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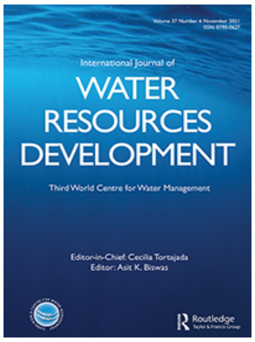

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Impacts of climate change on the flow of the transboundary Koshi River, with implications for local irrigation

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ABSTRACT

This study assesses climate change impacts on the hydrological regime of a river basin and its implications for future irrigation water availability in the Koshi River basin using RCPs 4.5 and 8.5 over short-term (2016-2045), mid-century (2036-2065) and end-of-century (2071-2100) periods. Average flow in the Koshi River is projected to increase. Projections of average minimum monthly river flow suggest that the areas of winter wheat and monsoon paddy rice could be increased. However, the planting period of paddy rice should be delayed by one month (July to August) to capture the expected increased water availability in the river.

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Climate change; hydrological modelling; SWAT; RCP scenarios; irrigation; Koshi River basin

Introduction

Irrigation is a key driver for expansion of crop area coverage and an important input for increased agriculture production per hectare. The irrigation sector plays a crucial role in agricultural food production system, and utilizes about 70% of total annual water consumption in the world (FAO, 2016; Fischer et al., 2007; Moreno-Pérez & Roldán-Cañas, 2013; Schultz et al., 2009). Climate variability has an important influence on water availability for agriculture, which in turn affects global food security (Alcamo et al., 2007). Studies have shown that climate change will reduce crop yields in South Asia if appropriate adaptation measures are not implemented (Gupta et al., 2017; Tesfaye et al., 2017). Adaptation measures for irrigated agriculture production systems are almost impossible to plan without assessing the likely availability of water, especially in river systems supplying water to the gravity irrigation schemes common in developing countries.

Climate-driven changes in precipitation and temperature patterns are expected to affect the water availability in the Himalayan region (Hock et al., 2019) and the hydrological regime of associated upstream basins (Immerzeel et al., 2012; Lutz et al., 2014; Nepal, 2016). Average annual river flows in the Bagmati, Kaligandaki, Karnali and Mahakali River basins in Nepal Himalaya are projected to increase with climate change (Bajracharya et al., 2018; V. Dahal et al., 2016; P. Dahal et al., 2020; Pandey et al., 2019, 2020). Climate

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change effects on the hydrological regime of river basins will directly affect irrigation water availability and irrigation crop area coverage in the region (Elliott et al., 2014; Malek et al., 2018). Climate change is anticipated to have profound implications for downstream water availability and dependent sectors in the Himalayan region (Eriksson et al., 2009; Hock et al., 2019; Nepal et al., 2014), and it is of great concern to global scientific communities as well. Thus, studies on climate change impacts on the hydrological regime of the Himalayan rivers are important.

High-resolution climate data increase the accuracy of hydrological predictions and hence allow better projection of water availability in a catchment. Without high-resolution climate input data, the direct use of general circulation models (GCMs) outputs at a catchment level are of limited use for hydrological prognostication because of their coarse spatial resolution (Willems & Vrac, 2011). GCM outputs typically have a spatial resolution of 100–250 km, and temporal resolution of daily or monthly. Hence GCM outputs do not capture local spatial scales (Trzaska & Schnarr, 2014). However, they can be downscaled to a finer resolution to generate climate data that represent local and regional climatic and topographic conditions.

Previous studies which focused on climate change impacts on the hydrology of the Koshi River basin were based on low-resolution spatial data (e.g. 50 km × 50 km) and lacked high-resolution precipitation and temperature data. For example, Bharati et al. (2014) projected water availability in the Koshi River basin for the 2030s and the 2050s. They used weather data at a spatial resolution of 0.5° × 0.5° (~50 km × 50 km) and used the A2 and B1 climate scenarios from the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC-SRES). The study divided the entire Koshi basin down to Chatara into about 80 sub-basins. In a similar study, Devkota and Gyawali (2015) assessed climate change impacts on water availability in the Koshi River basin using 25 km × 25 km spatial resolution data considering the IPCC-SRES A1B scenario and dividing the Koshi basin into about 20 sub-basins. Nepal (2016) projected the water availability of the Dudh Koshi River basin (about 3710 km^2), a sub-basin of the Koshi River basin, considering the IPCC-SRES A1B scenario, using dynamically downscaled precipitation and temperature data with a spatial resolution of 50 km × 50 km. Likewise, Bhatta et al. (2019) assessed climate change impacts on water availability in the Tamor River basin (about 4380 km^2), also a sub-basin of the Koshi River basin, using 50 km × 50 km spatial resolution data and RCPs 4.5 and 8.5. Bharati et al. (2019) investigated water availability in the Koshi River basin (about 87,300 km^2) using weather data at a spatial resolution of 25 km × 25 km and RCPs 4.5 and 8.5.

Bharati et al. (2014) and Bharati et al. (2016) projected no significant change in average annual flow in the Koshi River, although seasonal changes in runoff were significant in the 2030s and 2050s. Devkota and Gyawali (2015) reported that climate change would not pose a major threat to average water availability in the Koshi River basin, although temporal flow variations are likely to increase in the coming decades. Nepal (2016) projected an increase in annual discharge in the Dudh Koshi River basin by 2045 and a slight decrease thereafter. Bharati et al. (2019) also projected an increase in annual discharge in 2045. They reported that seasonal variation in contribution to annual flow volume would remain unchanged. All these studies were based on coarse-resolution climate data ranging from 25 km × 25 km to 50 km × 50 km; this study uses hydrological simulations with 10 km × 10 km spatial resolution.

Seasonal variations in river flow can significantly affect water availability for irrigation schemes with no impoundment infrastructure (e.g. weir or dam). Bhatt et al. (2014) assessed climate trends and their impacts on crop production in the Koshi River basin based on measured precipitation and temperature data. Bastakoti et al. (2016) also evaluated climate trends in the Koshi River basin and their impacts on agricultural systems based on observed climate data and field survey. They reported a decline in irrigation water availability over the last 20 years. These empirical studies were based on historic data, and the concern is whether past behaviour predicts future crop production behaviour.

In this article, we explore the use of high-resolution (10 km × 10 km spatial resolution) downscaled precipitation and temperature data to project likely climate change impacts on the hydrological regime of the transboundary Koshi River basin, and assess the implications of future water availability for agricultural production in the Sunsari Morang irrigation system in particular and on the wider Nepal Terai and Indian irrigation areas. Assessment is carried out using the recent Representative Concentration Pathways (RCPs) 4.5 and 8.5 for short-term (2016–2045), midcentury (2036–2065) and end-of-century (2071–2100) periods. Downscaled precipitation and temperature data from four GCMs/ensembles representing cold/dry, warm/dry, cold/wet and warm/wet climatic extremes for each study period and climate change scenario are used in the Soil and Water Assessment Tool (SWAT) for hydrological modelling. Such analysis will be useful for policy makers for developing adaptation strategies to cope with expected changes in water resources and the planning of water resources projects.

The specific objectives of this article are (a) to develop and apply a generalized methodology to investigate the impacts of climate change on the hydrological regime of the transboundary Koshi River basin, (b) to develop a range of likely future water availability scenarios for the Koshi River basin based on high-resolution downscaled daily precipitation and temperature data (10 km × 10 km spatial resolution) with recent climate scenarios (RCP4.5 and RCP8.5), and (c) to assess the implications of future water availability on agriculture production in the Sunsari Morang irrigation systems and the wider irrigation areas of the Koshi River system in Nepal Terai and India.

This article initially focuses on the methodology for investigating climate change impacts on the hydrological regime of a river basin and thus on irrigation water availability. Then it focuses on the application of the methodology with SWAT model setup and its calibration and validation for case study area. The validated SWAT model is forced with climate projection data to produce hydrological projections for the Koshi River basin. Finally, based on the SWAT simulations for future periods, the hydrological flow regimes of the Koshi River basin are used to assess the likely implications of projected water availability scenarios for irrigation schemes in the region.

