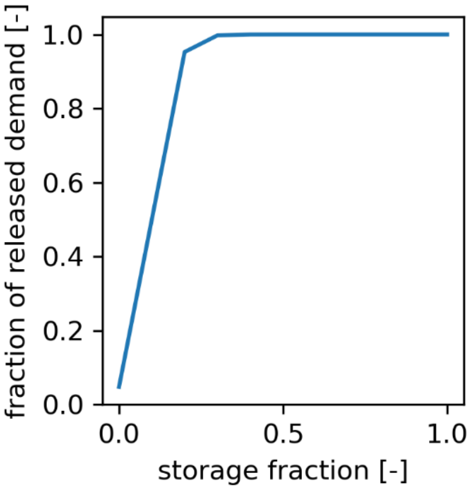

Figure 6-1 Fraction of the demand being released as a function of the storage fraction of the reservoirs. When the storage fraction is below 0.3, the fraction of released demand is reduced.

The resulting time series of the released demand and the reservoir volume are shown in Figure 6-2 for the different strategies. In the current situation with limited storage capacity, in most years the demand cannot be met for some period of the year. The demand in these cases is (much) higher than the storage volume. Over the years, the demand is met in around 75% of the time in the 3 dry months.

In the scenario with doubled storage capacity, the demand is not met in only a few extreme years. As can been seen from the top panel, extreme years are not only determined by the total rainfall amounts, but also by the number of dry days. In fact, the most extreme year, 1999, in terms of “not met demands” is a year with relatively a lot of rainfall. However, the rainfall appears to fall in a shorter amount of time, which is reflected in the high number of dry days in the same year. As the storage capacity in both the current situation as well as in the double storage capacity strategy it too limited, the extra amount of rainfall cannot be stored for later in the season, resulting in not met demand. When doubling the storage capacity, the demand is met in around 95% of the time in the 3 dry months.

The third strategy where the small storage tanks are replaced by big storage tanks results in an almost 100% met demand under the current assumptions and based on the selected dry scenario.

The results show that investing in more storage capacity can highly improve water availability in the dry season. The required storage capacity is a function of the amount of people, their daily consumption, and the amount of rainfall. In the current assumptions, based on input gathered during a field visit in May 2022, only a very low daily consumption of 20 liters per person per day is assumed in the model. Improving the living standards often reflects in higher water consumption (e.g. in The Netherlands the water consumption per person per day is around 120 liters). This can be taken into consideration when implementing these type of adaptation measures.

