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Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, Nepal

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ABSTRACT

Study region: Koshi River basin, Eastern Nepal.
Study focus: Climate change is increasingly evident as the global surface temperature is warming with erratic rainfall patterns across the globe. In this regard, the Koshi Basin in the Himalayan region is also impacted, and it is important to understand the spatio-temporal details of the impact in the basin under future climate change. This study assessed the potential climate change and its impact on the hydrological regime using the Soil and Water Assessment Tool (SWAT) and Indicators of Hydrological Alteration (IHA) based on RCP4.5 and RCP8.5 of ensemble downscaled CMIP5 GCM runs.
New hydrological insights for this region: Results show the upper part of the basin warming faster than the lower part, the pre-monsoon season warming more than other seasons. There is no clear uniform trend in precipitation. However, the southeastern part of the basin will get more precipitation. Sub-basins will get more precipitation during the post-monsoon under RCP4.5, and during the monsoon under RCP8.5. The annual water availability will not decline but water availability within seasons and regions is projected to be highly variable. There is also a change in the spatial pattern of river discharge and the western part of the basin is likely to experience more impact. Therefore, these findings will be valuable in identifying how particular sub-basins within the Koshi Basin will be impacted by climate change and in stipulating effective planning and management of water resources for the future.

1. Introduction

The Himalayas are one of the world's regions that are highly sensitive to changing climates (Yao et al., 2019). There is a noticeable increase in temperatures in the Himalayas, higher than the global average with an increase in erratic rainfall patterns (Sharma et al., 2019). The area has warmed by around 1.8 °C over the past half-century, considerably higher than the warming rates for the Northern

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Hemisphere and the global mean (Yang et al., 2014; Kang et al., 2010; Liu and Chen, 2000). Seasonal and annual temperatures have also risen in higher-elevation areas across the Himalayas (Yao et al., 2019; Liu and Chen, 2000). This fast warming has had a great effect on the Himalayan environment and most noticeably in the rapid retreat of Himalayan glaciers and shrinking snow areas (Kulkarni et al., 2013). Similarly, earlier studies have reported that Hindu-Kush Himalayan (HKH) region and Tibetan Plateau have experienced a significant change in precipitation events over the past decades (Zhan et al., 2017). However, some studies have revealed a significant change in recent extreme precipitation events in some regions of the HKH (Zhan et al., 2017). These changes in the temperature and precipitation ultimately affect the volume and timing of river flows. More broadly, climate change has notably altered the hydrological cycle, the shift in snowline, water availability, water balance, flow regime and soil moisture in the Himalayan region.

Temperature is one of the vital factors and also the most sensitive parameter in climate science. An ongoing temperature analysis conducted by scientists at NASA reported the average global temperature on earth has increased by about 1.1 °C since 1880 (Source: https://earthobservatory.nasa.gov/world-of-change/global-temperatures). In addition, the global annual average temperature rises by 1 °C in 2016 and 0.98 °C in 2020 resulting in the first and second warmest year since 1880 (NOAA, 2021). Looking at the rate of change, it can be projected that there is likely to be an ongoing significant increase in temperature in the Himalayan region in the future. Earlier studies indicate projected temperature change, but those changes might vary according to space and time in terms of magnitude and rate of change (Kulkarni et al., 2013; Knutti and Sedláček, 2013; Lutz et al., 2016a). For instance, Kulkarni et al. (2013) highlighted that warming was projected to rise by 4.6 °C in Western Himalayas, 4.3 °C in Central Himalayas and 4.1 °C in Eastern Himalayas by 2100. As far as the Koshi Basin, the mean temperature is likely to increase by 4.6 °C under RCP4.5, while 7 °C under RCP8.5 by 2100 (Kaini et al., 2019).

Precipitation in the Himalayan region is most affected by the Indian summer monsoon as well as the winter westerlies precipitation and varies according to space and time. The monsoon decreases from southeast to northwest whereas the influence of the westerlies decreases from west to east (Nie et al., 2021). Precipitation is the major freshwater contribution to the hydrological system in the Himalayan region (Perry et al., 2020). Kulkarni et al. (2013) showed that Indian summer monsoon precipitation is likely to increase by 20–40% at the end of this century. In the Koshi Basin, most studies project that rainfall is likely to increase during the monsoon and decrease during winter, while the increase is likely to be more in the southern part compared to the northern part (Kaini et al., 2019; Rajbhandari et al., 2016). Furthermore, there is likely to be an increase in the future frequency and intensity of extreme precipitation events, for instance, the number of dry days, consecutive dry days, and very wet days. Overall, several studies suggest that the irregularities in precipitation are expected to increase in the coming periods (Kulkarni et al., 2013; Immerzeel et al., 2012; Kumar et al., 2011; Jeelani et al., 2012).

Projected changes in the temperature along with precipitation patterns and intensity are likely to change river flow regimes resulting in flow variability and uncertainty in water availability (Dixit et al., 2009). The visible impact of climate change is even more palpable in the upstream part of the Himalayan region (Immerzeel et al., 2010; Viviroli et al., 2007). However, the response of changing climate to river flow is likely to differ within the basins of the Himalayas due to the source of runoff and hydrological processes varying by location and season (Immerzeel et al., 2012). For instance, the runoff is governed by snow and glacier melt in most of the upper part of the Himalayan basin whereas the runoff in the lower part of the basin is governed by rainfall and groundwater with minimal contribution of snow and glacier melt. Climate change is likely to impact the long-term monthly, seasonal, and annual flow of rivers together with changes in the timing of peak flow and variability of high and low river flows under future climate scenarios (Stagl and Hattermann, 2016). Thus, changes in river flows have an important impact on water such as water availability, irrigation, flood management, and overall water resources planning. Furthermore, changes in water availability can affect the water-dependent ecosystem and its associated services (hydropower, fisheries, irrigated agriculture etc.) which will influence many people's livelihoods depending on riverine ecosystem services. The Koshi Basin is one of the most populated basins in Nepal where the livelihood of these communities is mainly dependent upon the hydrological regime and its associated river ecosystem services. Studies suggest that there are likely to be considerable impacts on water resources with severe consequences for the livelihoods of communities in the Koshi Basin due to climate change projection (Macchi and ICIMOD, 2010; Bhatta et al., 2015). Thus, there is an urgent need to understand the potential climate change and its impact on the hydrological regime in the Koshi River basin.

The Koshi Basin is characterized by extreme topographic and climate heterogeneity. The orography (mountain land altitude) and lapse rate (the rate at which air temperature falls with increasing altitude) in the Koshi Basin differ vastly across the sub-basins, from the southern plains to the northern Himalayas as well as from the eastern to the western region of the basin. This means the regional differences in climate in the Koshi Basin. Thus, changes in climate and their impacts will vary across the sub-basins of the Koshi Basin as well as regional differences in the response of flow in the basin. Detail regional studies highlighted that Himalayan regions are likely to experience noticeable climate change with an increase in temperature and erratic rainfall that will lead to significant hydrological changes but what is unknown is how much of a spatio-temporal impact Koshi Basin will have in future in terms of climate change as well as what will be the response of the hydrological regime to this changing climate. In this regard, the major consequences of climate change will depend on the temporal and spatial scales. Therefore, we hypothesize that the impacts of climate change are scale-dependent, and impacts are likely to be highly variable depending on temporal (intra-seasonal) and local spatial scale rather than being uniform across the entire basin and on an annual scale. Furthermore, most climate change studies to date have considered the Koshi Basin as an entirety (MoFE, 2019) as well as only occasional consideration of future climate change scenarios up to 2100 including comparisons among different sub-basins. Therefore, spatiotemporal impact assessment and comprehensive multi-scale assessments are needed to understand the nature and extent of the expected climate change as well as the response of the hydrological regime and that's what this paper is all about.

2. Data and methods

2.1. Study area

The Koshi Basin is a lifeline for local inhabitants because it provides fresh water for household use, irrigation, farming, and livestock (Shrestha et al., 2017). The basin has a large potential for hydropower development and plays a key role in the irrigation of downstream areas. It contains rich biodiversity and is a source of valuable ecosystem services that directly sustain the lives and livelihoods of the 40 million basin residents, including the population in the Indian part of the basin (Wahid et al., 2017). It is a transboundary basin shared by China, Nepal and India. In this study, we included only the Chinese and Nepalese parts until the Koshi River flows into the plains (Fig. 1). It has a catchment area of 55,930 km^2 at Nepal – India border, of which approximately 51% is in China and 49% in Nepal. The river originates in the Tibetan Plateau, passing across eastern Nepal and ultimately joining the Ganges. Within the basin, the elevation varies from about 65 m in the southern region to 8848 m (Mount Everest peak) in the northern regions above the mean sea level. The slopes in the basin range from 0° in the south to 84° in the north (Mishra et al., 2019). This variation in elevation results in vastly different climatic zones, from humid tropical in the lower plain area to arctic in the high Himalayas (Dixit et al., 2009). In the Nepalese section, there are four distinct climatic seasons: winter (December–February), pre-monsoon (March--May), monsoon (June–September) and post-monsoon (October–November). The Koshi River basin is comprised of six major physiographic zones – the Tibetan Plateau, High Himalaya, High Mountains, Middle Mountain, Siwalik, and Terai; each with unique geology, topography and climate.

The Koshi Basin is characterized by extreme topography, climate heterogeneity and seasonal flow variability. The orography and lapse rates of the Koshi Basin differ vastly within the basin (Pandey et al., 2020a). Furthermore, the basin is influenced by two synoptic circulation systems i.e, easterlies (South Asian monsoon precipitation) during summer and westerlies (winter precipitation) during winter. The climate in the southern part of the basin is strongly influenced by the South Asian monsoon, whereas the northern part of the basin (Tibetan Plateau) lies in a rain shadow area. As a result, precipitation varies from 207 mm per year in the trans-Himalaya region to 3000 mm per year in the eastern mountains (Shrestha et al., 2017). Winter precipitation plays a vital role in the accumulation and melt of snow and ice. About 80% of the precipitation occurs in the monsoon season, intense with large local variation because of orographic effects (Kaini et al., 2019). A large southern part of the basin in Nepal receives an average annual precipitation of about 1800 mm (Bhatt et al., 2014). The upper part of the basin contains a huge amount of snow and glacier as a freshwater reserve

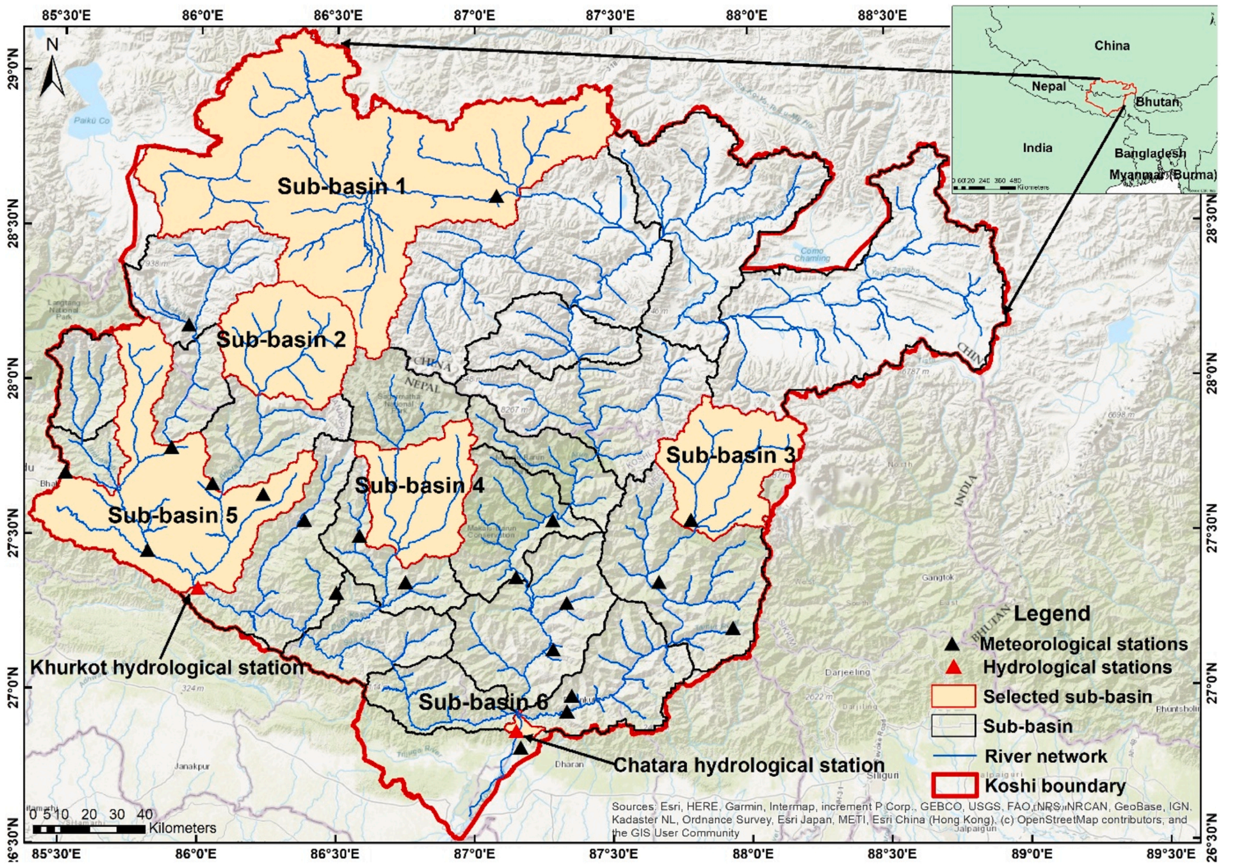


Fig. 1. Location map and location of used hydrological and meteorological stations in the Koshi Basin, with the six sub-basins covered in this study.