Methodology: climate change impacts on river flows and irrigation area coverage

A generalized methodology for investigating climate change impacts on the hydrological regime of a river basin and its impact on irrigation area coverage is shown in Figure 1.

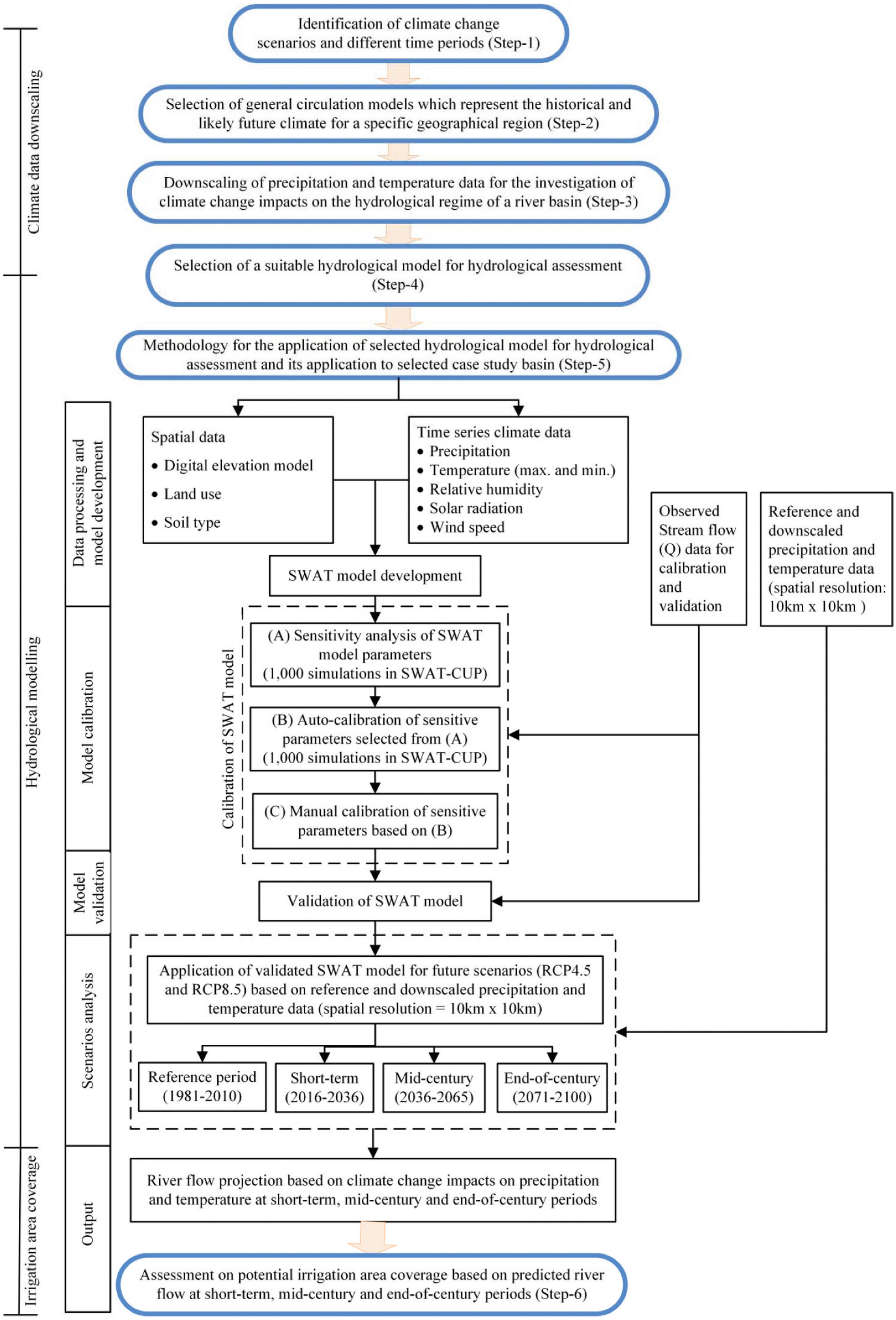

Figure 1. Methodology for investigating climate change impacts on the hydrological regime of a river basin and thus on potential irrigation area coverage.

It has the following steps:

1. Identification of climate change scenarios and time periods for assessment.
2. Selection of GCMs representing historical and possible future climate for a specific geographical region.
3. Downscaling of precipitation and temperature data for the investigation of climate change impacts on the hydrological regime of a river basin.
4. Selection of a suitable hydrological model for hydrological assessment.
5. Application of the selected hydrological model to the selected basin.
6. Assessment of potential irrigation area coverage based on projected river flow.

In Step 1, climate change scenarios and study periods are identified. In this study, RCP4.5 and RCP8.5 climate scenarios for short-term (2016–2045), midcentury (2036–2065) and end-of-century (2071–2100) periods are considered. In Step 2, representative GCMs are selected for the study area for each climate change scenario and period. In Step 3, precipitation and temperature data based on selected GCMs from Step 2 are downscaled. Steps 1–3 are described in detail in Kaini et al. (2020b) with application to the Koshi River basin in China and Nepal. The downscaled precipitation and temperature data are applied to the hydrological assessment in this study. Steps 4–6 are described in this article, including application to the Koshi River basin in the Himalayan region.

Selection of hydrological model for hydrological assessment (Step 4)

Physically based distributed hydrological models with input parameters which have physical understanding, as well as explicit representation of spatial variability, have been used to understand the impacts of climate change on water resources (Cao et al., 2006). Physically based hydrological models are derived from conventional physical principles, and imply consistency with observations (Beven, 2002). Distributed hydrological models attempt to address spatial distribution of landscape, soil characteristics, land use, temperature, rainfall and evapotranspiration in the watershed. Physically based models are mathematically idealized representations of the real phenomena (Devi et al., 2015) and simulate runoff at selected points within the catchment. They are advanced models compared to alternative empirical and conceptual models.

SWAT (Arnold et al., 1998), is a physically based distributed model developed by the US Department of Agriculture and is used in this study as it has been shown to be a robust watershed modelling tool capable of evaluating climate change impacts on hydrology in various river systems around the globe (Gassman et al., 2007). The SWAT model is computationally efficient and capable of continuous long-term simulations of the effects of climate change on the hydrological behaviours of a watershed. SWAT can handle spatially and temporally distributed input data for estimating streamflow through various hydrological process (Arnold et al., 1998). Borah and Bera (2003) compared 11 different hydrological models and reported that SWAT is a promising model to assess long-term hydrological changes as well as basin management. An overview of major applications of SWAT worldwide is reported by Gassman et al. (2007). Khoi (2016) compared Hec-HMS and SWAT models to produce streamflow in a catchment and concluded that SWAT is suitable for hydrologic processes with high accuracy. SWAT has been successfully used in various catchments in Nepal: Chamelia (Mahakali), Karnali, Bagmati, Dudh Koshi and Koshi Himalaya (Agarwal et al., 2015; Bharati et al., 2016; Devkota & Gyawali, 2015; Gurung & Bharati, 2012; Manjan & Aggarwal, 2014; Pandey et al., 2019, 2020; Thakuri & Salerno, 2016). Furthermore, if properly calibrated SWAT provides good hydrologic projections (Devi et al., 2015).

Application of selected hydrological model for hydrological assessment (Step 5)

The main processes in SWAT modelling include water balance, surface runoff, snowfall-snowmelt, evapotranspiration and soil water storage. The hydrologic cycle is modelled as

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \quad (1)$$

where SW_t and SW_0 are the final and initial soil water content on day *i* (mm water), respectively; *t* is the time (days); R_{day} is the amount of precipitation on day *i* (mm water); Q_{surf} and Q_{gw} are the amount of surface runoff and base flow on day *i* (mm water), respectively; E_a is the amount of evapotranspiration on day *i* (mm water); and W_{seep} is the amount of deep drainage entering the unsaturated zone from soil profile on day *i* (mm water).