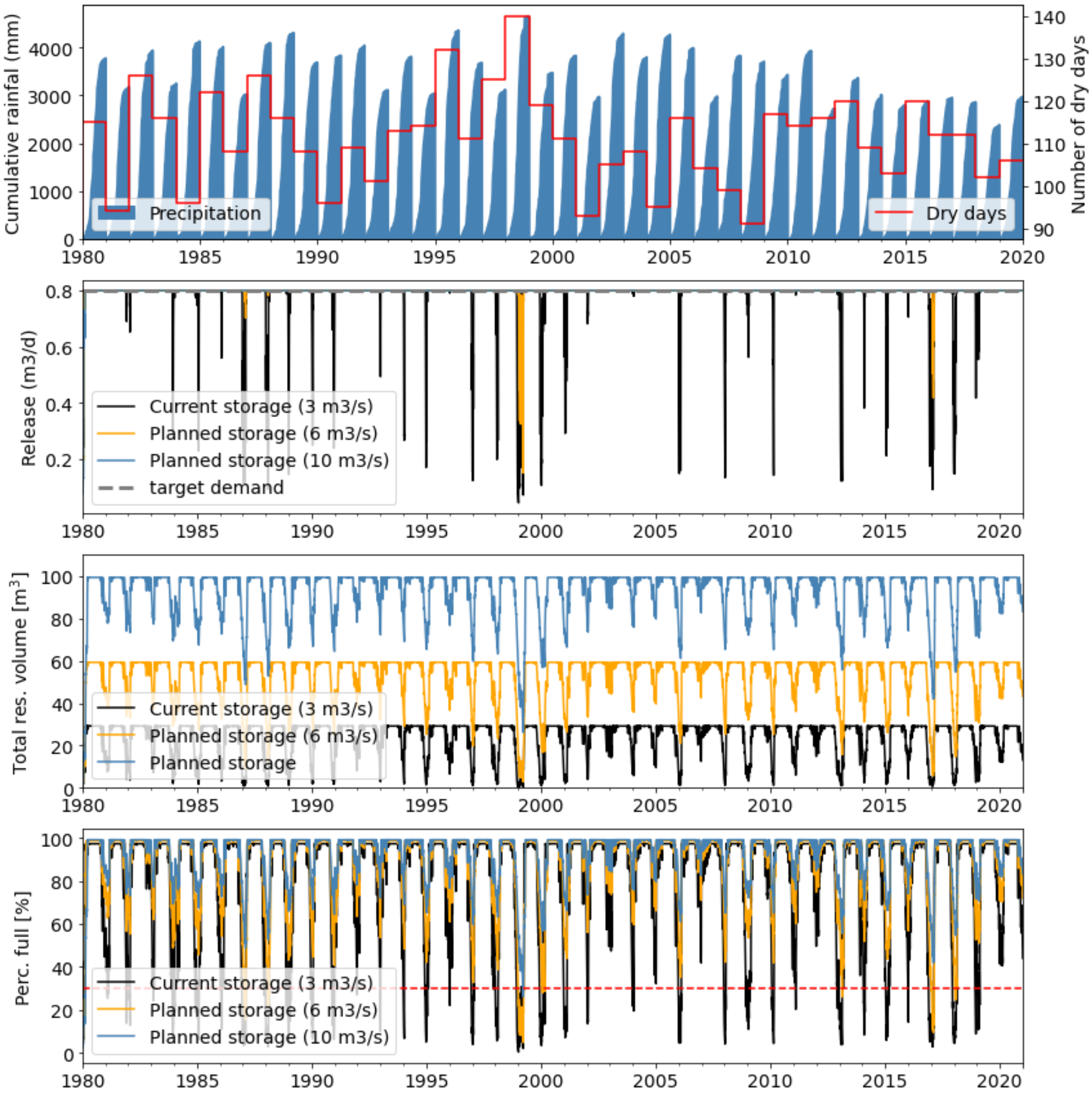

Figure 6-2 Top: Cumulative rainfall per year and the number of dry days per year. Second row: daily release from the reservoir for the current storage capacity (3 m^3 tanks), and two options for increased storage capacity (6m^3 and 10 m^3 tanks). The target demand is equal to 0,8 m^3 d^{-1}. Third row: the daily reservoir volume for the 3 storage scenarios (3, 6 and 10 m^3 storage tanks). Bottom: Fraction of the storage in the reservoir over the maximum storage of the reservoir for the 3 storage scenarios (3, 6 and 10 m^3 storage tanks).

6.1.2 Nature-based solutions

Nature-based solutions are defined as actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature (IUCN, 2022). They can play an important role in the portfolio of potential climate change adaptation measures. The implementation of measures, such as payment for ecosystem services, soil enhancement measures, agroforestry, terracing or forest restoration, further contributes to the continued conservation effort and sustainable forest management in Bhutan. These measures are typically implemented at a small scale in the upstream catchment area to positively impact the downstream water quality and availability.

In this study, we evaluate the potential effect of upscaling these small-scale measures over the whole study area in a sensitivity analysis.

We assume that the small-scale measures implemented across the study area contribute to increasing infiltration and recharge, which decreases the risk of flooding and land degradation, and improves crop productivity and dry spells management.

The saturated hydraulic conductivity is an important parameter of the wflow_sbm model. It characterizes the ease with which pores of a saturated soil transmit water. Bonetti et al. (2022) show that the soil hydraulic conductivity is enhanced by the presence of vegetation, through the effects of biologically induced soil macro porosity (e.g., presence of roots). Following the equations of Bonetti et al. (2022), we tested how an increase in vegetation modifies the parametrization of the saturated hydraulic conductivity and thereby the infiltration response of the landscape, as an example of an adaptation measure like spring watershed management.

In a sensitivity analysis, we quantified that an increase of the leaf area index of 50% results in a factor 2 increase of the saturated hydraulic conductivity. In this way, we implement a roughly estimated increase of the permeability of the soil to represent the implementation of measures which improve the infiltration capacity of the soil. It should be noted that this is only a first step in the sensitivity analysis of the potential impact of nature-based solutions on the hydrological response. Additional runs are necessary to meaningfully quantify the uncertainty.

