Climate Risk and Adaptation Assessment

TA-6598 BHU: Renewable Energy for Climate Resilience

REPORT 222

CLIENT Asian Development Bank

AUTHORS Dr Corjan Nolet
Dr Arthur Lutz

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FutureWater Report 222

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Authors
Dr Corjan Nolet – Remote Sensing and GIS expert (c.nolet@futurewater.nl)
Dr Arthur Lutz – Senior Hydrologist & Climate Change Expert (a.lutz@futurewater.nl)

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April 2021

FutureWater

ADDRESS
FutureWater B.V.
Costerweg 1V
6702 AA Wageningen
The Netherlands

TELEPHONE
+31 317 460 050

WEBSITE
www.futurewater.eu

Executive Summary

Bhutan's power sector almost exclusively relies on hydropower generation. Hydropower, however, is vulnerable to climate change and natural disasters caused by climate change. The first deployment of non-hydro renewables at utility scale in Bhutan will be the first step to diversify the power generation portfolio, increase the resilience against severe weather events such as droughts, and complement the hydropower generation profile during the dry season. Other renewable energy resources such as solar photovoltaic (PV) and wind can complement hydropower in forming a more diversified electricity generation portfolio, which is, in healthy mix, resilient to changes in seasonal weather patterns and weather extremes that can adversely affect power supply. For this project ADB develops 2 solar and one wind plant.

The objectives of this Climate Risk and Adaptation assessment (CRA) are two-fold:

1) Validate the underlying rationale for diversification of Bhutan's energy generation portfolio. The rationale is that more unreliable flows under climate change adversely affect the hydropower generation, in particular in the low flow season outside the monsoon season. This are the seasons with high potential for solar and wind energy, under the current climate conditions. The diversification of Bhutan's energy generation portfolio is considered as type 2 adaptation, related to system change and resilience building in the climate change context.
2) Assess the vulnerability of the project components to future climate change and recommend adaptation options for climate-proofing of the design. This is considered as type 1 adaptation, related to climate proofing.

For the short-term horizon (2015-2045), changes in temperature in the range of around 1 – 2 °C with respect to the historical reference are projected by the climate model ensemble, for the longer-term horizon (2045-2075), this increases to around 1.5 – 4°C, with a larger spread in model projections.
For the short-term horizon (2015-2045), changes in precipitation in the range of around 10% are projected by the climate model ensemble, for the longer-term horizon (2045-2075), this increases to around 20 – 25%, with a larger spread in model projections and higher divergence between emissions pathway RCP 4.5 and RCP 8.5. Increases in precipitation as well as temperature extremes are projected.

For hydrology a clear increase in high extreme flows is projected. For changes in low flows the projections are rather uncertain. For future hydropower the main risk is posed by increases in the risk of damage due to floods, glacier lake outburst floods, and landslides. This supports the rationale for diversification of the energy portfolio.

Projections for incoming solar radiation and surface wind speeds do not indicate clear changes for the future and are therefore not considered to impact the generation potential for wind and solar energy. It has to be noted however that climate models in general have difficulty in accurately simulating changes in incoming solar radiation as well as wind speed.

The main risks for the infrastructure to be developed for the project are related to the future increases in extreme weather. The infrastructure is in particular at risk of flooding, erosion, and possibly land slides. Recommended adaptation measures are related to reducing these risks. These are 1) to have sufficient drainage capacity on the project locations; 2) to reduce erosion rates with vegetation; 3) strong foundations that can withstand extreme weather. Specific details are listed in the report.

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1 Introduction

1.1 Background

ADB is assisting Bhutan in the energy sector. Bhutan's development has been heavily dependent on climate-sensitive sectors such as agriculture and hydropower, with hydropower making a major contribution to the growth. Hydropower contributes about 25% to total gross domestic product (GDP) annually, accounts for 32% of total exports, and generates about 25% of the government's total domestic revenue.

Bhutan's power sector almost exclusively relies on hydropower generation. Hydropower, however, is vulnerable to climate change and natural disasters caused by climate change. The Alternative Renewable Energy Policy (AREP) prepared by the Royal Government of Bhutan in 2013 therefore aims to diversify the energy mix by harnessing other domestic sources of clean renewable energy to ensure energy security, economic development, and protection of the environment and promote renewable energy technologies such as solar PV and wind power. The first deployment of non-hydro renewables at utility scale in Bhutan will be the first step to diversify the power generation portfolio, increase the resilience against severe weather events such as droughts, and complement the hydropower generation profile during the dry season. Other renewable energy resources such as solar photovoltaic (PV) and wind can complement hydropower in forming a more diversified electricity generation portfolio, which is, in healthy mix, resilient to changes in seasonal weather patterns and weather extremes that can adversely affect power supply.

An assessment of future impact of climate change on Bhutan's hydropower assets and their performance is required to validate the underlying project's rationale for diversification of Bhutan's energy portfolio. Therefore, the objectives of this Climate Risk and Adaptation Assessment (CRA) are to (i) validate the underlying rationale for diversification of Bhutan's energy generation portfolio and (ii) assess the vulnerability of the project components to future climate change, and recommend adaptation options for climate-proofing of the design. Therefore this CRA covers both type 2 adaptation, related to system change and resilience building (i.e. the diversification of the energy generation portfolio), as well as type 1 adaptation related to climate-proofing (i.e. climate proofing of the solar and wind power infrastructure designed for the project).

1.2 Climate Risk Management

Since 2014, the Asian Development Bank (ADB) has required that all investment projects consider climate and disaster risk and incorporate adaptation measures in projects at-risk from geo-physical and climate change impacts. This is consistent with the ADB's commitment to scale up support for adaptation and climate resilience in project design and implementation, articulated in the Midterm Review of Strategy 2020: Meeting the Challenges of a Transforming Asia and Pacific (ADB, 2014a), in the Climate Change Operational Framework 2017–2030: Enhancing Actions for Low Greenhouse Gas Emissions and Climate-Resilient Development (ADB, 2017), and in the Climate Risk Management in ADB Projects guidelines (2014b).

Climate risk management (CRM) is a mandatory part of project development. Climate risk screening is applied to all ADB investments, with a more detailed Climate Risk and Adaptation assessment (CRA) undertaken for projects that are assessed to be at medium or high risk. The principal objective of a CRA is to identify those components of the project that may be at risk of failure, damage and/or deterioration, reduction, interruption, and/or decreased reliability of service delivery from natural hazards, extreme climatic events or significant changes to baseline climate design values (ADB, 2011, 2014 and 2017). Adaptation measures consistent with the risk assessment serve to improve the resilience of the infrastructure to the impacts of climate change and geo-physical hazards, to protect communities and provide a safeguard so that infrastructure services are available when they are needed most. As part of this process, the nature and relative levels of risk are evaluated and determined to establish appropriate actions for each proposed investment to help minimize climate change associated risk.

Earlier the terminology “Climate risk and vulnerability Assessment (CRVA)” was used. However, since vulnerability is part of risk, ADB now recommended to use the term “Climate Risk and Adaptation Assessment (CRA)”. The CRA process embodies the recognition that many of the future impacts of climate change are fundamentally uncertain and that project risk management procedures must be robust to a range of uncertainty. The CRA therefore includes a technical and economic appraisal of adaptation options for the project design.

ADB has developed specific guidelines regarding CRAs. These guidelines mentioned that the main characteristics of a CRA are (i) to characterize climate risks to a project by identifying both the nature and likely magnitude of climate change impacts on the project, and the specific features of the project that make it vulnerable to these impacts. (ii) To identify the underlying causes of a system’s vulnerability to climate change, and (iii) to ensure that adaptation measures are locally beneficial, sustainable, and economically efficient.

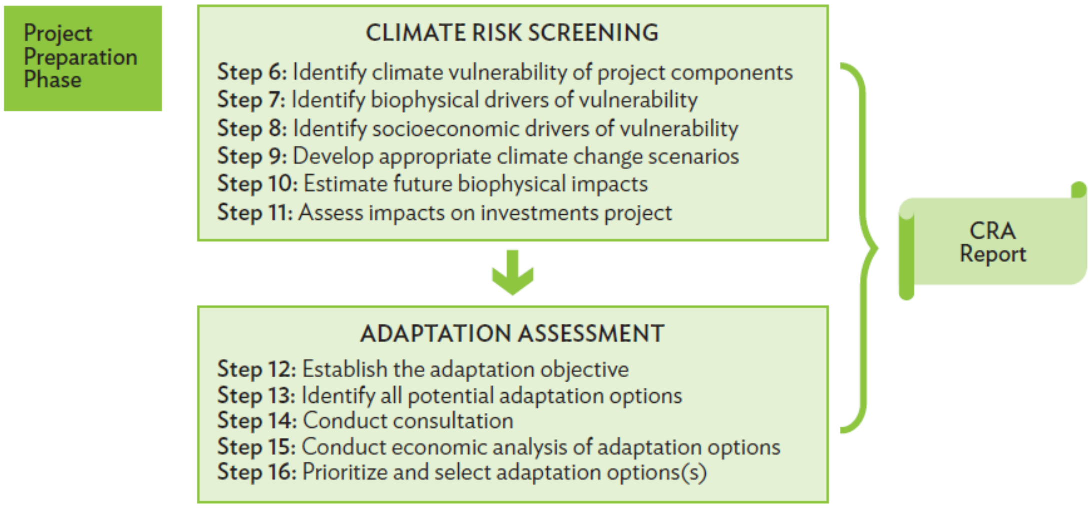


Figure 1. Climate Risk and Adaptation Assessment components. (ADB, 2015a)

CRAs use a variety of definitions relating to risk and climate change. In this study the following definitions are used (adapted from IPCC, 2014), with links between concepts shown in **Figure 2**:

- Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected by climate change and variability.
- Sensitivity: The degree to which a system, asset, or species may be affected, either adversely or beneficially, when exposed to climate change and variability.
- Potential impact: The potential effects of hazards on human or natural assets and systems. These potential effects, which are determined by both exposure and sensitivity, may be beneficial or harmful.
- Adaptive capacity: The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences of hazards.
- Vulnerability: The extent to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. It depends not only on a system’s exposure and sensitivity but also on its adaptive capacity.

– Likelihood: A general concept relating to the chance of an event occurring. Generally expressed as a probability or frequency.
– Risk: A combination of the chance or probability of an event occurring, and the impact or consequence associated with that event if it occurs.

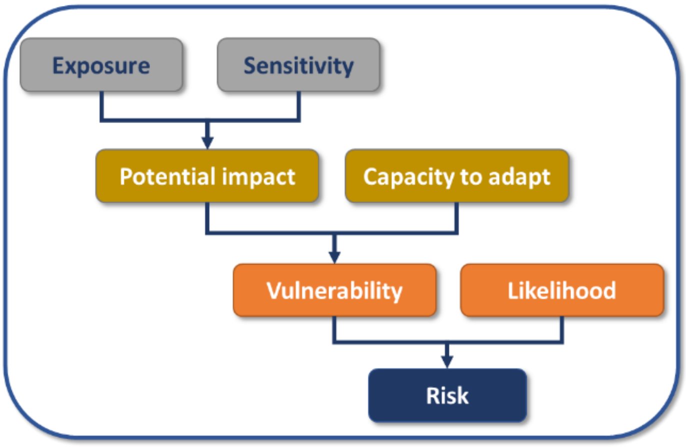


Figure 2 Climate Risk components. (based on http://www.ukcip.org.uk).

1.2.1 'Top-down' vs 'bottom-up'

Many recent studies make a distinction between climate scenario driven impact assessment approaches, often referred to as "top-down" and vulnerability-oriented approaches, often called "bottom-up" (**Figure 3)**. The ADB guidelines are less restrictive and recognize that both approaches can work and can be conducted in parallel:

While current good practice in adaptation emphasizes risk management, and increasing recognition of the fundamental uncertainty of future climate discourages the overinterpretation of model generated climate projections, impact and vulnerability assessments should be understood as complementary processes in project climate risk management, and they can be conducted in parallel:

- *An impact assessment is useful in narrowing and illuminating the potential range of future conditions with which project designers must be concerned.*
- *A vulnerability assessment provides an understanding of how robust the project and specific project components are to departures from design assumptions and identifies critical thresholds of vulnerability past which the project fails to perform as designed.*

In summary the main difference between the top-down and the bottom-up approach are in the use of GCM projections. The top-down approach is constraint (limited) to the GCM projections, while the bottom-up approach considers a range of potential changes in climate. **Figure 4** summarizes in one graph a typical example of the result of a bottom-up approach.

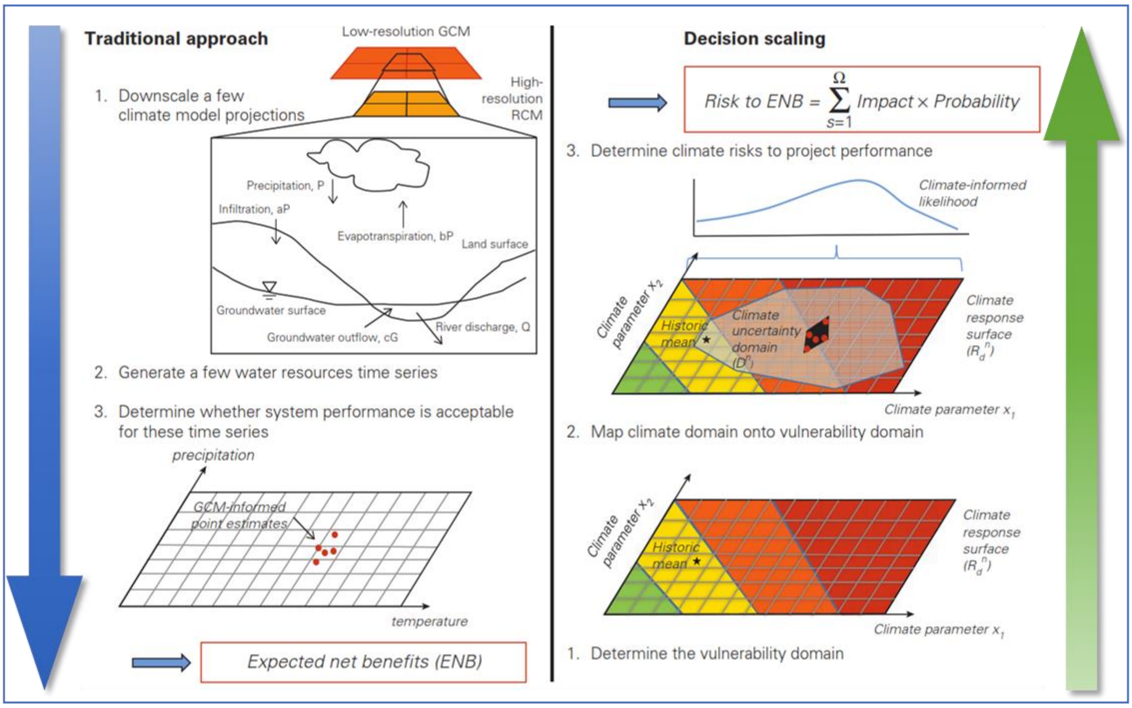


Figure 3. Schematic comparison of decision scaling (right) with traditional approach (left) to Climate Change Risk Assessment. (Based on World Bank, 2015)

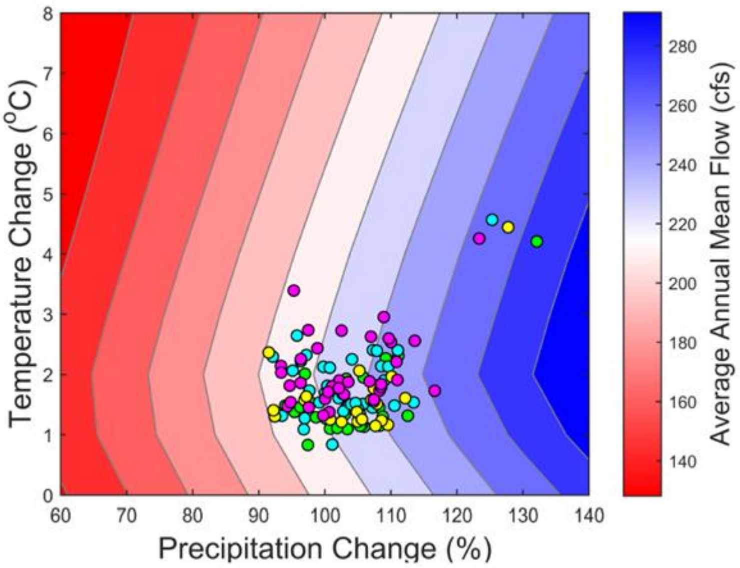


Figure 4. Example of outcome of a "bottom-up" CRA approach (example from Nepal study on hydropower): response function of mean annual streamflow under changes in precipitation (x-axis) and temperature (y-axis). Coloured circles represent mean climate change projections 2050 from a multi-model ensemble of GCMs (RCP2.6 - green; RCP4.5 - blue; RCP6.0 - yellow; RCP8.5 - purple).

1.3 Climate Risk and Adaptation Assessment

The approach towards the development of the Climate Risk and Adaptation Assessment (CRA) is described in this section, while the specific details regarding methodologies and results are presented in the subsequent chapters. Overall, the CRA will consist of the following steps:

1) Analysis of historic climate events
2) Projections of future climate change
3) Impact and vulnerability of climate change
    - For the hydropower sector in Bhutan in general, to validate the rationale for energy portfolio diversification
    - For the planned project components (i.e. solar and wind power plants and related infrastructure)
4) Adaptation options and recommendations for the planned project components

1.3.1 Analysis of historic climate events

A credible and acceptable Climate Risk and Adaptation Assessment (CRA) starts at analyzing historic observations of climate related events and to perform a trend analysis. Obviously, trends, or the absence of trends, do not imply that future changes will follow those historic trends. Any statistical trend analysis should be accompanied by understanding the underlying physical processes. Analysis of historic climate events should go beyond looking at weather parameters (e.g. temperature and wind) and should include parameters that might have been influenced by historic weather conditions. Given the climate risks and vulnerabilities associated to components of the energy sector in general and specific to this project (hydropower, wind power, solar power in mountainous terrain), the following climate change parameters and hazards were prioritized:

1. Precipitation and temperature
2. Extreme precipitation, related to extreme runoff and flooding events, and landslide and erosion risks
3. Drought hazards
4. Heatwave hazards

1.3.2 Projections of future climates

Projections of future climates are provided by GCMs (Global Circulation Models). The IPCC (Intergovernmental Panel on Climate Change) is the credible body on climate change projections. The IPCC is an intergovernmental body under the auspices of the United Nations “dedicated to the task of providing the world with an objective, scientific view of climate change and its political and economic impacts”. The IPCC does not carry out its own original research, nor does it do the work of monitoring climate or related phenomena itself. The IPCC bases its assessment on the published literature, which includes peer-reviewed and non-peer-reviewed sources.

An important source of the climate projections to date are the results from the CMIP 5 activities. CMIP 5 is the Coupled Model Intercomparison Project Phase 5 that has led to a standard set of model simulation and a (more or less) uniform output. Since downscaling and local adjustment of GCMs are needed, NASA has developed the so-called NEX-GDDP projections (NASA Earth Exchange Global Daily Downscaled Projections). The dataset is provided to assist in conducting studies of climate change impacts at local to regional scales, and to enhance public understanding of possible future global climate patterns at the spatial scale of individual towns, cities, and watersheds.

The NASA-NEX-GDDP exist out of 21 GCM outputs for two RCPs (4.5 and 8.5) for a historic period (1950-2005) and for the future (2006-2100. For the CRA these data are used for two purposes. First, the projections are analyzed using a set of indicators ranging from more direct ones (e.g. change in temperature) to more meaningful integrated and advanced indicators (e.g. monthly maximum consecutive 5-day precipitation). Second, the NASA-NEX-GDDP are used in the bottom-up approach of the impact and vulnerability assessment. As described later in this report, the projections of future climate vary strongly per climate model, forming one important dimension of future climate uncertainty. It is key to consider this uncertainty by including an ensemble of climate models in the analysis. Based on the range (uncertainty) in the projections, a confidence threshold can be used to benchmark infrastructural developments to in the context of future climate change.

1.3.3 Impact and vulnerability of climate change

A standardized approach to climate change impact and vulnerability assessment does not exist. There is however a clear trend in CRAs to move from a climate projections (GCM) focus to a vulnerability-oriented approach. This change started by the aforementioned often non-consistent projections of GCMs (especially in precipitation) and at the same time the desire to put stakeholders' perspectives back into the analysis. This distinction between climate scenario driven impact assessment approaches is often referred to as "top-down", while the vulnerability-oriented approaches is referred to as "bottom-up." The ADB guidelines are less restrictive and recognize that both approaches are complementary and can even be conducted in parallel. In this CRA we combine the approaches, and present the full scope of possible futures in terms of climate change, but for the final chapters on vulnerability and adaptation options we take the perspective from the designers to come up with actionable recommendations.

1.3.4 Adaptation options and recommendations for design

Adaptation policy design requires considerations in time-horizon ("when"), spatial ("where") and decision-level ("how") terms: in fact, there is a need to assess the location of current and future impacts; to identify people, resources, sectors at risk; to gather information about the timeframe of impacts; to define and implement appropriate adaptation actions at appropriate levels of decision-making.

ADB has developed some specific guidelines regarding CRAs that are used as source:

- Climate risk management in ADB projects (ADB, 2014)
- Climate Risk and Adaptation in the Electric Power Sector (ADB, 2012)
- Guidelines for Climate Proofing Investment in the Energy Sector (ADB, 2013)
- Guidelines for Climate Proofing Investment in the Transport Sector: Road Infrastructure Projects
- Guidelines for Climate Proofing Investment in the Water Sector: Water Supply and Sanitation (ADB, 2016)

For the project some initial potential climate adaptation options are outlined. These options are based on the desktop study as described in this report. Results of the projections as described in this report can be used by the PPTA team and Design Institute (DI) to adjust their detailed plans. A close collaboration between the CRA team and the other teams working on the project will lead to a more specific list of recommendations for adaptation and design, and some of the recommendations may require further specification and investigation per project site.

1.4 Scope of work

This climate risk and adaptation assessment (CRA) assesses historic trends in relevant climate-related variables and analyses climate projections for the Project Area. Based on these projections, an assessment is presented on the current and future climate risks and vulnerabilities relating to the proposed project activities. Based on this, recommendations are presented for climate adaptation measures to be considered for a robust design of the investments.

1.4.1 Objectives of the assignment

Based on an initial climate risk screening assessment of the project, the performance of the proposed Project investment is likely to be affected by future changes in climate conditions and their impacts including temperature increase, precipitation increase, flood, and landslide risk. To achieve the impact and outputs of the proposed investments, a climate risk and adaptation assessment (CRA) is required to provide a detailed and focused risk and vulnerability assessment that will identify and, to the extent possible quantify risks to the project from climate change and variability, and provide corresponding adaptation measures. Outputs of the CRA will be used to finalize detailed design, ensuring that the proposed investment is climate-proofed to the extent feasible. Bhutan's power sector almost to 100% relies on hydropower generation. Hydropower is vulnerable to climate change and natural disasters caused by climate change. An assessment of future impact of climate change on Bhutan's hydropower assets and their performance is required to validate the underlying project's rationale for diversification of Bhutan's energy portfolio. Therefore, the objectives of this CRA are two-fold and can be summarized as follows:

3) Validate the underlying rationale for diversification of Bhutan's energy generation portfolio. The rationale is that more unreliable flows under climate change adversely affect the hydropower generation, in particular in the low flow season outside the monsoon season. This are the seasons with high potential for solar and wind energy, under the current climate conditions. The diversification of Bhutan's energy generation portfolio is considered as type 2 adaptation, related to system change and resilience building in the climate change context.
4) Assess the vulnerability of the project components to future climate change and recommend adaptation options for climate-proofing of the design. This is considered as type 1 adaptation, related to climate proofing.

1.4.2 Detailed tasks and deliverables

- Conduct a climate change vulnerability and risk assessment for the project area to identify vulnerability of the planned infrastructure, and adaptation measures to be incorporated into the project design
- Review all available relevant project documents and, in close consultation with ADB mission leader and/or project team from Bhutan, define the scope of climate risk and adaptation assessment as required by the project.
- Collate, organize and review available baseline biophysical, environmental, demographic, socioeconomic and policy data and information relevant to climate risk management within the context of the project, ensure liaison with the individual environment consultants to avoid conflict in data presented in the resulting assessments.
- Review existing studies, data and information on current and projected climate change risks and vulnerability for the proposed specific geographic areas and sectors covered by the project.
- Develop detailed scenarios of climate change variables as required for future time horizons pertinent to the project, including documentation of scenario method, data sources, uncertainties, and caveats.
- Identify climate risks and vulnerabilities and potential adaptation options and practices as inputs to modelling and/or assessment of climate change impacts on relevant aspects of the project.
- Identify and discuss the implications of projected climate change impacts and associated uncertainties for the design and operations of the project
- Conduct technical and economic assessments of potential climate risk and adaptation adaptation options and practices relevant to the project.
- Submit a comprehensive report on the potential risks of climate change to the project and possible adaptation interventions, including practical advice on the use of the CRA results for project design and operation.
- Coordinate with the technical team to ensure climate adaptation measures are incorporated into the consideration of alternatives and the proposed subproject to the extent possible.

2 Project Description

2.1 Project rationale

ADB is assisting Bhutan in the energy sector. Bhutan's development has been heavily dependent on climate-sensitive sectors such as agriculture and hydropower, with hydropower making a major contribution to the growth. Hydropower contributes about 25% to total gross domestic product (GDP) annually, accounts for 32% of total exports, and generates about 25% of the government's total domestic revenue. The power generation sector almost exclusively relies on hydropower, with an installed capacity of 2,326 megawatt (MW), and power export to India is an important source of revenue.

The Alternative Renewable Energy Policy (AREP) prepared by the Royal Government of Bhutan in 2013 aims to diversify the energy mix by harnessing other domestic sources of clean renewable energy to ensure energy security, economic development, and protection of the environment and promote renewable energy technologies such as solar PV and wind power. This policy sets out a preliminary minimum target of 20 MW by 2025 through mix of renewable energy technologies. Although Bhutan already has experience in construction of a small pilot scale wind power plant (2 x 300 kilowatt) and is planning to test small scale rooftop solar PV systems in a limited amount of households, the country has not tapped into its solar and wind resources at utility scale level and lacks capacity and experience in that field. The first deployment of non-hydro renewables at utility scale in Bhutan will be the first step to diversify the power generation portfolio, increase the resilience against severe weather events such as droughts, and complement the hydropower generation profile during the dry season.

Other renewable energy resources such as solar photovoltaic (PV) and wind can complement hydropower in forming a more diversified electricity generation portfolio, which is, in healthy mix, resilient to changes in seasonal weather patterns and weather extremes that can adversely affect power supply. In addition, Bhutan's run−of−the−river hydropower generation drastically drops during the winter dry season (December to March) due to low precipitation and snow melt, almost falling short to meet peak demand. The hydropower generating utility of Bhutan experienced poor hydrology in 2018 and for the first time since its formation in 2008, experienced net energy import from India in the dry season of February and March. In the future, climate change could even amplify this effect. The use of renewable energy sources such as solar and wind in Bhutan have complementary annual generation profiles to hydropower, producing most power during the dry season from December to March. Estimates for the technical potential in the country range from 12,000 MW for solar PV and 760 MW for wind power.