The division of the watershed into sub-basins enables the SWAT model to represent spatial and temporal variation in evapotranspiration for various soils and crop types. The sub-basins are also divided into hydrologic response units (HRUs) which define the spatial heterogeneity within a sub-basin in terms of land cover, soil type and slope class (Setegn et al., 2008). Runoff is estimated separately for each HRU, and they are summed to estimate the total runoff for the catchment. This way of estimating total runoff increases accuracy and describes the physical processes of water balance in the catchment (Neitsch et al., 2011). The details of water balance, surface runoff, snowfall-snowmelt, evapotranspiration and soil water components, and relationships among these components, can be found in Neitsch et al. (2011).

Methodological approach for SWAT modelling

The main steps in the SWAT hydrological modelling (Figure 1) include input data processing and model development/set-up, sensitivity analysis and calibration, validation, and scenario analysis and future hydrology. These steps are described in the following sections.

SWAT input data processing and model development

SWAT input data include spatial data and time-series data. The spatial data are digital elevation model, land use and soil type. The time series data are daily precipitation, temperature (minimum and maximum), relative humidity, solar radiation and wind speed. The SWAT model is developed with the spatial and time series data for the reference (base) period. A subset of the measured discharge flow data is used for calibration, and an independent subset is used for validation.

Sensitivity analysis and model calibration

Physically based distributed hydrological models lack adequate data to completely represent spatial variability and have scale problems of field measurement integration and model parameter estimation. Thus model use requires both a calibration and a validation step (Cao et al., 2006). The SWAT Calibration and Uncertainty Program (SWAT-CUP), with the Sequential Uncertainty Fitting, version 2 (SUFI2) optimization algorithm, was used in this study for sensitivity analysis and calibration. In SWAT-CUP, a *t*-test is used to assess the relative weight of each model parameter. Multiple regression analysis is applied to obtain statistics on model parameter sensitivity. The *t*-stat and *p*-value are used to measure model parameter sensitivity. The *t*-stat estimated the precision with which the regression coefficient is measured, using the coefficient of any given model parameter divided by its standard error. The model parameter is sensitive when the coefficient is large compared to its standard error. The *p*-value is used to test the null hypothesis that the coefficient is zero (i.e. it has no effect). A low *p*-value (less than 0.05) represents the rejection of null hypothesis, indicating that the coefficient makes a meaningful contribution to the model. A coefficient with a low *p*-value is most likely to be a sensitive model parameter, as changes in the predictor's value are linked to changes in the responsible variable. In contrast, a large *p*-value indicates that changes in the predictor's value are not correlated with changes in the responsible variable, so the corresponding model parameter is not very sensitive. The null hypothesis can be rejected when a *p*-value is less than 0.05 (Abbaspour, 2015).

After the SWAT model setup (described in the section on SWAT input data processing and model development), sensitivity analysis is conducted to identify the sensitive SWAT parameters. The sensitive SWAT parameters are then used to calibrate the model with measured river discharge flow data.

Model performance evaluation

Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and coefficient of determination (R^2) are performance indicators commonly used to evaluate hydrological models (Bharati et al., 2019; Bouraoui et al., 2005; Cao et al., 2006; Neupane et al., 2014; Yan et al., 2013). Kling-Gupta efficiency (Kling et al., 2012; Gupta et al., 2009) has also been used in recent studies.

Model validation

The calibrated SWAT model is used for validation testing, with an independent discharge flow data set different from the data set used in calibration.

Scenario analysis (future hydrological analysis)

The validated SWAT model is used to project hydrological changes using the downscaled precipitation and temperature data for different future periods and climate scenarios.

Assessment of potential irrigation area coverage based on projected river flow (Step 6)

Based on projected future river flow rates and irrigation water requirements for different crops, the potential irrigation areas are estimated for the main crops in different seasons.

These estimates are based on the projected minimum water availability for any given month for a given crop (e.g. wheat, paddy rice). The potential irrigation area for a crop varies on a monthly basis, mainly due to variation in irrigation water demand as well as water availability at the canal intake point for supply from the river. The minimum area that can be irrigated throughout the cropping period should be taken as the potential irrigation area for the crop. The changes in irrigated crop area are estimated based on the average irrigation water availability from the main canal given the projected changes in minimum average monthly flow at the intake point of the river source. This will help us understand the variability of potential irrigation areas due to changes in hydrological regime.

Application of methodology for SWAT hydrological modelling

The application of the methodological framework described in Figure 1 is discussed in the following sections.

Study area

The Koshi River basin is one of the major river systems of the Ganges River basin and the largest river system in Nepal. Around 22% of Nepal's population of around 27 million live in the Koshi River basin (Dixit et al., 2009). The catchment area of the Koshi River basin, down the valley to Chatara in Nepal (Figure 2), is around 54,000 km^2 (28,000 km^2 and

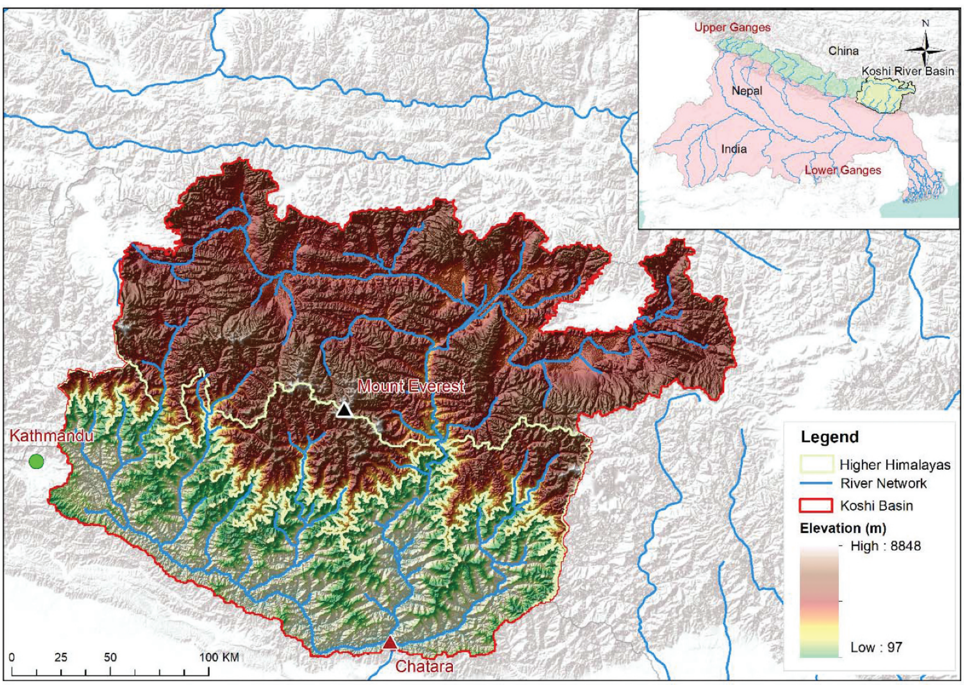

Figure 2. Catchment area of the Koshi River basin, down the valley to Chatara in Nepal (inset shows location of Koshi basin in the larger Ganges catchment).

26,000 km^2 in China and Nepal, respectively). The elevation of the China part varies from 1018 m to over 8800 m above mean sea level. As seen in Figure 2, the uppermost part of the Koshi basin is in China and the Higher Himalaya and the downstream basin parts are in Nepal. In Nepal, the catchment area of the High Himalaya (above 3000 m) is 8300 km^2, and of the Lower Himalaya (below 3000 m), 17,700 km^2 (Figure 2). The elevation of the Koshi River basin in Nepal varies from 97 m in the southern part to 8848 m in the northern part. The low-elevation plains in the southern part are also called the Terai.

There is wide spatial and temporal variation in rainfall, with 70–80% of the total occurring in June to September, the monsoon season (Dixit et al., 2009; Water and Energy Commission Secretariat, 2005). Average annual precipitation varies from 900 mm to 4500 mm among the weather stations. Increasing magnitude and duration of droughts in the dry season (December to May), and floods in the monsoon season, are the main climate trends in the Koshi basin (NCVST, 2009). The large annual and seasonal variation in rainfall results in annual and seasonal variation in river flow. The case study area is the same as was used for downscaling of climate data in Kaini et al. (2020b).