We evaluate the effect of adaptation measures on the hydrological response considering the following three model runs:

- Historical run (which uses the historical IMDAA precipitation and ERA5 temperature and derived potential evaporation as meteorological input and the current estimates of the saturated hydraulic conductivity),
- Dry scenario run for the near future (based on the delta change factors of the MRI-ESM2-0 for scenario SSP 585 and current estimates of the saturated hydraulic conductivity).
- Dry scenario run for the near future with adaptation measures, which is based on the same meteorological forcing as the dry scenario run but with a proxy for enhanced vegetation, imposed by an adjustment of the hydraulic properties.

An increase of the vertical saturated hydraulic conductivity results in an increase of the recharge through increased permeability. This enhanced recharge allows for a larger total volume of spring discharge, thereby increasing the water resources available for the local communities. Also, this discharge occurs at a faster rate due to the enhanced conductivity, which slightly alters the seasonal timing of the discharge cycle. Figure 6-3 shows the mean monthly recharge and spring discharge for an illustrative source in the Dzongkhag of Trashiyangtze. In the run with assumed adaptation measures, there is an increase of the recharge during the wet season in the months June to August. The steep slopes in combination with the increased horizontal hydraulic conductivity result in a faster decline of the spring discharge at the end of the wet season (October and November) and a faster rise of the spring discharge at the end of the dry season (in the months of March, April and May). This pattern is similar across sources although the magnitude of change varies between sources.

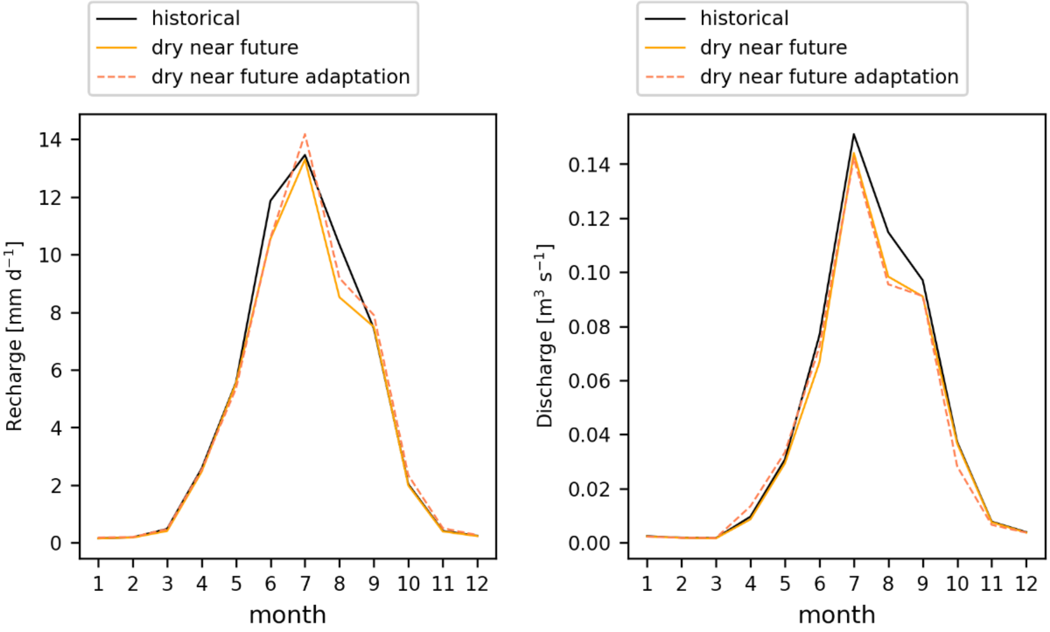

Figure 6-3 Mean monthly recharge and spring discharge for a small source in the Trashiyangtze dzongkhag for the historical, dry scenario and dry scenario with adaptation measures enhancing vegetation.

The mean annual and cumulative recharge is lower in the dry scenario for the near future compared to the historical cumulative recharge (Figure 6-4 and Table 6-1). In contrast, if we account for improved infiltration and permeability of the soil, we see an increase in recharge under the projected dry scenario for the near future (Figure 6-4 and Table 6-1).