2.2 Project objectives

The project will be aligned with the following impact: carbon neutrality and improved climate and disaster resilience. The project's outputs will result in the following outcome: Bhutan's clean energy generation system diversified to non-hydro resources. Based on collected radiation and wind data for a period of one year and a feasibility study prepared by the government, the proposed project will finance the construction of (i) two solar PV power plants (**Figure 5**) located in central-west Bhutan with a total capacity of 48 megawatt peak (MWp), (ii) one wind power plant (**Figure 6**) located in western Bhutan with a total capacity of 23 MW, and (iii) respective transmission lines for grid connection. This will be the first step to diversify the generation portfolio of Bhutan's hydropower dominated energy sector. The proposed project will strengthen the EA's institutional capacity on solar and wind power project design, financial evaluation, implementation, operation, renewables grid integration, and environment safeguard monitoring.

The first introduction of solar PV and wind power technologies at utility scale is a novelty and innovation to the hydropower dominated power sector in Bhutan and will support the further development of non-hydro renewable energy sources in the country by providing Bhutan's utilities with important expertise in this field. ADB will be able to bring in its own experience and lessons from within and outside of the region where ADB has been closely involved in clean energy development at all levels.

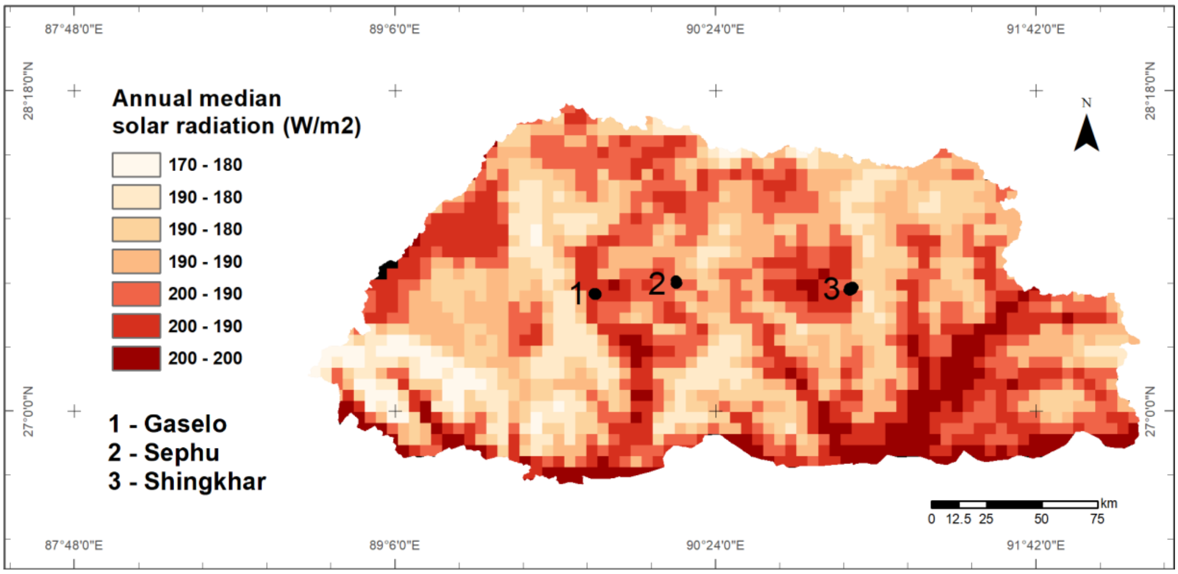


Figure 5. Annual median (2010-2019) downward surface shortwave solar radiation (w m-2) Bhutan[1]

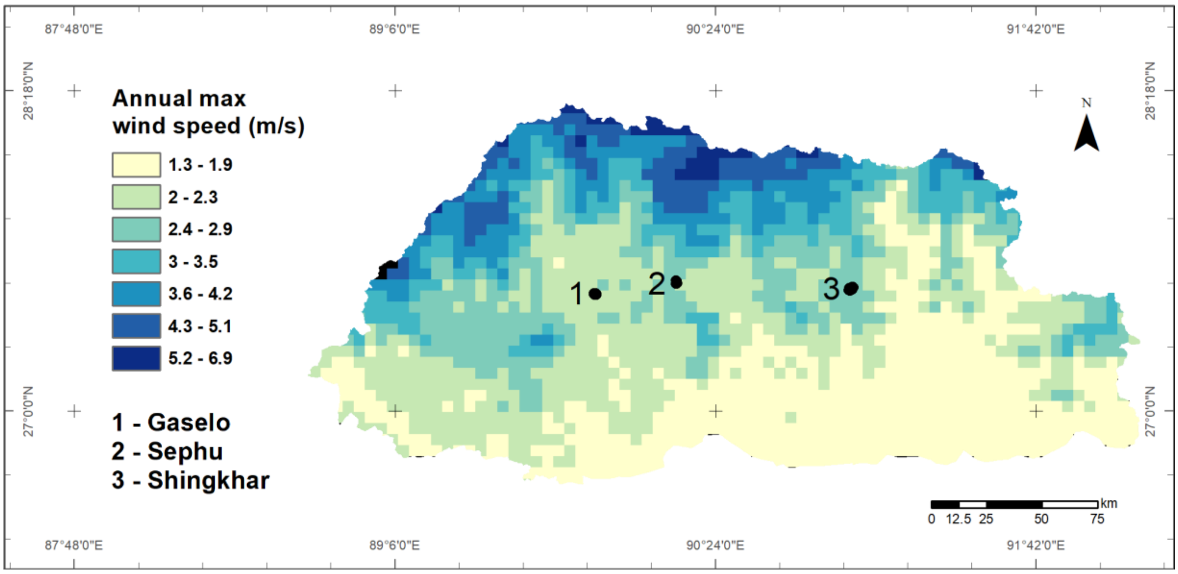


Figure 6. Annual (2010-2019) max wind speed (m s^{-1}) Bhutan (Abatzoglou et al., 2018)

2.3 Climate change in Bhutan

Bhutan is a landlocked and mountainous country in the Eastern Himalayas with elevations ranging from 160 meters to over 7,000 meters above sea level (**Figure 7**), abundant water resources and with a geographical area of 38,394 square kilometer (km^2). Climate varies due to the country's topography and geographical location at the edge of the tropical circulation in the north and Asian monsoon circulation in the south. The summer monsoon typically lasts from June to late September and delivers most of the annual precipitation in Bhutan. The great geographical diversity combined with equally diverse climate conditions contributes to Bhutan's outstanding range of biodiversity and ecosystems (**Figure 8**). Bhutan's northern region consists of an arc of Eastern Himalayan alpine shrub and meadows reaching up to glaciated mountain peaks with an extremely cold climate at the highest elevations.

More than 80% of annual precipitation in the central–eastern part of the Himalaya is delivered by the summer monsoon (Nepal and Shrestha, 2015). Recent studies point to a decline in rainfall in the country's wettest regions (Khandu et al., 2017) changes in the Indian Summer Monsoon over the subcontinent (Singh et al., 2014). While long-term future (projected) precipitation trends in the region, and in specific river basins, are subject to considerable uncertainty, several patterns have emerged. Based on the most recent climate modeling efforts (CIMP5) (Taylor et al., 2012), summer monsoon rainfall is likely to increase by mid to late 21st century in the central and eastern Himalayas, while winter precipitation is projected to decline (Wester et al., 2019). It is projected with high confidence that glaciers, snow-covered areas, snow and ice volumes will decrease within these regions over the coming decades in response to increased temperatures, and that snowline elevations will rise, affecting seasonal water storage and seasonal patterns of discharge, particularly in the high elevation sections of river basins. The loss of buffering capacity increases susceptibility to both extreme runoff due to increasingly frequent extreme rainfall events, and to prolonged low flows (Westra et al., 2014). These and other impacts of climate change including seasonal reductions in flow, more unpredictable flow patterns and changes in rates of sediment transport can potentially decrease the reliability of hydropower generation, particularly for systems with limited storage or run-of-river facilities which are common in Bhutan. Climate change is also expected to contribute to increasingly frequent and severe extreme weather events, resulting in flooding due to extreme precipitation, droughts, and heatwaves; and to elevated risk of glacial lake outburst floods (GLOF) which are a major hazard in Bhutan.

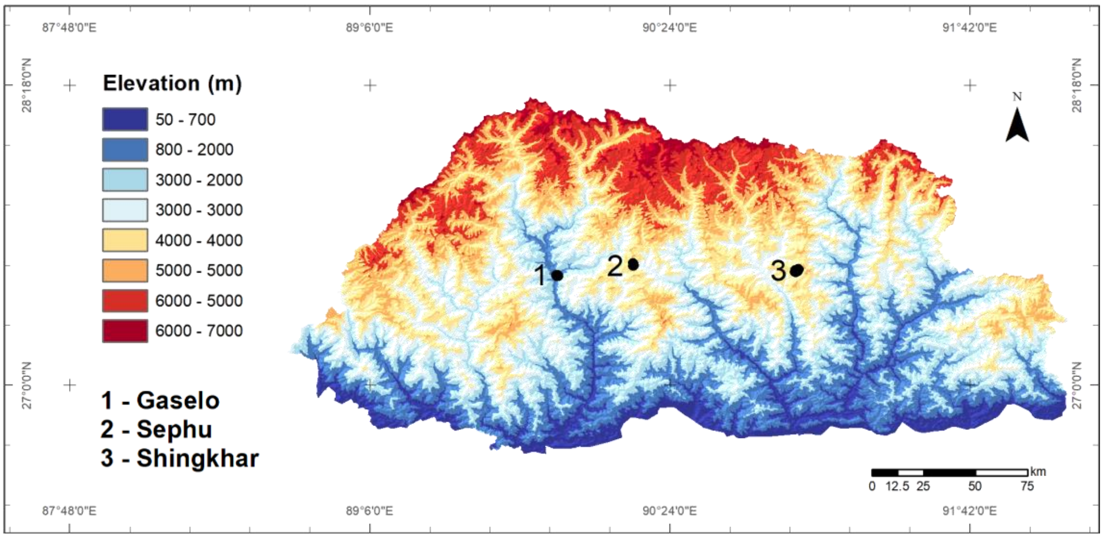


Figure 7. Elevation Bhutan and location of project areas Shingkhar, Sephu and Ghaselo for solar and wind power (Farr et al., 2007)

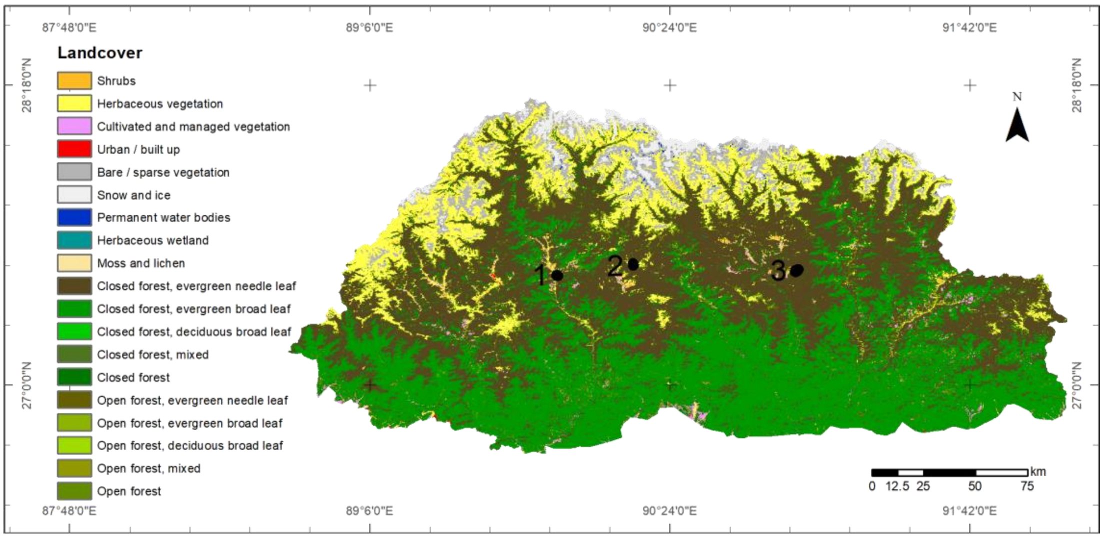


Figure 8. Landcover Bhutan (Buchhorn et al., 2020)

2.4 Climate risks and vulnerabilities energy sector Bhutan

Energy production and distribution infrastructure can be highly vulnerable to the impacts of climate change. These impacts will have consequences for the design, construction, location, and operations of power infrastructure. Inadequate attention to these impacts can increase the long-term costs of energy sector investments and reduce the likelihood that these investments deliver intended benefits (ADB, 2013). Bhutan's energy sector is vulnerable to projected changes in mean climate conditions (such as mean temperature and rainfall), in climate variability (climate variability is expected to increase in a warmer climate), and in the frequency and intensity of extreme weather events. Bhutan's current and planned power sector's vulnerability to projected climate changes includes the following (Table 1):

Table 1. Potential Impacts on Energy Sector of Bhutan (ADB, 2013)

Climate Change	Potential Impacts on Energy Sector
Hydropower	
Precipitation (including drought)	– Changing annual or seasonal patterns can affect river flows and water levels behind dams, either reducing or increasing power output – Siltation can reduce reservoir storage capacity – Increased uncertainty in water flows can affect power output and generation costs
Extreme events (glacier melting, floods)	– Floods and glacial lake outburst floods can damage or destroy infrastructure
Higher air temperature, wind speeds, and humidity	– Can increase surface evaporation, reducing water storage and power output
Wind Power	
Wind speed	– Changes in wind speed can reduce generation (turbines cannot operate in very high or very low winds). – Within operational wind speeds, output is greatly affected by wind speed – Changes in wind patterns and duration affect output (e.g., ability to forecast output)
Air temperature	– Changes in extreme cold periods can affect output (e.g., through turbine blade icing)

Extreme events (hurricanes, cyclones)	– Damage to infrastructure
Solar Photovoltaic Power	
Temperature increases	– Lowers cell efficiency and energy output – Lowers capacity of underground conductors if high ambient temperature increases soil temperature
Precipitation increases	– Can wash away dust (short term) but reduces panel efficiency (less solar radiation) – Snow accumulation on panel reduces efficiency
Wind speed; turbidity	– Increased efficiency and output with cooling effect of wind – Scouring of panel and lower output if air is gritty/dusty
Cloud cover	– Increase lowers efficiency/output – Rapid fluctuations in cloud cover can destabilize grid
Extreme events	– Can damage systems (e.g., lightning strikes)
Transmission and Distribution	
Temperature increase	– Can reduce electricity carrying capacity of powerlines – Can increase losses within substations and transformers
Increase in precipitation intensity and flooding events	– Heavy rains and flooding can undermine tower structures through erosion – Snow and ice can damage transmission and distribution lines – Flooding can damage underground cables and infrastructure in general
Increase in wind speed	– Strong winds can damage transmission and distribution lines
Increase in occurrence of extreme weather events (flood, storm, drought)	– High temperatures, storms, erosion, or flooding can damage control systems through loss of information and communications technology service or reduce quality of service – Ice storms can do devastating damage to power transmission and distribution networks – Drought can increase dust damage

Table 1 lists impact for the supply side of the energy sector. However, the demand for energy in Bhutan is also growing rapidly, mainly related to socioeconomic development. With increasing standards of living, and more people connected to the electricity grid demand grows. Electricity demand has increased between three and four fold between 2005 and 2020 (Agarwal et al., 2019).

2.5 Project sites

The proposed project will finance the construction of (i) two solar PV power plants located in central-west Bhutan with a total capacity of 48 megawatt peak (MWp), (ii) one wind power plant located in western Bhutan with a total capacity of 23 MW, and (iii) respective transmission lines for grid connection.

2.5.1 Shingkhar (Solar)

As reported by the *Detailed Feasibility Report for 30.73 MWp Solar Park at Shingkhar,* the proposed Shingkar Solar Power project site is located at a government owned land near the Shingkhar village of Ura gewog under the Bumthang district. The site has been divided into three land parcels separated by forests or natural water streams. The aggregated area of all land parcels is 116.66 acres. All three parcels are relatively flat with slopes ranging from 5º to 16º North to South, which is advantageous to solar power generation (**Figure 9**). The site is within the low seismic hazardous zone of Bhutan and experiences heavy rainfall during the Monsoon period (June to August). Provisions have been made while planning the PV array field segment placement and in designing the drainage system for diversion of rainwater to mitigate the risks of flash floods and erosion. The site is free from any encroachment and is not likely to face any opposition from the local population.

Figure 9. Stream running along one side the of proposed solar park site at Shingkhar[1]

According to the feasibility study, the two major concerns with respect to climate hazards for the proposed Shingkar project site are **heavy rain** and **heavy snowfall**. To avoid **flash floods** and **soil erosion**, design measures have been taken in overall site layout, field segment placement and planning of a drainage system and water flow capacity enhancement of the natural streams present at the site. To mitigate any risks from snow loading the PV module mounting structure is designed such that there will be no heavy deposition of snow and deposited snow will slide away at minimum time. After the construction phase, bare soil will be re-vegetated with trees and plants of local variety. To stabilize and upgrade the most effected parts of the project area, a suitable restoration and slope stabilization plan will be carried out on a yearly basis.

The identified site is a large catchment area surrounded by mountains in the north, east and west and there is a continuous slope from north to south. As a result, the risk of flash floods and soil erosion is high if water can flow through the land parcels identified for installation of the solar power plant. The surface water collected in the entire catchment area drains into the two major streams fed through multiple small streams flowing through the land parcels. To prevent any damage to the power plant from flash floods and soil erosion, construction of diversion channels and drains are proposed as shown in **Figure 10**. Diversion channels will be created using barriers and shallow artificial drains and the existing natural streams will be strengthened to carry more water without any obstruction or causing erosion. To collect and divert water collected within the plant area, shallow drains will be constructed along the internal roads to streamline run-off water collected within the power plant area. The existing streams will be not disturbed or grossly diverted but will be strengthened with minimum earth and masonry work to increase water carrying capacity and thus eliminating the possibility of overflow during heavy rain.

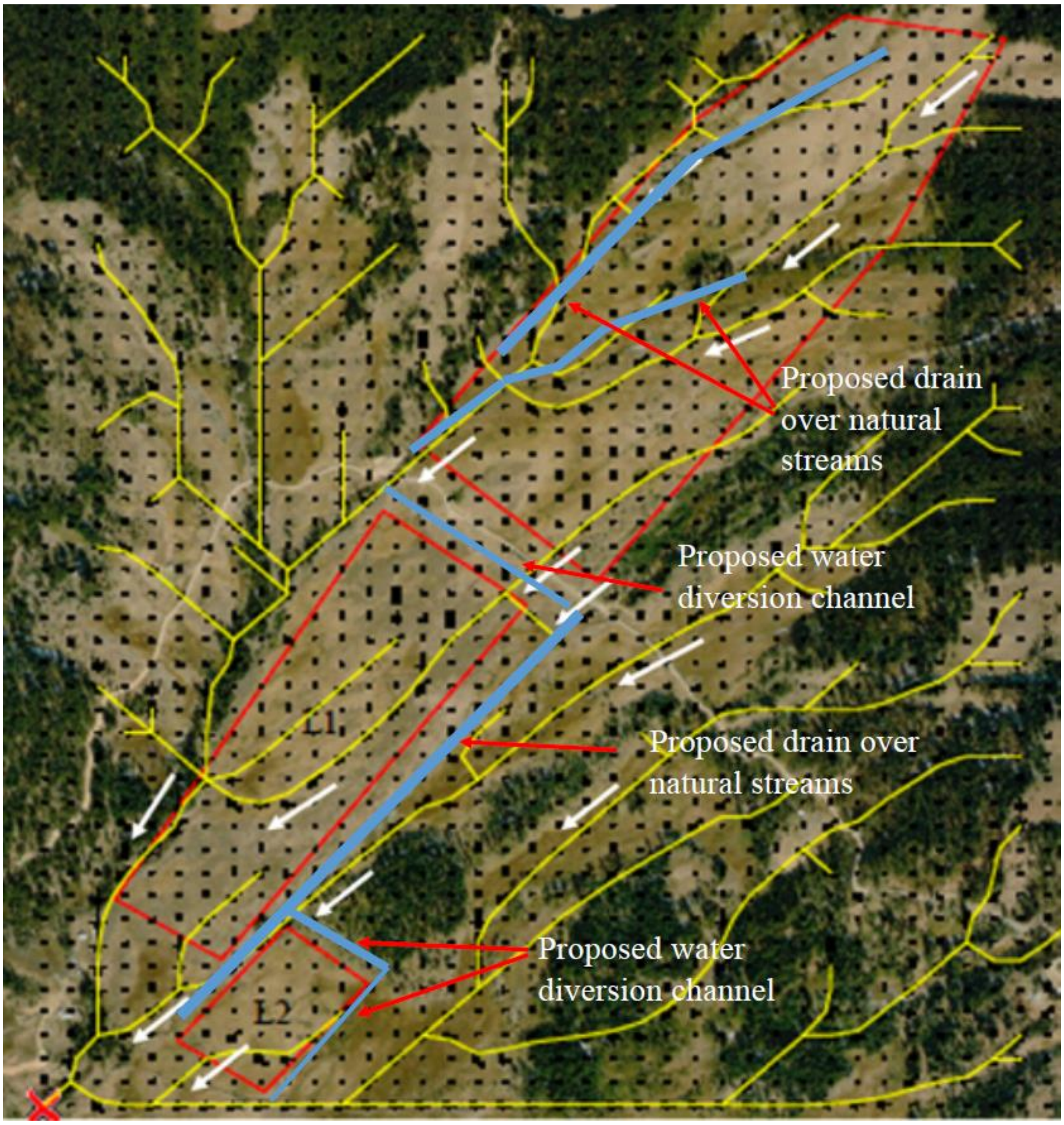


Figure 10. Watershed analysis for Shingkhar site (GSES, 2020c)

The electrical power system of the solar PV power plant will be designed to meet the requirements of`export of power to the Bhutan Power Corporation (BPC). The proposed solar park site at Shingkgar is connected to a 33kV line coming from the Garpang substation which is connected to the Yurmoo substation via a 66kV line (presently operating at 33kV). The Yurmoo substation is connected to the Tingtibi substation via 132kV line (presently operating at 33kV), which is further connected to the Jigmeling Pooling station with a 132kV line. Total transmission network will be 27 km in length.

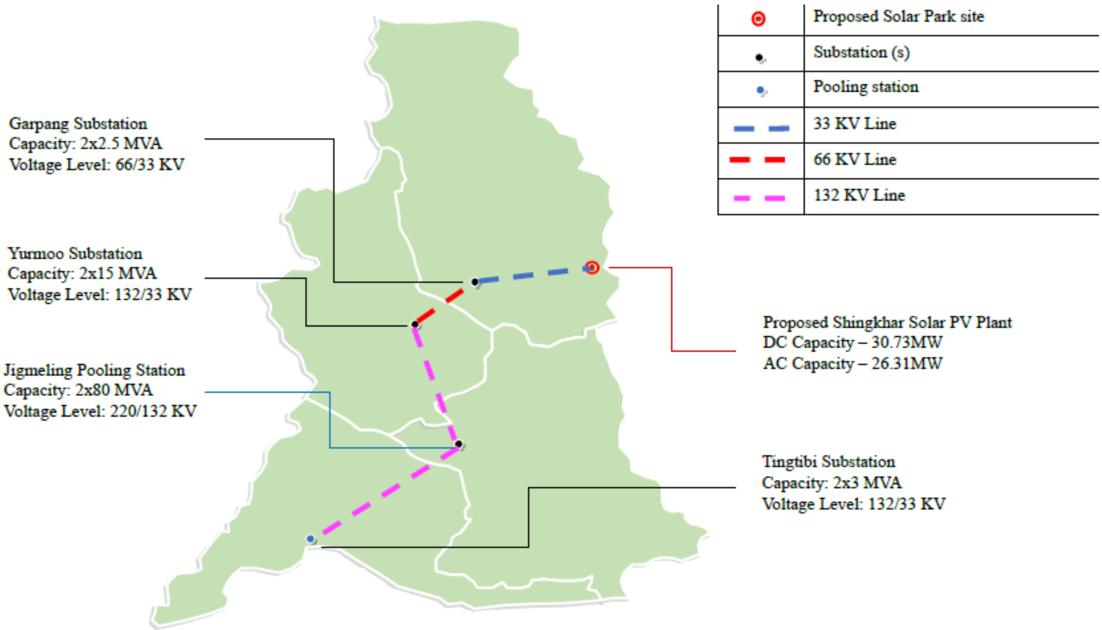


Figure 11. BPC power distribution substations and connecting power lines for Shingkhar Solar site

2.5.2 Sephu (Solar)

As reported by the *Detailed Feasibility Report for 17.38 MWp Solar Park at Sephu,* the proposed Sephu Solar Power site is located at a government owned land near Yongtru village under Yongtu Chiwog of Sephu gewog under Wangdue Phodrang district. The site has been divided into five land parcels which are separated by the Bumthang-Ura highway, natural water streams and marshy land. The aggregated area of all land parcels is 65.49 acres. All five land parcels are relatively flat: three land parcels (56.78 acres) have a slope of 4º to 13º from north to south, and two land parcels (8.71 acres) have a slope of 2º to 12º from south to north (**Figure 12**). The site is within the moderate seismic hazardous zone of Bhutan. Therefore, risk hazard of an earthquake is considered moderate but not avoidable.

The site experiences heavy rainfall during the monsoon period. Provisions have been made while planning the PV array field segment placement and in designing the drainage system for diversion of rainwater to mitigate the risks of flash floods and erosion. After the construction phase, bare soil will be re-vegetated with trees and plants of local variety. To stabilize and upgrade the most effected parts of the project area, a suitable restoration and slope stabilization plan will be carried out on a yearly basis.

According to the feasibility study, the two major concerns with respect to climate hazards for the proposed Sephu project site are **heavy rain** and **heavy snowfall**. To avoid **flash flood** and **soil erosion**, measures have been taken in overall site layout, field segment placement and planning of a drainage system and water flow capacity enhancement of the natural streams present at the site. To mitigate any risks from snow loading the PV module mounting structure is designed such that there will be no heavy deposition of snow and deposited snow will slide away at minimum time.

Figure 12. Overview (top) of proposed solar park site at Sephu and closer view of marshy land within the site (GSES, 2020a)**.**

The project area comprises of grassland, forests, marshy land, and a natural water stream water. The identified site is a large catchment area surrounded by mountains in the north, east and west and there is a continuous slope from north to south. As a result, the risk of flash floods and soil erosion is high if water can flow through the land parcels identified for installation of the solar power plant. To prevent any damage to the power plant from flash floods and soil erosion, diversion channels and drains are proposed as shown in **Figure 13**. Diversion channels will be created using barriers and shallow artificial drains and the existing natural streams will be strengthened to carry more water without any obstruction or causing erosion. To collect and divert water collected within the plant area, shallow drains will be constructed along the internal roads to streamline run-off water collected within the power plant area. The existing streams will not be disturbed or grossly diverted but will be strengthened with minimum earth and masonry work to increase water carrying capacity and thus eliminating the possibility of overflow during heavy rain.

The electrical power system of the solar PV power plant will be designed to meet the requirements of export of power to the Bhutan Power Corporation (BPC). The solar park site at Sephu is connected to a 33kV line coming from the Lobeysa substation which is connected to the Semtokha substation via a 66kV line (**Figure 14**). Total transmission network will be 47 km in length.