SWAT input data processing and model development

The SWAT model requires input data on topography (based on a digital elevation model), land use, soil type, slope, precipitation, and potential evapotranspiration (driven by temperature, relative humidity, solar radiation and wind speed). The SWAT model was populated with spatial data as well as time series data for the calibration period. SWAT version 2012.10.21, which is included in the ArcSWAT extension of ArcGIS, was used for this study.

Digital elevation model

The Shuttle Radar Topography Mission's 90 m × 90 m resolution digital elevation model for the transboundary Koshi River basin was used to represent the topography of the basin (http://srtm.csi.cgiar.org). The maximum and minimum elevations in the catchment are 8848 m and 97 m, respectively (Figure 2). The digital elevation model was then used to generate the stream network and delineate the watershed using ArcSWAT. The 54,000 km^2 Koshi basin was divided into 294 sub-basins.

Land use

The land use and land cover map for the Koshi River basin was obtained from the International Centre for Integrated Mountain Development (http://geoportal.icimod.org/) to represent the different land use practices in the Koshi River basin. The spatial resolution of the processed land use map is 90 m × 90 m; 23 different land-use practices have been processed in the model. Grassland is the dominant land use in the Koshi River basin, covering around 26,000 km^2, which is almost 50% of the catchment. Around 12% of the catchment is covered by snow and glaciers. Other land uses include open forest, closed forest, rock outcrop and agricultural cropland.

Soil

The soil map for the Koshi River basin was downloaded from the SOTER (soil and terrain) database (https://www.isric.org) to represent the different soil types of the Koshi River basin. The spatial resolution of the processed soil map is 90 m × 90 m, and 12 major soil types were processed in the model. Gelic leptosols (shallow stony soils in high-altitude mountainous terrain) are the dominant soil type in the Koshi River basin, covering almost 22,000 km^2, or around 40% of the catchment. Eutric cambisols (soils with little profile differentiation and base saturation over 50%) cover around 13% of the catchment, and snow and glaciers cover around 12%. Other dominant soil types include chromic cambisols (red soils with little profile differentiation), eutric leptosols (shallow stony soils with base saturation over 50%), humic cambisols (soils with little profile differentiation and organic carbon over 1% up to 50 cm deep), and eutric regosols (deep soils with little profile differentiation and base saturation over 50%, over unconsolidated fine-grained material).

Slope classification

A maximum of five slope categories can be defined in SWAT. The categories were chosen as 0–17%, 17–32%, 32–46%, 46–64% and over 64%, so that the areas covered are almost equal, or around 20% (10,800 km^2) of the total catchment area. This ensures equal representation of all slope categories in the catchment. The spatial resolution of the processed slope map is 90 m × 90 m.

The HRUs were defined using 20% thresholds for land use, soil class and slope class, giving 1870 HRUs. That is, the 294 sub-basins are further divided into 1870 HRUs for high-resolution assessment.

Precipitation

Precipitation data for the Nepalese part of the basin were obtained from the Department of Hydrology and Meteorology (DHM) of Nepal. Asian Precipitation Highly Resolved Observational Data Integration towards Evaluation (APHRODITE) data (downloaded from http://aphrodite.st.hirosaki-u.ac.jp/) were used for the precipitation in Tibet. The spatial resolution of the APHRODITE data was 50 km × 50 km. Eighty-one precipitation data sources (59 DHM stations and 22 APHRODITE grids) were used. The precipitation stations are shown as pink circles in Figure A1 in the supplemental online data.

Temperature

Temperature data for the Nepalese part were obtained from the DHM of Nepal. Data from the European Centre for Medium-Range Weather Forecast Re-analysis (ERA) were used for the temperature for Tibet part (downloaded from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). The spatial resolution of ERA5 data was 25 km × 25 km. Sixty-eight temperature data sources (16 DHM stations and 52 ERA5 grids) were used. The temperature stations are shown as red dots in Figure A1 in the supplemental online data.

Relative humidity, solar radiation, and wind speed

Relative humidity, solar radiation, and wind speed data for the Nepalese part were obtained from the DHM of Nepal. As the main purpose of this study is to assess the climate change impacts on hydrological regime of the Koshi River, only those DHM stations with data for relative humidity, solar radiation, and wind speed were used.

Twelve relative humidity stations, five solar radiation stations and seven wind speed stations were used.

Sensitivity analysis, calibration and validation of the SWAT model

Observed discharge flow data in the Koshi River basin at Chatara for 1996–2000 were used to calibrate the SWAT model. Initially 22 SWAT parameters were selected (Table 1), based on the literature (Bharati et al., 2019, 2014; Devkota & Gyawali, 2015). The sensitivity analysis of these parameters was carried out for 1000 simulations; the results are shown in Figure A2 in the supplemental online data.

Of the 22 SWAT parameters, seven were found to be the most sensitive: baseflow alpha factor (ALPHA_BF.gw), initial curve number (CN2.mgt), lateral flow travel time (LAT_TTIME.hru), effective hydraulic conductivity in the main channel alluvium (CH_K2.rte), temperature lapse rate (TLAPS.sub), groundwater delay time (GW_DELAY.gw) and soil evaporation compensation factor (ESCO.hru). A second iteration was carried out with 1000 simulations for these parameters. As mentioned in the section on sensitivity analysis and model calibration, a coefficient with a high absolute *t*-stat value and low *p*-value is likely to be a sensitive model parameter. After auto-calibration, manual calibration was carried out to fine-tune the parameter values for the 1996–2000 calibration period (Table 2). The daily observed and simulated flows for the calibration and validation periods are shown in Figure 3.

SWAT model performance evaluation

The measured river flow discharge data for the Koshi River basin at Chatara were used to evaluate the SWAT model performance. NSE, PBIAS, R^2 and Kling-Gupta efficiency were used to evaluate the precision/accuracy of the stream flow projections (Table 3). The NSE,

Table 1. 22 SWAT parameters selected for sensitivity analysis.

Parameters	Description
SMTMP.bsn	Snow melt base temperature (°C)
SMFMN.bsn	Melt factor for snow on 21 December (mm H_2O/day-°C)
SMFMX.bsn	Melt factor for snow on June 21 (mm H_2O/day-°C)
SURLAG.bsn	Surface runoff lag coefficient
TIMP.bsn	Snow pack temperature lag factor
SFTMP.bsn	Snowfall temperature (°C)
PLAPS.sub	Precipitation lapse rate (mm H_2O/km)
TLAPS.sub	Temperature lapse rate (°C/km)
ALPHA_BF.gw	Baseflow alpha factor (1/days)
GW_REVAP.gw	Groundwater revap coefficient
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)
RCHRG_DP.gw	Deep aquifer percolation fraction
GW_DELAY.gw	Delay time for aquifer recharge (days)
SOL_K(.).sol	Saturated hydraulic conductivity (mm/h)
SOL_Z(.).sol	Depth from soil surface to bottom of layer (mm)
SOL_AWC(.).sol	Available water capacity of the soil layer (mm H_2O/mm soil)
CH_N2.rte	Manning's *n* for the main channel
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/h)
CANMX.hru	Maximum canopy storage (mm H_2O)
ESCO.hru	Soil evaporation compensation factor
LAT_TTIME.hru	Lateral flow travel time (days)
CN2.mgt	Initial SCS runoff curve number for moisture condition II

Table 2. Calibrated values for the seven SWAT parameters that were identified as highly sensitive to model predictions.