(Shrestha et al., 2017). The total glaciated area in the basin was 2984 km^2 with an estimated ice reserve of 295 km^3 and the total snow cover area was 5458 km^2 (Khadka et al., 2016; Bajracharya et al., 2011). The annual average discharge in the Khurkot hydrological station at Sun Koshi is 469 m^3/s and in the Chatara hydrological station at Sapta Koshi is 1545 m^3/s (Sinha et al., 2019).

The elevation variation within the basin is very sharp within a short areal distance, from 65 − 300 m a.s.l. in the southern plains, to 100 – 300 m a.s.l. in the foothills of the Siwalik region, while the middle mountain region has steep slopes and deep-cut valleys with an elevation of 1000 - 3000 m a.s.l. The northern Himalayas with elevations above 3000 m a.s.l. up to 8848 m a.s.l., is generally above the snow line (Dhital, 2015). Temperature varies considerably in the basin according to elevation. The northern part of the basin is very cold with temperatures reaching − 19 °C (Dingri meteorological station) in winter and the southern lower part of the basin is very warm with the temperature reaching 45 °C (Rajbiraj meteorological station) in summer. The mountains record the maximum temperature in May, while the southern plains (Terai) reach the maximum in April. The annual evapotranspiration (ET) rates are generally less than 1000 mm. However, some parts of the basin such as Sun Koshi have extremely high potential evapotranspiration and suffer from frequent droughts and soil erosion (Wahid et al., 2017).

There is also a diversity of land-use across the basin. There is a clear dominance of grasslands (40.34%), followed by native forests (24.45%), and then agriculture (12.45%). Other land-use types include barren land (11.26%), snow/ glaciers (9.45%), shrubland (1.52%), natural water bodies (0.5%), and urban areas (0.03%) (Uddin et al., 2015).

2.2. Observed and historical data

Climate data (temperature and precipitation) in Nepal was collected from the Department of Hydrology and Meteorology (DHM), Nepal. Additional climate data from Nielamu and Dingri stations within the Chinese part of the Koshi Basin was acquired from the Tibet Meteorological Bureau. The network of temperature, precipitation and hydrological stations used in the SWAT model is given in Fig. 1. Overall, daily data for the period of 1981–2010 from 11 temperature stations, 21 precipitation stations, and 2 hydrological stations (Khurkot and Chatara) was used in this analysis. The land use data for 2010 at a 30 m resolution was obtained from International Centre for Integrated Mountain Development (Uddin et al., 2015). The soil data was obtained from the Soil and Terrain Database Programme (SOTER) (Dijkshoorn and Huting, 2009). SRTM DEM of 90 m × 90 m resolution was used to delineate the watershed in the model.

2.3. Future climate scenario for the basin

For this study, we used a 10 km resolution future climate scenario dataset developed by Lutz et al. (2016a) for the Indus, Ganges, and Brahmaputra (IGB) domains as a part of the Himalayan Adaptation, Water and Resilience (HI-AWARE) project. In this dataset, the GCMs were tested using AR5 data downloaded from the CMIP5 model archive. In total 94 GCMs were tested for Representative Concentration Pathway (RCP) 4.5 and 69 for RCP8.5 (Lutz et al., 2016b). This ensures that the entire range of possible future climates in terms of temperature and precipitation change is included. For each model run, the normal annual difference in temperature and precipitation for future 2071–2100 climate conditions over a reference period 1971–2000 was determined in terms of temperature anomaly (ΔT) and percentage change of precipitation (ΔP), respectively (Lutz et al., 2016b). Based on the 10th and 90th percentile values of these projected changes, four combinations of climatic conditions – dry and cold, dry and warm, wet and cold, and wet and warm – were derived for each RCP. Finally, the model runs that were closest to the percentile values were selected to be included in the model ensemble used for the climate change impact study as well as the percentile values were used to avoid outlier GCMs, which are likely to be unreliable (Rajbhandari et al., 2016). Finally, eight GCMs were selected (Table 1), four for RCP4.5 and four for RCP8.5 based on the average annual response, changes in extreme behaviour in precipitation and temperature as well as validation of model performance to climatic reference data. These climate models cover a wide range of possible futures and are also able to replicate the most important processes in the region (Lutz et al., 2016b).

Overall, the following methods were used for the selection of climate models which perform better for the IGB domain (Lutz, a, b et al., 2016).

1) The initial selection of the climate model from the entire pool of climate models is based on changes in mean air temperature and annual precipitation mean sum.
2) Refined selection based on the projected change in four indices for climatic extremes.

Table 1
Selected climate models and scenarios as part of a study done by Lutz et al. (2016a).

RCP	Projected Climate Conditions	Selected GCM
RCP4.5	Warm, dry	CMCC_CMS_r1i1p1
	Warm, wet	CSIRO-MK3–6.0_r4i1p1
	Cold, wet	BNU_ESM_r1i1p1
	Cold, dry	inmcm4_r1i1p1
RCP8.5	Warm, dry	CMCC_CMS_r1i1p1
	Warm, wet	CanESM2_r3i1p1
	Cold, wet	bcc-csm1–1_r1i1p1
	Cold, dry	inmcm4_r1i1p1

3) Final selection based on model skills in simulating the annual cycle of temperature and precipitation.

The selected climate scenario data was statistically downscaled and bias-corrected using the quantile mapping (QM) method. The bias-corrected data was downscaled to 10 × 10 km spatial resolution by applying bilinear interpolation. The downscaled climate scenario data from Lutz et al. (2016a) can be downloaded from http://rds.icimod.org/clim. For a detailed description of model selection, statistical downscaling and bias correction method of climate data, readers are suggested to refer to Kaini et al. (2019), MoFE, (2019), (Trzaska and Schnarr, 2014) and Lutz et al. (2016a); b). The Koshi River basin is a part of the Ganges Basin and Lutz et al. (2016a) dataset was clipped by our study area for climate change analysis.

The selected eight GCM data were used to prepare an ensemble average of the four GCMs for each RCP4.5 and RCP8.5. This provided two ensemble average data, each one for RCP4.5 and RCP8.5. These average ensemble data were prepared for daily time steps for analysis. An ensemble average can reduce the overall uncertainty in model predictions (Pandey et al., 2019). Among four RCPs, we used only two RCPs: i) extreme RCP8.5 which assumes the increased radiative forcing will stabilize at 8.5 W/m^2 in 2100 and ii) medium stabilization scenario, RCP4.5 considers stabilization at 4.5 W/m^2 in 2100. We chose not to include RCP2.6 in the climate model ensemble because robust, realistic climate change scenarios are required to support adaptation planning, as RCP2.6 requires that carbon dioxide (CO_2) emissions start declining by 2020 and go to zero by 2100 which is highly unlikely. Furthermore, we excluded RCP6 scenarios too because the range of changes from RCP4.5 and RCP8.5 scenarios covers the entire range of radiative forcing resulting from RCP4.5, RCP6 and RCP8.5 (Lutz et al., 2016b). Table (1) shows the chosen climate model used for the study.

The climate change impact over the sub-basins was investigated by using future climate scenario data up to 2100. We used the GCM climate dataset 1995 s (1981 −2010) as the reference data period and 2025 s (2011–2040), 2055 s (2041–2070), and 2085 s (2071 −2100) as the projected future data period covering 30 years to determine the change in climate as well as its response on hydrology between the reference and future projection in the Koshi Basin.

2.4. Uncertainty analysis

There will always be some degree of uncertainty in future climate projections because of the different representation of atmospheric processes in the GCMs and the development of future socio-economic pathways. As well as a lack of understanding of atmospheric processes and observation, limitations in the structure of GCM models and highly variable simulation uncertainty also contribute to the overall uncertainty in projection scenarios. Considering these uncertainties in climate change projections is important for decision-making and developing adaptation strategies (MoFE, 2019). The uncertainties in the future projections can be understood using responses among the selected models and the RCPs (Change, 2014).

In this study, uncertainty analysis for precipitation and temperature projections was carried out based on the following approaches.

1) The uncertainties are represented by the responses among the models for RCP4.5 and RCP8.5.
2) The uncertainties are represented by the inter-quantile range among the models for RCP4.5 and RCP8.5 for the different time periods.
3) Agreement on decrease or increase in the change of climate variables among multiple models compared to the reference period.

2.5. Hydrological modelling

The hydrological model SWAT (Winchell et al., 2013; Arnold et al., 1998) was used to simulate the hydrological processes under present and future climate conditions. It is the combination of the basin-scale model with GIS (Srinivasan and Arnold, 1994) and uses spatial data (soil type, land cover/land use and elevation) and temporal data (climate data) to represent the hydrological performance of the heterogeneous catchments. It is a complete model incorporating surface land and channel environmental processes as well as combining studies of water quality, water quantity and climate change. It is capable of simulating hourly, daily, monthly and yearly data over long periods (Picchio et al., 2020).

The final outlet was defined at the Chatara hydrology station to delineate the sub-basins of the Koshi River Basin (Fig. 1). This resulted in the creation of 27 sub-basins and 35 hydrological response units (HRU). HRU is the smallest unit of the basin and is a combination of unique soil types, land features, and slope classification (Shrestha et al., 2016). From 27 sub-basins, we selected only six sub-basins 1, 2, 3, 4, 5 and 6. These sub-basins were spatially distributed in the Koshi Basin from east to west and north to south, where sub-basin 1 is the northern sub-basin; 2 is the western sub-basin; 3 is the eastern sub-basin; 4 is the central sub-basin; 5 is the southwestern sub-basin, and 6 is the southeastern sub-basin in the lower outlet in Koshi (Fig. 1). The reason for selecting these sub-basins compared to other sub-basins was based on the criteria of influence of monsoon (east to west and south to north precipitation gradients) and the criteria of influence temperature variability (north to south). As well as these sub-basins represent the trans-Himalayan, high Himalayas, middle mountain and southern plain - the physiographic region of the basin. Most sub-basins where no observation and monitoring stations are excluded from analysis and reporting. For instance, the northern part of the sub-basins (Fig. 1).

Elevation bands were created to model the process of snowmelt and orographic distribution from temperature and precipitation in SWAT. The model generates the elevation band automatically based on the area coverage percentage. An elevation band helps in discretizing the topographic influence of temperature and precipitation on snowmelt and discharge (Bajracharya et al., 2018). Each sub-basin in the model was divided into ten elevation bands, and each band was assigned a mean elevation and area coverage percentage. The SWAT model applies the following mass balance equation (Arnold et al., 1998) to simulate the hydrology within a sub-basin:

$$SW_t = SW_0 + \sum_{i=1}^{n} \left(R_{day} - Q_{surf} - E_a - _{wseep} - Q_{gw} \right) \tag{1}$$

Where SW_t: soil water content at time step t, SW_0: initial soil water content, R_{day}: daily precipitation, Q_{surf}: runoff, E_a: evapotranspiration, w_{seep}: percolation, and Q_{gw}: groundwater flow.

To accommodate the snowmelt (i.e., melted water from snowfall and snow cover) dynamics in the hydrological analysis, SWAT classifies precipitation as rain or snow by comparing the mean daily temperature with the user-defined air temperature threshold. The snowmelt in SWAT is calculated as a linear function of the difference between average snowpack-maximum air temperature and snowmelt threshold temperature by using the following formula (Neitsch et al., 2011):

$$SNO_{mlt} = b_{mlt} SNO_{COV} \theta \left[\frac{T_{snow} + T_{max}}{2} - T_{mlt} \right] \tag{2}$$

Where SNO_{mlt}: daily snowmelt amount (mm), b_{mlt}: daily melt factor (mm/day°C), $SNO_{cov:}$ the fraction of HRU area covered by snow, T_{snow}: daily snowpack temperature (°C), $T_{max:}$ daily maximum air temperature, and T_{mlt}: the optimum temperature for snowmelt (°C).