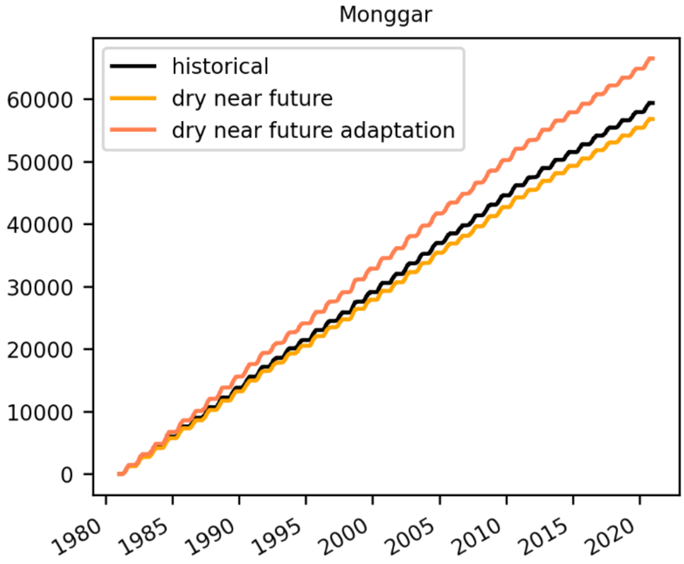

Figure 6-4 Modelled cumulative recharge spatially averaged for the Dzongkhag of Monggar for the historical, the dry scenario without natural water retention adaptation and the dry scenario with natural water retention adaptation options for the near future.

Table 6-1 Mean annual recharge [mm yr^{-1}] for the historical simulation for each of the 6 Dzongkhags. Change in the annual recharge for the dry scenario and the dry scenario with adaptation option enhancing vegetation for the near future [%]. The large differences in last column can be explained by the spatial variability of where the measures are implemented, which is only the land suitable for enhancing vegetation.

Dzongkhag	**Historical** (recharge mm yr^{-1})	**Dry scenario for the near future** (change [%])	**Dry scenario for the near future (with adaptation) (change [%])**
Lhuentse	137	-3.4	1.9
Monggar	124	-4.3	12.0
Pema Gatshel	103	-2.4	34.4
Trashiyangtse	135	-4.8	0.7
Trashigang	141	-6.1	3.6
Samdrup Jongkhar	138	-3.8	20.2

The simulation of adaptation measures, represented by an increase in the saturated hydraulic conductivity, result in an increase in recharge and an increase in average spring discharge at the end of the dry period and the start of the wet period (months of March, April, May) for at least half of the sources, as shown in Figure 6-5.

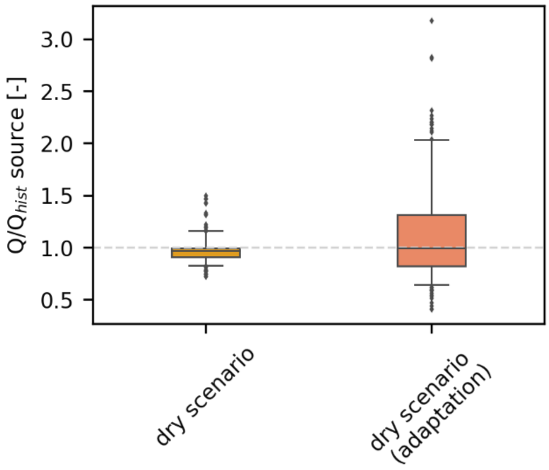

Figure 6-5 Ratio of the average modelled streamflow for the months March, April, May for the dry and the dry scenario with natural water retention measures over the historical model run for the near future. The height of the boxplot indicates the variability across the different sources.

The quantification of the impact of nature-based solutions is complex and measures such as watershed restoration and the enhancement of soil properties impacts several connected aspects of the hydrological response. Here, we make a first step in quantifying the potential effects of nature-based solutions on the hydrological response. We show that the adaptation measures (through enhanced saturated conductivity) alter the hydrological response and result in an increased recharge during the wet period and an increased spring discharge at the end of the dry season, which may benefit the local communities.