Sensitivity analysis rank	Parameter	Calibrated value
1	ALPHA_BF.gw	0.097
2	CN2.mgt	97.976
3	LAT_TTIME.hru	12.225
4	CH_K2.rte	119.8975
5	TLAPS.sub	−6.059
6	GW_DELAY.gw	168.985
7	ESCO.hru	0.2885

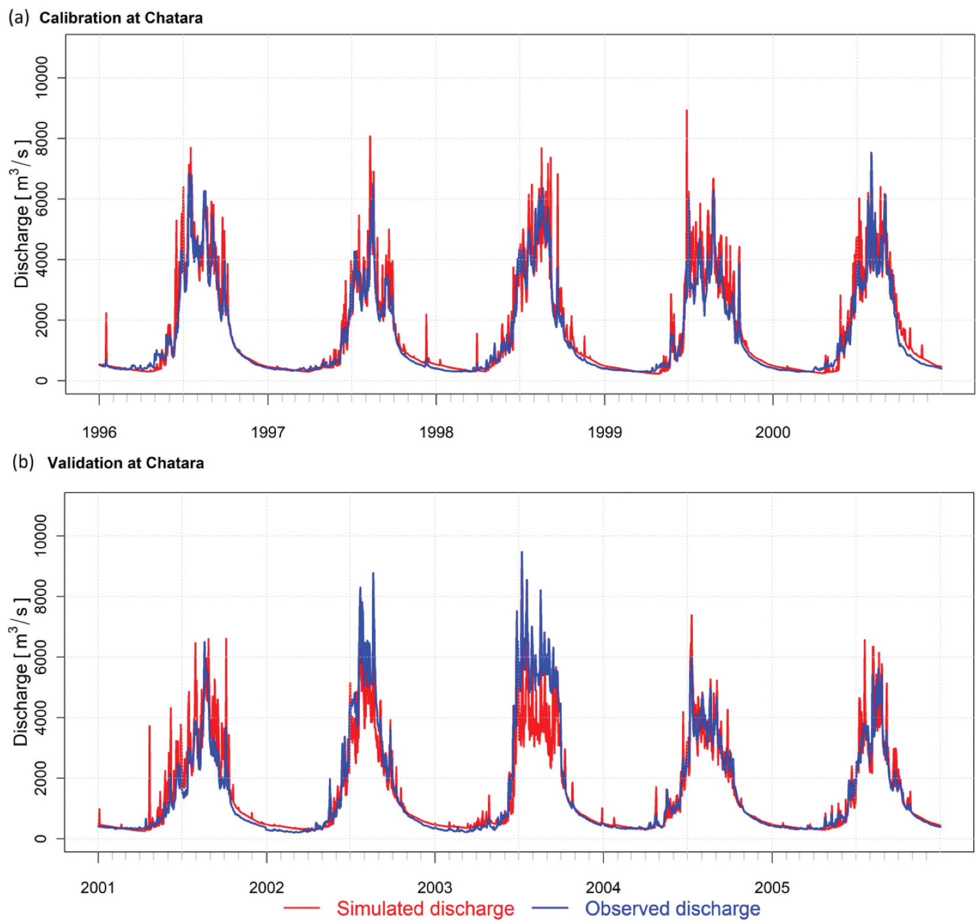

Figure 3. Comparison of measured and simulated daily flows of the Koshi River at Chatara for the calibration period (1996–2000) and the validation period (2001–2006).

PBIAS, R^2 and KGE for calibration period are 0.87, −9.46, 0.95 and 0.75 respectively. A model is considered to fit the data well when NSE > 0.65 and PBIAS < 10% (Moriasi et al., 2007). The ideal value of KGE is unity (Gupta et al., 2009). Clearly the calibrated SWAT model achieved this standard, which is supported qualitatively in Figure 3(a), where most of the observed and simulated flows match well with the measured data.

Table 3. Metrics to assess the predictive performance of the SWAT model during the calibration and validation periods.

Model performance index	Calibration	Validation
NSE	0.87	0.86
PBIAS	−9.46	−2.73
R^2	0.95	0.93
KGE	0.75	0.65
Performance	Very good	Very good

Model validation

Using the calibrated parameters, the SWAT model was then run on an independent data set for the 2001–2005 period. The observed and simulated daily flows are shown in Figure 3(b). The NSE, PBIAS, R^2 and KGE for the validation period are 0.86, −2.73, 0.93 and 0.65 respectively, which is considered very good performance. Moreover, most of the observed and simulated flows visually match very well. Thus, the calibrated model could be used to assess the impact of climate change on river flow and irrigation water availability for dry-season crops.

Scenario analysis (future hydrological analysis)

The validated SWAT model was used with downscaled precipitation and temperature data to calculate future river flow behaviour. Precipitation and temperature data with a spatial resolution of 10 km × 10 km were used for the reference period (1981–2010) which can be downloaded from http://rds.icimod.org/clim. Lutz and Immerzeel (2015) developed a climate data set for the Indus, Ganges and Brahmaputra river basins using watch forcing based on the ERA-interim data set, bias corrected with Global Precipitation Climatology Centre (GPCC) and glacier mass balance data. It was assumed that the climate data represent the regional climatic patterns, as the ERA-interim and GPCC data were also based on observations. Variability can be expected in the subset because of its regional nature. These data sets have been used in various studies (Kaini et al., 2020b; MOFE, 2019; Wijngaard et al., 2017).

The short-term (2016–2045), midcentury (2036–2065) and end-of-century (2071–2100) periods, with downscaled precipitation and temperature data (spatial resolution of 10 km × 10 km) for climate scenarios RCP4.5 and RCP8.5 (Kaini et al., 2020b), were used for the future scenario simulations. Based on the downscaled data, the total number of grid stations for precipitation and temperature was 581 for the whole Koshi basin. They are shown as green diamonds in Figure A1 in the supplemental online data.

The validated SWAT model was run for the reference period (1981–2010) using the reference data set, and the downscaled future (2016–2100) data set for each climatic extreme (Kaini et al., 2020b) for RCP4.5 and RCP8.5. As four GCMs were selected for each RCP for each study period, the SWAT model was run with eight different climate data sets (four for RCP4.5 and four for RCP8.5) for the entire study period.

Hydrological assessment results and discussions

Figure 4 shows the projected mean monthly flow of the Koshi River at Chatara based on the four GCMs/ensembles during the short-term, midcentury and end-of-century periods as well as the reference (base) period. The black line represents the mean monthly river flow for the reference period (1981–2010). The blue and red lines represent the corresponding mean monthly river flow based on ensemble outcome of GCMs selected for RCP4.5 and RCP8.5, respectively. The sky-blue and pink shaded areas represent the standard deviation based on ensemble outcome of GCMs selected for RCP4.5 and RCP8.5 respectively.[1] The purple shaded areas represents the intersection of standard

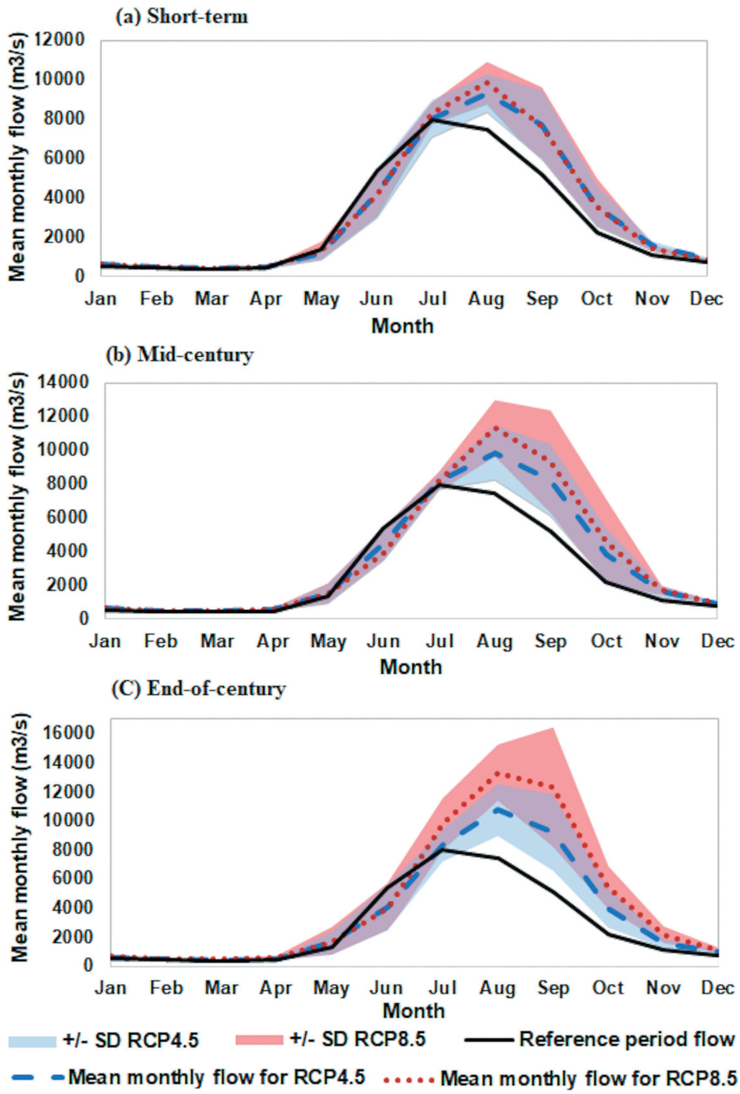

Figure 4. Projected average monthly river flow (ensemble mean) with standard deviation for the Koshi River at Chatara for the short-term, midcentury and end-of-century periods. Projections are relative to the reference data for 1981–2010.