2.6. Evaluation of the performance of the SWAT model

Model evaluation is essential to measure the consistency of its output. It is considered reliable if the evaluation statistics fall within an acceptable limit (Moriasi et al., 2007). Accordingly, a model is considered suitable for monthly river flow simulation, if Percent Bias (PBIAS) is within ± 15% and Sutcliffe Simulation Efficiency (NSE) is above 0.75 (Bajracharya et al., 2018). We calculated the PBIAS, NSE, and Coefficient of Determination (R^2) to verify our SWAT results. The SWAT model was calibrated and validated at two points: the Khurkot hydrological station on Sun Koshi River which is the tributary of the Koshi River and the Chatara hydrological station on the Sapta Koshi which is the main outlet of the Koshi Basin (Fig. 1). SWAT was calibrated for 1986–1994 and validated for 2000–2008 at Khurkot hydrological station, Furthermore, SWAT was also calibrated for 1986–2001 and validated for 2002–2010 at Chatara hydrological station on a daily scale. The following suggestion was made by Fontaine et al. (2002), we used a warm-up period of 5 years for calibration to develop suitable initial conditions for groundwater and soil water storage.

The model was calibrated by using SWAT-CUP (Abbaspour, 2013). SWAT-CUP enables sensitivity analysis, calibration, validation and uncertainty analysis of SWAT models. Calibration parameters were based on literature review, volume, baseflow and adjustment of peak flows. During calibration, lapse rate, water capacity of the soil layer, SCS runoff curve number, Manning N, and snowmelt were found to be the most sensitive parameters. The temperature lapse rate was adjusted to 5.6 °C/km based on Khadka et al. (2014). The SCS curve number varied from 40 to 90 based on land use type. The Manning N for the main channel was calibrated from 0.03 to 0.06. Snowmelt parameters, such as snowfall temperature and minimum snowmelt rate, were adjusted to the values of 0ºC and 7 mm/ºC-day, respectively (Bajracharya et al., 2018).

The calibrated and validated SWAT model was forced with historical ensemble climate variables from the period of 1981–2010. The discharge obtained from the simulated SWAT model for this period was treated as baseline data to evaluate changes in future flow.

2.7. Capabilities and limitations of the SWAT model

For a heterogeneous river basin like the Koshi, it requires calibrating and validating the model if not for every sub-basin but for a cluster of sub-basins or large watersheds to simulate a reliable result. The key difficulty of calibrating and validating a hydrological model developed in a river basin like Koshi with limited data availability is the absence of observed streamflow data. Due to the unavailability of observed data and accurate information on snowmelt and glacier melt in the high Himalayan areas of Tibet and Nepal, results may have limitations. Even though the model performs all its estimates at a very small areal unit, the model has not been built and calibrated to simulate small catchments. Furthermore, SWAT's snow/glacier component is relatively weaker than the rainfall-runoff component (Pandey et al., 2020b; Bharati et al., 2019) Thus, the use of other snow/glacier models is recommended, if these components are important and need to be analyzed in detail (Adnan et al., 2019; Bharati et al., 2019).

However, the model was capable to reproduce or capture reasonably the hydrograph patterns, average flow conditions, high flow conditions, and flow duration curves in the Koshi Basin. The calibration and validation statistics based on available data, mostly downstream, show the satisfactory performance of the SWAT model in Khurkot and Chatara (the hills and Terai of Nepal) hydrological stations, and the results obtained from these stations can be confidently used for further activities. Our results are in line with earlier studies done in the Koshi Basin (Bharati et al., 2014, 2016, 2019; Devkota and Gyawali, 2015; Kaini et al., 2021).

2.8. Indicators of hydrological alteration

The Indicators of Hydrological Alteration (IHA) version 7.1 tool (The Nature Conservancy, 2009) was used to calculate parametric statistics of flow components from daily time series river flow data as mentioned by Richter et al. (1996). In Parametric statistics, the assumption is that data are normally distributed, and the data are characterized by a mean and standard deviation. Parametric statistics with advanced calibration were used to compare reference period flow datasets (pre-impact) with future climate change scenario flow datasets (post-impact). The advanced calibration will involve adjusting up to four parameters i) the high flow threshold ii) the low flow threshold iii) the high flow starts rate threshold and iv) the high flow end rate threshold whereas non-advanced calibration only a single flow parameter the high flow threshold (The Nature Conservancy, 2009). This software can calculate a total of 67 statistical parameters. These parameters are subdivided into 2 groups: the 33 IHA parameters (median and coefficient of dispersion) corresponding to 5 fundamental characteristics of the flow regime (magnitude, frequency, duration, timing, and rate of change) and 34 Environmental Flow Components (EFC) parameters corresponding to 5 fundamental characteristics of the flow regime (extreme low flow, low flows, high flow pulses, small floods, and large floods). As per the suggestion made by Wijngaard et al. (2017), high and low flow indices are used to evaluate changes in hydrological extremes. Thus, we used only two components of flow i) extreme low flow and ii) large flood (high flow) out of five characteristics as hydrological extremes. An extreme low flow was defined as a flow value less than or equal to the 10th percentile of the daily average flows of the period and a large flood event was defined as an initial high flow with a peak flow greater than 10 years return interval event. In other words, future changes in the 90th percentile of daily discharge levels, and the discharge levels of high flow events with a return period of 10 years (Wijngaard et al., 2017). The software finds the flow value equal to or less than the 10th percentile of all annual minimum flow as well as the 90th percentile of all annual maximum flood peaks (Bharati et al., 2019; The Nature Conservancy, 2009; Mathews and Richter, 2007). For in-depth parameters and characteristics of the flow regime, readers are suggested to refer to the Indicators of Hydrological Alterations User's Manual (The Nature Conservancy., 2009). Overall, the method for a systematic approach for investigating climate change and its potential impact on the hydrological regime in the Koshi River basin is presented in Fig. 2.

3. Results and discussions

3.1. Calibration and validation of the SWAT model

The SWAT model result shows a good agreement between simulated and observed stream values at the two hydrological stations. The daily simulation results at Chatara showed that peaks matched for most of the years, however, they were underestimated for a few years between 1992 and 1995 for calibration. The model performance for the Chatara outlet is shown in Fig. 3(a, b). Based on hydrograph and statistical evaluations, the model was able to simulate the flow during calibration and validation and correlated well with the observed data. The goodness of fit statistics showed that both Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2) are above 0.75 and Percent Bias (PBIAS) is within ± 15% in both stations, which makes the model a good representative of the Koshi River basin. This result is consistent with the findings of (Shrestha et al., 2016) and Bharati et al. (2014). Therefore, it showed

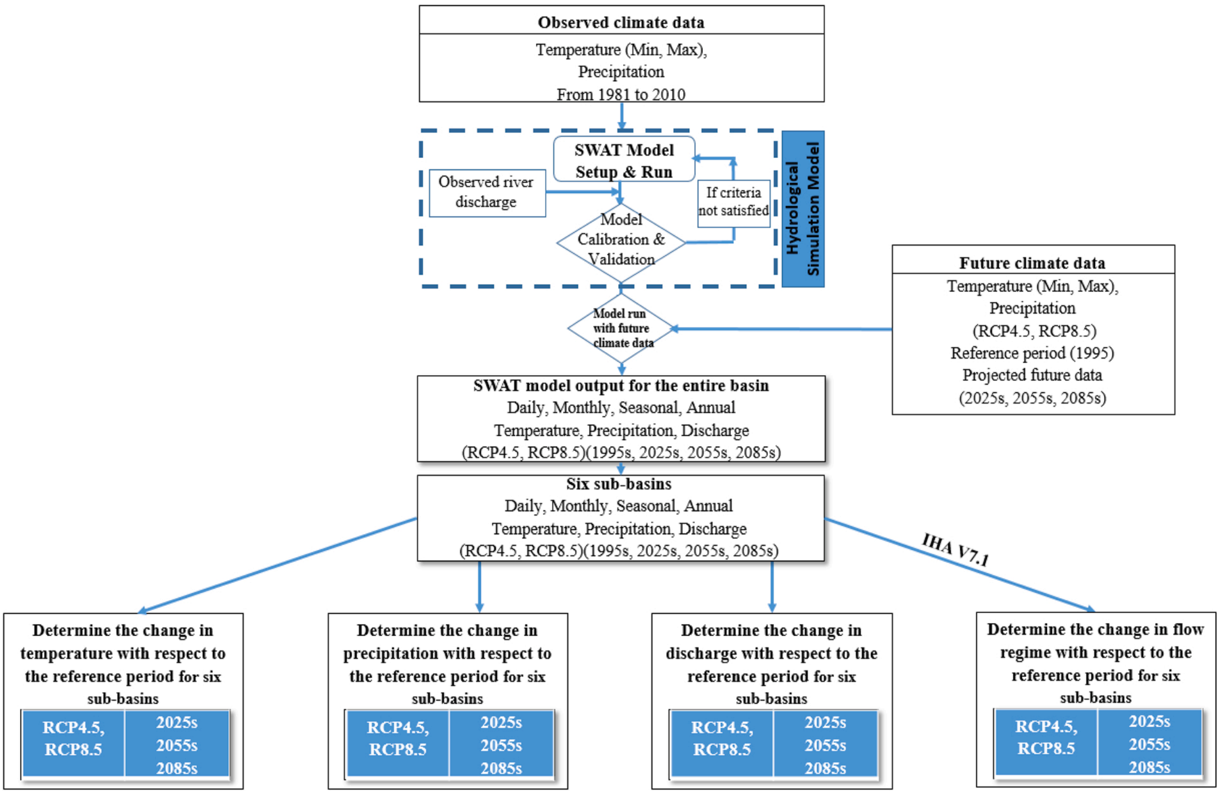


Fig. 2. Method for investigating climate change and its potential impact on the hydrological regime in the Koshi River basin.

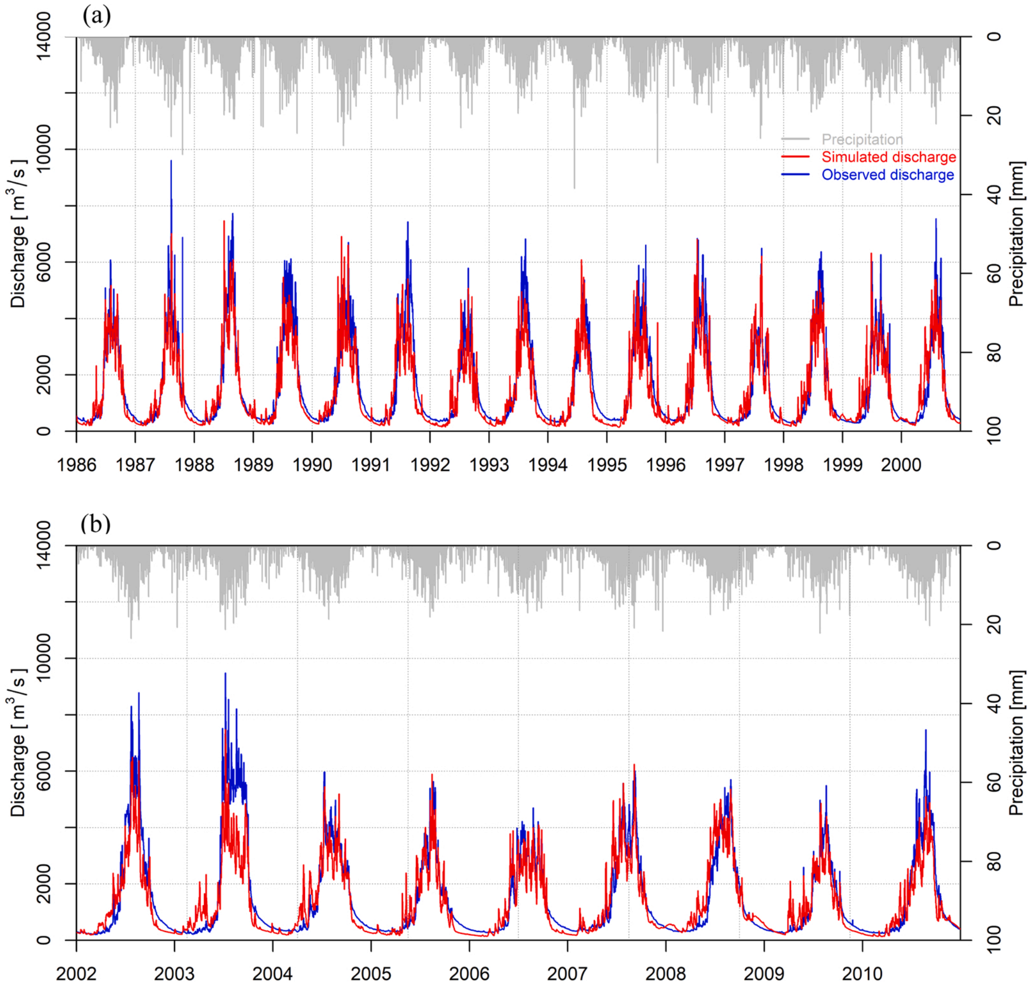


Fig. 3. (a) Calibration of the SWAT model of the Koshi Basin at Chatara hydrological station from 1986 to 2001, (b) Validation of the SWAT model of the Koshi Basin at Chatara hydrological station from 2002 to 2010.

that the SWAT model was able to simulate the discharge at the outlet of the catchment with reasonably high accuracy. The calibration and validation output value of NSE, R^2 and PBIAS is provided in Table 2.