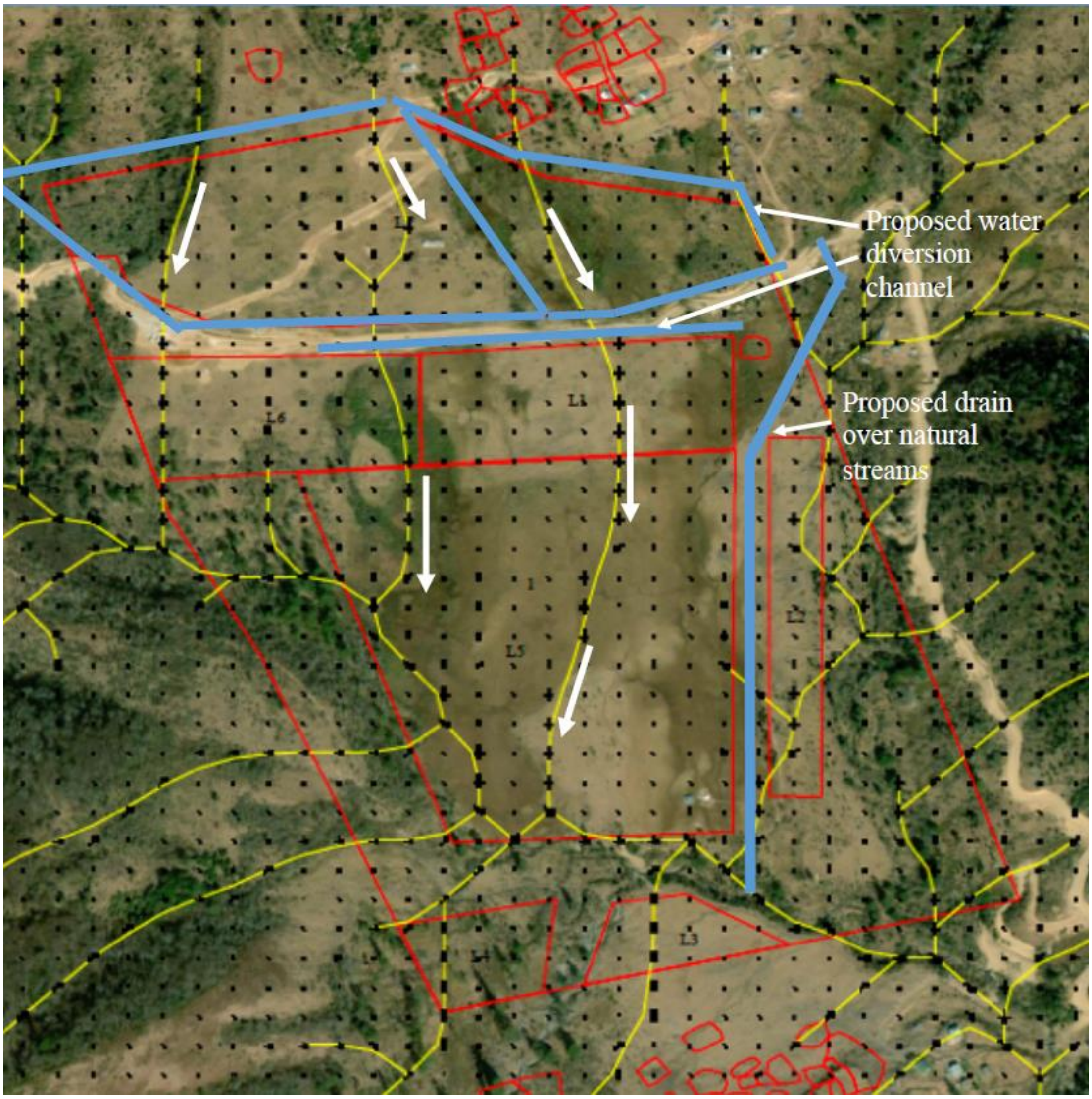


Figure 13. Watershed analysis for Sephu site (GSES, 2020a)

Figure 14. BPC power distribution substations and connecting power lines for Sephu Solar site

2.5.3 Gaselo (Wind)

As reported by the *Detailed Feasibility Report for 23 MW Wind Farm at Gaselo,* the proposed Ghaselo Wind Power site is located at a government owned land at Gaselo under Gasetsho Gom gewog of Wangdue Phodrang district. The proposed site is around 10 km away from the Wangdue-Tsirang highway. The wind farm site at Gaselo has 23 locations where the wind turbines can be placed. The final wind farm layout was designed considering the topographical and hydrological characteristics of the site. The land considered for the wind farm has an area of around 312 Acres. The available area is enough for placing around 23 MW of wind turbines. The Gaselo site has a river on the east side and has greater elevations on the west and south side. The elevation varies within the provided boundaries of the land which makes the site a complex terrain. The site slopes upward from the river in the East to West and South-West directions.

Figure 15. View of Gaselo Wind Site (GSES, 2020b)

According to the feasibility study, concerns with respect to climate hazards for the proposed Gaselo project site are related to the possibility of **soil erosion** from **heavy rainfall** and **landslides.** Possible implications of **heavy snowfall** should also be kept in mind. The Gaselo site is located at 400-1200 m above the riverbed in Wangdue Phodrang valley and hence, there is no probability of water logging or flooding at the wind farm site. However, during the construction as well as operational phase, the probability of soil erosion from heavy rainfall and landslide and possible implications of heavy snowfall should be kept in mind. The slopes, which vary from point to point, will have implications on foundation design and this is an additional aspect that needs to be considered while designing the foundations.

The proposed site is situated in a low seismic hazard risk zone. Therefore, the risk hazard from earthquakes is considered minimum but not avoidable. In the event of an earthquake in this area, the likely impact on the windfarm would be damage to the foundations and other civil infrastructure. Therefore, to minimize this risk, the design of the foundations and review of the designs of wind turbines and structure should accordingly be carried out. The climate at Gaselo has not been found to be extremely harsh with very high temperatures or very low temperatures. Also, there are no issues of salinity or corrosion or cyclones etc. that could cause damage to the wind turbines.

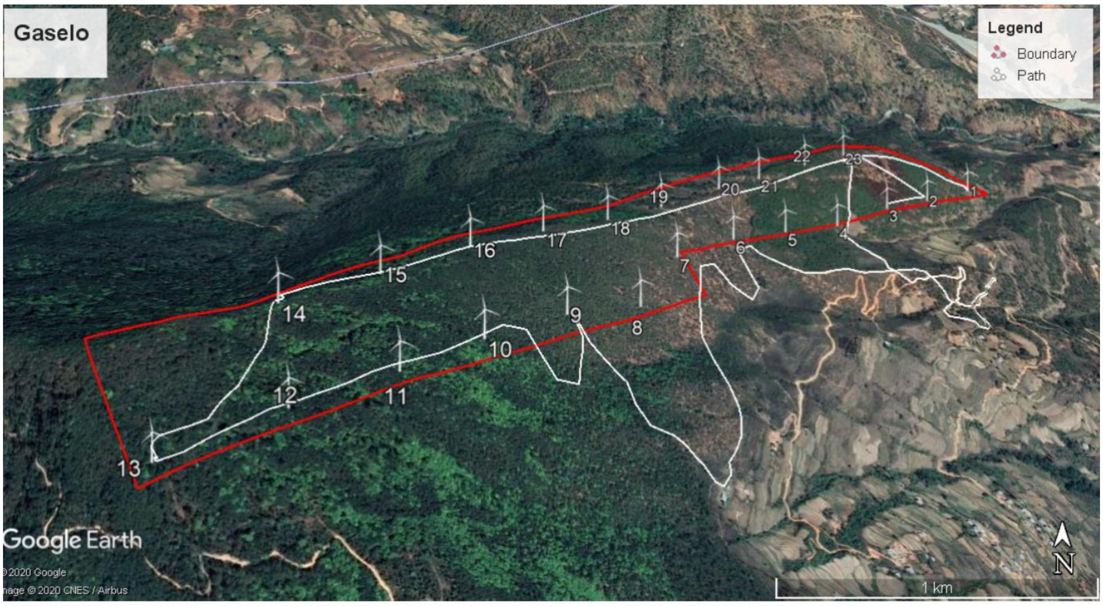


Figure 16. Gaselo wind farm site with boundary (GSES, 2020b)

The transmission and distribution networks in Bhutan are operated and maintained by Bhutan Power Corporation limited (BPC). The transmission network in the country operates at 66kV, 132kV, 220kV and 400kV voltages. The distribution network in the country operates at 33 kV and 11kV voltages. Gaselo is connected to a 33 kV line coming from Lobeysa substation which is connected to Semtokha substation and Basochhu via 66 kV line (**Figure 17**).The total transmission network will be 40 km in length.

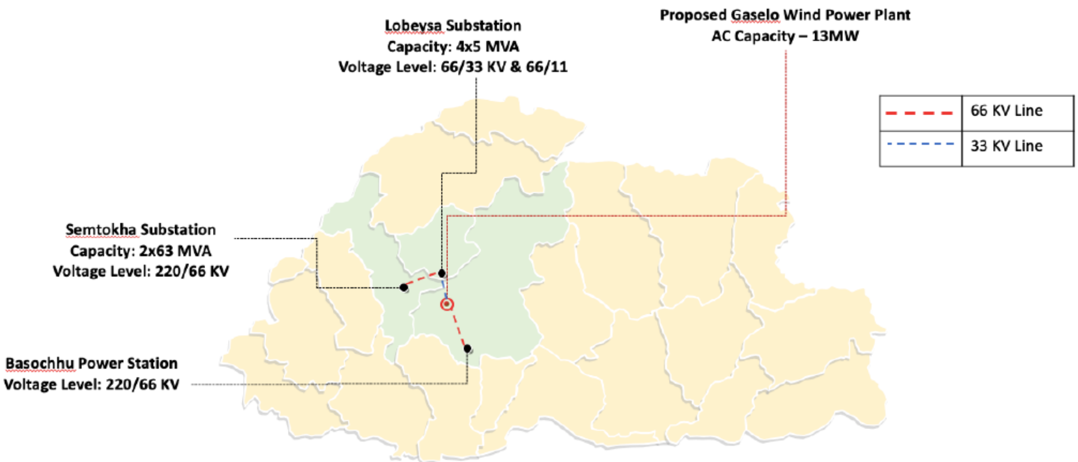


Figure 17. BPC power distribution substations and connecting power lines for Gaselo wind site

3 Historic Climate Trends

An essential step in developing a credible and acceptable Climate risk and adaptation Assessment (CRA) is to look at historic observations of climate and to perform trend analyses. This can reveal whether trends in climate variables can already be observed based on historic data. Obviously, trends, or the absence of trends, do not imply that future changes will follow the historic patterns. Any statistical trend analysis should be accompanied by understanding the underlying physical processes and future projections using GCMs.

3.1 Global climate reanalysis dataset

Reanalysis of past weather (model) data provides a clear picture of past weather. Through a variety of methods of observations from various instruments (in situ, remote sensing, models) are assimilated onto a regularly spaced grid of data. Placing all instrument observations onto a regularly spaced grid makes comparing the actual observations with other gridded datasets easier. In addition to putting observations onto a grid, reanalysis also holds the gridding model constant keeping the historical record uninfluenced by artificial factors. Reanalysis helps ensure a level playing field for all instruments throughout the historical record.

ERA5 and ERA5-Land Reanalysis Data

ERA5 is the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the global climate and weather for the past 4 to 7 decades. Currently data is available from 1979 until near-present. Reanalysis combines observations from different sources into globally complete fields using the laws of physics with the method of data assimilation (4D-Var in the case of ERA5). ERA5 provides hourly estimates for many atmospheric, ocean-wave and land-surface quantities and fluxes.

ERA5-Land is a reanalysis dataset at an enhanced resolution compared to ERA5. ERA5-Land has been produced by replaying the land component of the ECMWF ERA5 climate reanalysis. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. Reanalysis produces data that goes several decades back in time, providing a uniform and accurate description of the climate of the past.

Source: ECMWF

For the purposes of this CRA, the ERA5 reanalysis product (C3S, 2017) from the ECMWF is used to analyze historical trends in temperature and precipitation, and derived indicators, for the project area. This product is used as it provides global, spatially gridded time series of several climate variables at resolutions of 31km and sub-daily (3hr) timescales. The dataset is fully operational (updated every month) and runs from 1979 to near present. From this dataset, spatially averaged time series of precipitation and temperature are extracted for the project area at daily, weekly, and yearly timescales for the entire period that the dataset covers. This allows for the analysis of annual and seasonal trends in historical climate alongside extremes.

3.2 Temperature trends

Historical data on temperature shows that average annual temperatures are around 10 ºC for the project area (**Figure 18**). Fairly large intra-annual variations in temperature are evident, with average daily temperatures ranging from around -5 to 17 ºC (**Figure 19**). Analysis of temperature data shows that temperatures have increased in the time period 1979-2019 to almost 1.5 ºC in 40 years, see **Figure 18)**. This trend is extracted from the yearly average temperature time series and has medium statistical significance. A clear seasonality is evident in **Figure 20**, with high average monthly temperatures (around 15 ºC) prevailing during pre-monsoon and monsoon in May - September.

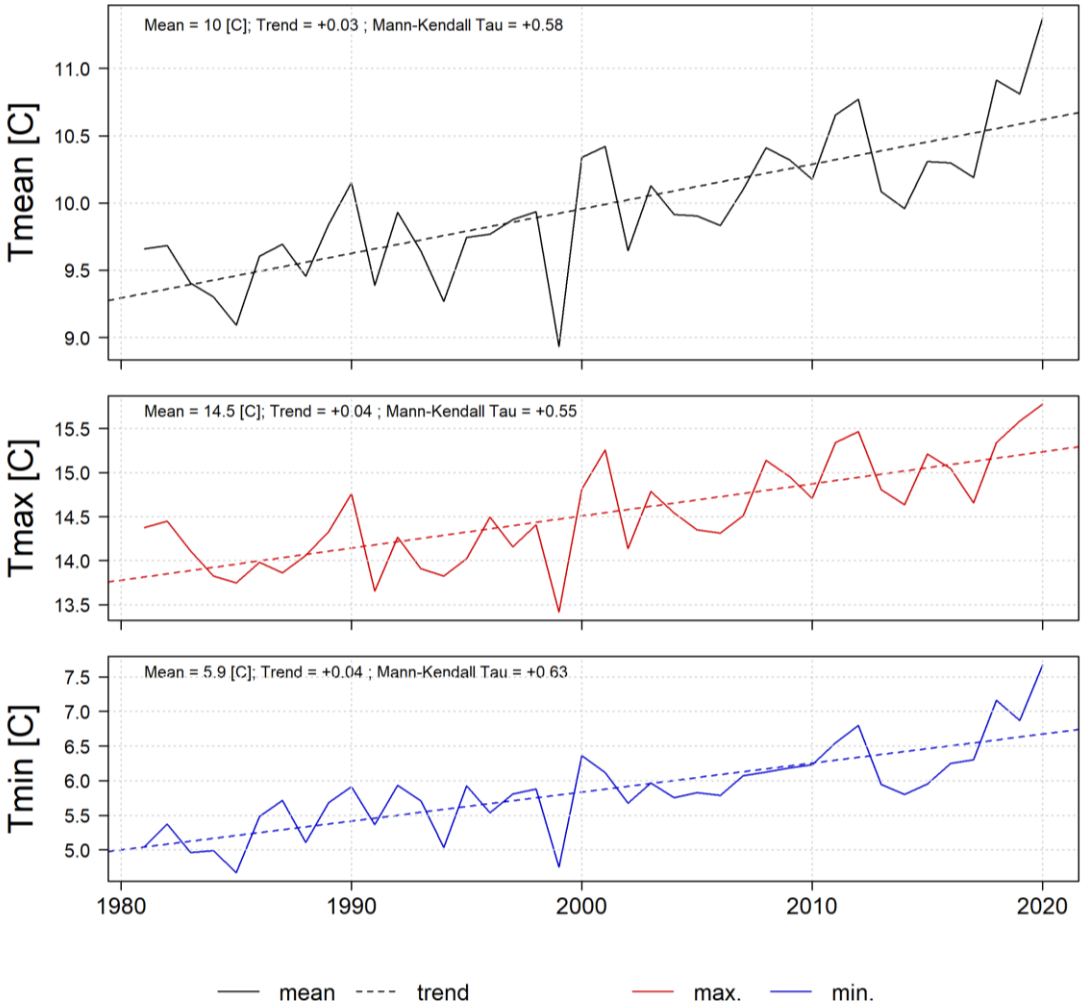


Figure 18. Average, maximum and minimum daily temperatures per year from ERA-5 dataset with trendline. *Mann Kendall Tau value indicates the strength of the monotonic trend of increase or decrease in a time series, with a value of 1 indicating a strong significant trend and -1 indicating no trend.*

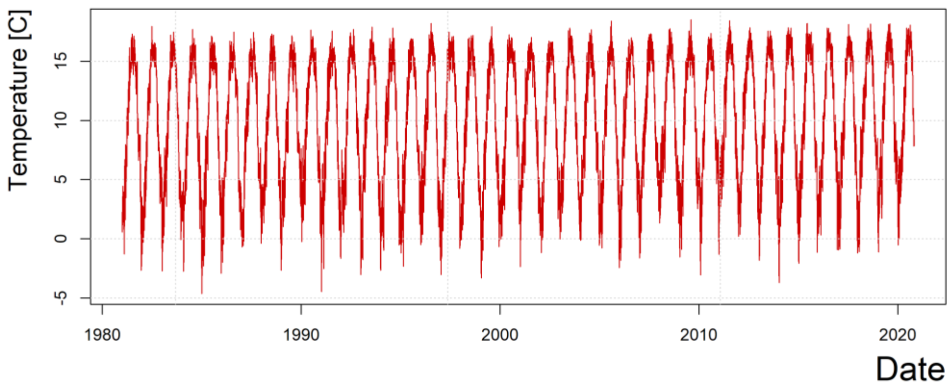


Figure 19. Daily average temperature from ERA-5 dataset

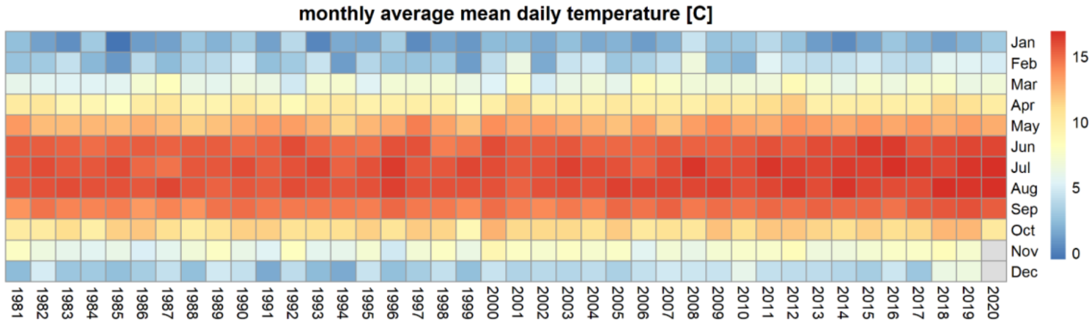


Figure 20. Seasonality in temperature from ERA-5 dataset for the project area

3.3 Precipitation trends

Historical ERA-5 data on precipitation shows that average total annual precipitation is around 3500 mm on average for the project area (**Figure 22**). This comes with some uncertainty because there may be biases in precipitation data of ERA-5 compared to stations over High Mountain Asia (HMA). The true amounts of precipitation over the High Mountains of Asia are highly uncertain in general (Immerzeel et al., 2015). Rain gauges are usually situated in the valleys because of accessibility, whereas the majority of precipitation falls at high altitude due to orographic effects. Besides, precipitation gauges usually undercatch snowfall. Remote sensing precipitation products on the other hand underestimate snowfall as well. Work analyzing glacier mass balances and observed discharge in the upper Indus in the western Himalayas and Karakoram indicates that station-based precipitation products may underestimate the total amount of precipitation by up to 50% (Immerzeel et al., 2012, 2015). The use of a weather model-based reanalysis product, like ERA5, which takes orographic effect into account, may be the better alternative.

A weak trend of increasing total annual rainfall is evident for the historical period, but with lots of interannual variability and low statistical significance. Most of the rainfall occurs during the Monsoon period in the months June, July, and August. The pre- and post-monsoon periods from November until February (**Figure 23**) are very dry. The clear patterning of precipitation according to a rainy season and dry season also becomes clear in **Figure 21**, which shows the daily precipitation values for the project areas. The maximum daily precipitation for individual years (Figure 22), which is an indicator for extreme precipitation does not indicate a clear trend and also demonstrates large interannual variability.

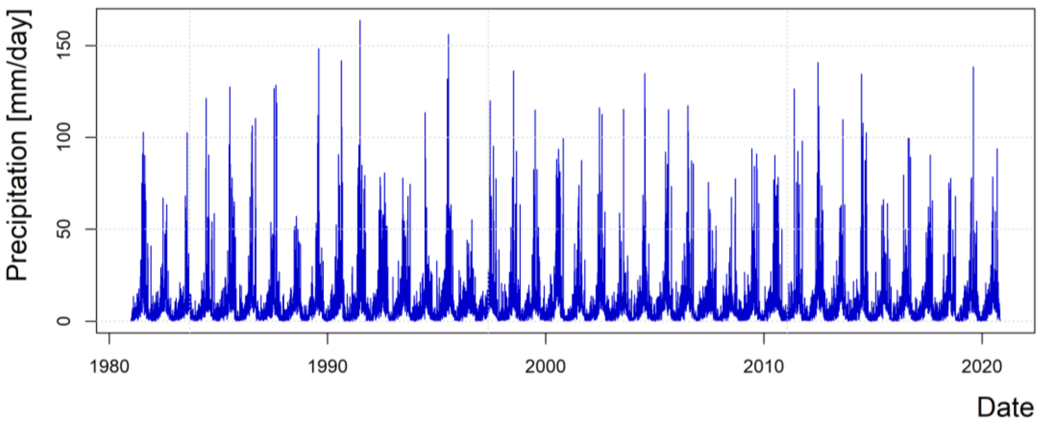


Figure 21. Daily precipitation from ERA-5 dataset

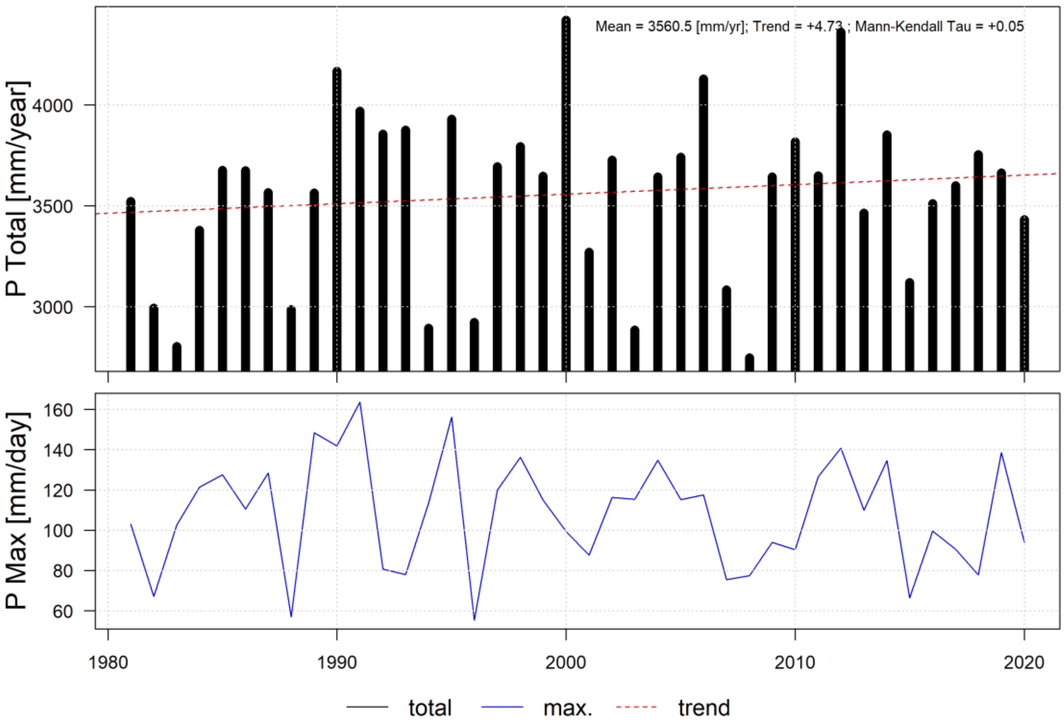


Figure 22. Total yearly and maximum one day precipitation from ERA-5 dataset with trendline.
Mann Kendall Tau value indicates the strength of the monotonic trend of increase or decrease in a time series, with a value of 1 indicating a strong significant trend and -1 indicating no trend.

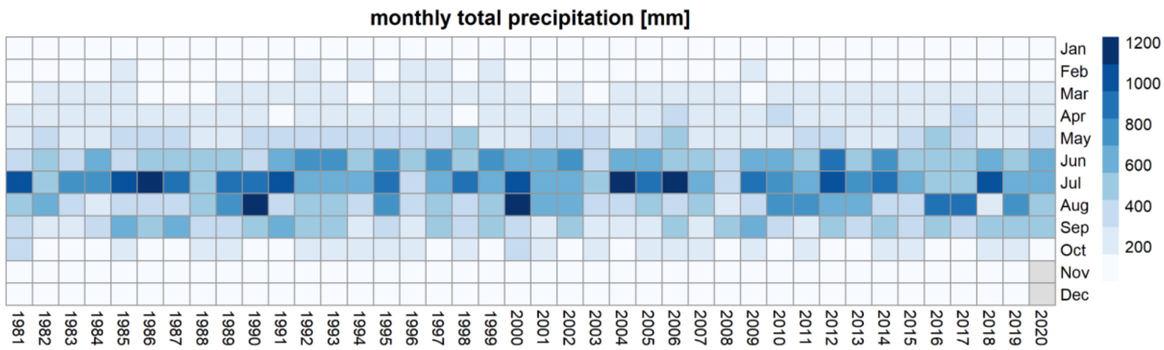


Figure 23. Seasonality of precipitation from ERA-5 dataset for the project area.

4 Future Climate Projections

4.1 Methodology

4.1.1 Climate Model Ensemble

For this CRA, the NASA-NEX (NASA, 2015) data is used to analyze future climate trends. This dataset is used to provide an analysis of trends in terms of temperature and precipitation, and derived climate change indicators. This product is used as it provides spatially gridded time series of temperature and precipitation derived from 21 General Circulation Models with global coverage (see **Table 2** for descriptions of models). Data is available at downscaled resolutions of ~25 km and daily timeseries, covering "historical" (1950 – 2005) and "future" (2006 – 2100) periods and varying emissions scenarios or Representative Concentration Pathways (RCP 4.5, 8.5), which are sufficient for the scale of the project.

From this dataset, spatially averaged time series of precipitation and temperature are extracted for the project area at daily, weekly, and yearly timescales for the entire period that the dataset covers. This allows for the analysis of annual and seasonal trends in future climate in terms of climatic means as well as extremes.