deviation based on ensemble outcome of GCMs selected for RCP4.5 and RCP8.5. The projected mean monthly flow decreases (slightly) in June, but increases in August, September, October and November for all scenarios and for all study periods. The flow under RCP8.5 is larger than the flow under RCP4.5 for all study periods, with the difference widening with time. In the short term (2016–2045), the flows for RCP4.5 and RCP8.5 are 17% and 24% higher, respectively, than in the reference period (1981–2010). In the midcentury period (2036–2065), they are 24% and 42% higher. In the end-of-century period (2071–2100), they are 35% and 67% higher. Clearly an increase in the average monthly flow is expected, with the increased concentrated in August and September.

Future changes in flows

These changes are shown in Table 4. The average annual river flow is projected to increase under all scenarios and in all study periods. Under the RCP4.5 scenario, the average annual flow is expected to increase by 16%, 22% and 28% in the short-term, midcentury and end-of-century periods, respectively. Under the RCP8.5 scenario, it is expected to increase by 18%, 31% and 57% in the short-term, midcentury and end-of-century periods, or nearly twice as much towards the end of the century. The seasonal flows are categorized as winter (December–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–November). The winter flow is expected to increase by 17–23% and 13–39% under RCP4.5 and RCP8.5, respectively. However, the absolute increase is considerably smaller than the projected monsoon and post-monsoon flows. The increase in winter flow could be due to groundwater contribution to the river flow. With the higher rainfall, higher infiltration is predicted, part of which will be translated into deep drainage and hence a greater groundwater contribution. The Koshi basin is a fertile zone for groundwater recharge, as around 47% of the catchment is grassland. Baseflow alpha factor and groundwater delay time are sensitive SWAT parameters for this basin. Baseflow alpha factor is related to baseflow recession, and groundwater delay time is related to the delay between when water leaves the root zone as deep drainage and when it arrives in the shallow aquifer.

The pre-monsoon flow is expected to decrease in the short term, which may be due to reduced precipitation, but likely to increase by 9–11% and 15–21% for the mid-century and end-of-century periods, respectively. The reason that the pre-monsoon flow is projected to decrease is that the precipitation could be in the form of rainfall rather than snowfall in the winter, due to higher temperatures. Therefore, the pre-monsoon river flow due to snowmelt in the reference period would happen less often in future periods. The monsoon flow is expected to increase by 13–15%, 18–26% and 24–52% in the short-term, midcentury and end-of-century periods, respectively. This is consistent with the precipitation increasing by 10–13%, 15–21%, and 20–44% in the short-term, midcentury and end-of-century periods, respectively. In the post-monsoon season, mean river flow is expected to increase by 50–54%, 62–87% and 68–128% in the short-term, midcentury and end-of-century periods respectively. Although the relative increase in flow in the post-monsoon season is greater than other seasons, the absolute increase is generally less than the increase in monsoon flow. The larger increase in the post-monsoon season is due to translation of the peak flow from July to early September. Changes in projected annual and seasonal river flows in the short-

Table 4. Absolute and relative changes in annual and seasonal flows of the Koshi River at Chatara based on average of 4 GCMs/ensembles.

	Short-term				Midcentury				End-of-century			
	RCP4.5		RCP8.5		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Average annual/ seasonal flow	Absolute (m^3/s)	Relative %	Absolute (m^3/s)	Relative %	Absolute (m^3/s)	Relative %	Absolute (m^3/s)	Relative %	Absolute (m^3/s)	Relative %	Absolute (m^3/s)	Relative %
Annual	404	16	452	18	567	22	785	31	720	28	1449	57
Winter	98	17	72	13	113	20	121	21	132	23	223	39
Pre-monsoon	−44	−6	−2	0	79	11	68	9	115	15	154	21
Monsoon	818	13	1001	15	1183	18	1682	26	1585	24	3362	52
Post-monsoon	906	54	828	50	1030	62	1451	87	1139	68	2131	128

Relative values are in % from reference period.

Table 5. Change in average minimum monthly flow relative to the measured river flow discharge (1982–2010).

Study period / climate change scenario flow rates (m^3/s)		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Short term	RCP4.5	88	69	46	−60	−445	−1530	−604	192	723	480	327	147
	RCP8.5	37	31	25	22	297	−344	561	545	236	287	77	42
Midcentury	RCP4.5	71	52	59	224	946	−612	−259	192	457	379	225	112
	RCP8.5	74	65	63	−30	−186	−1530	43	1122	944	333	194	100
End-of-century	RCP4.5	57	34	25	142	1095	−803	−302	641	693	441	189	104
	RCP8.5	122	89	68	0	−686	−1989	86	1507	1239	821	271	181

Change in minimum average monthly flow compared to measured river flow discharge (1982–2010). All values are in m^3/s.

term, midcentury and end-of-century periods are shown in Figure A3 in the supplementary online data.

The percentage change in annual average minimum river flows of the Koshi River at Chatara for the short-term, midcentury and end-of-century periods are shown in Figure A4 in the supplementary online data. Minimum average annual river flow is adopted from the projected annual river flows, minimum of the four GCMs/ensembles, for each climate scenario and study period. Average annual river flows were derived from projected daily river flows for each GCM/ensemble and study period. Under the RCP4.5 scenario, annual average minimum river flow is expected to change by −10 to 24% in 2016–2036, −9 to 30% in 2036–2065, and −14 to 54% in 2071–2100. Under the RCP8.5 scenario, equivalent projections are −19 to 53%, −5 to 60% and −3 to 56%. A similar analysis was carried out for maximum average annual river flow. Under the RCP4.5 scenario, this flow is expected to change by −21 to 77% in 2016–2036, 6 to 87% in 2036–2065, and 4 to 128% in 2071–2100. Under the RCP8.5 scenario, equivalent projections are −1 to 70%, 8 to 116% and 29 to 177%.

Uncertainty (variability) in projected river flows

The projections indicate high uncertainty (variability) in the future flows in the Koshi River. The uncertainty in projected annual and seasonal river flows is shown in Figure A5 in the supplementary online data. Percentage change in flow for each RCP scenario and time period are plotted based on flows derived from four GCMs/ensembles representing the four climatic extremes (cold/dry, warm/dry, cold/wet and warm/wet). Most of the results have increasing uncertainty with time. The relative uncertainty in projected mean annual flow under RCP4.5 is 6–23%, 11–39% and 15–40% for short-term, midcentury and end-of-century, respectively. Under RCP8.5 these numbers are 12–29%, 16–54% and 25–70%. Uncertainty is higher under RCP8.5 than under RCP4.5 in the midcentury and end-of-century periods. All the GCMs/ensembles project higher river flow in the winter and post-monsoon seasons for all scenarios and study periods. They also project higher river flow in the monsoon period for all scenarios and study periods, except for the RCP4.5 scenario in the short term.

Overall, average annual river flow (ensemble mean) is projected to increase in the Himalayan Koshi River basin. Immerzeel et al. (2012) and Lutz et al. (2014) also project that river flow in Himalayan river basins will increase, due to greater precipitation and higher temperatures. Temperature increases have resulted in rapid decline of the glacier area in Nepal (Shrestha & Aryal, 2011), and this is likely to continue, and contribute to greater river flow. Other studies project higher river flows in most of the rivers in Nepal, for example Shrestha et al. (2016), Dahal et al. (2016), Bajracharya et al. (2018), Mishra et al. (2018), Pandey et al. (2019), and Dahal et al. (2020) on the Indrawati, Bagmati, Kaligandaki, Bheri, Chamelia, and Karnali River basins in Nepal. Our results are consistent with other studies finding that water availability in the Koshi River basin will most likely increase (Bharati et al., 2019, 2014; Devkota & Gyawali, 2015; Nepal, 2016). However, those studies were based on low-resolution climate data. This study used high-resolution precipitation and temperature data. Uncertainty in future river flows needs to be taken into account in making decisions on water resources planning, development and management.