6.2 Reducing flood impact for Trashiyangtze

A detailed assessment of the floods at Trashiyangtze has not been performed. Detailed information about the amount of discharge and water levels was not available for a detailed study. Based on the cross-section information that was collected and shared, a simplified model was setup to demonstrate the effect of check dams on the flow patterns in Trashiyangtze. Different scenarios have been simulated. It must be noted that no conclusions can be drawn from these simulations, as the model could not be validated.

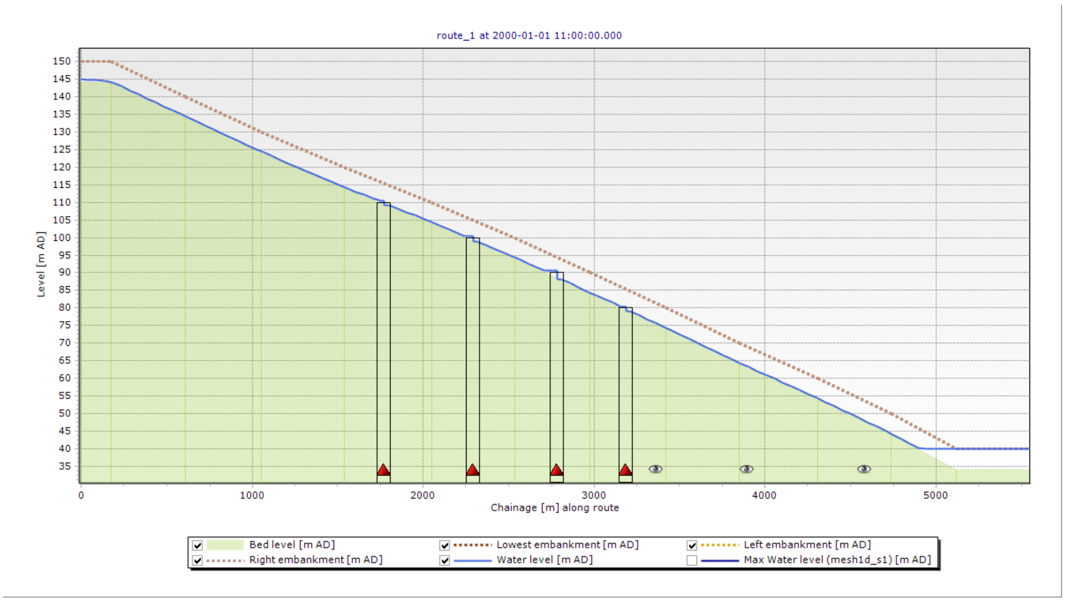

Figure 6-6 Schematization without the check dams being active (i.e., the top of the weir is equal to the bottom of the river). In blue the simulated water level.