3.2. The projected changes in temperature

This study quantifies the change in future temperature concerning the reference period across the sub-basins over time under two projection scenarios. Our results indicate an increase in the average temperature across the sub-basins in the future timeline. Annual average temperatures are expected to increase over time across the six sub-basins and the increase will be greater under the RCP 8.5 climate scenario. For example, the temperature is likely to increase by 2.3–2.7 °C in sub-basins under RCP4.5 while by 3.8–4.9 °C in sub-basins under the RCP8.5 scenario by 2100. Increases in annual temperatures differ among the six sub-basins under both scenarios over time. The increase in temperature will be highest in sub-basin 1 followed by sub-basins 3, 2, 4, 5 and sub-basin 6 under both RCPs (Fig. 4). Overall, the increase in average annual temperature will be greater in the northern sub-basins compared to the southern sub-

Table 2
Model performance of daily river flow during calibration and validation at Chatara and Khurkot outlet.

Station	Timeline	Evaluation Criteria		
		NSE	R^2	PBIAS
Chatara	Calibration Period (1986 – 2001)	0.87	0.87	-3.2
	Validation Period (2002 – 2010)	0.85	0.86	0.6
Khurkot	Calibration Period (1986 – 1994)	0.78	0.79	5.3
	Validation Period (2000 – 2008)	0.76	0.75	-4.6

basins which might most likely be attributed to elevation-dependent warming (Yao et al., 2019). This finding is consistent with the findings of Kaini et al. (2019), Shrestha et al., (2019, 2017), Rajbhandari et al. (2016), Bharati et al. (2014), Yao et al. (2019) and Wijngaard et al. (2018). The increasing temperature in the northern part means the upward shift of the snowline. As a result, the proportion of precipitation fall as rainfall instead of snowfall which decrease the accumulation and storage of snow at high altitude. In addition, increase temperature will accelerate the melting rate of remaining deposited snow and reduces the spatial extension of snow cover. Thus, a temperature change will change the snow cover area, as well as changes in the snowmelt rate which will impact the contribution of snowmelt, and the shift in discharge and flow regime.

Temperature increases will vary among the four seasons across the six sub-basins in both RCPs. The projected increases in temperature will likely be higher in the pre-monsoon and less during the monsoon season for all sub-basins and both scenarios. For

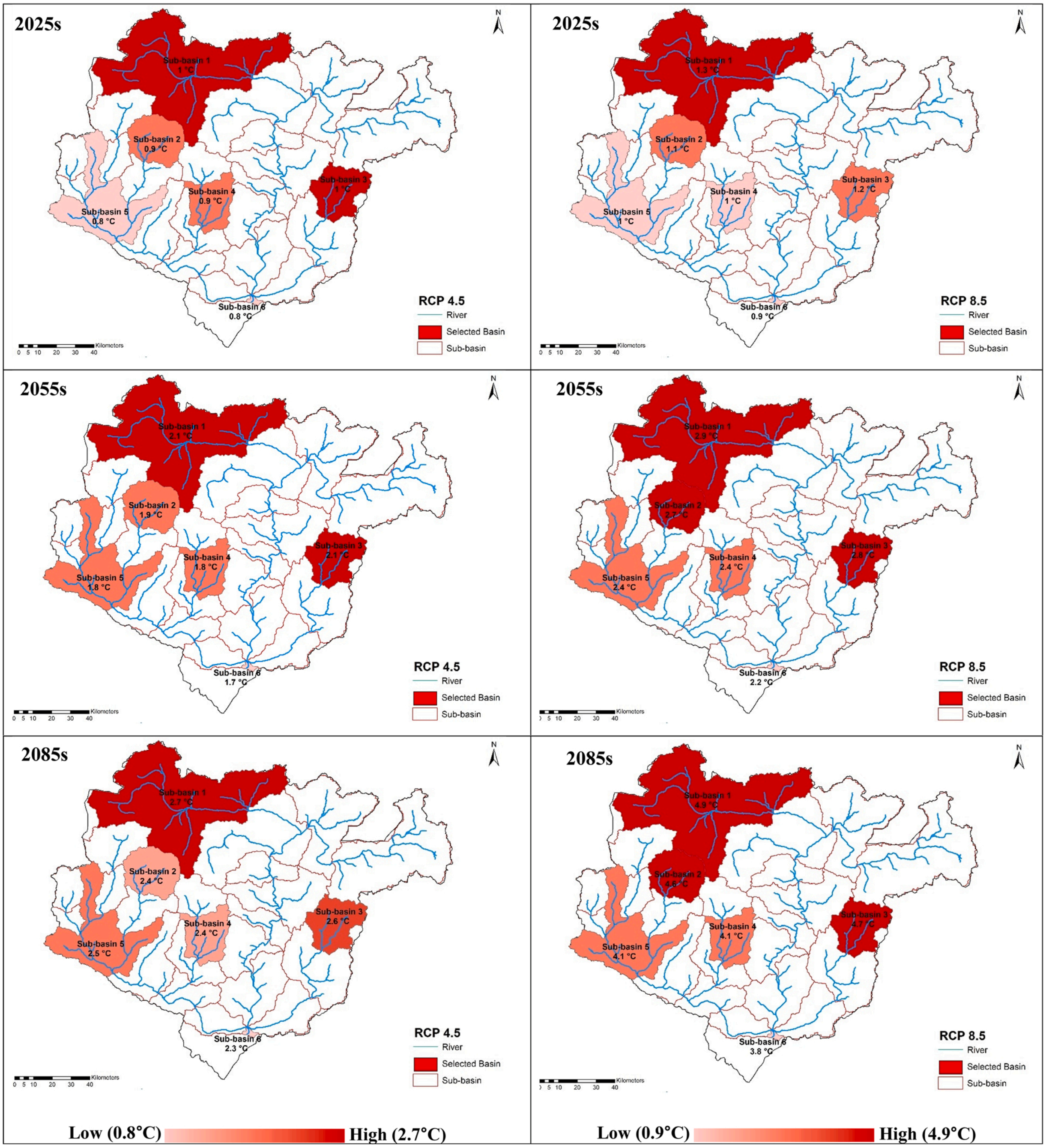


Fig. 4. Average annual temperature (°C) increases across the sub-basins in three time periods under both RCPs and the graduated colour ranges show the low (light) to high (dark) value.

example, temperature increases in sub-basin 1 will be greater in the pre-monsoon (3 °C) compared to the winter (2.9 °C), post-monsoon (2.4 °C) and monsoon season (2.4 °C) under the RCP4.5 scenario by 2100 (Table 3). This finding is consistent with the finding of Pandey et al. (2020a) in the Karnali-Mohana basin in western Nepal.

The rates of increase in temperature vary among time periods and sub-basins. For instance: annual temperature increases are projected to double between 2025 s and 2055 s for all sub-basins under the RCP4.5 scenario. However, for the RCP8.5 scenario, all sub-basins experience an approximate doubling of annual temperature increase between 2025 s and 2055 s as well as again between 2055 s and 2085 s (Fig. 4). Furthermore, seasonal temperature increases are projected to be around double across all sub-basins under RCP8.5 compared to RCP4.5 by 2100.

3.3. The projected changes in precipitation

Precipitation increases vary among the sub-basins. For instance, overall precipitation is likely to increase by 12.9–15.4% in sub-basins under RCP4.5 while increasing by 23.7–33.4% in sub-basins under the RCP8.5 scenario by 2100. The increase of annual precipitation will be highest in sub-basin 5 followed by sub-basins 2, 6, 4, 3 and sub-basin 1 under RCP4.5. In comparison, the increase of annual precipitation will be greatest in sub-basin 6 followed by sub-basins 3, 4, 5, 2 and finally sub-basin 1 under RCP8.5 (Fig. 5). Those sub-basins in the southeast (sub-basins 3, and 6) will experience more precipitation than northwestern regions (sub-basin 1) which might be because sub-basins 3 and 6 are impacted by the monsoon season first.

The rate of increases in average annual precipitation in future across the six sub-basins for both climate scenarios increases greater in the RCP8.5 scenario. Annual and seasonal precipitations are projected to double between 2055 s and 2085 s for all sub-basins under the RCP4.5 scenario. However, for the RCP 8.5 scenario, all sub-basins will experience a doubling of annual and seasonal precipitations (except for dry season) between 2025 s and 2055 s as well as between 2055 s and 2085 s

The projected precipitation changes show larger variations in seasons than on an annual basis for both scenarios. Winter season precipitation is expected to decrease under RCP4.5 but increase for RCP8.5 for most of the basin. The precipitation during the monsoon is projected to increase in all sub-basins for all time periods under both RCPs. Post-monsoon precipitation is expected to increase for all time periods except for RCP8.5 in 2025 s when four out of six sub-basins show a decrease. The projected changes in precipitation during monsoon and post-monsoon are in line with the finding by Rajbhandari et al. (2017) across the Koshi Basin.

Overall, results show that it is likely to be a potential decline in precipitation in winter and an increase in other seasons, especially the rainy season. Therefore, it can be predicted that the dry season is likely to be drier and the wet season is likely to be wetter under RCP4.5. In contrast, there is likely to increase precipitation in all seasons under RCP8.5. Therefore, all seasons are likely to be wetter in the mid and end of the twenty-first century under RCP8.5, except for sub-basin 5 in the winter season. The projections for precipitation show an annual increasing trend for both scenarios by 2100; this could positively affect on the riverine landscape ecosystem services. However, climate change is likely to disrupt precipitation regimes with alternating erratic rainfall and droughts, resulting in more repeated floods and droughts. For instance, the number of rainy days and consecutive wet days was projected to decrease whereas consecutive dry days were projected to increase in the Koshi Basin. Furthermore, the number of very wet days was projected to increase in Koshi Basin (Kaini et al., 2019; Rajbhandari et al., 2017). Changes in the frequencies of extreme rainfall events might impact land degradation processes such as mass movements, soil erosions, and removal of top fertile soil, which might reduce fertile land. Ultimately, change will impact the lives and livelihood of the people depending on agriculture in the Koshi Basin.

3.4. The potential impact of climate change on river discharge

Increases in annual discharge are projected across all sub-basins and these will be greater under RCP8.5 (84%) compared to RCP4.5 (61%) by 2100. The annual discharge is likely to increase by 19–151% in sub-basins under RCP4.5, while by 43–171% in sub-basins under the RCP8.5 scenario by 2100. The increase in annual discharge is projected to be highest in sub-basin 2 followed by sub-basins 3, 4, 5, 6 and sub-basin 1 under RCP4.5. In comparison, the increase in annual discharge is projected to be greater in sub-basin 2, followed by sub-basins 3, 4, 6, 5 and sub-basin 1 under RCP8.5 by 2100 (Fig. 6). Overall, there is a slight east-west spatial trend in annual discharge with an increase to the east to a decrease to the west. In terms of the future change in discharge, sub-basin 3 and sub-basin 2 dominate all other sub-basins in the degree of change under both RCPs. The discharge in sub-basin 2 is relatively low during the reference period (13.26 m^3/s annual mean discharge) but is projected to increase up to 150% (171%) by 2100 under RCP4.5 (RCP8.5). Sub-basin 2 shows a higher projected discharge than other sub-basins. It reflects that small absolute increases in sub-basin 2 can result

Table 3
Average seasonal temperature increases across the sub-basins under both RCPs by 2100.