Implications of future changes in Koshi basin flows for irrigation water availability and crop area coverage

Impacts on irrigation water availability

Monthly or half-monthly (as opposed to annual or seasonal) water availability is crucial for the design and management of irrigation schemes in developing countries. In many irrigation schemes in developing countries, water diversion mechanisms, from source to irrigation canal, are still operating on gravity flow, without pumping or impoundment. With a command area of 68,000 ha, the Sunsari Morang irrigation scheme is the largest in Nepal. It diverts water from the Koshi River near Chatara. There is no weir, barrage or pumping mechanism for this water diversion; inflow into the main canal depends only on hydraulic head differences. Thus, the water level (flow rate) of the river determines the water supply to the main canal. Although the river water level is high in the wet season, it is lower than desired in the dry period (November to May), limiting irrigation canal discharge and hence the cropping area that can be served in this period. The main crops grown in this period are wheat, pulses, oilseed, maize, sugarcane, potato and vegetables in the winter (November/December to March/April); and spring paddy rice, sugarcane, spring maize, jute and vegetables in the spring (April/May to June/July). Monsoon paddy rice is the dominant crop in the monsoon season.

The percentage changes in minimum and maximum average monthly flows in the Koshi River at Chatara for the three study periods are shown in Figure 5. Both the minimum and maximum flows for August through March are likely to increase. Minimum increase in projected river flow is around 17–26% for RCP4.5 and 11–36% for RCP8.5 in January, 19–26% for RCP4.5 and 9–26% for RCP8.5 in February, and 6–15% for RCP4.5 and 6–16% for RCP8.5 in March. The increase is greater in August, September, October, November and December than in January, February and March. However, the minimum average monthly flow in April, May, June and July is likely to decrease. The projections suggest that crop area (using the existing cropping pattern) could be expanded in the August-to-March cropping period, but might need to be reduced in the spring. Hence, either the crop area needs to be reduced during these months, or the cropping pattern should be changed, or water storage options should be added to overcome the climate-induced changes in the time distribution of water availability.

Water storage mechanisms, either surface or subsurface, can improve community resilience to seasonal water scarcity and help farmers grow crops when water is scarce (Vaidya, 2015). Sound development of infrastructure for water storage is needed immediately to buffer the projected changes in seasonal water availability and to improve access to water for irrigation and other water resources projects in the greater Koshi River basin (Molden et al., 2014). In the Indrawati River basin, a sub-basin of the Koshi River system, some farmers have already initiated surface water storage mechanisms at the local level (Pradhan et al., 2015). Annual renewable groundwater resources in the southern plains, also known as the Terai, of Nepal are 8.8 billion cubic metres, and only about 22% of the available dynamic groundwater recharge is being utilized (Shrestha et al., 2018). Groundwater resources can provide additional socio-economic benefits from agriculture production in the Terai (Nepal et al., 2019). Hence, extraction of underutilized groundwater resources and provision of surface water storage could aid irrigation during the dry season to cope with lower Koshi River flows in the future.

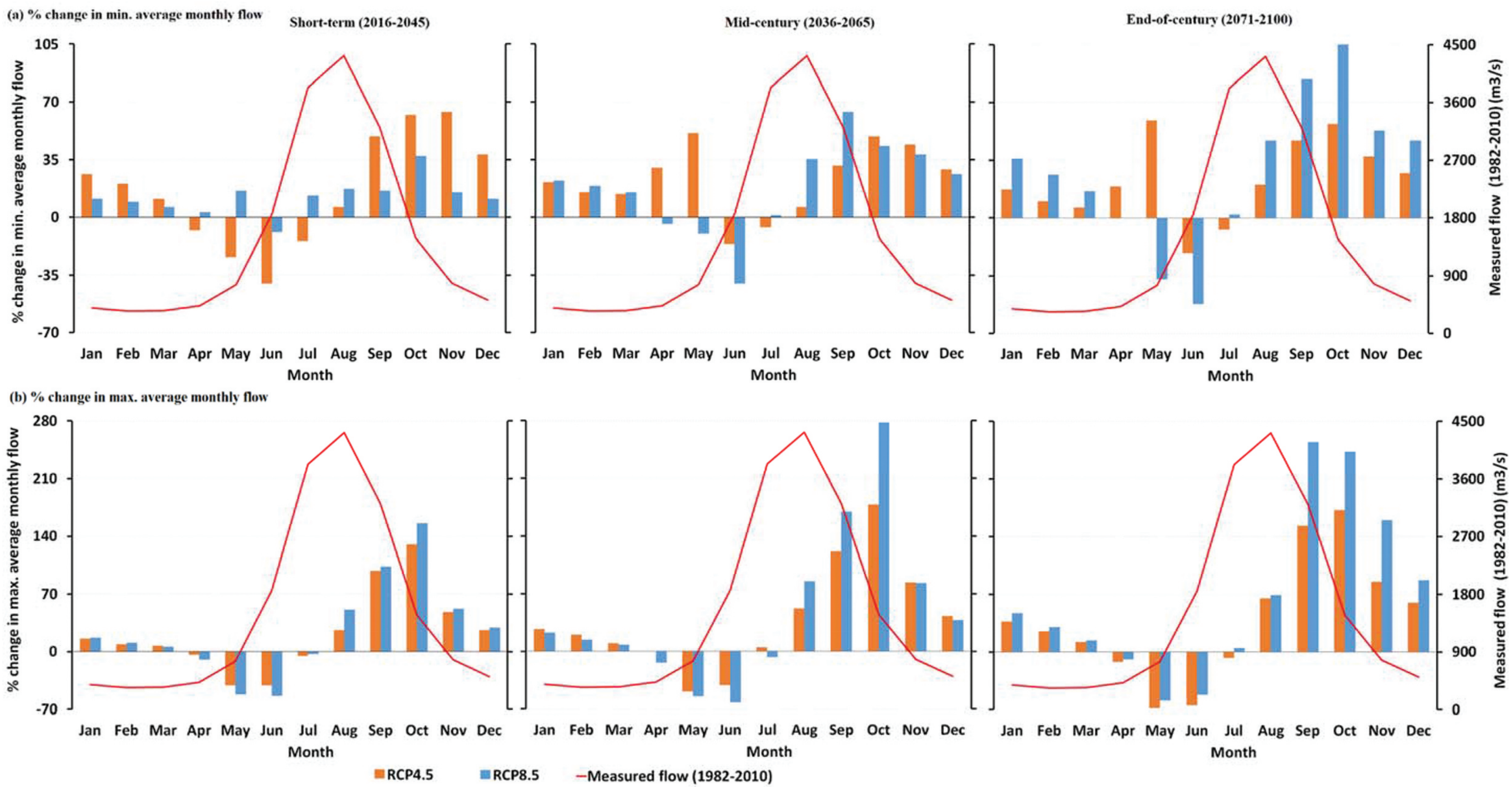

Figure 5. Projected change in average minimum and maximum monthly river flows of the Koshi River at Chatara, relative to the reference data for 1981–2010.