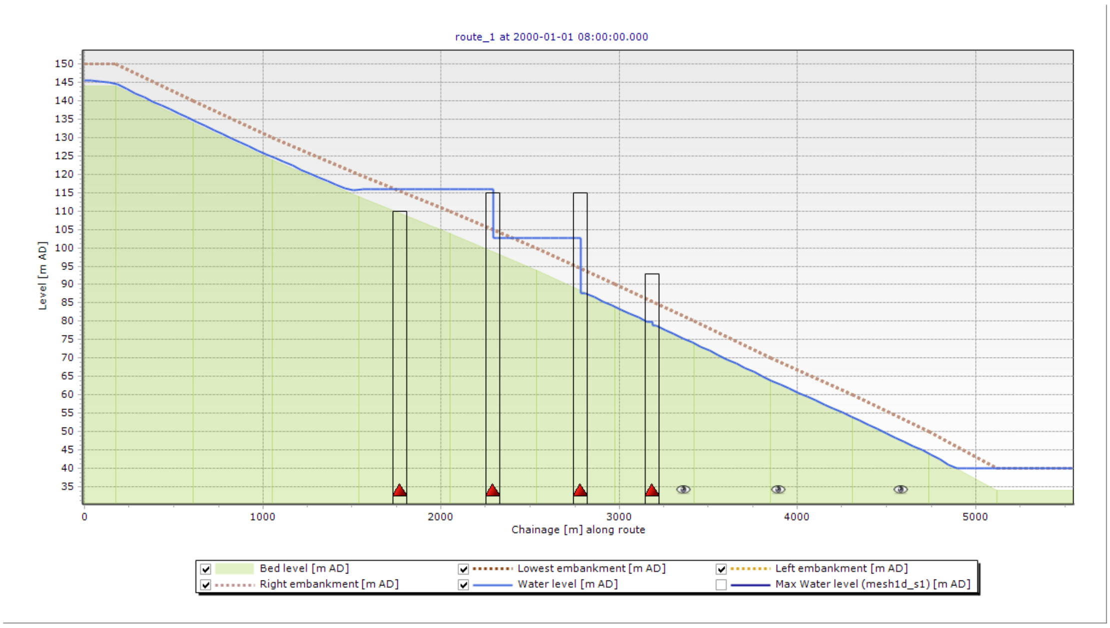

Figure 6-7 Schematization with 3 of the 4 check dams being active (i.e., the top of the weir is above the bottom of the river). In blue the simulated water level.

As can be seen in Figure 6-8, the peak water depth is similar between the situation with no upstream check dams and two upstream check dams. Only when 3 or more check dams are implemented in this theoretical case, the peak water depth can be reduced.

The number and dimensions of the check dams in the real situation should be investigated further, based on a detailed field survey and validated design discharge estimations. The results can also be further optimized by selection of the type of check dams and the controlled release of the base flow.

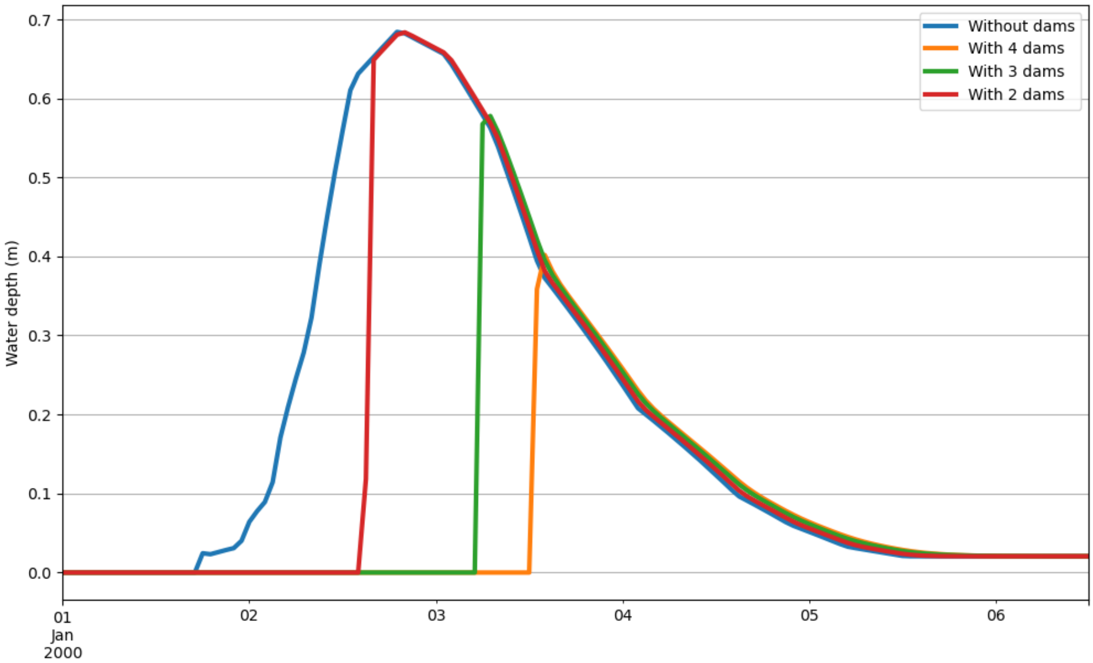

Figure 6-8 The simulated water depth downstream in Trashiyangtze for 3 different scenarios: the scenario without check dams (blue line), the situation with

7 Conclusions and recommendations

7.1 Conclusions

As a country Bhutan has an abundance of water, but most water is out of reach for practical usage. Most of the water is transported through the country by the main rivers, which are flowing in the deep valleys. Most communities and agricultural lands, however, are situated higher up the mountains. This vertical distance between the rivers and communities is often very long, making it unfavorable to pump up the water. This makes that **Bhutan is a country under water stress** where many communities face regular issues with water availability.

The climate in Bhutan is already changing. A historical trend analysis shows decreasing trends in annual rainfall amounts and annual average discharge and a strongly increasing trend in the annual average temperature. These trends seem to have accelerated over the last 10-20 years.