Basin	RCP4.5				RCP8.5			
	Winter (°C)	Pre-Monsoon (°C)	Monsoon (°C)	Post-Monsoon (°C)	Winter (°C)	Pre-Monsoon (°C)	Monsoon (°C)	Post-Monsoon (°C)
1	2.9	3.0	2.4	2.4	4.6	5.5	4.3	5.2
2	2.5	2.8	2.1	2.3	4.4	5.2	3.9	5.0
3	3.1	2.7	2.5	2.7	4.9	4.7	4.0	5.0
4	2.4	2.6	2.3	2.3	3.9	4.3	3.5	4.6
5	2.6	2.6	2.4	2.1	4.2	4.8	3.3	4.2
6	2.3	2.6	2.1	2.2	3.9	4.1	3.3	4.0

Change in precipitation (%)

RCP4.5

	2025s					2055s					2085s				
	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual
Basin 1	0.0	4.5	4.2	29.8	5.2	-11.2	2.9	7.2	20.0	6.5	-7.4	5.2	13.1	50.0	12.9
Basin 2	3.4	3.9	4.9	29.0	5.8	-7.9	3.1	9.0	15.9	8.1	-0.7	7.0	15.4	38.6	15.0
Basin 3	3.1	7.6	3.9	11.2	4.9	-6.7	2.9	7.1	12.4	6.2	-2.0	12.3	14.5	21.0	14.0
Basin 4	-1.3	7.4	4.5	15.2	5.3	-11.8	6.2	7.8	12.2	7.3	-7.4	13.7	14.3	26.7	14.2
Basin 5	-1.4	4.9	4.8	27.1	5.6	-12.6	4.4	8.6	16.8	7.9	-4.5	10.3	15.5	41.1	15.4
Basin 6	-1.4	8.5	4.0	14.5	5.1	-12.2	1.4	6.5	20.1	6.2	-8.8	16.8	13.7	33.2	14.8

RCP8.5

	2025s					2055s					2085s				
	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual
Basin 1	12.4	-0.1	6.4	2.4	5.6	20.3	4.2	11.4	21.0	11.2	9.5	10.0	26.6	26.5	23.7
Basin 2	20.1	0.0	7.5	-2.0	6.5	26.9	4.2	14.9	12.5	13.8	12.1	8.3	29.3	10.9	25.4
Basin 3	-2.9	1.0	8.2	-6.0	5.7	2.6	10.6	16.7	5.4	14.5	8.2	22.3	37.5	15.6	32.6
Basin 4	0.4	-0.1	7.9	-12.9	5.6	5.1	6.9	17.1	2.7	14.7	8.3	20.4	33.7	8.1	30.0
Basin 5	-1.3	7.4	4.5	15.2	7.0	-11.8	6.2	7.8	12.2	15.7	-7.4	13.7	14.3	26.7	28.3
Basin 6	-5.7	1.2	8.5	-10.8	6.1	1.4	13.6	16.6	5.2	15.2	11.1	32.3	35.5	14.9	33.4

Fig. 5. The heat map of the percentage change in precipitation for selected sub-basins under two projection scenarios compared to the reference period (1995 s) for three time periods. The color bar represents the percentage change in precipitation for the given period. The blue color indicates an increase, and the red color indicates a decrease in precipitation.

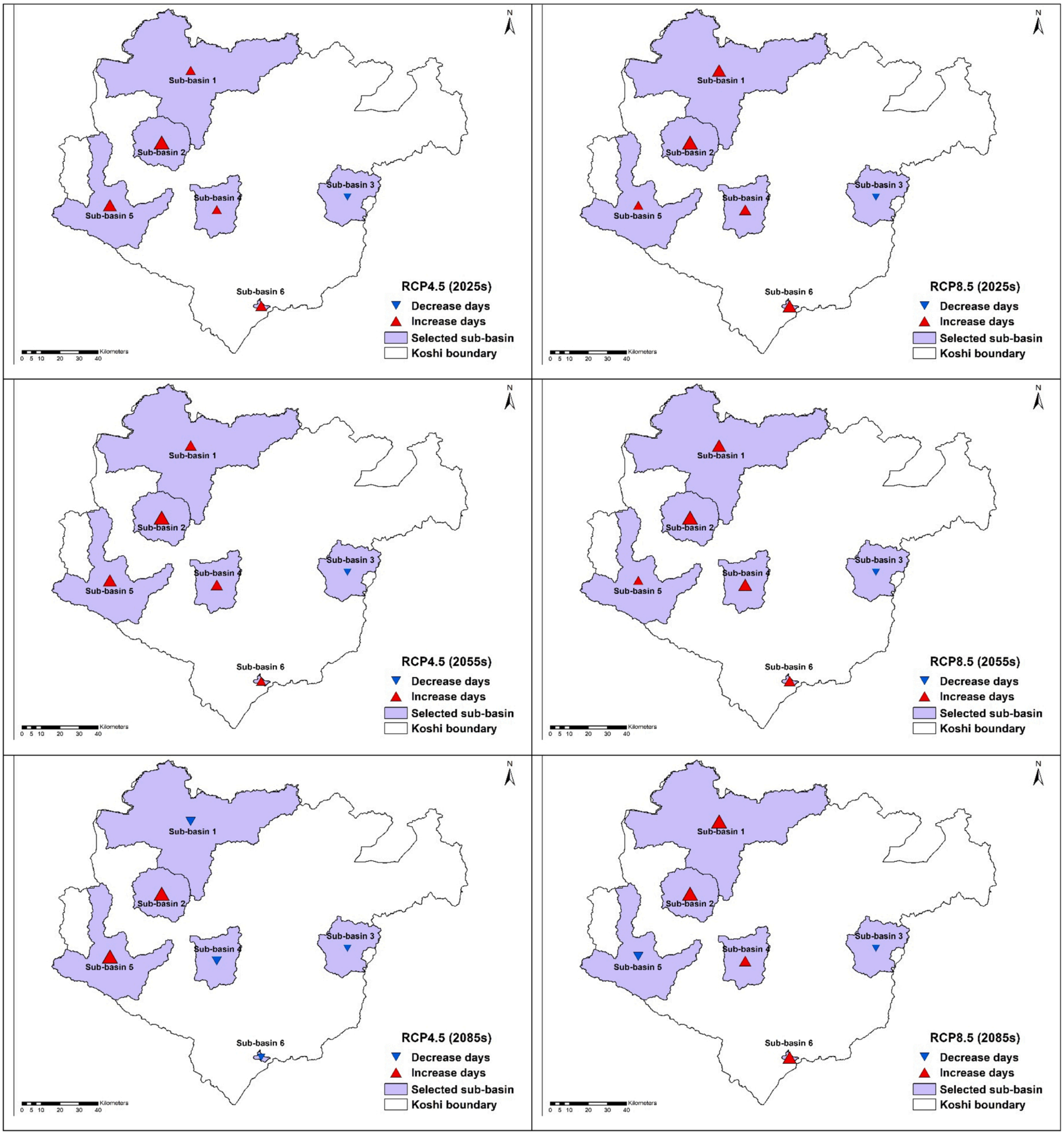
Change in discharge(%)

	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mon	Annual
RCP4.5															
	2025s					2055s					2085s				
Basin 1	-17.8	92.3	-7.7	37.0	0.6	-10.1	88.6	-4.4	47.1	3.8	21.9	72.9	9.0	150.6	19.3
Basin 2	-54.4	-66.0	-10.3	-3.2	-29.6	-36.7	61.6	118.1	90.8	66.5	9.1	-25.5	260.9	263.3	150.7
Basin 3	0.8	61.2	28.5	35.0	30.4	1.6	151.5	74.4	76.9	78.4	1.1	222.4	77.2	109.4	87.1
Basin 4	-10.4	-13.4	11.5	8.6	5.8	0.0	-2.1	46.2	21.3	31.3	7.4	13.2	68.5	28.5	48.3
Basin 5	-20.3	-18.5	3.4	9.5	0.1	-10.6	4.8	18.7	23.3	15.4	5.2	-2.2	33.9	53.4	30.4
Basin 6	-13.3	10.0	3.2	15.3	4.0	1.5	22.6	15.2	30.2	16.4	14.7	45.6	24.6	49.9	27.9
RCP8.5															
	2025s					2055s					2085s				
	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mon	Annual
Basin 1	-27.6	103.5	-3.9	7.4	3.0	-20.4	108.8	2.7	33.5	10.3	21.9	115.3	32.0	160.8	42.5
Basin 2	-56.6	-68.3	-7.3	-2.1	-29.9	-39.0	52.2	126.7	95.8	67.1	8.3	-28.3	312.1	286.2	171.1
Basin 3	0.8	53.2	33.7	23.3	34.0	1.7	180.7	89.5	61.4	93.6	1.1	266.6	117.3	109.6	125.5
Basin 4	-12.0	-17.2	15.7	6.2	7.4	-1.9	-2.3	59.4	22.1	39.1	7.4	20.6	101.7	30.5	69.1
Basin 5	-23.8	62.0	-3.1	-9.1	0.4	-16.4	115.7	16.1	12.0	20.7	8.4	123.2	41.7	47.0	45.7
Basin 6	-19.8	25.4	7.6	3.3	6.8	-8.6	47.4	26.2	25.5	25.5	11.6	79.3	51.7	50.8	51.1

Fig. 6. The heat map of the percentage change in discharge for all sub-basins and time periods under both scenarios compared to the reference period.

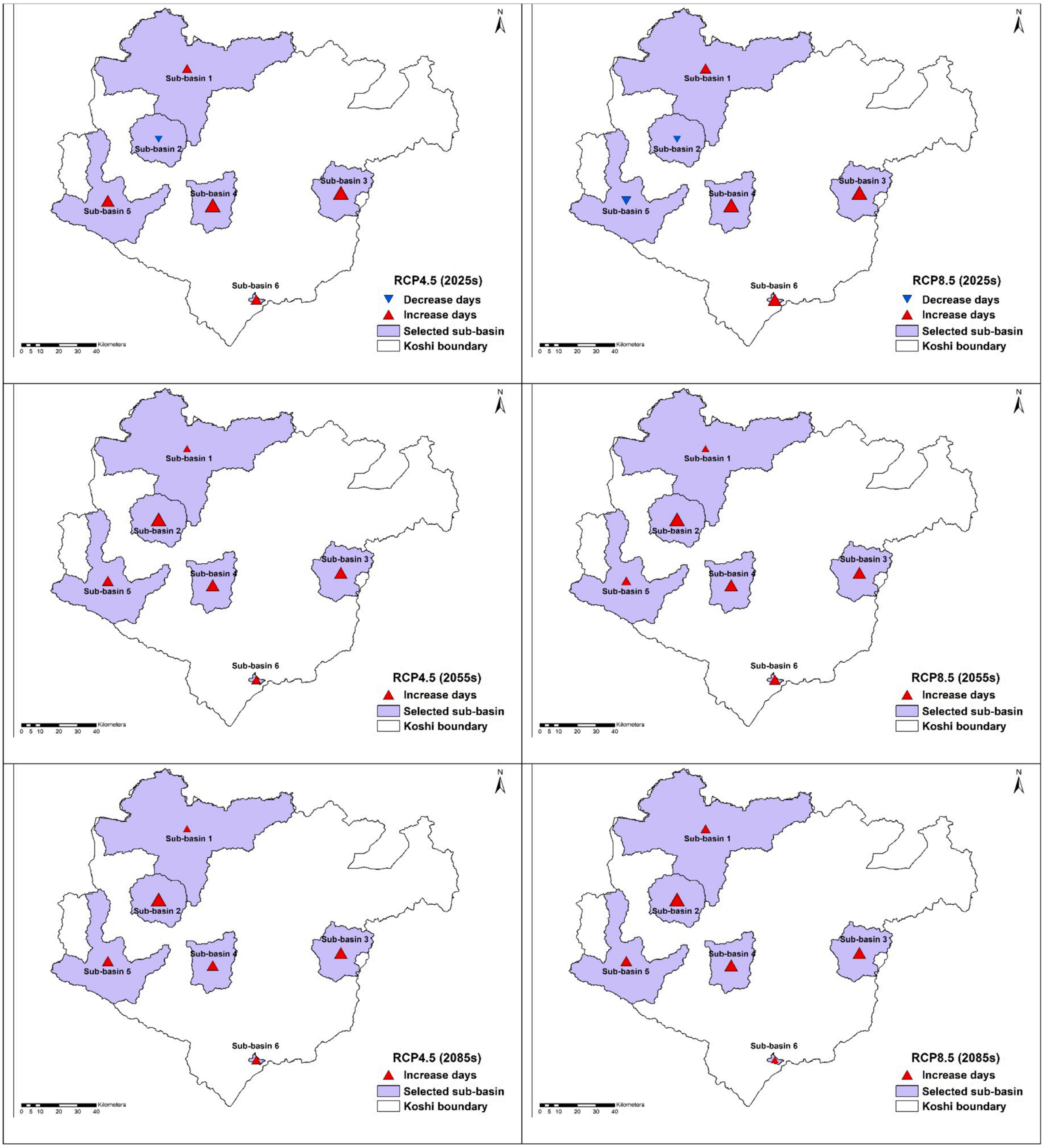
in large relative increases. Sub-basin 3 also shows high relative increases in discharge under both RCPs. It might be a reason that around 24% of the sub-basin 3 area is covered by snow and glacier, being higher than the other sub-basins (Khadka et al., 2020; Khadka et al., 2016). For instance, sub-basin 3 (upper part of Tamor Basin) consists of 358 sq km of glacier area (Khadka et al., 2020) and 784 sq km of snow cover area (Khadka et al., 2016). Due to an increase in temperature, the contribution of snow and glacier melt combined with monsoon rainfall will increase surface discharge. Thus, sub-basin 3 is the only basin that does not show any decrease in discharge in annual and seasonal intervals for all time periods up to 2100 compared to the reference period under both RCPs.