Impacts on potential increase in irrigated crop area coverage

The assessment of the potential increase in crop area coverage for winter wheat and monsoon paddy was based on the existing irrigation water requirement from the main canal (headwork) serving the nearby Sunsari and Morang irrigation area, and the projected increase in minimum average monthly flow in the Koshi River. Data on average irrigation water requirements at the headwork for winter wheat, spring maize, spring paddy and monsoon paddy, based on recent detailed feasibility study reports of 10 irrigation schemes in the Sunsari and Morang Districts, were collected from the provincial government's Irrigation Development Division (Figure A6 in the online supplemental data). Table 5 shows the changes in minimum average monthly flow in the Koshi River compared to the measured river flow (1982–2010). As minimum average monthly flows are expected to increase substantially, except in April, May, June, and July, it appears that only winter wheat and monsoon paddy rice are suitable for expansion, based on the timing of their irrigation needs (Figure A6). The current winter wheat and paddy rice crop areas are around 26,000 ha and 57,000 ha, respectively, and the potential increase in their irrigated crop area is shown in Figure 6. These increases were estimated based on the average irrigation water requirements from the main canal (Figure A6) and the projected increase in minimum average monthly flow in the Koshi River (Table 5).

Under the RCP4.5 climate scenario, winter wheat crop area could be increased by 68,660 ha (260%), 51,740 ha (200%) and 33,830 ha (130%) in the short-term, midcentury and end-of-century periods, respectively, compared to the existing irrigation area. Under the RCP8.5 climate scenario, the numbers are 30,850 ha (120%), 64,680 ha (250%), and 88,560 ha (340%). The peak of irrigation water requirements for winter wheat is the flowering period, which occurs in February (Figure A6), so the increase in crop area is governed by water availability in the Koshi River in February. Monsoon paddy crop area could also be increased, by 300%, 300% and 440% under the RCP4.5 climate scenario, and by 280%, 330% and 810% for the RCP8.5 climate scenario, in the short-term, midcentury and end-of-century periods, respectively (Figure 6). The peak irrigation water needs for

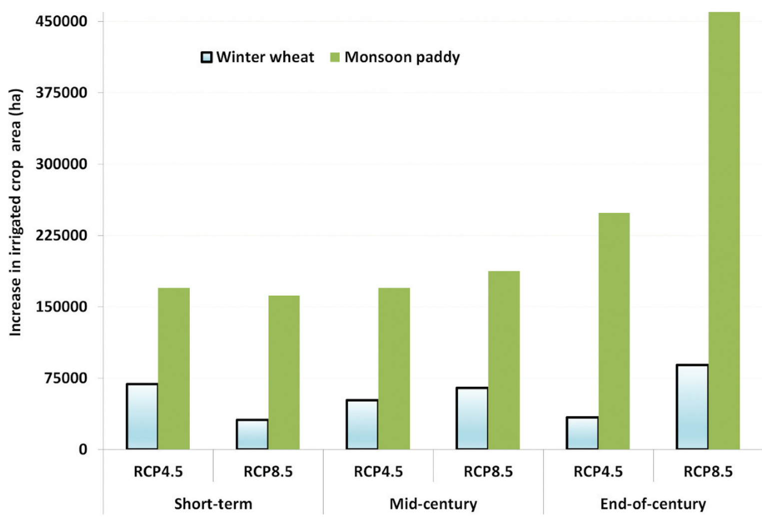

Figure 6. Potential increase in the areas of irrigated winter wheat and monsoon paddy rice in the short-term, midcentury and end-of-century periods.

monsoon paddy rice are in October (flowering period) and July (land preparation). Hence any increase in irrigated crop area is governed by water availability in October and July. As the increase in the average monthly flow is projected to shift to August and September, future rice plantings should be delayed by one month (from July to August) to take advantage of the increased water availability.

In addition to surface water, groundwater is being used to irrigate land that is not covered by irrigation infrastructure, and there is a possibility of extending groundwater use to irrigated land in the region (Nepal et al., 2019). However, assessment of this possibility is beyond the scope of this study.

Such an increase in crop area could only be captured (either entirely or partially) by developing additional irrigation canal infrastructure for the expanded command area of the Sunsari Morang irrigation scheme and constructing new irrigation schemes in the region. The rehabilitation of existing irrigation schemes in the region could consider expanding the irrigation command area while upgrading the irrigation infrastructure (Kaini et al., 2011). If appropriate irrigation infrastructure and other agricultural supporting systems are developed, the greater crop area would increase food production and boost food security in Nepal. Apart from using irrigation water in staple crops, multiple use of irrigation water such as in electricity generation (small-scale micro-hydro), fisheries and banana farming, which are increasing in Nepalese irrigation schemes, can boost local economies (Kaini, 2016). Although irrigation water availability is necessary for increased crop areas, other agricultural provisions such as fertilizers, proper market mechanisms, and agricultural support to farmers are also required. Research on irrigation schemes in Nepal finds that farmers are motivated to increase crop area if they have enough water for irrigation, proper market facilities, farm-level training, and some subsidies (Kaini et al., 2020a). And because the Koshi is a transboundary river, irrigation crop area could also be developed in India, where water from the Koshi barrage, around 40 km downstream of Chatara, is irrigating 1,000,000 hectares of agricultural land (Upadhyay, 2012).

Conclusions

In this study, a generalized methodology for investigating climate change impacts on the hydrological regime of a river basin and their implications for future water availability for local irrigation schemes has been demonstrated in a Himalayan river basin using high-resolution (10 km × 10 km spatial resolution) precipitation and temperature data and SWAT modelling to project future water availability in the Koshi River basin, which spans China and Nepal. For finer hydrological modelling outcomes, the river basin area was divided into 294 sub-basins and 1870 HRUs, with 581 climate data points over the basin area. The implications of the projected water availability scenarios for irrigation schemes in the region were also assessed.

River flows were projected for short-term, midcentury and end-of-century periods using the RCP4.5 and RCP8.5 climate change scenarios. The outcomes for the short-term period (2016–2045) could be used by the National Planning Commission of Nepal in its forthcoming Five-Year Periodic plan.

The selected GCMs/ensembles project the following likely future water availability in the Koshi River basin near the irrigation canal intake at Chatara.

- *Annual flow*. The average annual river flow is projected to increase for all scenarios and study periods. For the RCP4.5 scenario, the average annual flow in the Koshi River is expected to increase by 15–30% in all three periods. For the RCP8.5 scenario, the increases are even larger, ranging from 20% to 60%.
- *Seasonal flows*. Winter flows are projected to increase by 17–23% and 13–39% for RCP4.5 and RCP8.5, respectively. The pre-monsoon flow is expected to decrease slightly in the short term but increase by 9–11% and 15–21% in the midcentury and end-of-century periods, respectively. The monsoon flow is expected to increase by 13–15%, 18–26% and 24–52% in the short-term, midcentury and end-of-century periods, respectively. In the post-monsoon season, mean river flow is expected to increase by 50–54%, 62–87% and 68–128% in the short-term, midcentury and end-of-century periods, respectively.
- *Peak mean flows*. The projected peak mean flow under RCP4.5 is lower than the flow under RCP8.5 in all study periods, with the difference widening in later periods. The projected peak mean monthly flows are higher than in the reference period. Thus, higher floods can be expected. A shift in peak flow towards August and September is expected.
- *Uncertainty*. The projected flows of the Koshi River have high uncertainty, and the uncertainty is greatest for the end-of-century period. It is also greater for RCP8.5 than for RCP4.5 in the midcentury and end-of-century periods.

Given the projected impacts of climate change on the hydrological regime of the Koshi River basin, we project the following possible changes in irrigation in the region.

- Considering projections of minimum average monthly river flow and the time distribution of crop water requirements, winter wheat crop area could be increased (compared to the current irrigation area) by 260%, 200% and 130% under the RCP4.5 climate scenario, and by 120%, 250% and 340% under RCP8.5 climate scenario, in the short-term, midcentury and end-of-century periods, respectively.
- Monsoon paddy rice area could be increased by 300%, 300% and 440% under the RCP4.5 climate scenario, and by 280%, 330% and 810% under the RCP8.5 climate scenario, in the short-term, midcentury and end-of-century periods, respectively.
- However, the planting period of paddy rice should be delayed by one month (from July to August) to capture the expected increased water availability.
- The greater cropping area will significantly increase food production and food security in Nepal, but it is contingent on the adequate expansion of irrigation supply infrastructure, and appropriate agricultural supporting mechanisms for the farmers.

Note

1. Readers of the print issue can view the figures in colour in the online article, https://doi.org/10.1080/07900627.2020.1826292

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Disclosure statement

The authors declare that they have no conflict of interest.

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