Table 2. Climate models included in NASA-NEX dataset

Model	***Research center***	***Country***	***Resolution (Original)***		***Resolution (NASA-NEX)***	
			Lat (°)	**Lon (°)**	**Lat (°)**	**Lon (°)**
BCC-CSM1-1	GCESS	China	2.79	2.81	0.25	0.25
BNU-ESM	NSF-DOE-NCAR	China	2.79	2.81	0.25	0.25
CanESM2	LASG-CESS	Canada	2.79	2.81	0.25	0.25
CCSM4	NSF-DOE-NCAR	USA	0.94	1.25	0.25	0.25
CESM1-BGC	NSF-DOE-NCAR	USA	0.94	1.25	0.25	0.25
CNRM-CM5	CSIRO-QCCCE	France	1.40	1.41	0.25	0.25
CSIRO-MK3-6-0	CCCma	Australia	1.87	1.88	0.25	0.25
GFDL-CM3	NOAAGFDL	USA	2.00	2.50	0.25	0.25
GFDL-ESM2G	NOAAGFDL	USA	2.02	2.00	0.25	0.25
GFDL-ESM2M	NOAAGFDL	USA	2.02	2.50	0.25	0.25
INMCM4	IPSL	Russia	1.50	2.00	0.25	0.25
IPSL-CM5A-LR	IPSL	France	1.89	3.75	0.25	0.25
IPSL-CM5A-MR	MIROC	France	1.27	2.50	0.25	0.25
MIROC5	MPI-M	Japan	1.40	1.41	0.25	0.25
MIROC-ESM	MIROC	Japan	2.79	2.81	0.25	0.25
MIROC-ESM-CHEM	MIROC	Japan	2.79	2.81	0.25	0.25
MPI-ESM-LR	MPI-M	Germany	1.87	1.88	0.25	0.25
MPI-ESM-MR	MRI	Germany	1.87	1.88	0.25	0.25
MRI-CGCM3	NICAM	Japan	1.12	1.13	0.25	0.25
NorESM1-M	NorESM1-M	Norway	1.89	2.50	0.25	0.25

4.1.2 Scenarios and future horizons

Two RCP scenarios (van Vuuren et al., 2011) are analyzed to provide a range of future projections to be considered in project design. RCP 4.5 represents a “stabilization scenario” in which greenhouse gas emissions peak around 2040 and are then reduced. Although often used as ‘business as usual’, the RCP8.5 is above the business as usual emission scenarios, and designed as a worst case scenario (Hausfather and Peters, 2020). We include this scenario as an upper limit to the possible future climate. These scenarios are selected as they represent an envelope of likely changes in climate and hence cover a plausible range of possible future changes in temperature and precipitation relating to project implementation. Note that RCP2.6, which covers most optimistic scenarios, including scenarios where global temperature increase is limited to 1.5 °C with respect to preindustrial levels, is not included. Since already more than 1 °C global temperature increase is realized, and considerable emission are already committed to, this scenario is very unlikely, and therefore not suitable for robust climate change adaptation purposes.

Alongside the two RCP scenarios, projections are evaluated at the following time horizons:

- Reference period [1990]: 1976 – 2005
- Near future [2030]: 2016 – 2045
- Distant future [2060]: 2046 – 2075

These periods were selected as appropriate for the project as they are relevant to the lifetime of the project infrastructure as well as the existing hydropower infrastructure, and therefore cover a realistic range of climate changes which are likely to affect project functioning. A 30-year window was selected as appropriate for deriving average climate changes, effectively considering interannual variations in temperature and precipitation, and robust comparison.

Table 3. Summary of RCP scenarios and future time horizons used in this CRA

RCP Scenarios	***Time horizons***	***Model projections***
Historical	1990 (1975-2005)	21
RCP45	2030 (2015-2045)	21
	2060 (2045-2075)	21
RCP85	2030 (2015-2045)	21
	2060 (2045-2075)	21

4.1.3 Climate Extremes Indices

To determine future trends in extreme climate events, CLIMDEX[1] indicators are used. These represent a standardized, peer reviewed way of representing extremes in climate data and are widely used in climate analyses. They are derived from daily temperature and precipitation data. These are produced through processing the NASA-NEX dataset with Climate Data Operator (CDO) software. This takes as input spatially gridded daily time series and returns yearly series of CLIMDEX indices. This process is useful as it effectively reduces the amount of data analysis needed whilst retaining the ability to represent extremes within data in a comparable way.

For the purposes of the proposed project, the indices described here are considered most relevant out of the 27 available. The Rx1day index is representative of future trends in extreme precipitation and therefore likely to be a good measure of potential impacts related to flooding, slope instability, erosion and extreme snowfall on project components. CDD (Consecutive Dry Days) is important as it provides a useful indication of trends in meteorological drought, which may impact hydropower generation. TX_X and

[1] https://www.climdex.org/learn/

TN_N variables are good predictors of extreme temperature, which may have negative effects on project components through freezing (and heavy snowfall if combined with precipitation) and extreme heat events.

Table 4. CLIMDEX Precipitation Indices used in the project

Index name	***Description***	***Unit***
Rx1day	Annual maximum 1-day precipitation	mm
CDD	Annual maximum consecutive dry days: annual maximum length of dry spells, sequences of days where daily precipitation is less than 1mm per day.	days
TXx	Annual maximum of daily maximum temperature	Celsius
TNn	Annual minimum of daily minimum temperature	Celsius

4.2 Climate projections for the project area

4.2.1 Average trends in temperature and precipitation

In terms of average climate trends, it is clear that the climate model ensemble projects an increase in mean temperature for the project area in the upcoming 60 years (**Figure 24**). It is also clear that under the higher RCP scenario, a larger increase in temperature is expected. For the short-term horizon (2015-2045), changes in temperature in the range of around 1 – 2 °C with respect to the historical reference are projected by the climate model ensemble, for the longer-term horizon (2045-2075), this increases to around 1.5 – 4°C, with a larger spread in model projections **(Figure 26**).

The future trend for precipitation is less clear but, overall, the climate model ensemble projects an increase in mean precipitation for the project area in the upcoming 60 years (**Figure 25**). A large spread in model predictions is evident, with some models predicting (much) higher future increases in precipitation than others. For the short-term horizon (2015-2045), changes in precipitation in the range of around 10% are projected by the climate model ensemble, for the longer-term horizon (2045-2075), this increases to around 20 – 25%, with a larger spread in model projections and higher divergence between emissions pathway RCP 4.5 and RCP 8.5 **(Figure 26)**.

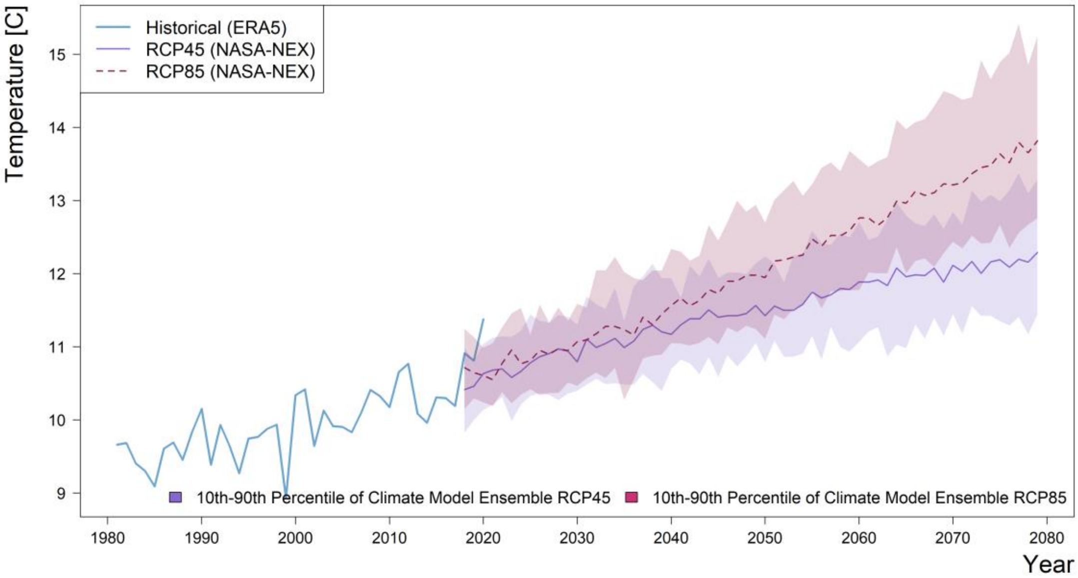


Figure 24. Time series of mean yearly temperature constructed using ERA5 dataset for the historical period (1979-2019), and NASA NEX (per model bias corrected to ERA5) for the future period. *Shaded areas show the 10th and 90th percentiles in the spread of model predictions (uncertainty in the future climate).*

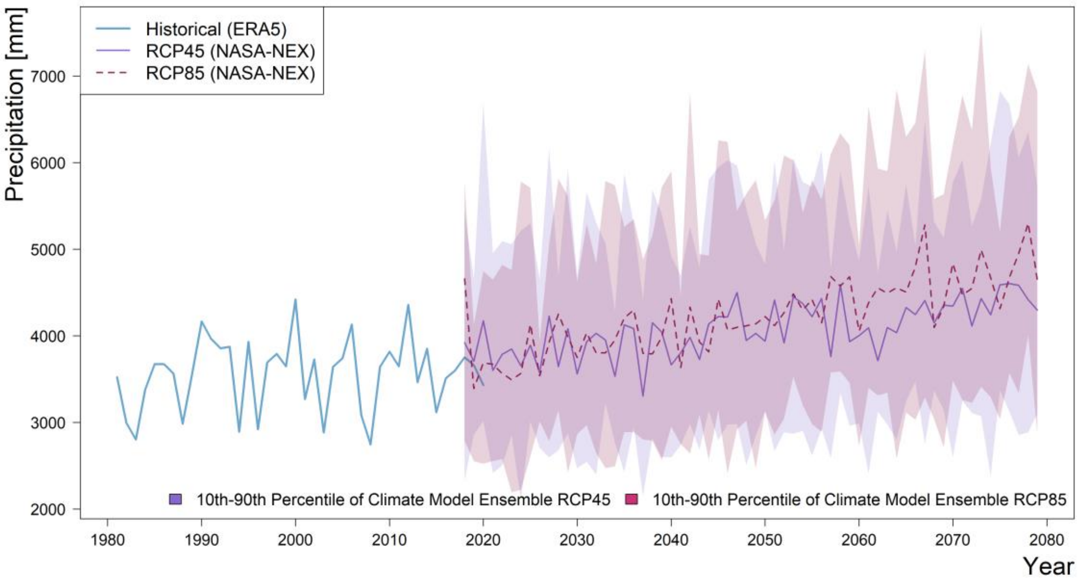


Figure 25. Time series of total yearly precipitation constructed using ERA5 dataset for the historical period (1979-2019), and NASA NEX (per model bias corrected) for the future period. *Shaded areas show the 10th and 90th percentiles in the spread of model predictions (uncertainty in the future climate).*

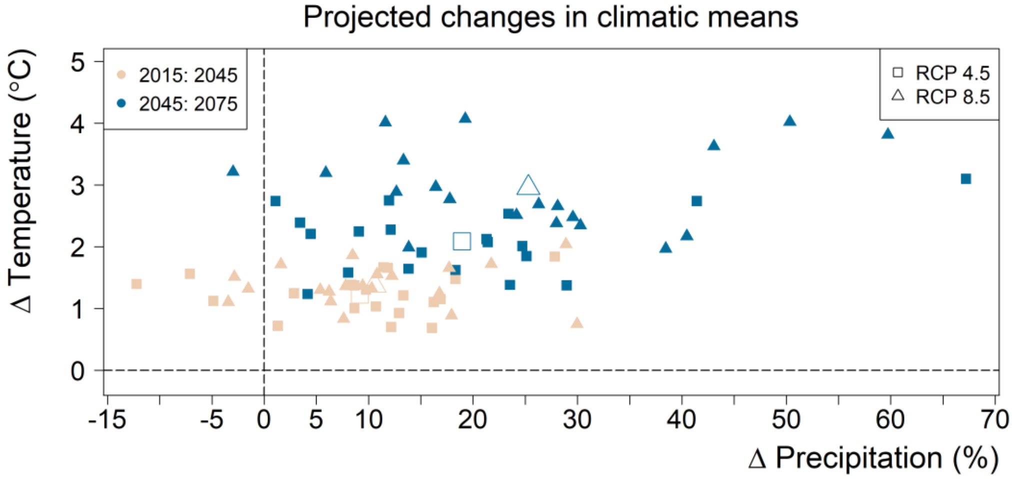


Figure 26. Average temperature and precipitation changes in the project area. These indicate the difference (Δ) between historical (1976-2005) and future (2015-2045; 2045:2075) time horizons for the two RCP scenarios.

4.2.2 Seasonality

In terms of seasonality, the climate model ensemble projects a general increase in both minimum and maximum temperatures for all months (**Figure 27**). A greater increase in temperatures is predicted in the longer term (2045-2075) timescale and under the higher RCP 8.5 scenario. However, the models do not suggest a greater increase in temperature during in the warmer months (May-September), which indicates that a change toward a more extreme seasonality in terms of temperature is not expected.

The GCM ensemble results for precipitation seasonality (**Figure 28**) suggest that a more intense rainy season may result from climate change, with increases in precipitation suggested for the Monsoon period from May-August. This trend is more extreme under the RCP 8.5 scenario compared to RCP4.5. This result must, however, be considered uncertain due to the variation shown in model predictions for precipitation. The amount of precipitation is projected to remain fairly stable during pre- and post-Monsoon months, though a slight decrease in precipitation is foreseen for the longer-term horizon (2045-2075) for both RCP scenarios.

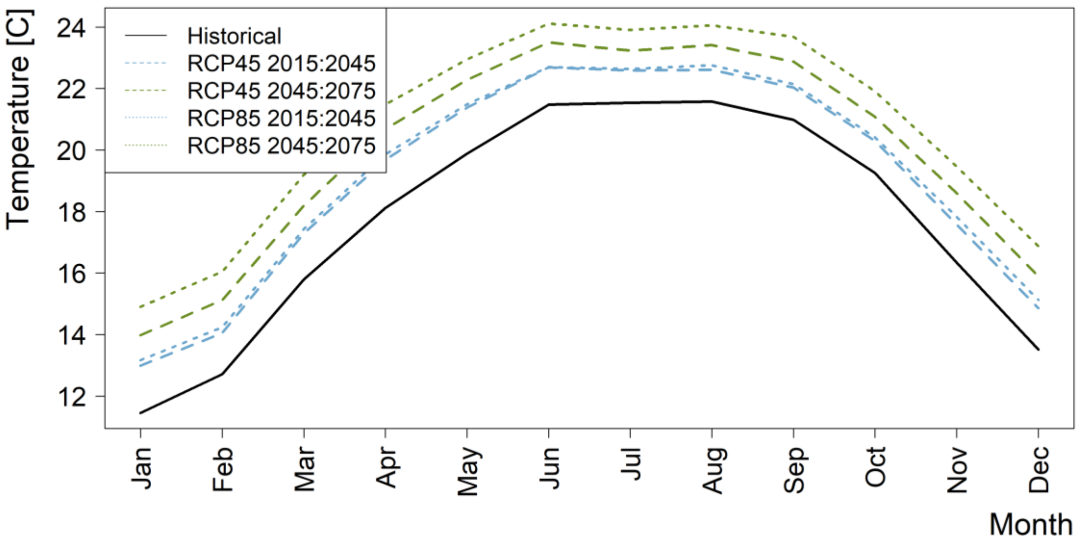


Figure 27. Average maximum daily temperature per month for historical (1976-2005) and future (2015-2045; 2045:2075) time horizons under the two RCP scenarios

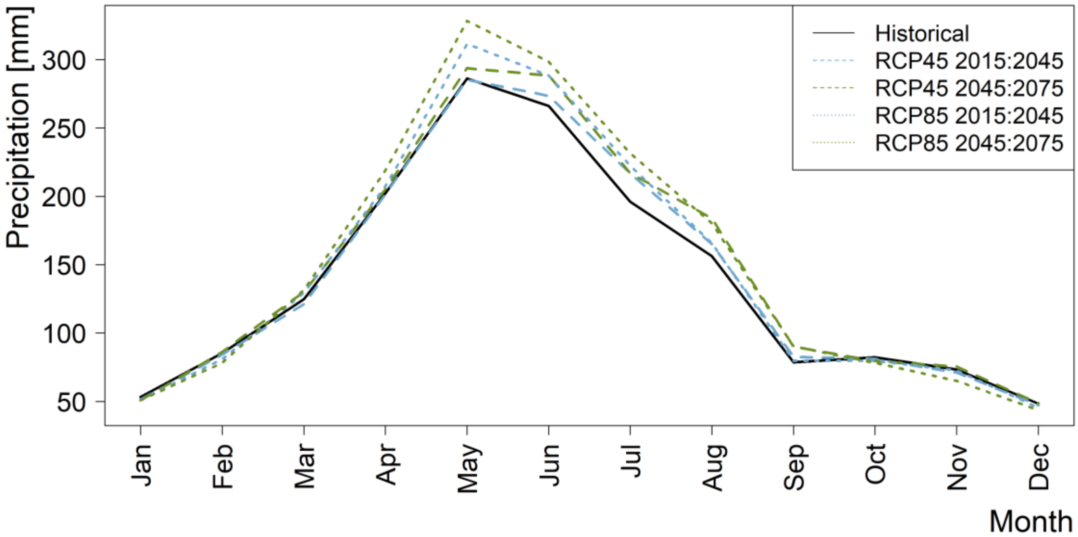


Figure 28. Average total monthly precipitation per month for historical (1976-2005) and future (2015-2045; 2045:2075) time horizons under the two RCP scenarios

4.2.3 Trends in Climate Extremes

<u>Temperature-related extremes</u>

When extreme trends are considered, a large level of variation is evident in climate model projections. This is expected since climate models are inherently limited in terms of predicting trends in extremes due to the stochastic nature of these events. The climate model ensemble does, however, show a clear trend of increasing extreme temperatures under both RCP scenarios and time horizons (**Figure 29, Figure 30**), suggesting an increase in the likelihood of heatwaves in the area. These processes are certain to affect seasonal water storage and seasonal patterns of discharge, particularly in the high elevation sections of river basins.

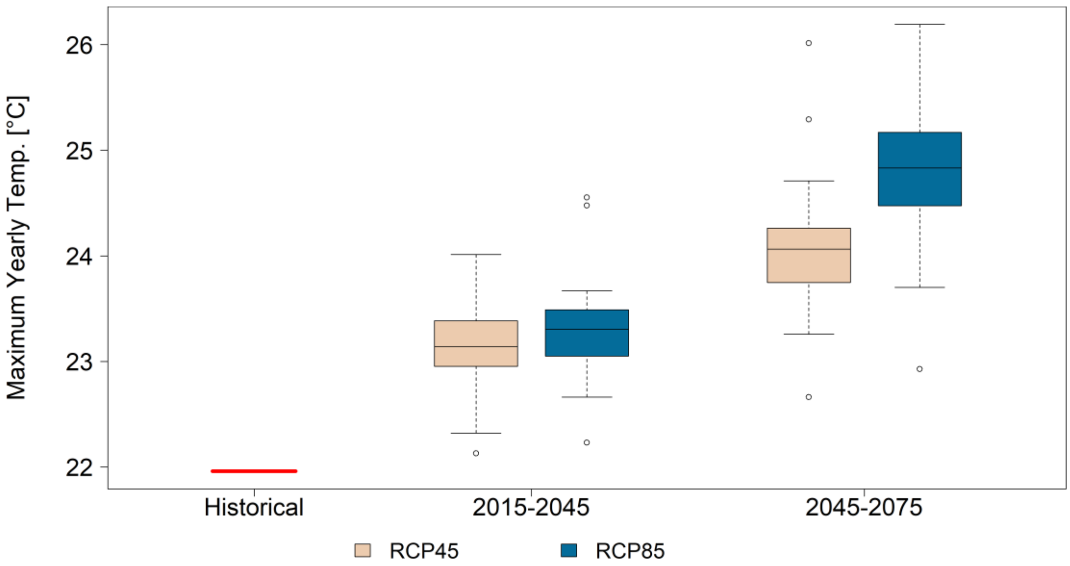


Figure 29. Boxplots indicating the spread in climate model predictions of maximum daily temperature per year (TXx) for the historical and future time periods under two RCP scenarios.

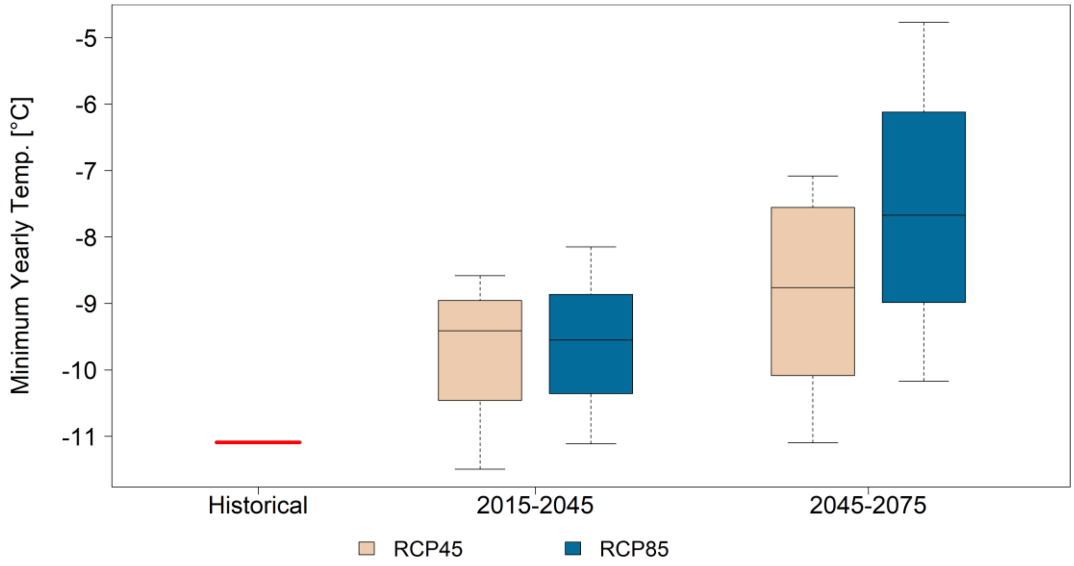


Figure 30. Boxplots indicating the spread in climate model predictions of minimum daily temperature per year (TNn) for the historical and future time periods under two RCP scenarios.

Precipitation-related extremes

The climate model ensemble shows a clear trend of increasing extreme precipitation events under both RCP scenarios and time horizons (**Figure 31, Table 5, Table 6**), suggesting also an increase in intense precipitation associated risks (flash flooding, soil erosion) in the future for the project area.

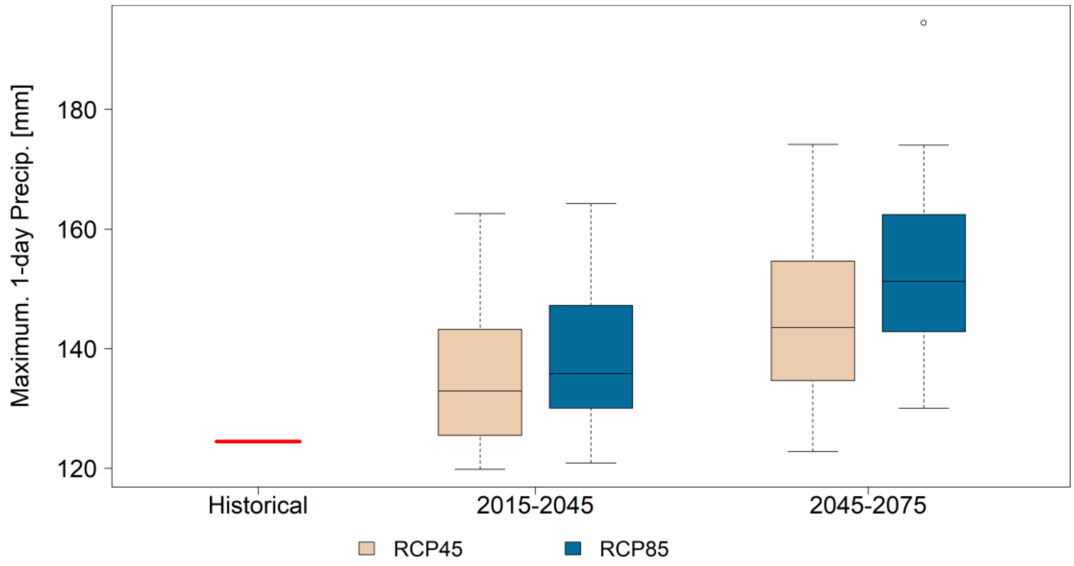


Figure 31. Boxplots indicating the spread in climate model predictions of yearly maximum 1-day precipitation sum (Rx1day, in mm/day) for the historical and future time periods under two RCP scenarios.

Table 5 Predicted change (%) in yearly maximum 1-day precipitation sum (Rx1day) for the full climate model (GCM) ensemble.

		bcc-csm1-1	BNU-ESM	CanESM2	CCSM4	CESM1-BGC	CNRM-CM5	CSIRO-Mk3-6-0	GFDL-CM3	GFDL-ESM2G	GFDL-ESM2M	inmcm4	IPSL-CM5A-LR	IPSL-CM5A-MR	MIROC-ESM-CHEM	MIROC-ESM	MIROC5	MPI-ESM-LR	MPI-ESM-MR	MRI-CGCM3	NorESM1-M
Rx1day (%)	2030_RCP45	1%	14%	48%	9%	11%	9%	3%	31%	16%	16%	-2%	22%	24%	-1%	10%	16%	12%	3%	1%	8%
	2060_RCP45	10%	35%	40%	25%	12%	19%	10%	46%	15%	36%	-5%	43%	35%	12%	26%	11%	16%	3%	32%	13%
	2030_RCP85	16%	19%	38%	10%	12%	13%	-7%	17%	18%	24%	-11%	42%	33%	5%	14%	12%	21%	4%	13%	-7%
	2060_RCP85	23%	31%	81%	23%	33%	33%	10%	52%	40%	41%	4%	48%	29%	27%	12%	27%	22%	16%	33%	10%

Table 6. Summary table showing statistics regarding spread in climate model (GCM) ensemble predictions for future changes (%) in max annual 1-day precipitation in the project area

	Median (%)	*25th Perc. (%)*	*75th Perc. (%)*	*GCMs dryer*	*GCMs wetter*
2030_RCP45	13%	3%	16%	2	18
2060_RCP45	22%	11%	35%	1	19
2030_RCP85	14%	6%	20%	3	17
2060_RCP85	30%	17%	38%	0	20

A simplified return period analysis for extreme precipitation events was conducted. For this the third quartile (75th percentile) of climate model ensemble predictions of yearly maximum 1-day precipitation events (Rx1day) were taken, which ADB frequently considers for robust climate change adaptation. Then the Gumbel extreme distribution Gumbel is fitted to the 75th percentile value of the projections in the GCM model ensemble distribution, to assess the design precipitation events at different return periods for each time horizon and RCP scenario. The relative changes (delta values) are then imposed on the historical reanalysis (ERA-5) data to allow for the projection of absolute values for 1-day precipitation events (**Figure 32, Table 7, Table 8**). Considering different return periods, in general the statement can be made that the precipitation amounts for events with that return period increase by 17-25% for the 2030 time horizon and 33-40% for the 2060 time horizon with respect to the historical period according to the 75th percentile value of the climate model ensembles. In addition, Table 6 indicates for the maximum 1 day precipitation sums that the 75th percentile value of the ensemble indicates 16-20% increase for the 2030 time horizon and 35-38% increase for the 2060 time horizon.

This analysis shows for the project area that under climate change, the intensity of the most severe precipitation events predicted by the climate model ensemble will increase, with the largest increases occurring at the more distant time horizon (2060) and more extreme emissions scenario (RCP85). This likely signifies an increase in intense precipitation associated risks (flooding, erosion, landslides) in the future for the project area. These and other impacts of climate change, including seasonal reductions in flow, more unpredictable flow patterns and changes in rates of sediment transport can potentially decrease the reliability of hydropower generation, particularly for systems with limited storage or run-of-river facilities which are common in Bhutan. The loss of buffering capacity (due to rising temperatures) increases the susceptibility to both extreme runoff due to increasingly frequent extreme rainfall events, and to prolonged low flows. These adverse impacts may be exacerbated due to increasingly frequent and severe extreme precipitation events.