The increasing trend in temperature and the decrease in precipitation are clear indications that the **drying up of the springs in Bhutan is linked to climate change**. Other potential causes of drying up of springs, such as earthquakes and land degradation have been qualitatively assessed, but no strong evidence was found that these factors play a dominant role. It is therefore very likely that drying up of the springs in Bhutan is largely driven by climate change.

For the near future, the large interannual and spatial variability dominate the climate signal in terms of precipitation, both in terms of total precipitation volumes and the occurrence of extreme precipitation events, for the near future. This variability exceeds the mean climate change signal and leads towards increasing and decreasing rainfall amounts at the short term. Previous climate projections based on CMIP5 showed a stronger climate signal with wetter conditions also in the near future. The **high variability in the climate change signal for the precipitation** is combined with the complex impact of Bhutan topography on rainfall patterns. Changes in rainfall volumes and patterns originate from both thermodynamic and dynamic processes. The amount of moist air being transported to Bhutan is strongly influenced by both local conditions, such as the topography and the orientation of hillslopes towards dominant air flow patterns, as well as large scale air flow patterns dominated by low-level jet streams (or Monsoon) and the occurrence of Westerlies. For the far-future, the climate signal is stronger, and the scenarios point towards a wetter climate, although the variability within the scenarios remains large.

There is a **very strong climate signal for changes in temperature**, both for the near- and the far-future scenarios, ranging between 1 and 6-degree Celsius increase between the moderate near-future and extreme far-future scenarios. The change spatially differs between the low, mid, and high altitudes, where the highest altitudes show the largest temperature increase, with extremes over 8-degree Celsius increase in temperature.

The combined effect of the projected changes in temperature and precipitation impacts the hydrology in Bhutan. For drying springs, the climate projections show that for the near future both decreasing and increasing spring discharge are governed by the high variability of the precipitation. The high variability makes it difficult to clearly assign regions in which a decrease or an increase is to be expected. The consistent increase in potential evaporation leads to a dominant signal of **dryer conditions and reduced spring discharge** across the scenarios and regional sources.

An increase in evaporation results in reduced recharge and runoff. In situations where the water availability of the springs is already under stress, an episode with reduced rainfall combined with increased evaporation will deteriorate the situation. The reduced spring discharge is impacting the already vulnerable, mostly rural, population.

Climate change also has a large impact on snow and glacier dynamics. The area with **permanent and frequent snow cover (>75% of the time) is projected to decrease by nearly 40-60%**. These changes mainly impact the river discharges and thus are mostly relevant for downstream usage, such as for hydropower production. As an effect, the elevation at which the permanent and frequent snow cover can be found is shifted upwards with several 100s of meters, exposing more land surface. The exposure of the land surface induces additional heating up as the bedrock has a low albedo compared to snow and ice.

Climate change also impacts soil erosion and sediment transport. More intense rainfall increases the soil erosion through more splash erosion as a result of the impact of the drop on the land surface and erosion from surface runoff. Increased temperature and retreat of the snow cover exposes the bare soil for soil erosion. Increasing temperature also potentially means that vegetation cover will change, impacting the soil erosion processes. Due to the snow and glacier retreat, the area also becomes more vulnerable to soil erosion, resulting in potential increased influx of sediment downstream.

Several adaptation options have been analyzed, focusing on the two dominant hydrological impacts: Drying up of the springs and the occurrence of the extreme (flash)flood events. For the drying up of the springs, 2 types of measures have been assessed, increasing the storage capacity, and increasing spring recharge. **Increasing the storage capacity at community level has a positive effect on the water availability** throughout the year and specifically in the driest months of the year. By increasing the storage capacity by a factor 2, the percentage of met demand increased from around 75% to 95% under a dry scenario. Implementing even larger tanks can increase the percentage demand met to nearly 100%.