Seasonal changes in discharge will differ among the four seasons. The winter discharge is projected to decrease under RCP4.5 in 2025 s and 2055 s, as well as under RCP8.5 in 2025 s, for all sub-basins except for sub-basin 3. Pre-monsoon discharge is projected to



a

Fig. 7. a. The map of the change in extreme low flow days for all sub-basins under both scenarios according to time compared to the reference period. The symbol size represents the number of days, **7b**. The map of the change in large flood days for all sub-basins under both scenarios according to time compared to the reference period. The symbol size represents the number of days.



b

Fig. 7. (*continued*).

increase in most sub-basins except in sub-basin 2 under both RCPs in 2025 s and 2085 s. In addition, discharge in sub-basin 4 is projected to decrease during pre-monsoon under both RCPs in 2055 s, as well as under RCP4.5 in 2025 s. There is a marked increase in discharge in monsoon and post-monsoon seasons under both RCPs where the highest increase is in the post-monsoon season under RCP4.5 and in the monsoon season under RCP8.5.

The rate of change of annual discharges is projected to increase by 2100. For instance, the annual discharge between 2025 s and 2055 s in all sub-basins is projected to at least double whereas the annual discharge in three sub-basins (1, 2 and 5) is projected to more than double between 2055 s and 2085 s under RCP4.5. Seasonal discharge change is more variable for both time periods under RCP4.5. However, for the RCP 8.5 scenario, all sub-basins will experience significant increases in annual and seasonal discharges between 2025 s and 2055 s as well as between 2055 s and 2085 s. The rate of increase of discharge in monsoon might be an increase in monsoon precipitation combined with an increase in meltwater after mid-century in the Koshi Basin (Khadka et al., 2020; Wijngaard et al., 2018).

Overall, the result shows that there is an increase in annual discharge, albeit with a large variation in seasonal discharge. There might be water stress during the winter season but surplus water during the monsoon season. Simulated flow results show that the annual flow is still dominated by monsoon flow in the future even under the impact of climate change (Fig. 6). Furthermore, most sub-basins show an increase in average seasonal flow except during the winter season. The decrease in winter river flow might be due to decreases in winter precipitation. This decrease in winter river flow and precipitation might impact highly winter cultivation.

3.5. The potential impact of climate change on flow extremes

Climate change is projected to influence components of the flow regime in each sub-basin. The response of flow alteration varies according to sub-basins and season for the different periods under both RCPs. The flow alteration results show that the magnitude and frequency of peak discharge in all sub-basins are projected to increase under both RCPs over all periods except for sub-basins 2 and 5 in 2025 s under RCP8.5. Furthermore, the duration of low flow, as well as high flow, are likely to increase under both RCPs for all periods, except for sub-basin 3 in terms of low flows (Fig. 7a). In other words, hydrological extremes (high flow and low flow) are projected to occur more frequently in all sub-basins in the Koshi Basin. The change in the number of extremely low flow days varies from − 15–100 days under RCP4.5 and − 8–60 days under RCP8.5 across sub-basins by 2100. Similarly, the change in the number of large flood days varies from 5 to 18 days under RCP4.5 and 7–28 days under RCP8.5 across sub-basins by 2100. The spatial change in hydrological extremes across the sub-basins is shown in Fig. 7(a,b). The increase in the duration of low flow is greater than the high flow. The projected changes in flow extremes are in line with the finding by Nie et al. (2021) in the Himalayas, Wijngaard et al. (2018) for the Upper IGB River basins, Wijngaard et al. (2017) for the upper Ganges and Bharati et al., (2019, 2016) and Khadka et al. (2016) for Koshi. However, at the beginning of climate change (in the 2025 s), there will most likely be influence on low flow than high flow, but it will then reverse as time passes. Low flow duration will be shortened whereas high flow duration will be extended. During the low flow season, the surface water availability will be low which is likely to affect the environmental flow requirement and lead to high water demand, resulting in high competition between water users (Wijngaard et al., 2018). This might impact people who rely on water-dependent ecosystem services.

Furthermore, the timing of the projected average monthly discharge will also change. For instance, the most flow-generating month may shift for one month, from July to August in 2085 s in sub-basin 4 and 5 under RCP8.5 (Fig. 8) whereas for the other remaining sub-basins, the projected average monthly discharge period timing remains the same. This finding is supported by studies by Bajracharya

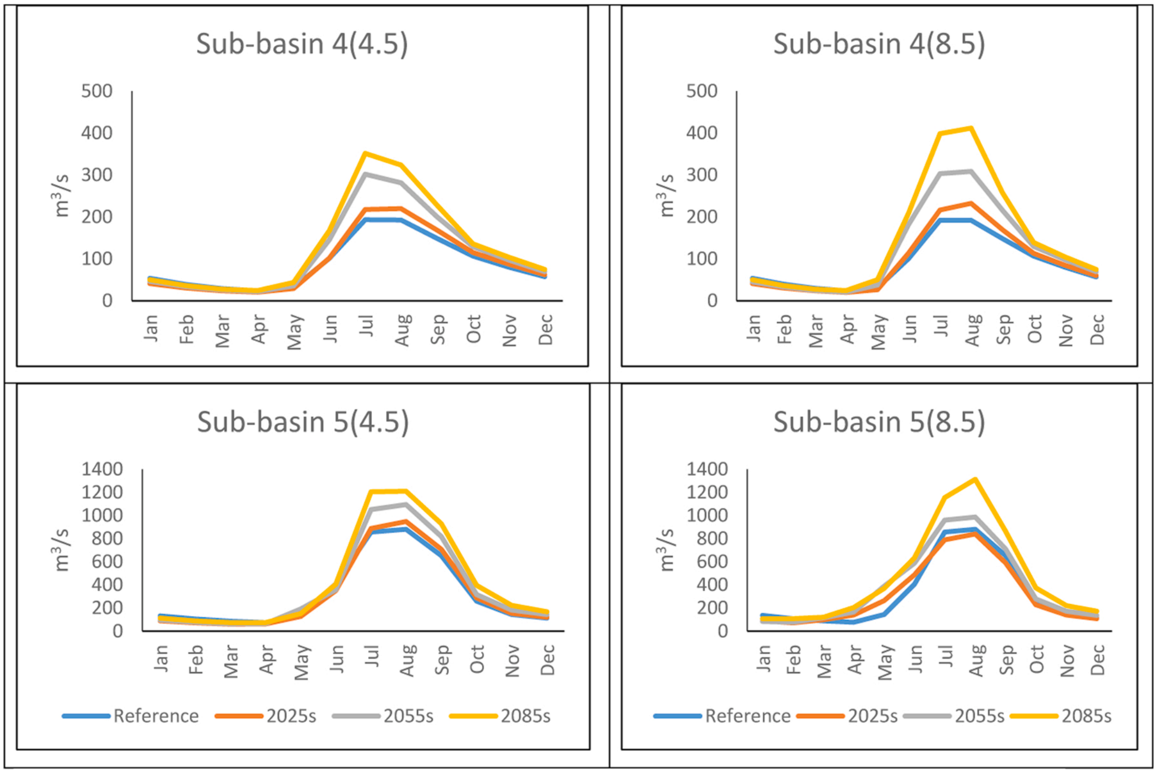


Fig. 8. Projected average monthly discharge for sub-basin 4 and 5 under RCP4.5 and RCP8.5 in 2085 s compared to the reference period.

et al. (2018) of the Kaligandaki basin adjacent to the Koshi Basin, and by Khadka et al. (2016) of the Koshi Basin.

Overall, the flow regime in the Koshi Basin is projected to be significantly impacted by climate change. The frequency in occurrence of high and extremely low flow events demonstrates the "too much or too little water" problem. This means the basin is vulnerable to both floods and drought, resulting in a high risk to people and their livelihood. Furthermore, the change in flow regime will in all probability change the biological and physical processes of the river which will have an effect on quality, quantity, hydro-geomorphology and biodiversity in riverine ecosystems (Bharati et al., 2016).

3.6. Uncertainties in climate projection

We used the robust HI-AWARE datasets of maximum and minimum temperature, and precipitation of 8 GCMs (4 each for RCP4.5 and RCP8.5) as input data for the SWAT model to simulate the future scenarios for the study basin. However, there is uncertainty in the climate data as these trajectories are dependent upon many factors including human intervention, atmospheric processes as well as international climate negotiations. To account for these uncertainties, the models were selected based on simulating the four corners of the projection spectrum, i.e. one each for cold-dry, cold-wet, warm-dry and warm-wet condition of the future for each RCP and their ensemble was used as representative of the future states. However, there are significant uncertainties within the projections in the study area for RCP4.5 and RCP8.5 scenarios. (Cui et al., 2018) reported that the uncertainties from climate models together with the uncertainty from a hydrological model pose a great challenge to the accurate projection of hydrological regime alteration. Therefore, we should cautiously use the output of the model results considering the uncertainty range given by all datasets.

These uncertainties can be understood from the ensemble plot in Fig. 9a where it can be seen that even though the projection for both precipitation and temperature increases, the response of models has higher variability for precipitation than for temperature for both RCPs. Also, Fig. 9b suggests that there is more variability in projection for 2085 s than for 2025 s or 2055 s. The future projection for precipitation shows higher uncertainties in RCP4.5 than in RCP8.5. However, for temperature, the uncertainties are similar for both RCPs, although lower than those for precipitation. This can be understood by the higher value of the coefficient of variation in

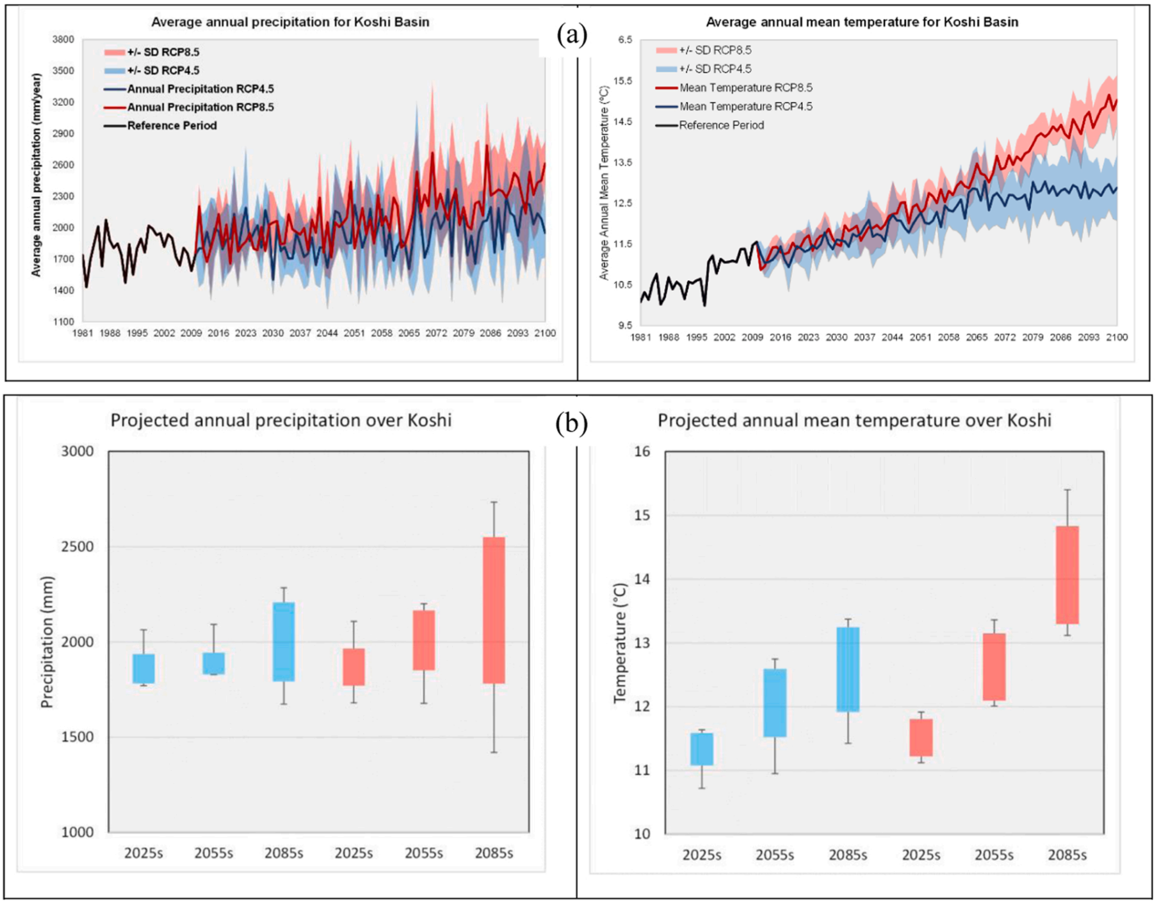


Fig. 9. **a**. Ensemble plot of precipitation and temperature under RCP4.5 (blue) and RCP8.5 (red) for the period of 1981–2100. The coloured band represents the standard deviation from the select GCMs. The black line represents the reference period, **9b**. Projected annual precipitation (mm) and temperature (°C) for three-time periods for RCP4.5 (blue) and RCP8.5 (red).