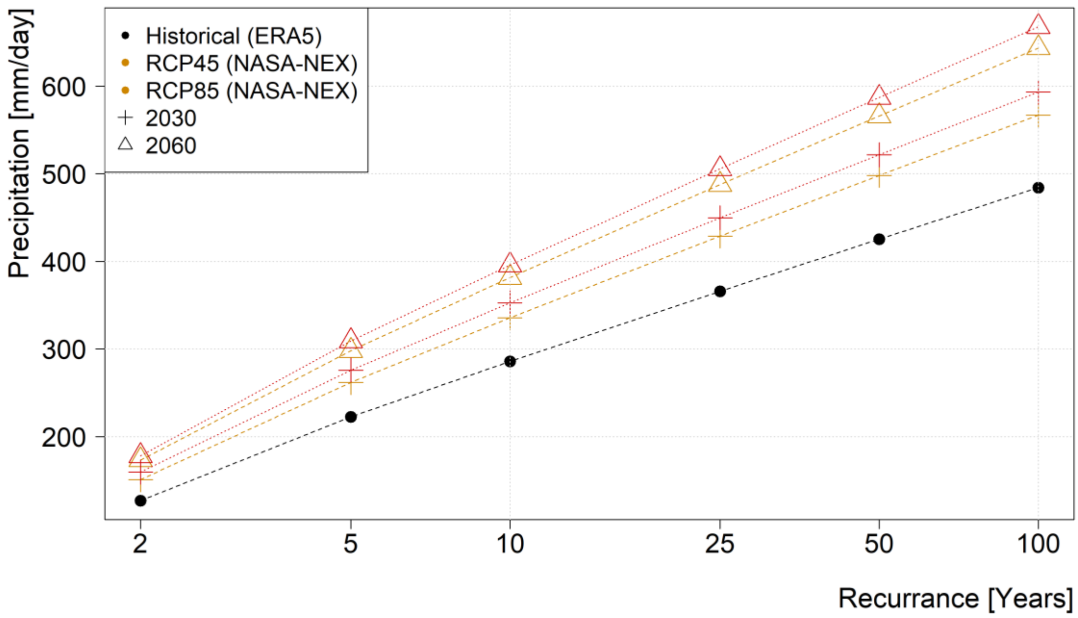


Figure 32. Recurrence intervals of daily precipitation for 5 scenarios (at 75th percentile of model projections): ERA5 is historic (1976-2005); 2030-RCP45; 2050-RCP45; 2030-RCP85; 2050-RCP85

Table 7. Absolute intensity (mm/day) of precipitation events at different return periods under a variety of emissions scenarios (at 75th percentile of model projections) and time horizons

	Return Period [years]					
	2	**5**	**10**	**25**	**50**	**100**
Historical daily maximum precipitation [mm/day]						
ERA5	127	223	286	366	425	484
*Future (**75th percentile of climate model ensemble predictions**) daily maximum [mm/day]*						
RCP45 2030	151	262	336	429	498	567
RCP45 2060	173	298	382	488	566	644
RCP85 2030	160	276	353	450	522	593
RCP85 2060	178	309	396	506	587	668

Table 8. Predicted change (%) in the intensity of precipitation events at different return periods under a variety of emissions scenarios and time horizons

	Return Period [years]					
	2	**5**	**10**	**25**	**50**	**100**
Historical daily maximum precipitation [mm]						
ERA5	127	223	286	366	425	484
Change in daily max. precipitation [%], format = **median (25th, 75th percentile** *of GCM ensemble)*						
RCP45 2030	15 (4,19)	13 (4,18)	12 (3,17)	12 (3,17)	11 (4,17)	11 (4,17)
RCP45 2060	21 (12,37)	21 (12,34)	21 (12,34)	20 (12,34)	20 (12,33)	20 (12,33)
RCP85 2030	13 (7,26)	12 (8,24)	12 (8,24)	12 (8,23)	12 (8,23)	12 (8,23)
RCP85 2060	28 (23,40)	28.7 (22,39)	29 (22,39)	29 (21,39)	29 (21,38)	29 (21,38)

There is no clear increasing (or decreasing) trend for the number consecutive dry days per year (**Figure 33)**. This indicates that on average more prolonged meteorological droughts are not necessarily expected, although the model uncertainty increases over longer time horizons. However, taking into account also the loss of the water buffering capacity of snow and ice (see chapter 5), hydrological droughts are likely to become more frequent.

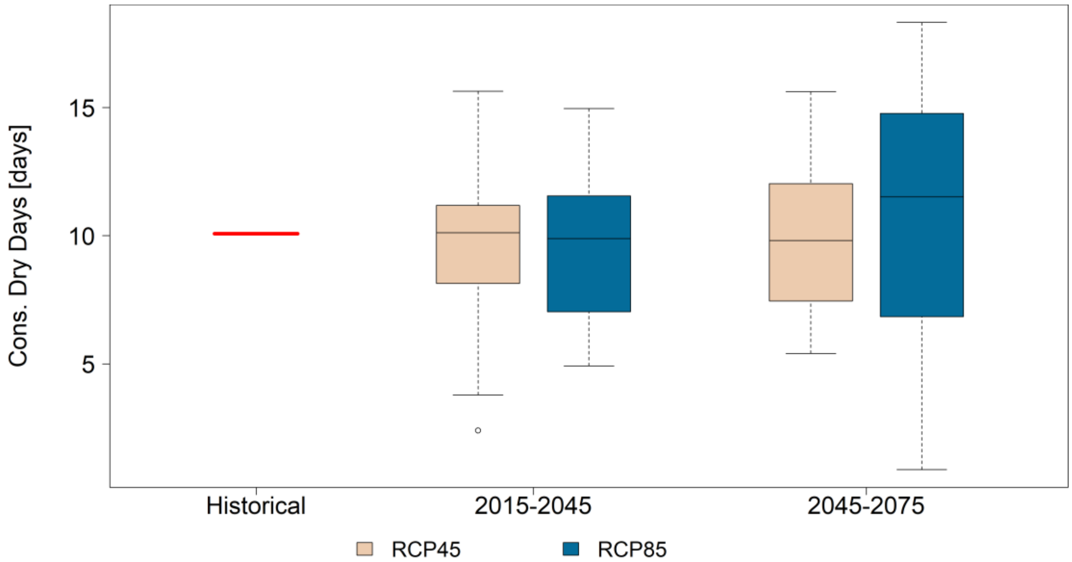


Figure 33. Boxplots indicating the spread in climate model predictions of consecutive dry days per year (CDD) for the historical and future time periods under two RCP scenarios.

4.3 Summary tables

The combination of 21 GCMs, two RCPs and two time-horizons leads to a total of 84 (21 x 2 x 2) projections for the future. **Table 9** shows detailed results for all 84 projections of changes in mean annual temperature and total annual precipitation. Delta values indicate the difference between historical (1976-2005) and future (2015-2045; 2045:2075) time horizons for the two RCP scenarios. This shows consistency between GCMs in terms of projecting a warmer future climate in the project area (especially for the longer-term horizon) but indicates the large uncertainty in the future precipitation.

Table 10 and **Table 11** show the main statistics (median, 10th percentile and 90th percentile) of the changes in precipitation and temperature, respectively. It also includes the number of GCMs that are showing a positive versus negative change for precipitation, and number of GCMs that are predicting a change above 2ºC and 4ºC. In summary, all GCMs predict a hotter future, with most predictions lying between 2 and 4ºC. There is no clear consensus in precipitation predictions, but a slight majority of GCMs predict a drier future under the RCP45 scenario.

Also here, when considering the 75th percentile value of the projections as a benchmark for robust climate change adaptation, the statement can be made that wetter conditions with 15% (2030) and 22-34% (2060) increases should be anticipated.

Table 9. Average climate change (delta values) in total annual precipitation and mean annual temperature predicted by the full climate model (GCM) ensemble.

		bcc-csm1-1	BNU-ESM	CanESM2	CCSM4	CESM1-BGC	CNRM-CM5	CSIRO-Mk3-6-0	GFDL-CM3	GFDL-ESM2G	GFDL-ESM2M	inmcm4	IPSL-CM5A-LR	IPSL-CM5A-MR	MIROC-ESM-CHEM	MIROC-ESM	MIROC5	MPI-ESM-LR	MPI-ESM-MR	MRI-CGCM3	NorESM1-M
Precip (%)	2030_RCP45	9%	12%	13%	13%	9%	11%	2%	27%	19%	16%	3%	21%	17%	-12%	-7%	14%	7%	2%	7%	7%
	2060_RCP45	17%	19%	24%	23%	13%	20%	19%	67%	13%	20%	4%	43%	16%	3%	3%	23%	7%	3%	21%	21%
	2030_RCP85	7%	11%	9%	1%	11%	14%	0%	29%	9%	15%	7%	20%	22%	0%	7%	16%	12%	-2%	24%	-1%
	2060_RCP85	25%	15%	45%	22%	27%	34%	17%	51%	30%	39%	16%	61%	25%	13%	14%	29%	5%	-2%	33%	20%
Tavg (oC)	2030_RCP45	1.16	1.24	1.77	1.26	1.44	0.70	1.16	1.91	1.03	1.07	0.86	1.65	1.94	1.54	1.71	1.21	1.57	1.41	0.60	1.46
	2060_RCP45	1.72	2.16	2.63	1.99	2.06	1.39	2.32	3.16	1.68	1.71	1.38	2.92	3.03	2.91	2.51	2.09	2.42	2.39	1.29	2.14
	2030_RCP85	1.46	1.58	1.98	1.42	1.46	0.90	1.14	2.08	1.21	1.41	0.99	1.90	1.93	1.87	1.46	1.32	1.75	1.67	0.65	1.38
	2060_RCP85	2.61	3.01	3.75	2.78	2.84	1.97	2.94	4.05	2.48	2.37	2.14	3.99	4.36	4.14	3.56	2.56	3.39	3.39	2.08	2.83

Table 10. Summary table showing statistics regarding spread in Climate Model (GCM) ensemble predictions for future changes in mean annual precipitation in the project area

	Median (%)	*25th Perc. (%)*	*75th Perc. (%)*	*GCMs dryer*	*GCMs wetter*
2030_RCP45	9%	4%	15%	2	18
2060_RCP45	19%	9%	22%	0	20
2030_RCP85	11%	2%	16%	3	17
2060_RCP85	26%	16%	34%	1	19

Table 11. Summary table showing statistics regarding spread in Climate Model (GCM) ensemble predictions for future changes in mean annual temperature in the project area

	Median (ºC)	*25th Perc. (ºC)*	*75th Perc. (ºC)*	*GCMs > 2ºC*	*GCMs > 4ºC*
2030_RCP45	1.3	1.1	1.6	0	0
2060_RCP45	2.2	1.7	2.6	13	0
2030_RCP85	1.5	1.2	1.8	1	0
2060_RCP85	3.1	2.5	3.7	19	3

Note that although the projections presented here are based on spatially downscaled data, there still is a scale gap between the used climate projections, based on a scale around 25 km, and the specific sites. In particular in a mountainous country like Bhutan, with high climatic variability over short horizontal and vertical distances, site-specific projections may deviate.

5 Climate change impacts for hydrology and hydropower

5.1 Future impacts for glaciers and snow

Mountains serve as water towers. Their key hydrological feature is to store water as snow and ice, which is released to flow downstream more gradually than direct rainfall-runoff (Immerzeel et al., 2020). The fact that mountain ranges in High Mountain Asia (HMA) are the highest on Earth combined with monsoon-dominated precipitation regimes (implying large amounts of precipitation), makes the amount of water generated in those mountain ranges particularly large (Viviroli et al., 2003; Bookhagen and Burbank, 2010). In particular glaciers have strong modulating effect on the flows, ensuring constant water supply during droughts (Pritchard, 2019).

Because of its large areas and volumes of snow and glacier ice, HMA is also referred to as the “Asian Water Tower”, or the “Third Pole”. Glaciers in Bhutan are retreating rapidly, with area loss between 1980 and 2010 in the order of 20-25% (Bajracharya et al., 2014). Remote sensing derived glacier mass balance estimates (Brun et al., 2017) indicate the glacier mass balance over Bhutan is around -0.7 to -0.8 meters water equivalent per year (Figure 34). Similar trends were found by (Shean et al., 2020).

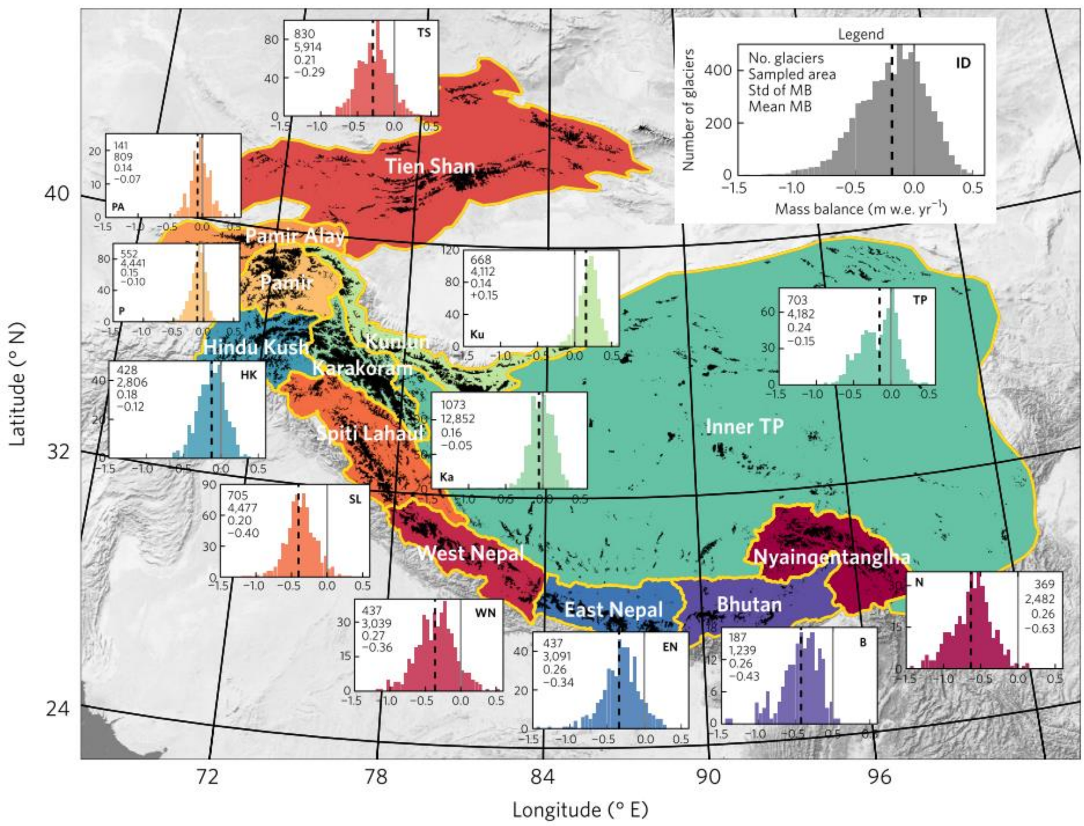


Figure 34: Remote sensing derived geodetic mass balance for High Mountain Asia (2000–2016). For each region, the distribution of glacier-wide mass balance for every individual glacier (>2km2) is represented in histograms of the number of glaciers (y axis) as a function of MB (x axis in mw.e. yr−1). The black dashed line represents the area-weighted mean. The numbers denote the total number of individual glaciers (first), the corresponding total area (in km2, second), the standard deviation of their mass balances (in mw.e. yr−1, third) and the area-weighted average mass balance (in mw.e. yr−1, fourth). Initials of the respective regions are repeated in bold. Source: Brun et al., 2017

Modeling simulations at the HMA scale indicate for the Eastern Himalaya where Bhutan is located that ice mass loss towards the end of the century varies from 40% to 90% loss, depending on the climate scenario (Kraaijenbrink et al., 2017) (Figure 35). Another modelling study (Rounce et al., 2020) showed similar results for the Eastern Himalayas.

Snow melt is an important contributor to flows in Bhutan (Lutz et al., 2014). Snow cover monitoring on a regional scale has started only recently. With the availability of satellite data, near real-time spatial maps of snow cover have become available. However, long term trends in snow cover cannot be established since these analyses cover a maximum of ten years. Most of the available studies are based on MODIS satellite products. They do not show clear general temporal changes in the snow-covered area over the whole HMA region. There is a large inter-annual variation in snow cover and an increasing trend from west to east for HMA from 2000 until 2008 (Immerzeel et al., 2009). Slightly decreasing trends were found for Bhutan (Gurung et al., 2011). Future simulations of snow cover show overall decreases, with the magnitude of decline mostly related to the temperature scenarios (Lutz et al., 2014; Wijngaard et al., 2017).

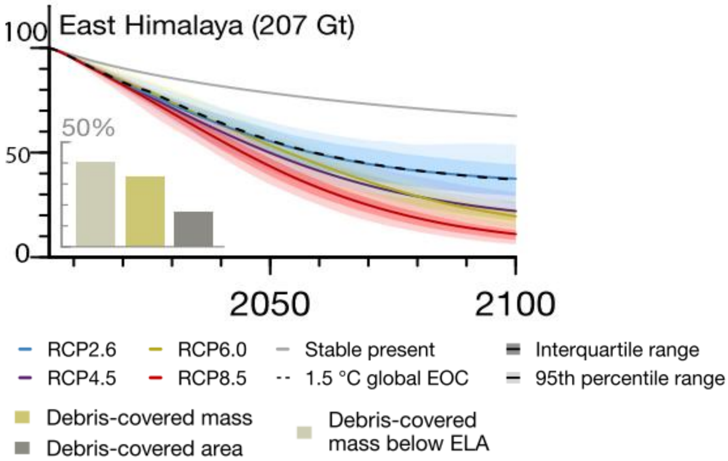


Figure 35: Projected ice mass loss for the Eastern Himalaya for 4 RCP scenarios, stable present climate, and a 1.5 °C global temperature increase scenario. The y-axis indicates the remaining ice mass compared to 2005 as baseline. Source: Kraaijenbrink et al. 2017.

5.2 Future impacts for hydrological flows and hydropower generation

Climate change impacts flows in various ways by affecting different water balance components. Input of water changes with precipitation changes. Changes in glaciers and snow cover alter the buffering capacity of the hydrological system. How this affects the stream flow depends strongly on the role of glacier melt and snow melt in the stream flow composition (Lutz et al., 2014). Climate change impacts glaciated catchments at different time scales (IPCC, 2019) (Figure 36). Changes at the yearly and decadal time scale are of interest for changes in hydropower generation. Glaciated catchments first witness an increase in melt water generation with increasing temperature. When glaciers have lost a significant amount of their mass, the melt water generation starts to decline. This concept is commonly referred to as 'peak water' (Huss and Hock, 2018). The time when peak water is reached strongly depends on the degree of glaciation of a catchment. For the Eastern Himalayas in Bhutan, this is generally expected around 2040, albeit with a large uncertainty band (Huss and Hock, 2018). Changes in total flows however, depend mostly on the precipitation projections, which mostly project increasing precipitation for Bhutan (Lutz et al., 2014). With declining glacier mass and snow cover however, the hydrograph will become more erratic when the hydrological system shifts towards a more rainfall dominated system. This can imply more frequent hydrologic droughts and periods of low flows outside the monsoon season, as well as more frequent extremely high flows or floods during the monsoon season.

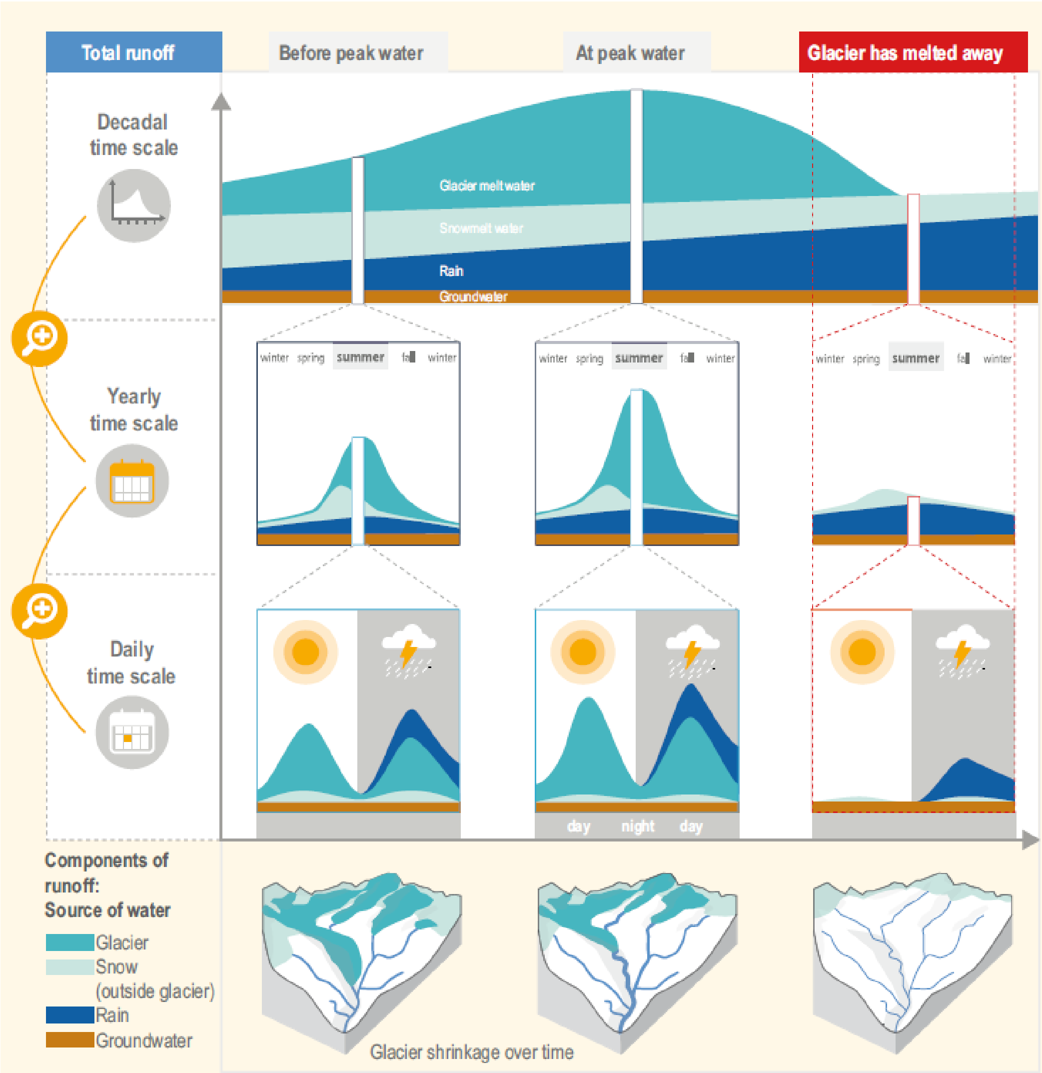
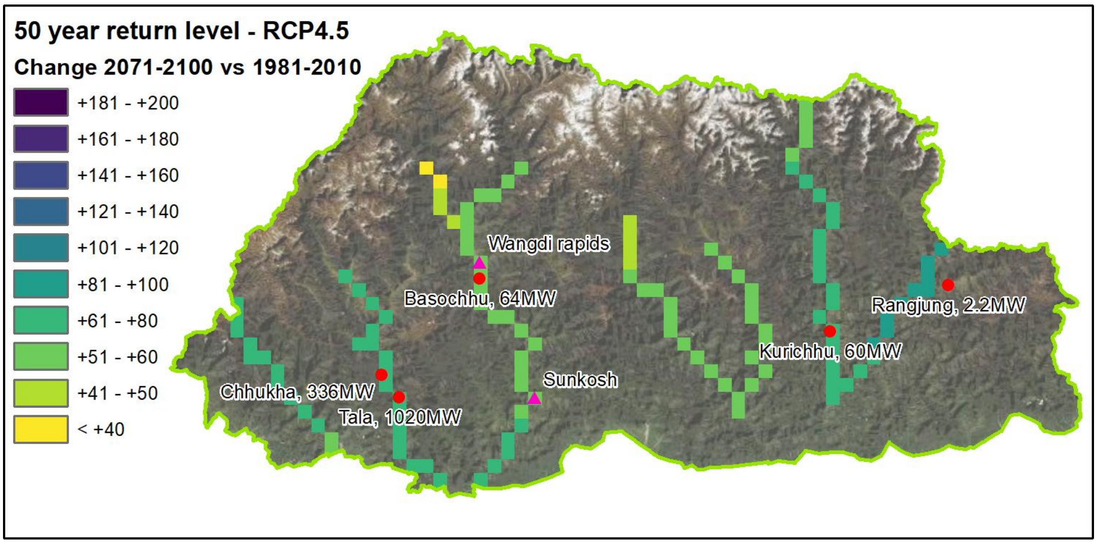


Figure 36: A simplified overview of changes in runoff from a river basin with large (e.g., >50%) glacier cover as the glaciers shrink, showing the relative amounts of water from different sources – glaciers, snow (outside the glacier), rain and groundwater. Three different time scales are shown: annual runoff from the entire basin (upper panel); runoff variations over one year (middle panel) and variations during a sunny then a rainy summer day (lower panel). Note that seasonal and daily runoff variations are different before, during and after peak flow. The glacier's initial negative annual mass budget becomes more negative over time until eventually the glacier has melted away. This is a simplified figure so permafrost is not addressed specifically and the exact partitioning between the different sources of water will vary between river basins. Source: IPCC SROCC 2017

Hydropower infrastructure is designed to operate at flows between a design minimum and maximum. The projected changes in flows can indicate a longer flow duration outside the turbines design range, and therefore less generation during the low flow season, when generation is at present already at its minimum. A study into future changes in extreme flows in three of South Asia's river basins, including Bhutan, shows this effect (Wijngaard et al., 2017). This study indicates changes in the discharge level of events with a present 50-year return period to increase in Bhutan by around 40 to 180%, strongly depending on the scenario (Figure 37). The strong increase in extreme flows not only indictes more flows at the high tail of the distribution outside the turbine range, but also significantly increases the risk of damage to hydropower infrastructure due to floods. (Wijngaard et al., 2017) also did a detailed assessment of flow changes at two representative locations in Bhutan: Sunkosh station and Wangdi rapids station. Flows in these locations are constituted by approximately 25-30% snow melt and glacier melt. For these locations, present and future flow duration curves are shown in Figure 38 and Figure 39. These figures reveal for these 2 locations that flows in general increase, in particular at the flows with low exceedance probability. Interestingly, also the low flows are projected to increase according to the ensemble mean. However, the uncertainty range indicates that low flows could also decrease, depending on the climate scenario, in particular for the RCP4.5 climate scenario. Also in the middle of the distribution, likely near the optimum for hydropower generation, the projections are uncertain. The exact impacts of these projections for hydropower generation depend on the operational ranges of the turbines. Note also that these projections are based on a large river basin scale study covering the upper Indus, upper Ganges and upper Brahmaputra river basins at a spatial scale of 5x5 km, and may therefore lack reliability at smaller scales, like the current application. Detailed hydrological modelling for exact existing or envisioned hydropower infrastructure sites would be required to provide better insights.

Table 12 indicates the projected percentual changes in the discharge volume of a 1 in 50 years recurring extreme flow event, for 4 major hydropower generation locations included in the Global Power Plant database (Byers et al., 2019). This shows substantial projected increases for each of the locations. Note the substantial uncertainty in the projections indicated by the standard deviation listed in the table. Despite this large uncertainty there it is likely that the future will show an increase in extreme flow events. The uncertainty is mostly related to the actual magnitude of this increase.