The second adaptation option related to the drying springs is improving spring watershed recharge. The hydrological model was used to assess the impact of changes in the subsurface flow parameters on the amount of recharge and resulting spring discharge. It was shown that for at least half of the springs, **the recharge increases when improving infiltration capacity** over a considerable area in the spring watershed. The changes in the model have only been applied on specific land use types for now and a more detailed assessment is required on the suitability of the land for these types of measures. Under the current assumptions of the areas that can be adapted, the recharge can be increased from around 1% in Trashiyangtze up to around 35% in Pema Gatshel. In reality, these numbers are likely to be (much) less, depending on which percentage of the suitable land can actually be improved. The result of the improved recharge is that in many cases the spring discharge also goes up in the end of the dry season.

For a specific case in Trashiyangtze, adaptation measures to reduce the impact of (flash)floods were tested using a hydrodynamic model. The model could not be validated against field observations, so the results presented here should be seen as a theoretical exercise. Based on this exercise, the building of **check dams in small streams can be an effective way to reduce peak flows and flow velocity**, reducing the flood risk in such streams. These kind of adaptation options can also be applied in other, similar small stream. Detailed information on slope and cross-sections of these streams is required to make such an assessment tailored to local conditions. Validated design rainfall and discharge events should be used to design the measures.

In summary, it can be concluded that **there is a very strong link between the climate, climate change and the hydrological climate impacts**. Although the climate variability is high, there are clear signals that climate change is happening and will continue in the near- and far future. And although not all issues originate from climate change, there are clear signals that climate change will increase the probability and severance of these issues.

7.2 Recommendations

Based on the current work, many recommendations can be made. Here the recommendations are divided in two categories:

- Recommendation related to further improving the climate rationale.
- Recommendation for the government of Bhutan.

7.2.1 Improving the climate rationale

In the current study, statistically downscaled climate projections are used. For future work, it is highly recommended to also evaluate dynamically downscaled climate projections, using local or regional high-resolution climate models. These regional high-resolution models have the advantage of considering the complex topography of Bhutan Therefore, a good alternative may be to use the CORDEX-CORE dataset (Remedio et al., 2019), as it was also used in Bhutan in a World Bank project of the FAO. Unfortunately, the CORDEX-CORE datasets based on the CMIP6 experiments were not yet available at the time of this study.

It is also recommended to further explore the options to use bias-corrected climate scenarios instead of using the delta-change method that was used in this study. This requires availability of high-detail climate models for Bhutan that simulate the current climate conditions sufficiently well. The advantage of directly using the output of the climate models is that they better account for changes in large scale patterns and persistent weather conditions.

Furthermore, it is recommended to further improve the hydrological model. The model was evaluated, but no detailed calibration was done with the model. Especially the snow and glacier modules need a more thorough calibration and validation to further improve the model.

A sensitivity analysis was performed to evaluate the impact of adaptation measures, which were related to increasing the rainwater harvesting storage capacity and enhance groundwater recharge. A more robust assessment of the effect of adaptation options and associated uncertainties is recommended when the actual extent and type of measures are known. Such a detailed assessment is possible using the current data and models but zooming in to specific areas may be required for more detailed analyses.

7.2.2 Proposed next steps for Bhutan

The current hydrometeorological network is not sufficient to capture the weather patterns well in the complex topography in Bhutan. The high spatial and temporal variability require a dense network of hydrometeorological stations to accurately capture the spatial and temporal patterns. It is recommended to start with a review of the current hydrometeorological observation network and a design for an improved network. Important questions are how to best capture the high-altitude rainfall, temperature, and snow dynamics, as well as other meteorological parameters as relative humidity and wind speed.

To further increase our understanding related to the drying springs, it is recommended to improve the mapping of the spring watersheds. It is also recommended to setup a continuous monitoring of key springs around the country to detect changes in time. Such datasets are very much needed to link spring discharge to changes in the climate or other changes happening over time. Involving the local communities by training them to do the observations could be a good example of a community mapping initiative in Bhutan. Guidelines to revive springs in the Hindu Kush Himalaya are available through the ICIMOD practitioner’s manual (Shrestha, 2018).

At the national level it is recommended to further improve the hydromet services by combining all data stream into a single hydrometeorological data platform that can be used for historical climate and hydrological impact studies, as well as for real-time monitoring and forecasting. As accurate forecasting could be a very cost-effective way of reducing the vulnerability of local communities, it is recommended to invest in improving the capacity for detailed and accurate hydromet forecasts and services. The models developed under this project can be used for this purpose. Training in the use of such system and model for the local hydromet service (NCHM) is highly recommended to improve in-house capacity.

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