Table 4
Quantitative estimates of uncertainties for the entire Koshi Basin.

	Variable	Statistics	RCP4.5			RCP8.5		
			2025 s	2055 s	2085 s	2025 s	2055 s	2085 s
Multi-model ensemble for Koshi basin	Precipitation (mm)	Mean	1884	1911	2053	1921	2072	2317
		Standard deviation	129	124	222	139	155	405
		Co-efficient of variation	0.07	0.07	0.11	0.07	0.08	0.18
	Temperature (°C)	Mean	11.5	12.3	12.8	11.6	12.7	14.2
		Standard deviation	0.30	0.50	0.70	0.30	0.60	1.00
		Co-efficient of variation	0.02	0.04	0.05	0.03	0.05	0.07

precipitation than in temperature in Table 4. For example, the coefficient of variation for precipitation is 0.11 (0.18) for RCP4.5 (RCP8.5) in 2085 s - suggesting the range of projected change in precipitation is large. In the case of temperature, the coefficient of variation is 0.05 (0.07) for RCP4.5 (RCP8.5) in the 2085 s

Projections of mean air temperature indicate an increase ranging from 1.3 °C to 4.9 °C between 1995 s and 2085 s, with stronger warming at higher altitudes. The maximum range of uncertainty in the change of temperature is observed during the 2085 s under the RCP8.5 scenario, whereas it is the least during the 2025 s under the RCP4.5 scenario. The uncertainty in future precipitation is also large, with projections ranging from − 7% to + 33% between 1995 s and 2085 s. The uncertainty range is expected to be small in the winter season and more during the monsoon season because during winter basin receives only around 2–5% of total rainfall. The range is expected to be highest during the 2085 s under both scenarios. The range of uncertainty in temperature is not expected to vary much, unlike precipitation, but is expected to increase towards the 2085 s. The finding of our result is consistent with the findings of Kaini et al. (2019), MoFE (2019), Bajracharya et al. (2018) and Lutz et al. (2016a).

4. Conclusion

This study assessed changes in the future climate and their influence on hydrology in six sub-basins in the Koshi Basin. We use the SWAT model to simulate the surface hydrology of the Koshi Basin up to the Chatara hydrological station and the IHA V7.1 tool to assess the characteristics of the flow regime as hydrological extremes. The hydrological model is forced with an ensemble of downscaled GCMs – representing a wide range of regional RCP4.5 and 8.5 climate conditions for 2025 s, 2055 s and 2085 s. The model output was analyzed in terms of projected change in temperature, precipitation, river discharge and flow extremes. Overall, the results show the sub-basins are likely to be markedly affected by changing temperature and precipitation, as well as the response of river flow in the three-time periods under both scenarios. Furthermore, the responses are varied among sub-basins with impacts being more noticeable at local and seasonal scales. The impacts strongly accelerate with increasing annual mean temperature, and precipitation will result in an altered flow regime up to 2100 with the largest projected increases for RCP8.5 scenarios.

Temperature rise showed differences among the sub-basins, with the greatest increase in the northern sub-basin (sub-basin 1) and the least increase in the southern sub-basin (sub-basin 6) under both scenarios by 2085 s. The increase in temperature clearly showed a north-south trend. Regarding the seasonal warming, most sub-basins showed that pre-monsoon is most likely to increase temperature faster than the rest of the seasons under both scenarios. An increase in temperature is likely to be lower in the monsoon season compared to other seasons under both RCPs. Furthermore, among all sub-basins and seasons, the eastern sub-basin (sub-basin 3) showed the highest warming during winter.

Annual precipitation showed an increasing trend among all basins under both RCP4.5 and RCP8.5. The southwestern sub-basin (sub-basin 5) is likely to get more precipitation at the end of the century compared to other basins under RCP4.5 whereas the southern sub-basin is likely to get more precipitation under RCP8.5. However, the seasonal breakdown of the precipitation showed different aspects. The dry season is drying more, and the wet season is becoming wetter under RCP4.5, whereas all seasons are becoming wetter under RCP8.5, except for pre-monsoon and post-monsoon in 2025 s

In both RCPs, the annual flow at the outlet of the sub-basins is expected to increase significantly in the 2055 s and 2085 s compared to the 2025 s. But there is high variability in seasonal discharge among sub-basins. Most sub-basins show a decrease in flow during the winter season in all time periods except in 2085 s under both RCPs. The western sub-basin (sub-basins 2) and eastern sub-basin are most likely to get surplus water under both scenarios compared to other basins in the 2085 s. As the discharge in the western sub-basin is projected to be a significant increase in some seasons as well as a significant decrease in other seasons under both RCPs, it will most likely face the issue of too much or too little water scenario. The western sub-basin will most likely be more vulnerable to climate change than other sub-basins. Furthermore, the eastern sub-basin is likely to have a surplus of water under both scenarios by 2085 s. There is a shift in average monthly flow in the central sub-basin (sub-basin 4) and the southwestern sub-basin during the 2085 s under RCP8.5. Our findings also show that there will be an increase in extreme events i.e. extremely low flows and large floods in future for all sub-basins.

Finally, our findings show that water availability during the century is likely to increase in sub-basins at an annual scale but water availability within inter-annual and seasonal periods will become highly variable. It seems climate change is expected to have greater effects seasonally rather than annually. This change in hydrology could affect water distribution (timing and quantity) in the basin. For instance, a month shift of the average monthly discharge will impact the riverine ecosystem functions that rely on appropriately timed high flows, thus affecting the dispersal of seeds onto the floodplain, survival of certain fish species, and water demand of crops etc. are likely to heavily impact. Our results suggest that the impacts of climate change are scale-dependent in terms of temperature, precipitation, and river flow response. However, there are still large uncertainties associated with the quantitative estimates for future time periods. Thus, the impact of climate change can only be understood if uncertainties are also considered.

The finding of this study will be valuable in identifying how sub-basins are likely to be impacted by climate change and in stipulating effective planning and management of water resources in the future decades.

4.1. Limitations

The major limitations of the present study lie with the spatial coverage of ground-based monitoring stations as well as the availability of time series observed hydrometeorological data. In the Koshi Basin, the network of hydrometeorological stations is sparse (Fig. 1), for instance, most parts of the northern basin do not have meteorological stations even though on the Nepal side the stations are extremely uneven and the number of gauge stations is also small. This is indeed a limitation for understanding the larger variability of the precipitation patterns as well as it is difficult to infer the high-altitude precipitation in rugged topography. Furthermore, limitations for understanding the snow and glacier hydrology of a river basin in mountainous terrain as well as difficulty for model calibration and validation. Thus, we took only two stations (Fig. 1) for calibration and validation of the hydrological model. It is well known that the more observed data is available, the chance of developing a more accurate model is increased.

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CRediT authorship contribution statement

S.R.B conceptualised the research study, S.R.B, S.P, A.B.S and R.T designed the method and wrote the original draft as well as prepared, reviewed and edited the manuscript; data analysis and preparation by S.R.B, R.T and S.P, the model calibration and validation was done by S.P and contributed on writing for evaluation of SWAT model. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101316.

References

Abbaspour, K.C., 2013. *SWAT-CUP 2012. SWAT Calibration and uncertainty program—a user manual.*

Adnan, M., Kang, S.C., Zhang, G.S., Anjum, M.N., Zaman, M., Zhang, Y.Q., 2019. Evaluation of SWAT Model performance on glaciated and non-glaciated subbasins of Nam Co Lake, Southern Tibetan Plateau, China. J. Mt. Sci. 16 (5), 1075–1097. https://doi.org/10.1007/s11629-018-5070-7.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment Part I: model development. J. Am. Water Res. Assoc. 34 1, 73–89.

Bajracharya, A.R., Bajracharya, S.R., Shrestha, A.B., Maharjan, S.B., 2018. Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. Sci. Total Environ. 625, 837–848. https://doi.org/10.1016/j.scitotenv.2017.12.332.

Bajracharya, S.R., Shrestha, B., 2011. The Status of Glaciers in the Hindu-Kush Himalayan Region. ICIMOD, Kathmandu, p. 125. ⟨https://lib.icimod.org/record/9419⟩. accessed on 7 December 2022.