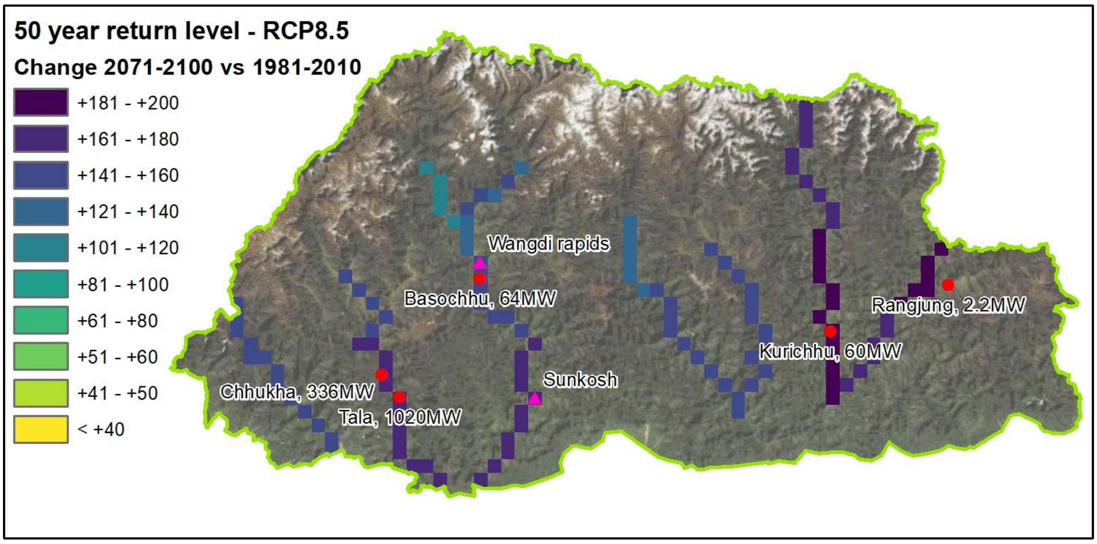


Figure 37: Relative changes in 50-year return period discharge level. Maps showing the mean relative changes in 50-year return period discharge levels (%) at the end of the 21st century (2071–2100) under RCP4.5 (top) and RCP8.5 (bottom). Maps show the ensemble mean projections. Red dots indicate major hydropower generation locations. Pink triangles indicate locations where flow duration curves described in this section have been established. Data sources: (Wijngaard et al., 2017; Byers et al., 2019)**.**

(Wijngaard et al., 2017) also did a detailed assessment of flow changes at two representative locations in Bhutan: Sunkosh station and Wangdi rapids station. Flows in these locations are constituted by approximately 25-30% snow melt and glacier melt. For these locations, present and future flow duration curves are shown in Figure 38 and Figure 39. These figures reveal for these 2 locations that flows in general increase, in particular at the flows with low exceedance probability. Interestingly, also the low flows are projected to increase according to the ensemble mean. However, the uncertainty range indicates that low flows could also decrease, depending on the climate scenario, in particular for the RCP4.5 climate scenario. Also in the middle of the distribution, likely near the optimum for hydropower generation, the projections are uncertain. The exact impacts of these projections for hydropower generation depend on the operational ranges of the turbines. Note also that these projections are based on a large river basin scale study covering the upper Indus, upper Ganges and upper Brahmaputra river basins at a spatial scale of 5x5 km, and may therefore lack reliability at smaller scales, like the current application. Detailed hydrological modelling for exact existing or envisioned hydropower infrastructure sites would be required to provide better insights.

Table 12: Change in 50-year return period discharge level at major hydropower generation locations. Source: (Wijngaard et al., 2017)

Name	Capacity (MW)	Change in 50 year return level 2071-2100 vs 1981-2010 (%)			
		RCP4.5 ensemble mean	RCP4.5 ensemble standard deviation	RCP8.5 ensemble mean	RCP8.5 ensemble standard deviation
Basochhu	64	+54	22	+148	97
Chhukha	336	+67	34	+162	113
Kurichhu	60	+69	9	+185	100
Tala	1020	+67	34	+163	113

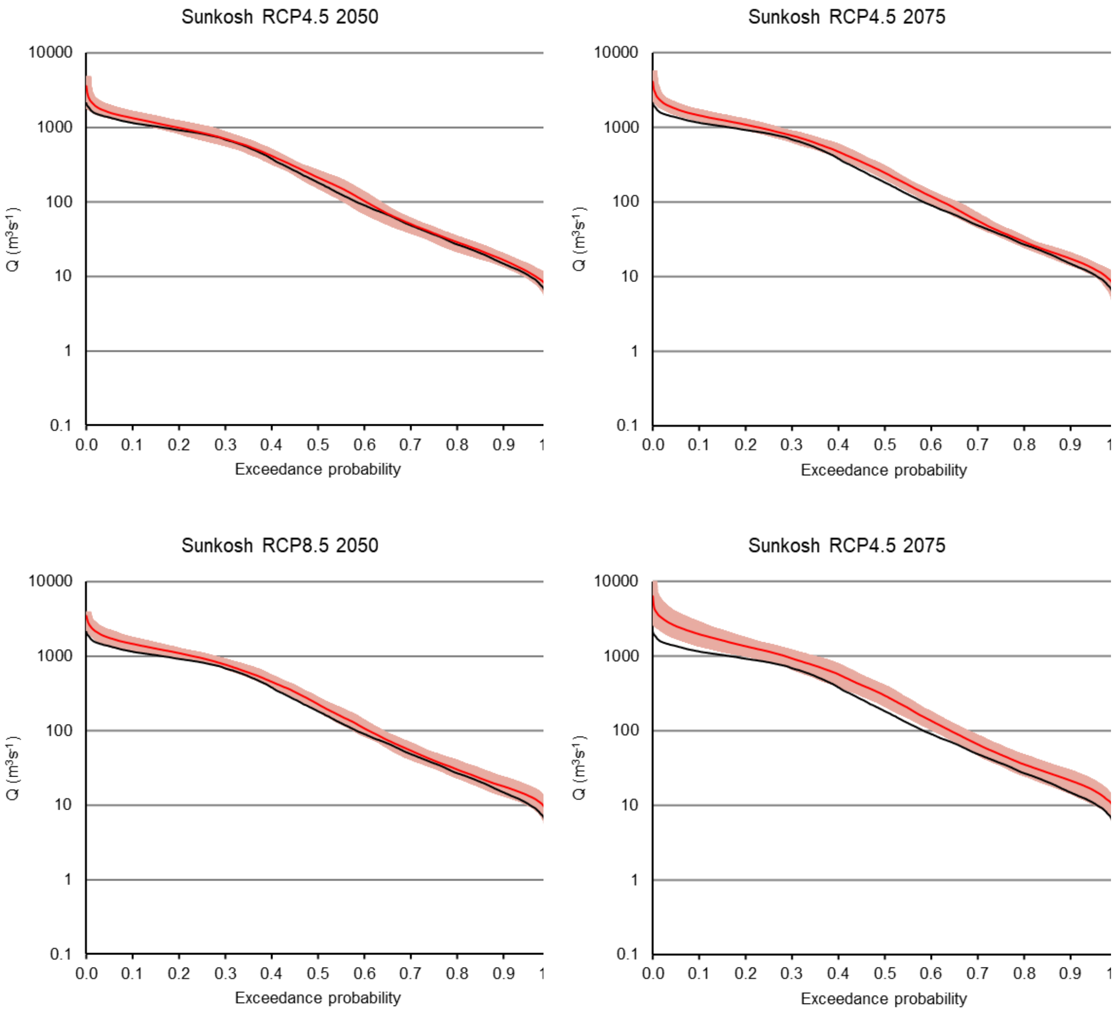
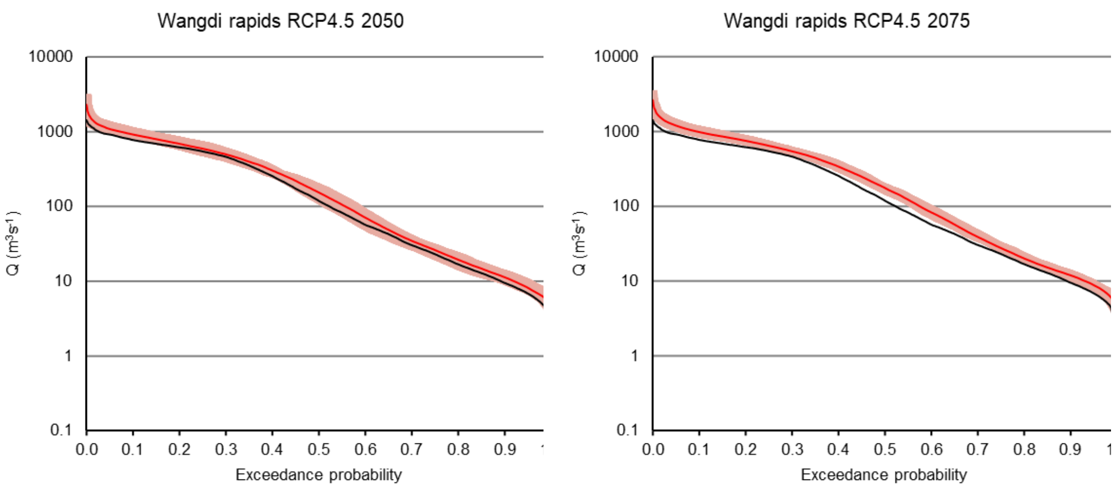


Figure 38: Flow duration curves for location Sunkosh. The black line indicates the flow duration curve for the historical reference (1981-2010). The red line indicates the future flow duration curve for the ensemble mean of 4 GCM runs, for the climate in 2035-2065 and 2070-2100, and RCP4.5 and RCP8.5 respectively. Source: (Wijngaard et al., 2017)



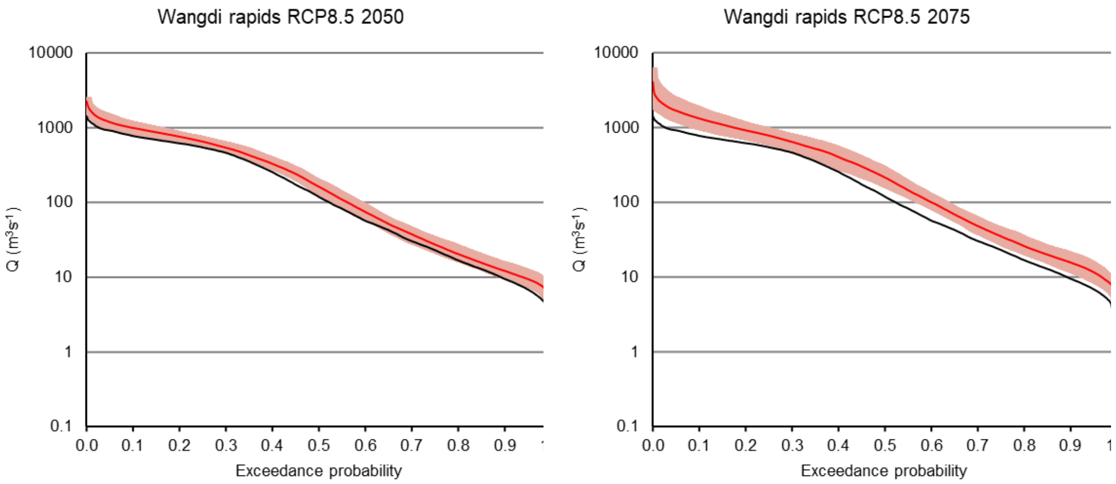


Figure 39: Flow duration curves for location Sunkosh. The black line indicates the flow duration curve for the historical reference (1981-2010). The red line indicates the future flow duration curve for the ensemble mean of 4 GCM runs, for the climate in 2035-2065 and 2070-2100, and RCP4.5 and RCP8.5 respectively. Source: (Wijngaard et al., 2017)

A study on climate change impacts for extreme flows in the Brahmaputra river basin under 1.5 and 2.0 °C global warming scenarios, indicates a slight increase in the discharge levels of low flows (Mohammed et al., 2017). However, this modeling study does not indicate whether future glacier changes are taken into account in the used SWAT model. When these are not taken into account, the results for projections of low flows have limited confidence.

As a general conclusion, in particular the steep projections for increase in magnitude and frequency of extreme flow events in the high flow tail of the distributions substantiates the rationale for the diversification of the energy portfolio beyond hydropower. The projections for low flows are uncertain.

5.3 Future impacts for hazards posing risk to hydropower infrastructure

The increases in extreme precipitation events, changes in glaciers, and changes in flow regimes pose risks for hydropower infrastructure. The projected increase in extreme precipitation events first leads to more frequent high flows and floods. This increases the risk of damage to hydropower infrastructure. On the other hand, an increase in extreme precipitation events leads to an increase in the number of landslides and similar natural hazards. As seen for example for the Chamoli disaster in Uttarakhand early 2021, increases in these types of hazards can be disastrous for hydropower infrastructure. In this case, hydropower infrastructure that was still under construction had already been destroyed. An increase in extreme precipitation events and high flows will lead to increasing sediment loads. These negatively impact hydropower infrastructure, by increased weathering of turbines, as well as filling of head ponds and reservoirs.

Another hazard which is increased by climate change is the risk of glacier lake outburst floods (GLOFs). With the retreat of glaciers, frequently proglacial lakes are formed between the former moraines and the retreating glacier front, filled with melt water. These can become unstable and burst, resulting in extreme flooding downstream (Shrestha et al., 2010; Allen et al., 2016; Zaginaev et al., 2016; Harrison et al., 2018). The Himalayas in Bhutan have more than 700 glacial lakes, of which several have the potential for severe GLOF (Nagai et al., 2017). Hydropower infrastructure in the pathway of a GLOF is at risk of severe damage.

5.4 Reflections on the future role of hydropower for Bhutan's economy

Hydropower contributes about 25% to the total gross domestic product (GDP) of Bhutan annually, accounts for 32% of total exports, and generates about 25% of the government's total domestic revenue. The power generation sector almost exclusively relies on hydropower, with an installed capacity of 2,326 megawatt (MW), and power export to India is an important source of revenue. At the same time, Bhutan is a country with enormous and largely untapped hydropower potential, where it is estimated that 95% of the potential is untapped (Alam et al., 2017; Gernaat et al., 2017). The potential (and current rates of generation) exceed domestic demand, and much of the existing and planned hydropower is generated for export to India. Indian private sector firms typically finance and build many of these facilities. The impact of climate change on hydropower generation will be mostly felt during the low flow season outside the monsoon season, which is when the generation capacity may become insufficient to meet demand within the country.

At present, the majority of hydroelectricty is exported. However, the domestic power demand is increasing annually around 17% due to increasing economic activities and small scale industrialization (Alam et al., 2017). India is facing energy deficits, whilst the demand for energy keeps growing rapidly. Bhutan's hydropower has helped to mitigate the energy deficit in northern India, and it is likely that this demand from India to purchase electricity generated in Bhutan persists in next years to decades. Besides, cross-border power trade among India, Bangladesh and Bhutan will promote greater regional integration and enhanced energy security in the region. It is therefore likely that hydropower will remain a major contributor to the Bhutanese economy.

Even in the context of climate change, the large investments being made in hydropower in electricity will likely pay off and further boost the economy of Bhutan (Lean and Smyth, 2014). Bhutan generates surplus power during the monsoon season from its run-of-river hydropower infrastructure and the surplus power is exported (Agarwal et al., 2019). This surplus of energy production during the monsoon season will remain; precipitation amounts during the monsoon season are projected to increase (Lutz et al., 2018), and flows are often larger than the turbines operational range. The rational for diversification of the energy generation portfolio targets the low flow seasons, when owing to reduced flow in the rivers, the country relies on energy imports. Adapting to this situation, and future climate change, Bhutan constructs or plans to construct mega projects with reservoirs (Amochhu Reservoir Hydroelectric Project, Sunkosh Reservoir, Wangchu Reservoir and Bunakha Reservoir) (Bisht, 2012).

6 Wind and solar energy under climate change

6.1 Future changes in solar potential

To assess the potential of future solar energy production for the project areas, the CMIP5 ensemble mean projections of Surface Downwelling Shortwave Radiation (rsds, in Wm^{-2}) variable as part of the CMIP5 dataset were analyzed. Downwelling surface shortwave radiation quantifies the radiative energy in the solar wavelength range reaching the Earth's surface per time and surface unit.

Figure 40 and Figure 41 show the projections, for RCP 4.5 and RCP 8.5 respectively. What stands out from both timeseries is that the project area is projected to experience a slight decrease in total incident solar radiation. This trend is expected to continue until 2050 or so, after which it starts to increase again, for RCP4.5. For RCP8.5 the decreasing trend persists. Future projections also indicate that seasonal variation in incident solar radiation will increase. The wet Monsoon period (June to August) is projected to experience a decrease in solar radiation (perhaps due to increased cloud cover) while the pre-Monsoon dry months Feb to May are projected to not change strongly in incoming solar radiation.

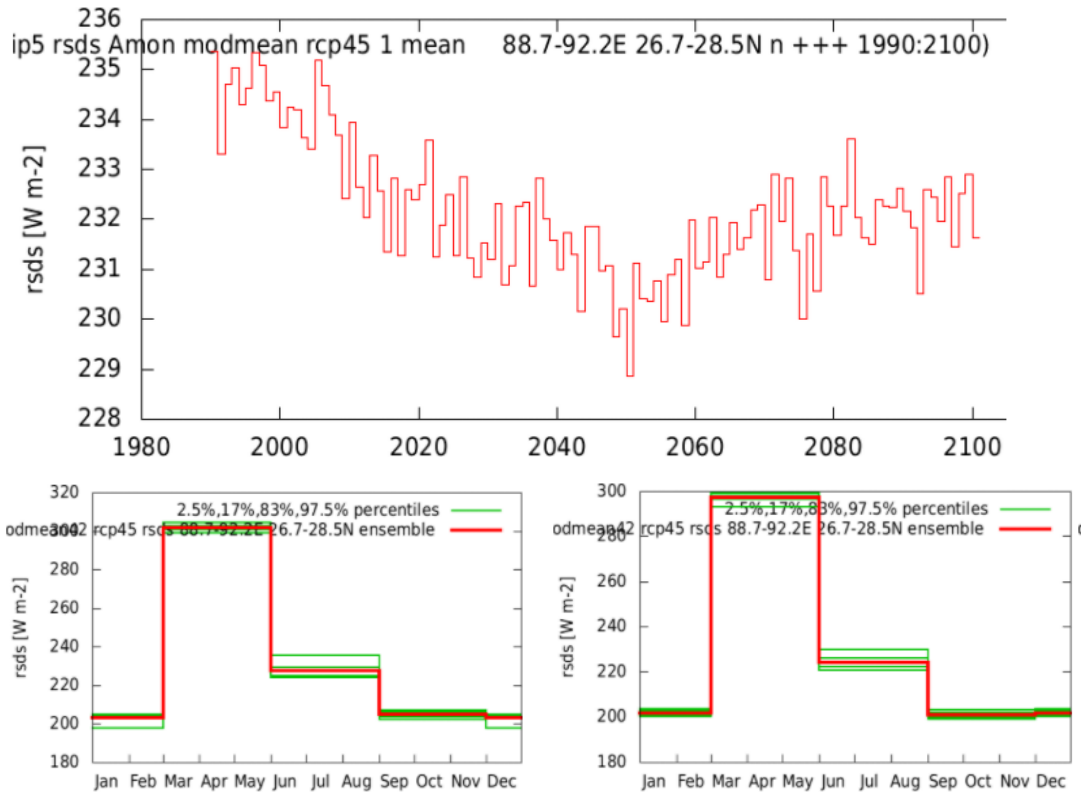


Figure 40: Projections for incoming short-wave radiation at the surface. The figures indicate the CMIP5 ensemble mean for RCP4.5. The top row indicates total annual incoming short-wave radiation. The bottom figures indicate the multi-year average and variation in incoming shortwave radiation, for 1990-2020 (left) and 2045-2075 (right).

These CMIP5 model ensemble results correspond to findings by (Ruosteenoja et al., 2019), who investigated future changes in incident surface solar radiation and contributing factors in India and adjacent regions using CMIP5 climate model simulations. According to the model ensemble mean response, solar radiation decreases by 0.5%–4% by the period 2030–2059 (relative to 1971–2000), in parallel with strengthening aerosol and water vapor dimming (**Figure 42**). The largest reduction is anticipated for northern India, but the evolution of incident radiation in the mid- and late twenty-first century depends substantially on the emission scenario. According to the representative concentration pathways RCP 2.6 and RCP 4.5, solar radiation would gradually recover close to the level that prevailed in the late twentieth century. This results from the peaking of aerosol loading before midcentury while the water vapor content continuously increases somewhat. Conversely, under RCP8.5, incident radiation would still decline, although more slowly than during the early century. This coincides with a substantial increase in atmospheric water vapor content and a modest decrease in aerosol forcing. In cloud forcing, model ensemble mean changes are minor, but divergence among the model simulations is substantial. Moreover, cloud forcing proved to be the factor that correlates most strongly with intermodal differences in the solar radiation response.

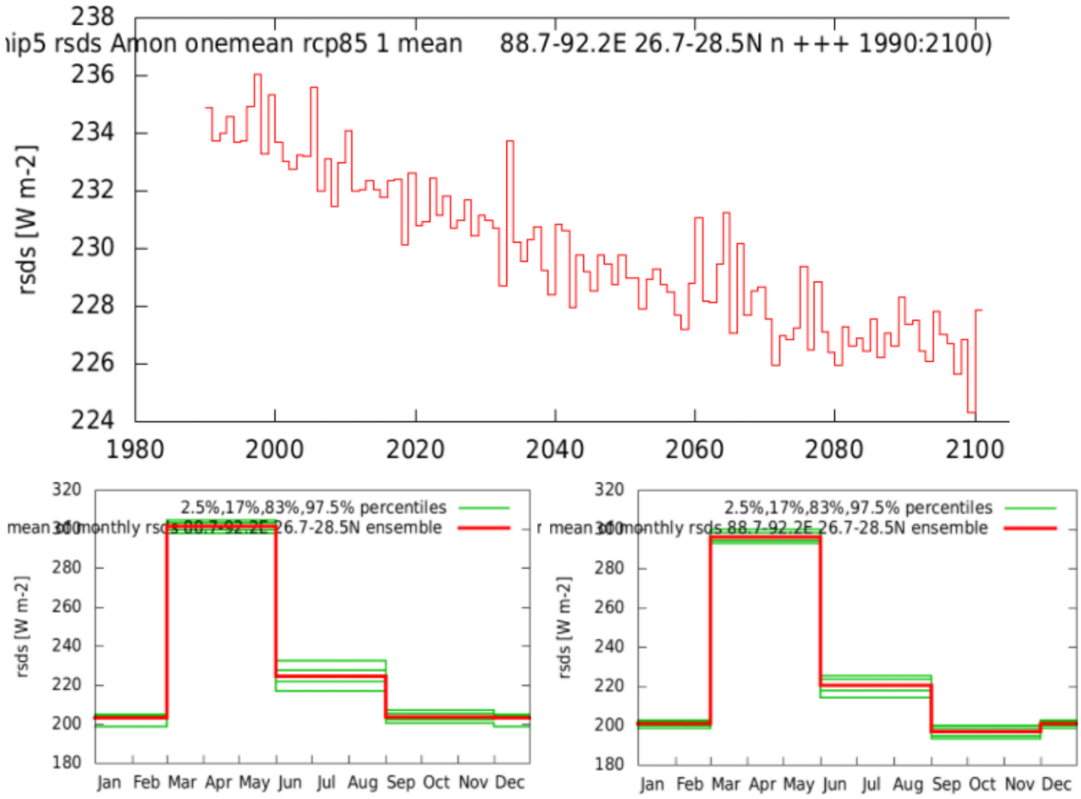


Figure 41: Projections for incoming short-wave radiation at the surface. The figures indicate the CMIP5 ensemble mean for RCP8.5. The top row indicates total annual incoming short-wave radiation. The bottom figures indicate the multi-year average and variation in incoming shortwave radiation, for 1990-2020 (left) and 2045-2075 (right).

Based on the small ensemble mean changes in solar radiation, Ruosteenoja et al. 2019 conclude that future projections of incident solar radiation in India and adjacent regions are not substantial enough to critically influence the conditions of solar energy production. Nevertheless, although the projected ensemble mean changes in incident radiation are fairly small, some individual models simulate far more substantial reductions up to about 10%. Also, while surface solar radiation is projected to decrease to some degree in all seasons, the most intense reduction takes place in the post-Monsoon season from September to November. In this season, the model ensemble mean decline is 4%–6% for the northern part of India and adjacent regions.

Additional factors that are likely to influence future solar electricity production conditions are the projected warming and soiling of solar panels. Rising temperatures will slightly reduce the electricity output, as the relative efficiency of current photovoltaic cell technologies typically decreases by 0.5% per 1°C increase in the cell temperature (Radziemska, 2003). Soiling of the panels by dust and anthropogenic particulate matter has also been found to cause significant reductions in electricity production (Bergin et al., 2017). Since both soiling and incident solar radiation depend on the aerosol burden of the atmosphere, they are likely to evolve in a similar manner in the future. As discussed above, this implies that local environmental policy measures thereby have a potential to improve the conditions for solar electricity production.

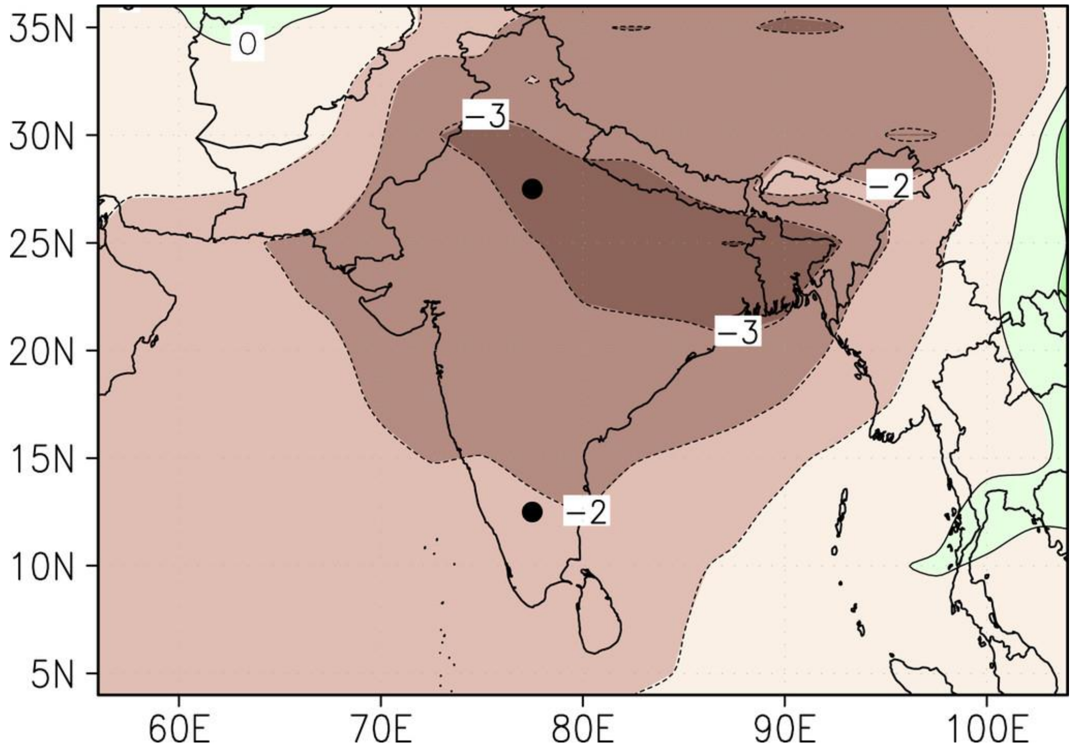


Figure 42. Projected changes in annual total incident solar radiation at the surface (%) in India and adjacent areas from 1971–2000 to 2030–59 under RCP8.5: an average over 27 GCMs (Ruosteenoja et al. 2019)

Despite the minor decrease in solar radiation, the rationale to diversify the portfolio of renewable energy sources in Bhutan holds since the decreases are very minor.

6.2 Future changes in wind potential

To assess the future changes in potential in wind energy production, future changes in the near-surface wind climate of the for the project areas was examined using the findings of (Abolude et al., 2020) and (Chen et al., 2012). Abolude et al. 2020 assessed the potential status of future wind power over China and adjacent regions using CMIP5 model projections. Changes in future wind power density, relative to the historical time-period of 1981–2005, were analyzed using near-surface wind speeds extrapolated to wind turbine hub-height of 90 m above ground level. Broadly, it was found that the potential wind power density changes per future time slice (**Figure 43**) are quite modest, with a range of approximately 40 Wm^{-2} for the decadal time slices considered. The spatial distribution also shows a large similarity to the current wind power density especially in terms of peak locations. Nonetheless there are significant differences in sizes (of these peak values), so the result suggests that the most notable changes in future wind power may be exhibited more in temporal than spatial form. In all, Abolude et al. 2020 find only relatively modest differences between the CMIP5 model projections and reanalysis data, and conclude that the expected future changes in wind power density are not significant enough to neither warrant a move away from wind energy nor threaten considerably the marketability and profitability under the present warming scenario rate. It must be noted though that the skill in simulating surface wind fields by general circulation models are not at the same level of model skill for simulating temperature and (to a lesser extent) precipitation. This decreases the reliability of global climate models to build robust future projections of surface wind-climate and other wind-dependent geophysical climatic variables (Morim et al., 2020).

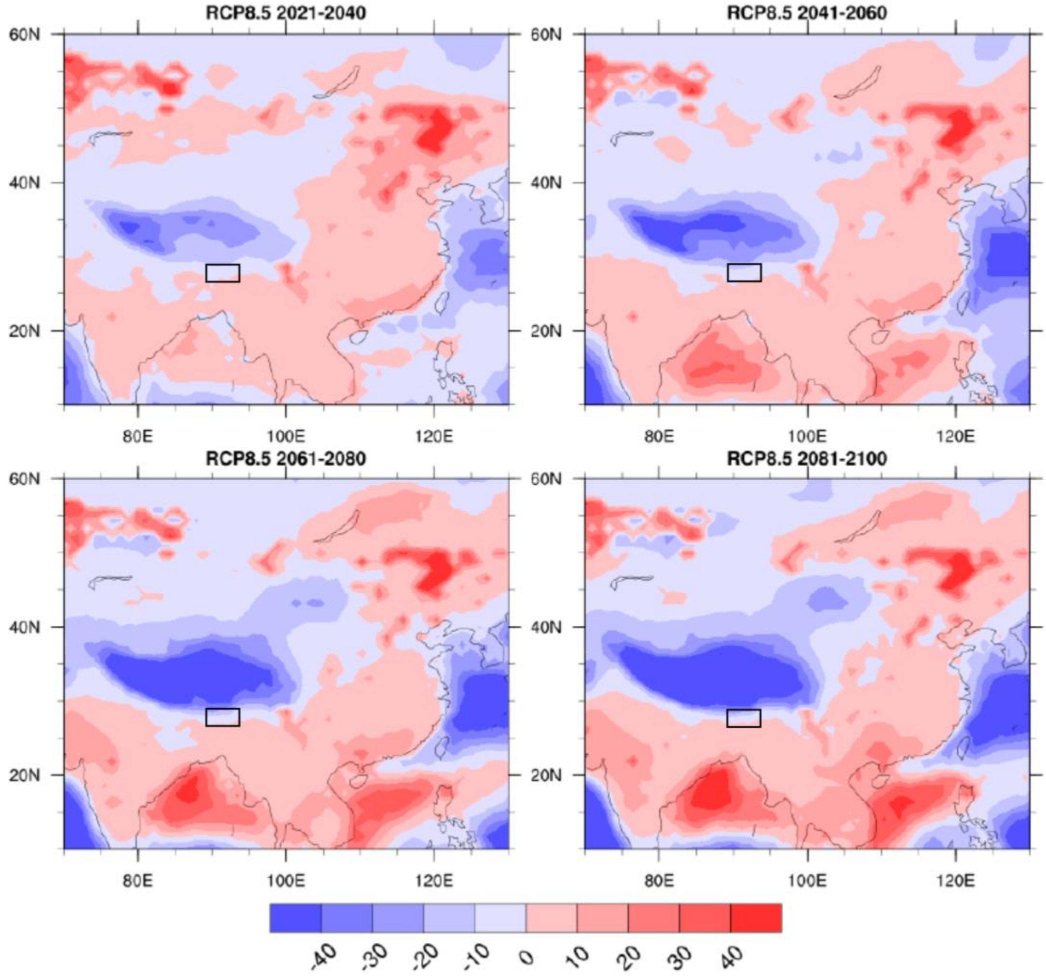


Figure 43: Projected multi-model mean changes in mean Wind Power Density (WPD) at 90 m hub-height in (Wm^{-2}) for four future time slices relative to the period 1981–2005 under the RCP8.5 scenario. Black squares indicate the approximate location of Bhutan.

Chen et al. 2012 present similar findings in their study. They show that modeled spatial fields of wind speed using CMIP5 at the end of the 21st century are projected to be very similar to those of the last 35 years with comparatively little response to the precise representative concentration pathway scenario applied (**Figure 44**). The spatially averaged and spatial fields of seasonal wind speeds for 2066–2100 exhibit very close accord with simulations for the historical period (1971–2005). The mean wind speeds from each model computed for 2066 to 2100 do not show a substantial, consistent dependence on the degree of radiative forcing, although there is some evidence that the modelled interannual variability in the future period is somewhat higher under scenarios of stronger radiative forcing.

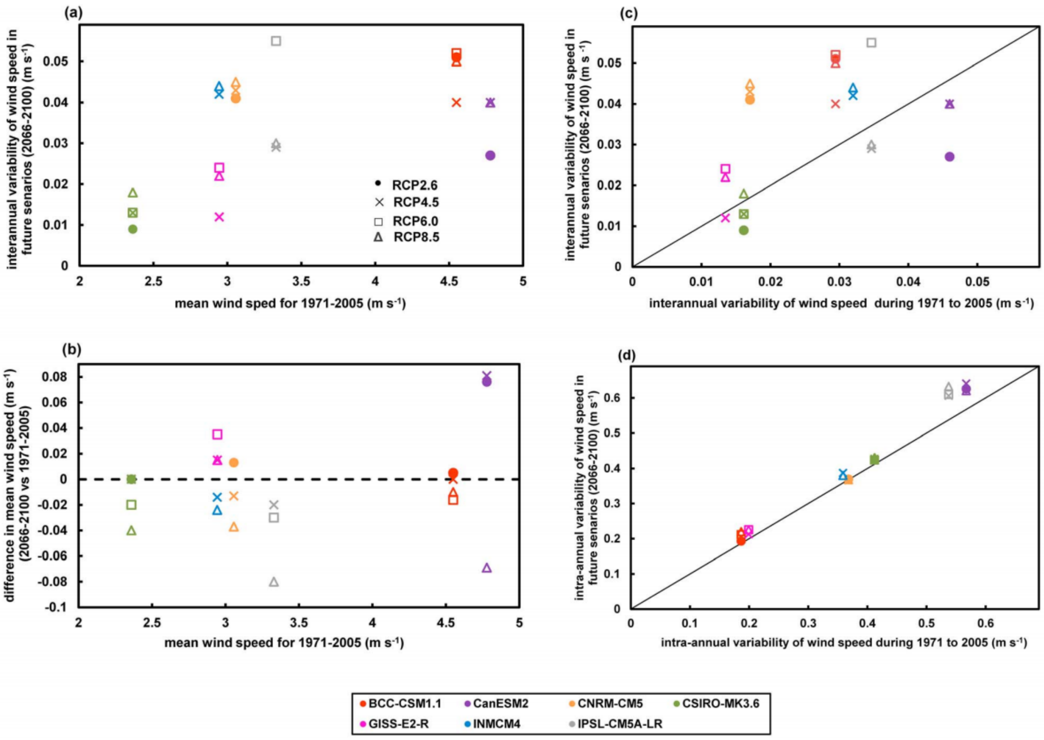


Figure 44. (a) Comparison of the projected interannual variability of wind speed from 2066 to 2100 and historical mean wind speed from 1971 to 2005. (b) Comparison of the climate change signal (i.e., difference in mean wind speed in 2066–2100 versus 1971–2005) and the historical mean wind speed from 1971 to 2005. (c) Comparison of the projected interannual variability of wind speed from 2066 to 2100 and interannual variability in the 1971–2005 simulation. (d) Comparison of the projected intra-annual variability of wind speed from 2066 to 2100 and intra-annual variability in the 1971–2005 simulation (Chen et al., 2012)**.**

Similar as for projections of solar radiation, the rationale to diversify the portfolio of renewable energy sources holds when considering projections for wind speed. Changes are very minor, and mainly point toward slight increases.

As with all projections presented in this report, uncertainty related to scale differences need to be considered. Projections for solar radiation and wind speed are based on large scale climate models, and in particular in a mountainous country like Bhutan with high variability over short horizontal and vertical distances, site-specific projections may deviate.

7 Climate Risks and Vulnerabilities

This chapter assesses the principal climate vulnerabilities for the proposed solar and wind power projects. Then, based on the likely changes in the related climate indicators described in the preceding chapters, climate risks are evaluated and scored. This assessment indicates the extent to which the key climate risks pose a threat to the project areas. Vulnerability in this context refers to the extent to which the solar and wind power projects (including its socio-economic characteristics) is unable to cope with hazardous climatic events and trends. The outcome of the assessment may reveal that the project's costs and/or benefits may or may not be affected by climate change. If the project's net present value (NPV) is unchanged because of climate change, the recommendation would be to proceed with the project provided that the NPV is positive. On the other hand, as a result of climate change, project costs may be expected to increase (e.g., damages to road and road maintenance costs may be expected to increase as a result of a projected increase in extreme precipitation and flooding), or project benefits may be expected to decrease. It is in those circumstances that the technical and economic analysis of climate proofing is of interest (ADB, 2015).

7.1 Climate impacts energy sector Bhutan

Bhutan's development has been heavily dependent on climate-sensitive sectors such as agriculture and hydropower, with hydropower making a major contribution to the growth. The power generation sector currently almost exclusively relies on hydropower, with an installed capacity of 2,326 megawatt (MW), and power export to India is an important source of revenue. The first deployment of non-hydro renewables at utility scale in Bhutan will be the first step to diversify the power generation portfolio, increase the resilience against severe weather events such as droughts, and complement the hydropower generation profile during the dry season. Other renewable energy resources such as solar photovoltaic (PV) and wind can complement hydropower in forming a more diversified electricity generation portfolio, which is, in healthy mix, resilient to changes in seasonal weather patterns and weather extremes that can adversely affect power supply. In addition, Bhutan's run−of−the−river hydropower generation drastically drops during the winter dry season (December to March) due to low precipitation and snow melt, almost falling short to meet peak demand.

Energy production and distribution infrastructure can be highly vulnerable to the impacts of climate change. These impacts will have consequences for the design, construction, location, and operations of power infrastructure. Inadequate attention to these impacts can increase the long-term costs of energy sector investments and reduce the likelihood that these investments deliver intended benefits (ADB, 2013). Bhutan's energy sector is vulnerable to projected changes in mean climate conditions (such as mean temperature and rainfall), in climate variability (climate variability is expected to increase in a warmer climate), and in the frequency and intensity of extreme weather events.

7.2 Solar power: Shingkar and Sephu

To identify the relevant vulnerabilities, information gathered from the available documentation and data on the area was used. From this process, the following key vulnerabilities were identified:

1. **Soil erosion** due to heavy rainfall during the Monsoon period
2. **Flash flooding** due to heavy rainfall and insufficient drainage during the Monsoon period
3. **Slope instability** and likelihood of **landslides** due to heavy rainfall during the Monsoon period
4. **Snow overloading** due to heavy snowfall during frost conditions
5. **Heat stress** causing reduced generation in panels and increased losses in transmission networks

Soil erosion

As outlined in more detail in sections **2.5.1** and **2.5.2** the Shingkar and Sephu Solar Power sites the two major concerns with respect to climate hazards are heavy rain and heavy snowfall. As a result, soil erosion may occur because of the steeply sloping topography (see **Figure 46**, **Figure 47**) and the risk is high if water can freely flow through the land parcels identified for installation of the solar power plants. Also, during the project construction phase, erosion of bare topsoil may occur during the monsoon season if the soil is left exposed and un-vegetated.

To obtain an estimate of the spatial differences in vulnerability for erosion within the projects area and the surrounding catchment area, **Figure 45** shows the rainfall erosivity R-factor map (Panagos et al., 2012), which quantifies the exposure to the energetic input of rainfall as one of the key factors controlling water erosion. The dataset provides a global rainfall erosivity record based on 3625 precipitation stations and around 60 years of rainfall records at high temporal resolution (1 to 60 minutes). Gaussian Process Regression (GPR) model was used to interpolate the rainfall erosivity values of single stations and to generate the R-factor map. According to rainfall erosivity data, the Shingkar and Sephu Solar Power sites have a comparable exposure to water erosion, which agrees with the field data and observations presented in the Detailed Feasibility and Environmental Assessment Reports for the sites.

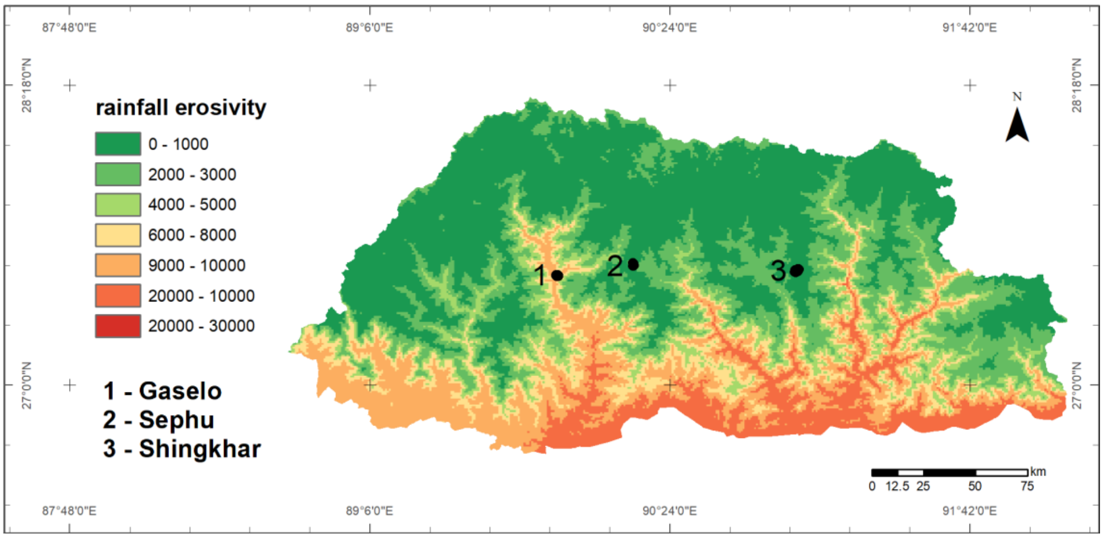


Figure 45. Rainfall Erosivity R-factor map Bhutan

Climate model projections of average trends for the project areas (see section **3.3**) predict an increase in the intensity of rainfall into the future, with increases predicted during the Monsoon season. Precipitation amounts during heavy precipitation events for events with return periods of 1:10 years, 1:50 years, 1:100 years likely increase by 20-30% by 2060. The ensemble predicts that the intensity of extreme precipitation events (see section **4.2.3**) could increase by as much as 200 mm/day for a 1:100 years precipitation event. Furthermore, although differing on specific amounts, most models predict an increase in the intensity of precipitation under both climate change scenarios and time horizons (see **Table 6**). Thus, the projected increase in extreme precipitation events increases the potential risk of soil erosion of solar power infrastructure, e.g. when water can flow freely over the project site due to overloading of drainage systems. As a result, there is high likelihood that the future trend in the climate factors driving erosion in this region will be negative.

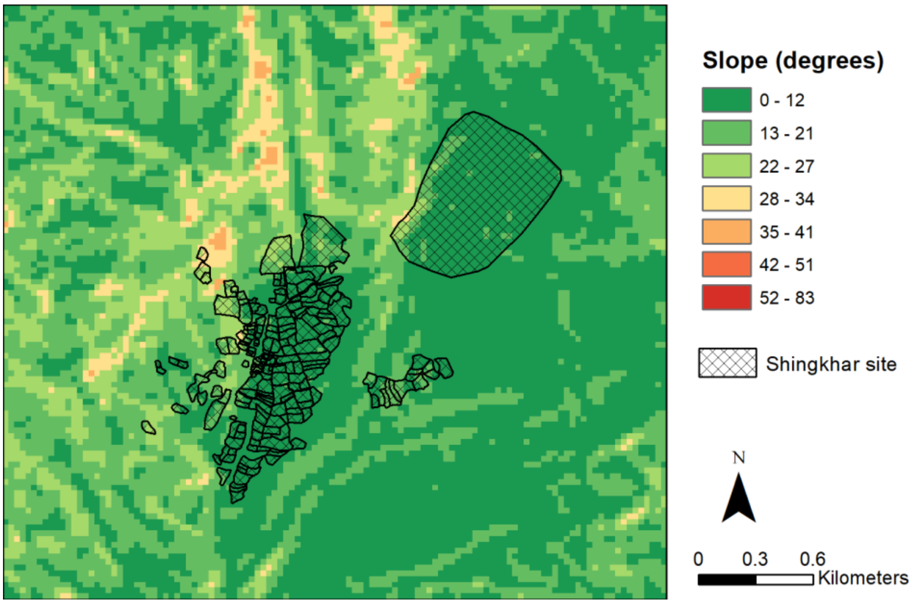


Figure 46. Slope map of Shingkar site

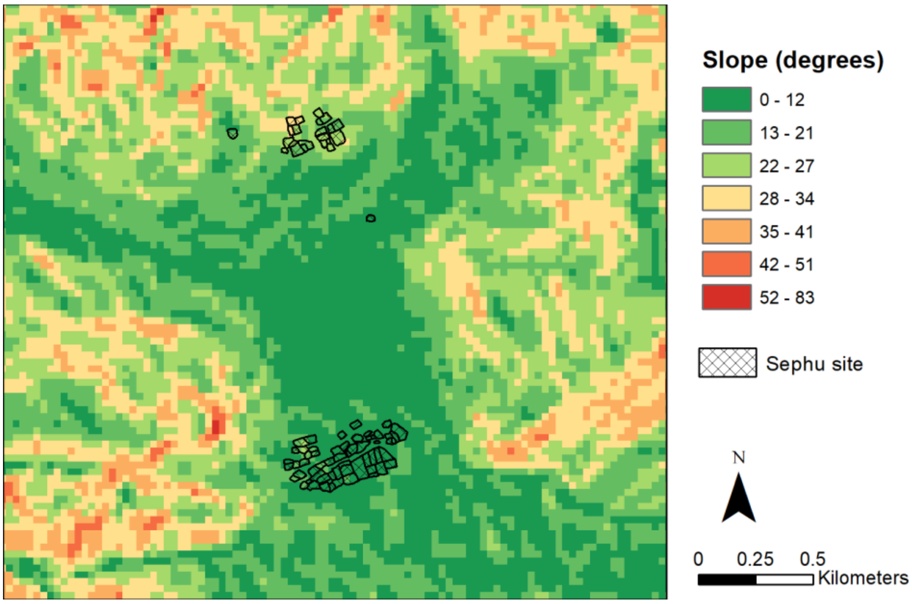


Figure 47. Slope map of Sephu site

<u>Flash flooding</u>

The Shingkar and Sephu Solar power sites may also be susceptible to flash flooding because of heavy rainfall and insufficient drainage in the Monsoon period. Both sites are large and relatively flat catchment areas surrounded by mountains in the north, east and west and there is a continuous slope from north to south. As a result, the risk of flash floods is high if water can flow freely through the land parcels identified for installation of the solar power plant.

For the Shingkar site, the surface water collected in the entire catchment area drains into two major streams fed through multiple small streams flowing through the land parcels. To prevent any damage to the power plant from flash floods (and soil erosion), construction of diversion channels and drains are proposed as shown in **Figure 10**. Diversion channels will be created using barriers and shallow artificial drains and the existing natural streams will be strengthened to carry more water without any obstruction or causing erosion. To collect and divert water collected within the plant area, shallow drains will be constructed along the internal roads to streamline run-off water collected within the power plant area. The existing streams will be not disturbed or grossly diverted but will be strengthened with minimum earth and masonry work to increase water carrying capacity and reducing the possibility of overflow during heavy rain.

The Sephu site has marshy lands and water drains through a natural stream. To prevent any damage to the power plant from flash floods and soil erosion, diversion channels and drains are proposed as shown in **Figure 13**. Diversion channels will be created using barriers and shallow artificial drains and the existing natural streams will be strengthened to carry more water without any obstruction or causing erosion. To collect and divert water collected within the plant area, shallow drains will be constructed along the internal roads to streamline run-off water collected within the power plant area. The existing streams will not be disturbed or grossly diverted but will be strengthened with minimum earth and masonry work to increase water carrying capacity and reducing the possibility of overflow during heavy rain.

To obtain an estimate of the spatial differences in vulnerability to flooding within the projects areas and the surrounding catchments, **Figure 48** shows a flood risk map constructed from a global estimated risk index for flood hazard with risk ranging from 1 (low) to 5 (extreme). The 30 arc-second resolution flow accumulation of the HydroSHEDS dataset (Lehner et al., 2006) (which is based on SRTM elevation data) is also shown. Flow accumulation defines the amount of upstream area (in number of cells) draining into each cell: the number of accumulated cells is essentially a measure of the upstream catchment area. The map shows that the Shingkhar site is exposed to a medium-high flood risk, but data does not indicate a flood risk for the Sephu site. This is likely due the relatively coarse data resolution; flash flooding can be a very local occurrence which is difficult to capture with satellite data. In effect, the map can be used to identify hotspots and areas to intervene but should be contrasted with field observations.

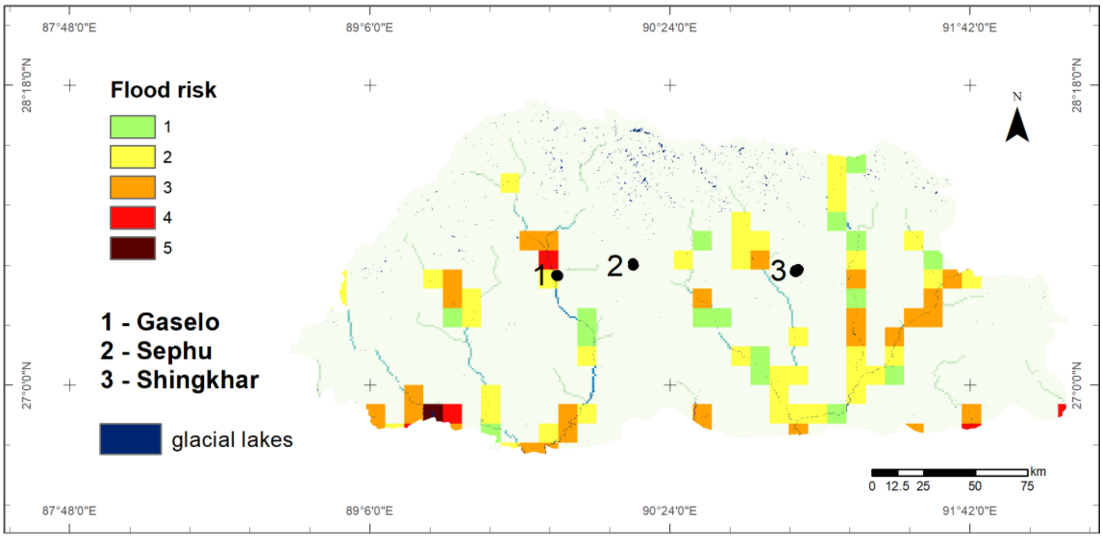


Figure 48. Flood risk map and glacial lakes of Bhutan

Climate model projections of average trends for the project areas (see section **3.3**) predict an increase in the intensity of rainfall into the future, with increases predicted during the Monsoon season. The ensemble predicts that the intensity of extreme precipitation events (see section **4.2.3**) could increase by as much as 200 mm/day for a 1:100-year precipitation event. Although differing on specific amounts, most models predict an increase in the intensity of precipitation under both climate change scenarios and time horizons. Thus, the projected increase in extreme precipitation events increases the potential risk of flash flooding of solar power infrastructure, e.g. due to overloading of drainage systems. The projected increase in intensity of extreme precipitation events implies that this risk increases in the future, which needs to be considered during the project design phase.

Slope instability and landslides

Due to the steeply sloping topography (see **Figure 40**, **Figure 41**) The Shingkar and Sephu Solar power sites may also be susceptible to landslides. Heavy rainfall and insufficient drainage in the Monsoon period may lead to slope instability which can trigger the onset of landslides. This risk may be exacerbated during the construction phase of the solar power infrastructure, when the vegetation is removed, and bare soil is exposed. After the construction phase, bare soil will be re-vegetated with trees and plants of local variety. To stabilize and upgrade the most effected parts of the project area, a suitable restoration and slope stabilization plan will be carried out on a yearly basis.

To obtain an estimate of the spatial differences in vulnerability for landslides within the projects area and the surrounding catchment area, **Figure 49** shows a landslide hazard map based the global landslide hazard dataset of the Global Risk Data Platform[1], which is multiple agencies effort to share spatial data information on global risk from natural hazards. Landslide hazards are indexed with risk ranging from 1 (low) to 5 (extreme). The data shows that The Shingkar and Sephu Solar power sites are exposed to a moderate to medium landslide risk. Given that the sites are within the low to moderate seismic hazardous zone of Bhutan, the risk hazard of an earthquake triggered landslide is considered moderate but not avoidable.

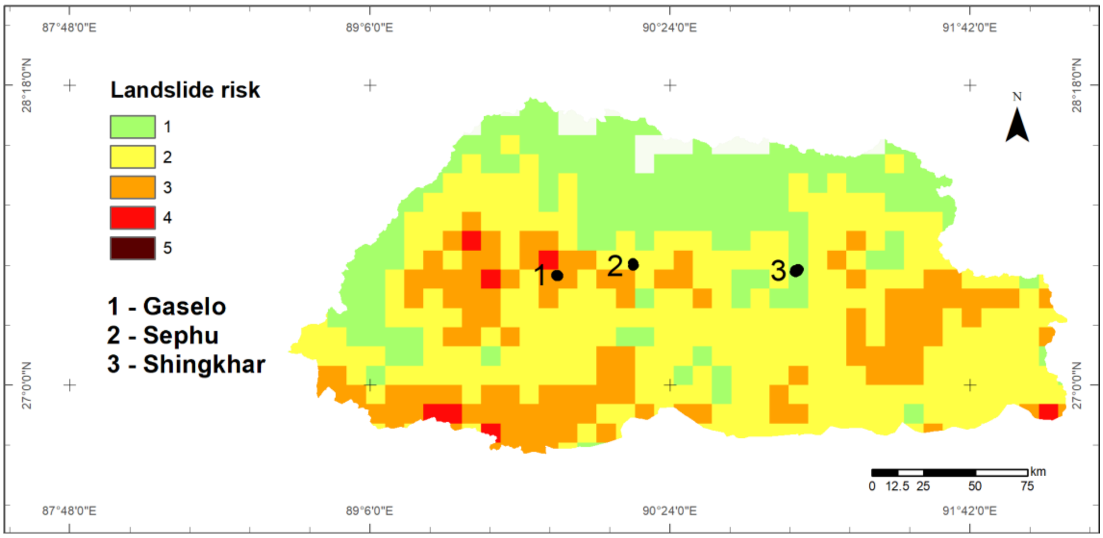


Figure 49. Landslide risk map Bhutan

Climate model projections predict an increase in the intensity of rainfall into the future, with increases predicted in the wetter parts of the year. Precipitation amounts during heavy precipitation events for events with return periods of 1:10 years, 1:50 years, 1:100 years likely increase by 20-30% by 2060. The ensemble predicts that the intensity of extreme precipitation events could increase by as much as 200 mm/day for a 1:100 years precipitation event. Furthermore, although differing on specific amounts, most models predict an increase in the intensity of precipitation under both climate change scenarios and time horizons. Thus, there is deemed a high likelihood that landslide risk will increase into the future without mitigation attempts.