Bharati, L., Gurung, P., Maharjan, L., Bhattarai, U., 2016. Past and future variability in the hydrological regime of the Koshi Basin, Nepal. Hydrol. Sci. J. 61 (1), 79–93. https://doi.org/10.1080/02626667.2014.952639.
Bharati, L., Gurung, P., Jayakody, P., Smakhtin, V., Bhattarai, U., 2014. The projected impact of climate change on water availability and development in the Koshi. Mt. Res. Dev. 34 (2), 118–130.
Bharati, L., Bhattarai, U., Khadka, A., Gurung, P., Neumann, L.E., Penton, D.J., … Nepal, S., 2019. From the mountains to the plains: Impact of climate change on water resources in the Koshi River Basin. IWMI Working Papers (Vol. 187). https://doi.org/10.5337/2019.205.
Bhatt, D., Maskey, S., Babel, M.S., Uhlenbrook, S., Prasad, K.C., 2014. Climate trends and impacts on crop production in the Koshi River basin of Nepal. Reg. Environ. Change 14 (4), 1291–1301. https://doi.org/10.1007/s10113-013-0576-6.
Bhatta, L.D., van Oort, B.E.H., Stork, N.E., Baral, H., 2015. Ecosystem services and livelihoods in a changing climate: understanding local adaptations in the Upper Koshi, Nepal. Int. J. Biodivers. Sci., Ecosyst. Serv. Manag. 11 (2), 145–155. https://doi.org/10.1080/21513732.2015.1027793.
Change, I.C. 2014. Synthesis Report. Contribution of working groups I. II and III to the fifth assessment report of the intergovernmental panel on climate change, 151 (10.1017).
Cui, T., Yang, T., Xu, C.Y., Shao, Q., Wang, X., Li, Z., 2018. Assessment of the impact of climate change on flow regime at multiple temporal scales and potential ecological implications in an alpine river. Stoch. Environ. Res. Risk Assess. 32 (6), 1849–1866. https://doi.org/10.1007/s00477-017-1475-z.
Devkota, L.P., Gyawali, D.R., 2015. Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. J. Hydrol.: Reg. Stud. 4, 502–515.
Dhital, M.R., 2015. Geology of the Nepal Himalaya: regional perspective of the classic collided orogen. Springer. https://link.springer.com/book/10.1007/978–3-319–02496-7.
Dijkshoorn, K., Huting, J., 2009. Soil and Terrain database for Nepal. *ISRIC – World Soil Information*. Wageningen June, 29.
Dixit, A., Upadhya, M., Dixit, K., Pokhrel, A., Rai, D.R., 2009. Living with water stress in the hills of the Koshi Basin, Nepal. In Icimod. http://books.icimod.org/demo/uploads/tmp/icimod-living_with_water_stress_in_the_hills_of_the_koshi_basin,_nepal.pdf. (accessed on 31 July 2021).
Fontaine, T.A., Cruickshank, T.S., Arnold, J.G., Hotchkiss, R.H., 2002. Development of a snowfall-snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT). J. Hydrol. 262 (1–4), 209–223. https://doi.org/10.1016/S0022-1694(02)00029-X.
Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate change will affect the Asian water towers. Sci. (N. Y., N. Y.) 328 (5984), 1382–1385. https://doi.org/10.1126/science.1183188.
Immerzeel, W.W., van Beek, L.P.H., Konz, M., Shrestha, A.B., Bierkens, M.F.P., 2012. Hydrological response to climate change in a glacierized catchment in the Himalayas. Clim. Change 110 (3–4), 721–736. https://doi.org/10.1007/s10584-011-0143-4.
Jeelani, G., Feddema, J.J., Van Der Veen, C.J., Stearns, L., 2012. Role of snow and glacier melt in controlling river hydrology in Liddar watershed (western Himalaya) under current and future climate. Water Resour. Res. 48 (12), 1–16. https://doi.org/10.1029/2011WR011590.
Kaini, S., Nepal, S., Pradhananga, S., Gardner, T., Sharma, A.K., 2019. Representative general circulation models selection and downscaling of climate data for the transboundary Koshi river basin in China and Nepal. Int. J. Climatol. (November 2019), 1–19. https://doi.org/10.1002/joc.6447.
Kaini, S., Nepal, S., Pradhananga, S., Gardner, T., Sharma, A.K., 2021. Impacts of climate change on the flow of the transboundary Koshi River, with implications for local irrigation. Int. J. Water Resour. Dev. 37 (6), 929–954.
Kang, S., Xu, Y., You, Q., Flügel, W.A., Pepin, N., Yao, T., 2010. Review of climate and cryospheric change in the Tibetan Plateau. In: In Environmental Research Letters, Vol. 5. Institute of Physics Publishing,. https://doi.org/10.1088/1748-9326/5/1/015101.
Khadka, A., Devkota, L.P., Kayastha, R.B., 2016. Impact of climate change on the snow hydrology of Koshi River Basin. J. Hydrol. Meteorol. 9 (1), 28–44. https://doi.org/10.3126/jhm.v9i1.15580.
Khadka, D., Babel, M.S., Shrestha, S., Tripathi, N.K., 2014. Climate change impact on glacier and snow melt and runoff in Tamakoshi basin in the Hindu Kush Himalayan (HKH) region. J. Hydrol. 511, 49–60. https://doi.org/10.1016/j.jhydrol.2014.01.005.
Khadka, M., Kayastha, R.B., Kayastha, R., 2020. Future projection of cryospheric and hydrologic regimes in Koshi River basin, Central Himalaya, using coupled glacier dynamics and glacio-hydrological models. J. Glaciol.
Knutti, R., Sedláček, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nat. Clim. Change 3 (4), 369–373. https://doi.org/10.1038/nclimate1716.
Kulkarni, A., Patwardhan, S., Kumar, K.K., Ashok, K., Krishnan, R., 2013. High-resolution regional climate model PRECIS Projected Climate Change in the Hindu Kush – Himalayan Region By Using the High-resolution Regional Climate Model PRECIS. Mt. Res. Dev. 33 (2), 142–151. https://doi.org/10.1659/MRD-JOURNAL-D-12-00027.1.
Kumar, K.K., Patwardhan, S.K., Kulkarni, A., Kamala, K., Koteswara Rao, K., Jones, R., 2011. Simulated projections for summer monsoon climate over India by a high-resolution regional climate model (PRECIS). Curr. Sci. 101 (3), 312–326.
Liu, X., Chen, B., 2000. Climatic warming in the Tibetan Plateau during recent decades. Int. J. Climatol. 20 (14), 1729–1742. https://doi.org/10.1002/1097-0088(20001130)20:14<1729::AID-JOC556>3.0.CO;2-Y.
Lutz, A.F., ter Maat, H.W., Biemans, H., Shrestha, A.B., Wester, P., Immerzeel, W.W., 2016a. Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. Int. J. Climatol. 36 (12), 3988–4005. https://doi.org/10.1002/joc.4608.
Lutz, A.F., Immerzeel, W.W., Biemans, H., Maat, H., Veldore, V., Shrestha, A., 2016b. Selection of Climate Models for Developing Representative Climate Projections for the Hindu Kush Himalayan Region. HI-AWARE Working paper1. HI-AWARE,, Kathmandu. ⟨http://lib.icimod.org/record/31874/files/HI-AWARE-WP1.pdf⟩. accessed on 6 December 2022.
Macchi, M., ICIMOD, 2010. Mountains of the World- Ecosystem Services in a Time of Global and Climate Change. Icimod. (accessed on 18 May 2021).
Mathews, R., Richter, B.D., 2007. Application of the indicators of hydrologic alteration software in environmental flow setting. J. Am. Water Resour. Assoc. 43 (6), 1400–1413. https://doi.org/10.1111/j.1752-1688.2007.00099.x.
Mishra, K., Sinha, R., Jain, V., Nepal, S., Uddin, K., 2019. Towards the assessment of sediment connectivity in a large Himalayan river basin. Sci. Total Environ. 661, 251–265. https://doi.org/10.1016/j.scitotenv.2019.01.118.
MoFE, 2019. MoFE. Climate Change Scenarios for Nepal: National Adaptation Plan, (February), 84. (accessed on 21 June 2021).
Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50 (3), 885–900.
Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool – Theoretical documentation (version 2009). Laboratory, Agricultural Research Service, Blackland Research Center, Texas Agricultural Experiment Station. Grassland, Soil and Water Research,, Temple, Texas accessed on 20 January 2021.
Nie, Y., Pritchard, H.D., Liu, Q., Hennig, T., Wang, W., Wang, X., Chen, X., 2021. Glacial change and hydrological implications in the Himalaya and Karakoram. Nat. Rev. Earth Environ. https://doi.org/10.1038/s43017-020-00124-w.
NOAA National Centers for Environmental Information, State of the Climate: Global Climate Report for March 2021, published online April 2021, accessed on April 24, 2021 from https://www.ncdc.noaa.gov/sotc/global/202103.
Pandey, V.P., Dhaubanjar, S., Bharati, L., Thapa, B.R., 2019. Hydrological response of Chamelia watershed in Mahakali Basin to climate change. Sci. Total Environ. 650, 365–383. https://doi.org/10.1016/j.scitotenv.2018.09.053.
Pandey, V.P., Dhaubanjar, S., Bharati, L., Thapa, B.R., 2020a. Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: Climate change impact assessment (Part-B. J. Hydrol.: Reg. Stud. 29 (April), 100691 https://doi.org/10.1016/j.ejrh.2020.100691.
Pandey, V.P., Dhaubanjar, S., Bharati, L., Thapa, B.R., 2020b. Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: Hydrological model development using multi-site calibration approach (Part-A. J. Hydrol.: Reg. Stud. 29, 100690 https://doi.org/10.1016/j.ejrh.2020.100690.
Perry, L.B., Matthews, T., Guy, H., Seimon, A., Gajurel, A., Mayewski, P.A., 2020. Article precipitation characteristics and moisture source regions on Mt. Everest in the Khumbu, Nepal Precipitation Characteristics and Moisture Source Regions on Mt. Everest in the Khumbu, Nepal. One Earth 3 (5), 594–607. https://doi.org/10.1016/j.oneear.2020.10.011.

Picchio, V., Cammisotto, V., Pagano, F., Carnevale, R., Chimenti, I., 2020. We are IntechOpen, the world ' s leading publisher of Open Access books Built by scientists, for scientists TOP 1%. *Intechopen*, (Cell Interact. -Regul. Immune Responses, Dis. Dev. Manag. Strateg.) 1–15.

Rajbhandari, R., Shrestha, A.B., Nepal, S., Wahid, S., 2016. Projection of future climate over the Koshi River basin based on CMIP5 GCMs. Atmos. Clim. Sci. 06 (02), 190–204. https://doi.org/10.4236/acs.2016.62017.

Rajbhandari, R., Shrestha, A.B., Nepal, S., Wahid, S., Ren, G.Y., 2017. Extreme climate projections over the transboundary Koshi River Basin using a high resolution regional climate model. Adv. Clim. Change Res. 8 (3), 199–211. https://doi.org/10.1016/j.accre.2017.08.006.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10 (4), 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x.

Sharma, E., Molden, D., Rahman, A., Khatiwada, Y.R., Zhang, L., Singh, S.P., Wester, P., 2019. Introduction to the Hindu kush himalaya assessment. In: *The Hindu Kush Himalaya Assessment*. Springer, Cham, pp. 1–16. https://doi.org/10.1007/978-3-319-92288-1.

Shrestha, A.B., Bajracharya, S.R., Sharma, A.R., Duo, C., Kulkarni, A., 2017. Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin 1975–2010. Int. J. Climatol. 37 (2), 1066–1083. https://doi.org/10.1002/joc.4761.

Shrestha, S., Shrestha, M., Babel, M.S., 2016. Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. Environ. Earth Sci. 75 (4) https://doi.org/10.1007/s12665-015-5150-8.

Shrestha, S., Yao, T., Kattel, D.B., Devkota, L.P., 2019. Precipitation characteristics of two complex mountain river basins on the southern slopes of the central Himalayas. Theor. Appl. Climatol. 138 (1–2), 1159–1178. https://doi.org/10.1007/s00704-019-02897-7.

Sinha, R., Gupta, A., Mishra, K., Tripathi, S., Nepal, S., Wahid, S.M., Swarnkar, S., 2019. Basin-scale hydrology and sediment dynamics of the Kosi river in the Himalayan foreland. Journal of Hydrology 570, 156–166. https://doi.org/10.1016/j.jhydrol.2018.12.051.

Srinivasan, R., Arnold, J.G., 1994. Integration of a basin-scale water quality model with GIS. 1. JAWRA *J. Am. Water Resour. Assoc.* 30 (3), 453–462. https://doi.org/10.1111/j.1752-1688.1994.tb03304.x.

Stagl, J.C., Hattermann, F.F., 2016. Impacts of climate change on riverine ecosystems: alterations of ecologically relevant flow dynamics in the Danube River and its major tributaries. Water 8 (12). https://doi.org/10.3390/w8120566.

The Nature Conservancy, 2009. Indicators of Hydrologic Alteration Version 7.1 User's Manual. The Nature Conservancy. https://www.conservationgateway.org/Files/Pages/indicators-hydrologic-altaspx47.aspx (accessed on 21 July 2021).

Trzaska, S., Schnarr, E., 2014. *A Review of Downscaling Methods for Climate Change Projections.* Washington. DC: U. S. Agency Int. Dev. Tetra Tech. ARD 1–42 accessed on 20 January 2022.

Uddin, K., Wahid, S.M., Murthy, M.S.R., 2015. Mapping of Koshi Basin Wetlands Using Remote Sensing. 5th International Conference on Water & Flood Management (ICWFM-2015), (July), 461–468.

Viviroli, D., Dürr, H.H., Messerli, B., Meybeck, M., Weingartner, R., 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resour. Res. 43 (7) https://doi.org/10.1029/2006WR005653.

Wahid, S.M., Kilroy, G., Shrestha, A.B., Bajracharya, S.R., Hunzai, K., 2017. River system analysis and management. (Nayan Sharma, Ed.), *Opportunities and Challenges in the Transboundary Koshi River Basin*. Springer,, Singapore. https://doi.org/10.1007/978-981-10-1472-7_18.

Wijngaard, R.R., Arthur, F.L., Nepal, S., Khanal, S., Saurav, P., Shrestha, A.B., Immerzeel, W.W., 2017. Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins. J. Auton. Nerv. Syst. https://doi.org/10.1016/0165-1838(91)90005-N.

Wijngaard, R.R., Biemans, H., Friedrich, Lutz, A., Shrestha, A.B., Wester, P., Willem Immerzeel, W., 2018. Climate change vs. socio-economic development: understanding the future South Asian water gap. Hydrol. Earth Syst. Sci. 22 (12), 6297–6321. https://doi.org/10.5194/hess-22-6297-2018.

Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2013. ArcSWAT Interface For SWAT2012: User's Guide. Texas Agricultural Experiment Station and United States Department of Agriculture, Temple, TX., 464.

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., Chen, Y., 2014. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. Glob. Planet. Change 112, 79–91. https://doi.org/10.1016/j.gloplacha.2013.12.001.

Yao, T., Xue, Y., Chen, D., Chen, F., Thompson, L., Cui, P., Li, Q., 2019. Recent third pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: multidisciplinary approach with observations, modeling, and analysis. Bull. Am. Meteorol. Soc. 100 (3), 423–444. https://doi.org/10.1175/BAMS-D-17-0057.1.

Zhan, Y.J., Ren, G.Y., Shrestha, A.B., Rajbhandari, R., Ren, Y.Y., Sanjay, J., Wang, S., 2017. Changes in extreme precipitation events over the Hindu Kush Himalayan region during 1961–2012. Adv. Clim. Change Res. 8 (3), 166–175. https://doi.org/10.1016/j.accre.2017.08.002.