[1] https://preview.grid.unep.ch/index.php?preview=home&lang=eng

Snow overloading

As outlined the two major concerns with respect to climate hazards for the Shingkar and Sephu Solar Power sites are heavy rain and heavy snowfall. Heavy rainfall may lead to soil erosion, flash flooding and can trigger landslides. Heavy snowfall may lead to snow overloading of the PV modules and the mounting structure, which poses risks to the structural integrity and cause damage.

Provisions have been made in the mechanical and electrical design to avoid any impact from heavy snowfall at the site. To avoid accumulation of snow on the PV modules, a steeper tilt angle of 30º has been chosen. This will help in self removal of snow. The PV array mounting structure was selected based on factors such as wind loading, snow loading, orientation, and tilt. System protection and safety components have been designed to comply with applicable standards and safety regulations. The minimum ground clearance has been kept at 500 mm to avoid modules touching deposited snow on the ground. The mounting tables are designed to install two PV modules in landscape orientation using vertical rails such that minimum generation loss occurs due to shading from snow deposition at the lower side of the PV modules. Vertical rails will be used to fix the modules, maintaining a gap of minimum 25mm between them. This will expedite the melting or shedding of snow deposited on the PV modules.

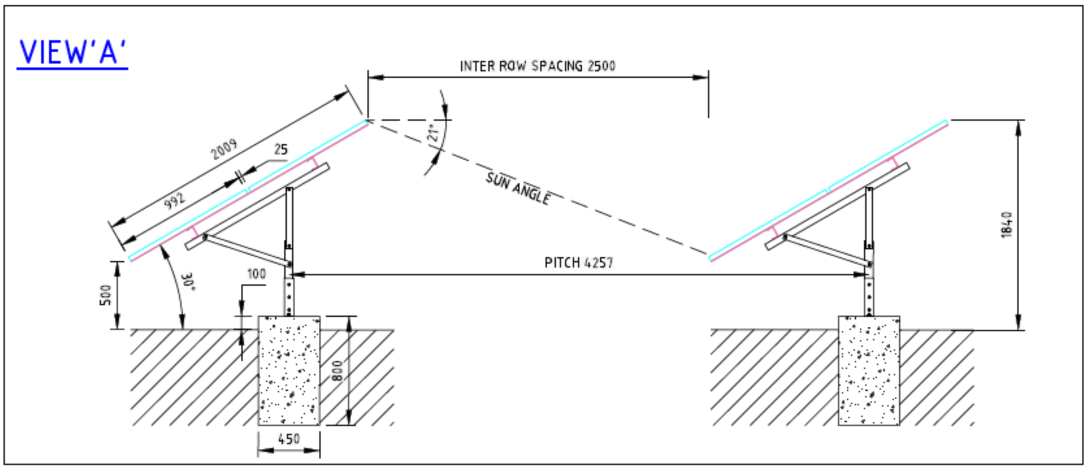


Figure 50. PV array mounting structure with foundation

Climate model projections predict an increase in the intensity of precipitation into the future, with increases predicted in the wetter parts of the year. At the same time, daily maximum air temperature is also projected to increase considerably by 2060 (up to 3-4 °C under RCP85), making the occurrence of prolonged periods of warm weather more likely and more frequent. The amount of precipitation is projected to increase, but this may be less often in the form as snow. However, the risk of snow overloading could still increase in the future because precipitation will likely be more erratic, also during winter months. The risk of snow overloading will likely remain high and has been considered during the design and construction phase.

7.3 Wind power: Gaselo

To identify the relevant vulnerabilities, available documentation and data on the area was used. From this process, the following key vulnerabilities were identified:

1. **Soil erosion** due to heavy rainfall during the Monsoon period
2. **Slope instability** and likelihood of **landslides** due to heavy rainfall during the Monsoon period

Soil erosion

As outlined in section 2.5.3 the Gaselo Wind Power site, the main concern with respect to climate hazards is the possibility of soil erosion due to heavy rain and heavy snowfall. Soil erosion may occur because of the steeply sloping topography (see Figure 51) and the risk is high if water can freely flow over the land identified for installation of the wind power farm. The slopes, which vary from point to point, will have implications on foundation design and this is an additional aspect that needs to be considered while designing the foundations. Also, during the project construction phase, erosion of bare topsoil may occur during the monsoon season if the soil is left exposed and un-vegetated. The Gaselo site is located at 400-1200 m above the riverbed in Wangdue Phodrang valley and hence, there is no probability of water logging or river flooding according to the feasibility study.

To obtain an estimate of the spatial differences in vulnerability for erosion within the projects area and the surrounding catchment area, **Figure 45** shows the rainfall erosivity R-factor map (Panagos et al., 2012), which quantifies the exposure to the energetic input of rainfall as one of the key factors controlling water erosion. According to rainfall erosivity data, the Gaselo Wind Power site has a medium-to-high exposure to water erosion, which agrees with the field data and observations presented in the Detailed Feasibility and Environmental Assessment Reports for the site. To mitigate the risk for soil erosion, proper drainage system is required at the site to avoid soil erosion during monsoon season.

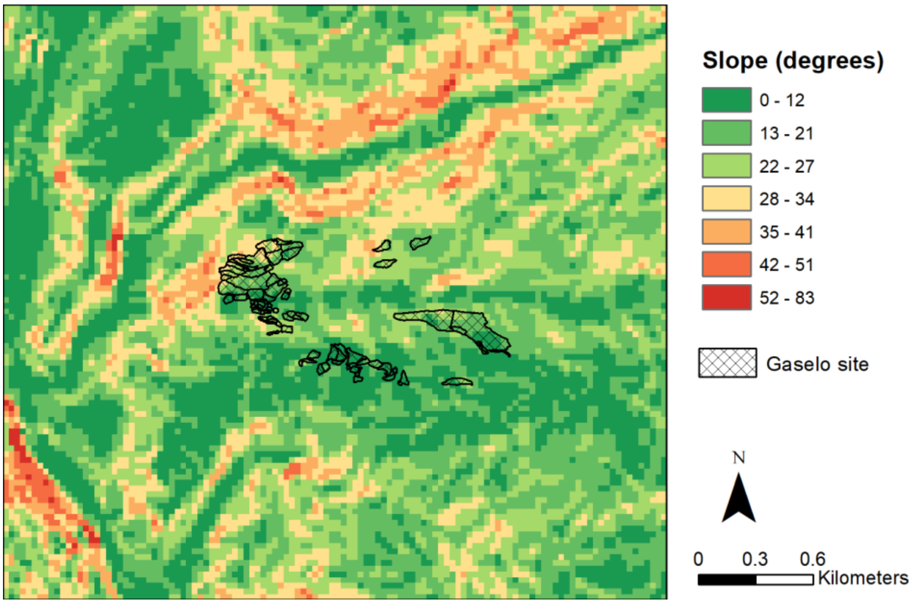


Figure 51. Slope map Gaselo site

Climate model projections of average trends for the project areas (see section **3.3**) predict an increase in the intensity of rainfall into the future, with highest increases predicted during the Monsoon season. Although differing on specific amounts, most models predict an increase in the intensity of precipitation under both climate change scenarios and time horizons (see **Table 6**). Precipitation amounts during heavy precipitation events for events with return periods of 1:10 years, 1:50 years, 1:100 years likely increase by 20-30% by 2060. In absolute numbers, the ensemble predicts that the intensity of extreme precipitation events (see section **4.2.3**) could increase by as much as 200 mm/day for a 1:100 years precipitation event. Thus, the projected increase in extreme precipitation events increases the potential risk of soil erosion of wind power infrastructure when water can flow freely over the project site due to overloading of drainage systems. As a result, there is high likelihood that the future trend in the climate factors driving erosion in this region will be negative.

Slope instability and landslides

Due to the steeply sloping topography (see **Figure 51**) The Gaselo wind power site may also be susceptible to landslides. Heavy rainfall and insufficient drainage in the Monsoon period may lead to slope instability which can trigger the onset of landslides. This risk may be exacerbated during the construction phase of the wind power infrastructure, when the vegetation is removed, and bare soil is exposed. After the construction phase, re-vegetation of the area should be carried out with local trees and plants after the completion of the project. Slope stabilization plans needs to be carried out on a yearly basis for the effected location along with storm drain and local drainage construction to avoid soil erosion. This is particularly important as the current site is a community forest. The slopes, which vary from point to point, will have implications on foundation design. The quality of the foundation is of the utmost importance to the wind turbine structure. The design specifications must be strictly adhered to. The pouring of concrete must be done carefully to prevent surface and thermal cracking to ensure final foundation is of the required quality and standard.

Figure 52. Wind turbine foundation Completed (Left) and Under Construction (Right)

To obtain an estimate of the spatial differences in vulnerability for landslides within the projects area and the surrounding catchment area, **Figure 49** shows a landslide hazard map based the global landslide hazard dataset of the Global Risk Data Platform[1], which is multiple agencies effort to share spatial data information on global risk from natural hazards. Landslide hazards are indexed with risk ranging from 1 (low) to 5 (extreme). The data shows that the Gaselo wind power site is exposed to a high landslide risk. Given that the site is within a moderate seismic hazardous zone of Bhutan, the risk hazard of an earthquake triggered landslide is considered moderate but not avoidable. Therefore, a factor of safety in accordance with design requirements in such seismic zone is also recommended.

Climate model projections predict an increase in the intensity of rainfall into the future, with highest increases predicted during the Monsoon period. Precipitation amounts during heavy precipitation events for events with return periods of 1:10 years, 1:50 years, 1:100 years likely increase by 20-30% by 2060, up to as much as 200 mm/day for a 1:100 years precipitation event. Thus, there is deemed a high likelihood that landslide risk will increase into the future without risk mitigation measures considered during the design and construction phase.

7.4 Power transmission and distribution network

To identify the relevant vulnerabilities available documentation and data on the area was used. From this process, the following potential key vulnerabilities were identified:

[1] https://preview.grid.unep.ch/index.php?preview=home&lang=eng

1. **Heat stress** hazards due to increases in average and extreme temperature
2. **Flooding and inundation** due to heavy rainfall in the Monsoon period

<u>Heat stress</u>

The projected increase in average and maximum air temperatures indicate that heat stresses to the power transmission and distribution network may be of concern. Prolonged periods of warm weather can not only put the electrical grid under increased pressure due to greater demand , higher temperatures can also impair the operation of key infrastructure such as substations, transformers, and transmission lines. Heat related stresses can place significant strain on the electricity system, leading to system faults and reduced power supply at peak demand. Transmission lines may also have its electricity carrying capacity reduced to avoid equipment damage resulting from high temperatures.

A DP structure and transformer (690 V/33 kV)

Control panel inside the Tower

Transformer attached to the Tower

DP Structure under installation

Figure 53. Transformer, Distribution Panel, and Control Panel of Gaselo wind power site

To obtain estimate of the current spatial differences in vulnerability of the power transmission and distribution network to temperature increases, **Figure 54** and **Figure 55** show a Normalized Temperature Anomaly Index (NTAI) and Drought Hazard Index (DHI) map for Bhutan. The NTAI is expressed in between -1 and 1 and provides a temperature anomaly indicator relative to its long-term mean. Lower and higher values indicate good and bad temperature related conditions, respectively. The DHI integrates 5 other drought indices based on NDVI, Land Surface Temperature (LST) and precipitation. Values closer to 1 indicate higher hazard with respect to drought conditions. The data shows that currently during the pre-Monsoon period the wind and solar power project areas and the foreseen transmission and distribution network get exposed to relatively high temperature extremes and drought hazards, compared to the multi-year average conditions. It is reasonable to assume that these trends may get exacerbated in the future, considering the projected temperature increases.

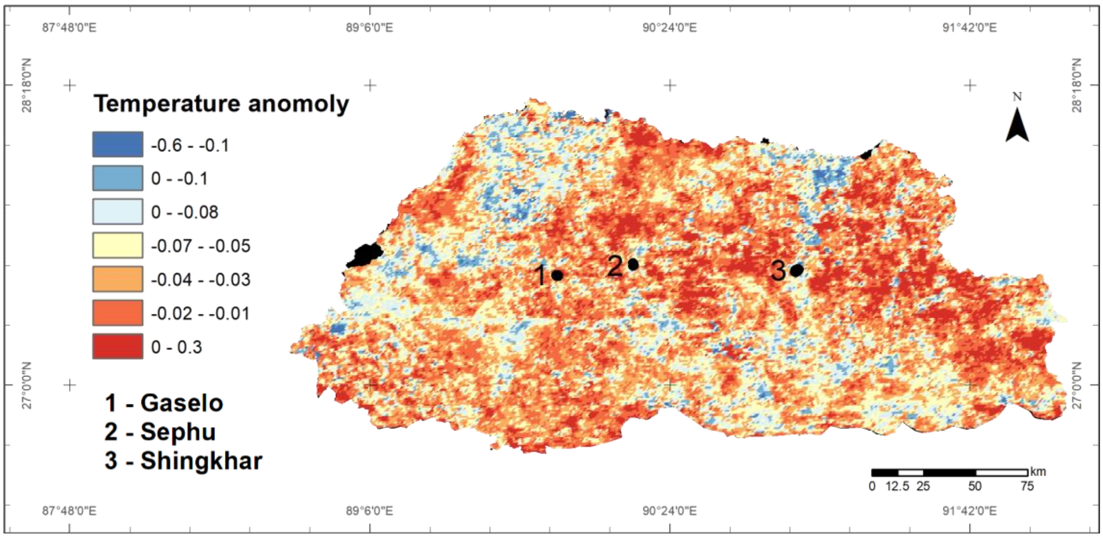


Figure 54. Normalized Temperature Anomaly Index (NTAI) for the pre-Monsoon period (Jan-Apr). The NTAI compares the current (2020) land surface temperature (LST) to the range of values observed in the same period in previous years (2001-2018).

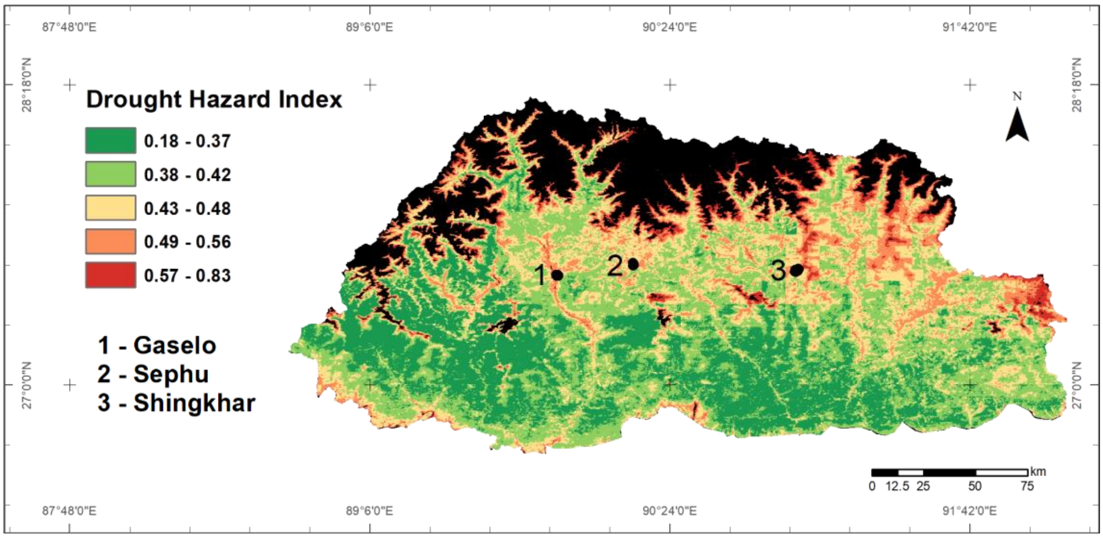


Figure 55. Drought Hazard Index (DHI) map Bhutan. The DHI compares the current (2020) drought hazard to the range of values observed in the same period in previous years (2001-2018).

Climate model projections predict an increase in daily maximum air temperature by 2060 (up to 3-4 °C under RCP85), making the occurrence of prolonged periods of warm weather more likely and more frequent. However, given the current ambient temperatures in the regions of interest, the data also suggests that even under RCP8.5 temperatures in the 2060's will largely remain below 30 °C in this region, so risks associated to heat stress are likely not very high. The amount of precipitation is projected to increase during the Monsoon period, while during pre- and post-Monsoon months a slight decrease in precipitation is foreseen for the longer-term horizon (2045-2075) for both RCP scenarios. This most likely implies more frequent droughts that may last longer, although model projections show large uncertainty in number of consecutive dry days. So overall the risks of prolonged periods of warm (and dry) weather are expected to increase in the future, which needs to be considered when designing the power transmission and distribution network.

Flooding and inundation

The projected increase in intensity of extreme precipitation events may increase the risk of flooding or inundation of electricity network infrastructure. Flooding and inundation can have major impacts on the electricity network, often causing partial or complete power outages. Serious, and often explosive, damage may occur when electrified infrastructure meets water, while moisture and dirt intrusion may require time-consuming repairs of inundated equipment. Erosion due to the floodwaters can also undermine the foundations of overhead transmission poles and cause them to collapse.

Figure 56. Underground cables being taken from wind turbine foundation to Distribution Panel structure

To obtain an estimate of the spatial differences in vulnerability of the power transmission and distribution network to flooding, **Figure 48** shows a flood risk map constructed from a global estimated risk index for flood hazard with risk ranging from 1 (low) to 5 (extreme). The data shows that the catchment area surrounding the Gaselo wind power site is exposed to a high flood risk. While the risk of flooding is restricted to a relatively small part of the project area, a local flash flooding event may have further reaching effects due to the interconnectedness of the energy distribution and transmission network. Also, the data used is relatively coarse; flash flooding can be a very local occurrence which is difficult to capture with satellite data.

The expected future increase in extreme precipitation events may lead to more frequent and powerful flash flooding events. Flooding and inundation of electricity network infrastructure can have major impacts, often causing partial or complete power outages. Also, changes in precipitation patterns may lead to changes in flood risks. So, areas that are currently not classified as flood-prone may get susceptible to flooding later, especially in relatively flat areas where water naturally drains towards. Such a possible increase of flood risk due to climate change needs to be considered when designing the power transmission and distribution network.

7.5 Overall risk classification

The climate vulnerability and risk analysis process has gathered several datasets in the public domain, together with local information, associated with each risk to determining the most important risks associated with the project area. Table 13 summarizes this and provides an expert judgement of the risk for the project components, and indicates possible adaptation measures.

Table 13. Screening of most important climate risks and vulnerable project components

Climate Hazard	Vulnerable Project Components	Risk	Potential adaptation options
Shingkar Solar Power site			
Soil Erosion	PV array foundation and mounting structure	**High**	• Specify stronger mounting structure • Assure minimum ground clearance (panels & mounting) to allow for drainage
Flash Flooding	PV array foundation and mounting structure	**High**	• Assure minimum ground clearance (panels & mounting) to allow for drainage • Specify appropriate drainage provisions • Specify cabling and components that can deal with high moisture content and flooding.
Landslides	PV array panels, foundation, and mounting structure	**Medium**	• Specify stronger mounting structure • Choose locations with lower probability of landslides
Snow overloading	PV array panels, foundation, and mounting structure	**Low**	• Assure free space (panels & mounting) to avoid snow deposition • Select appropriate tilt panel angle so snow can slide off
Sephu Solar Power site			
Soil Erosion	PV array foundation and mounting structure	**High**	• Specify stronger mounting structure
Flash Flooding	PV array foundation and mounting structure	**High**	• Assure minimum ground clearance (panels & mounting) to allow for drainage • Specify appropriate drainage provisions • Specify cabling and components that can deal with high moisture content and flooding.
Landslides	PV array panels, foundation, and mounting structure	**Medium**	• Specify stronger mounting structure • Choose locations with lower probability of landslides
Snow overloading	PV array panels, foundation, and mounting structure	**Low**	• Assure free space (panels & mounting) to avoid snow deposition • Select appropriate tilt panel angle so snow can slide off

Gaselo Wind Power site			
Soil Erosion	Wind turbine foundation	**High**	• Specify stronger foundation structure
Landslides	Wind turbine foundation	**Medium**	• Choose locations with lower probability of landslides
Power Transmission and Distribution			
Heatwaves and drought	Transmission network, substations, and transformers	**Low**	• Specify more effective cooling for substations and transformers
Flooding and inundation	Transmission network, substations, and transformers	**Medium**	• Build a resilient high-capacity transmission system Design improved flood protection measures for equipment mounted at ground level in substations • Increase the system's ability to return to normal operations rapidly if outages do occur. • Allow increased rerouting during times of disruption

8 Recommended adaptation measures

In general, more robust design specifications could allow structures to withstand more extreme conditions (such as higher wind or water velocity) and provide them with the ability to cope safely with higher air and/or water temperatures (Girard and Mortimer 2006). In some circumstances, it may also be necessary to consider relocating or refitting extremely vulnerable existing infrastructure. Furthermore, decentralized generation systems may reduce the need for large facilities in high-risk areas and minimize climate risk. Finally, the reliability of control systems and information and communications technology components may improve from redundancy in their design and from being certified as resilient to higher temperatures and humidity.

All design approaches for this project have been considered based on critical site parameters such as topography, slope, minimum and maximum temperature, rainfall, wind loading, snow loading and soil conditions etc.

8.1 Solar power: Shingkar and Sephu

For both sites drainage systems have been included in the design to reduce the risk of exposure to floods. It is recommended to validate if the sizing of these drainage systems is sufficient to cope with the projected increase in precipitation extremes by around 30% by 2060. It is reasonable to assume an increase in runoff of 30% during such events. More accurate estimates would require hydrological modeling.

For both sites, the risk of soil erosion has been considered, and the feasibility studies indicate that vegetation will be placed after the construction. It is recommended to carefully consider whether the planned vegetation has strong capacity in retaining erosion. If the terrain is steep, the inclusion of terracing in the design can be considered.

Considering the medium risk for landslides, a careful screening of slope stability on the site and adjacent areas sloping towards the site is recommended. If these are unstable areas prone to land slide risk in the current climate, expect that the risk will increase in the future and consider inclusion of stabilization and retaining structures in the design.

Original costing for the solar plant foundations was estimated at $240,000 (Sephu) and $425,000 (Shingkar). At the time of writing recalculation with incremental costs was still work in progress. For the moment an increase in costs of 30% is assumed. The costs for drainage systems are estimated at $6,000 (Sephu) and $16,000 (Shingkar).

8.2 Wind power: Gaselo

Where wind speeds are likely to increase, it may be possible to design turbines and structures better able to handle higher wind speeds and gusts, to capture greater wind energy with taller towers, or to design new systems better able to capture the energy of increased wind speeds. Since wind speeds are projected to not change much, this adaptation option is not recommended. At the same time projections for surface winds from General Circulation Models are uncertain, because of limited skill in simulating this.

The risk of soil erosion has been considered, and the feasibility studies indicate that vegetation will be placed after the construction. It is recommended to carefully consider whether the planned vegetation has strong capacity in retaining erosion. If the terrain is steep, the inclusion of terracing in the design can be considered. It is furthermore recommended to review the design of the turbine foundations in the subsurface.

Considering the medium risk for landslides, a careful screening of slope stability on the site and adjacent areas sloping towards the site is recommended. If these are unstable areas prone to land slide risk in the current climate, expect that the risk will increase in the future and consider inclusion of stabilization and retaining structures in the design.

At the time of writing the cost estimate for improved foundations and drainage had not been established yet. For replanting of the slopes, costs were not estimated exactly, but estimated to be low.

8.3 Power transmission and distribution network

For transmission and distribution (including substations), specifying redundancy in control systems, multiple T&D routes, relocation, and/or underground distribution for protection against high temperatures, flooding and landslides may be considered. This is very site-specific. Where stronger winds are expected, higher design standards for distribution poles may be adopted. Since the transmission and distribution network is located in mountainous terrain, it is in general recommended to anticipate an increase in mountain-specific hazards like floods, erosion and landslides. This is very site-specific and it is recommended to avoid locations which are at present exposed to these hazards, or take protective measures.

8.4 Costing

Estimates of costs of adaptation measures as far as could be estimated together with the design teams at this stage are listed in Table 14.

Table 14: Cost estimates for adaptation measures

Project site	Adaptation measure	Cost estimate
Shingkar (solar)	Drainage system	$16,000
	Improved foundations	$127,500 (30% of original)
	Vegetation to prevent erosion	Unknown
	Screening for landslide risk	Unknown
Sephu (solar)	Drainage system	$6,000
	Improved foundations	$72,000 (30% of original)
	Vegetation to prevent erosion	Unknown
	Screening for landslide risk	Unknown
Gaselo (wind)	Drainage system	Unknown
	Improved foundations	Unknown
	Screening for landslide risk	Unknown

9 Conclusions and Recommendations

The goal of the Asian Development Bank project 'Renewable Energy for Climate Resilience' in Bhutan is to diversify Bhutan's energy portfolio. At present, hydropower contributes about 25% to total gross domestic product (GDP) annually, accounts for 32% of total exports, and generates about 25% of the government's total domestic revenue. The power generation sector almost exclusively relies on hydropower, with an installed capacity of 2,326 megawatt (MW), and power export to India is an important source of revenue. Under the current project two solar PV power plants and one wind power plant are developed.

The rationale for diversification is related to the expectation that climate change impacts on the cryosphere and hydrology in Bhutan will lead to less reliable flows, in particular outside the monsoon season. This will make hydropower a less reliable source of energy, which may not be sufficient during the dry season. During these periods outside the monsoon season, the climate in Bhutan is characterized by clear skies and daily patterns of wind. This intuitively makes solar and wind suitable energy sources to complement hydropower.

The CRA concludes that this rationale holds when validated with future scenarios of climate change and hydrological changes. These project more erratic flows, meaning on one hand more extremes on the high end (floods), in itself posing risks for hydropower infrastructure, but also through increasing sediment loads and risks of exposure to landslides and glacier lake outburst floods. On the other hand, a small increase in frequency and length of hydrological droughts is projected. Furthermore, projections of wind speed and incoming solar radiation indicate more or less stable conditions compared to the present day climate, further substantiating the rationale for portfolio diversification.

The main risks for the proposed project components in the climate change context are related to a projected increase in extreme events like extreme precipitation and related hazards (flood, landslides, erosion), and heat stress. This poses risks to PV mounting structures and foundations, wind turbine foundations, and foundations of transmission network towers. In particular the projections of increase in magnitude of extreme precipitation events with return periods ranging from 5 to 100 years is significant. These increase by 20-30% by 2060. Temperature increases by around 2 °C by 2060 compared to the reference period, and the frequency of heat waves most likely increases. This may affect the generation capacity of solar panels, reduce the capacity of transmission lines, and increase losses in substations and transformers.

For adaptation and climate proofing the main recommendation is to verify that the proposed drainage systems at the sites are sized for extreme flows that are 20-30% larger in magnitude than current extremes. This is valid across return periods. The second high priority recommendation is to design foundations of solar, wind, and transmission infrastructure to withstand increased erosion rates and substantially increased risk of landslides in landslide prone areas. A third recommendation is to take into account lower production for solar panels at increased frequency of heat stress, as well as in the sizing of capacity of transmission infrastructure, which may have reduced capacity during periods of high heat stress.

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