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# The Projected Impact of Climate Change on Water Availability and Development in the Koshi Basin, Nepal

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Water has been identified as a key resource for Nepal's economic growth. Although the country has 225 billion cubic meters of water available annually, less than 7% has been utilized. Climate change is a frequent topic in national development

discussions in part because of its possible impact on future water availability. This study assessed the likely impact of climate change on water resources development in the Koshi River basin, Nepal, using the Soil and Water Assessment Tool to generate projections for the 2030s and 2050s. Results suggested that the impacts are likely to be scale dependent. Little impact is projected at annual, full-basin scales; but at sub-basin scale, under both the IPCC's A2 and B1 scenarios, precipitation is projected to increase in the upper transmountain subwatersheds in the 2030s and in most of

the basin in the 2050s and to decrease in the lower sub-basins in the 2030s. Water yield is projected to increase in most of the basin except for the A2 scenario for the 2030s. Flow volumes are projected to increase during the monsoon and postmonsoon but decrease during the winter and premonsoon seasons. The impacts of climate change are likely to be higher during certain seasons and in some sub-basins. Thus, if infrastructure is in place that makes it possible to store and transfer water as needed, the water deficit due to any changes in rainfall or flow patterns could be managed and would not be a constraint on water resources development. The risks associated with extreme events such as floods and droughts should, however, also be considered during planning.

**Keywords:** Climate change; water resources planning and development; scenario; Koshi River basin; Nepal; Himalayas.

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## Introduction

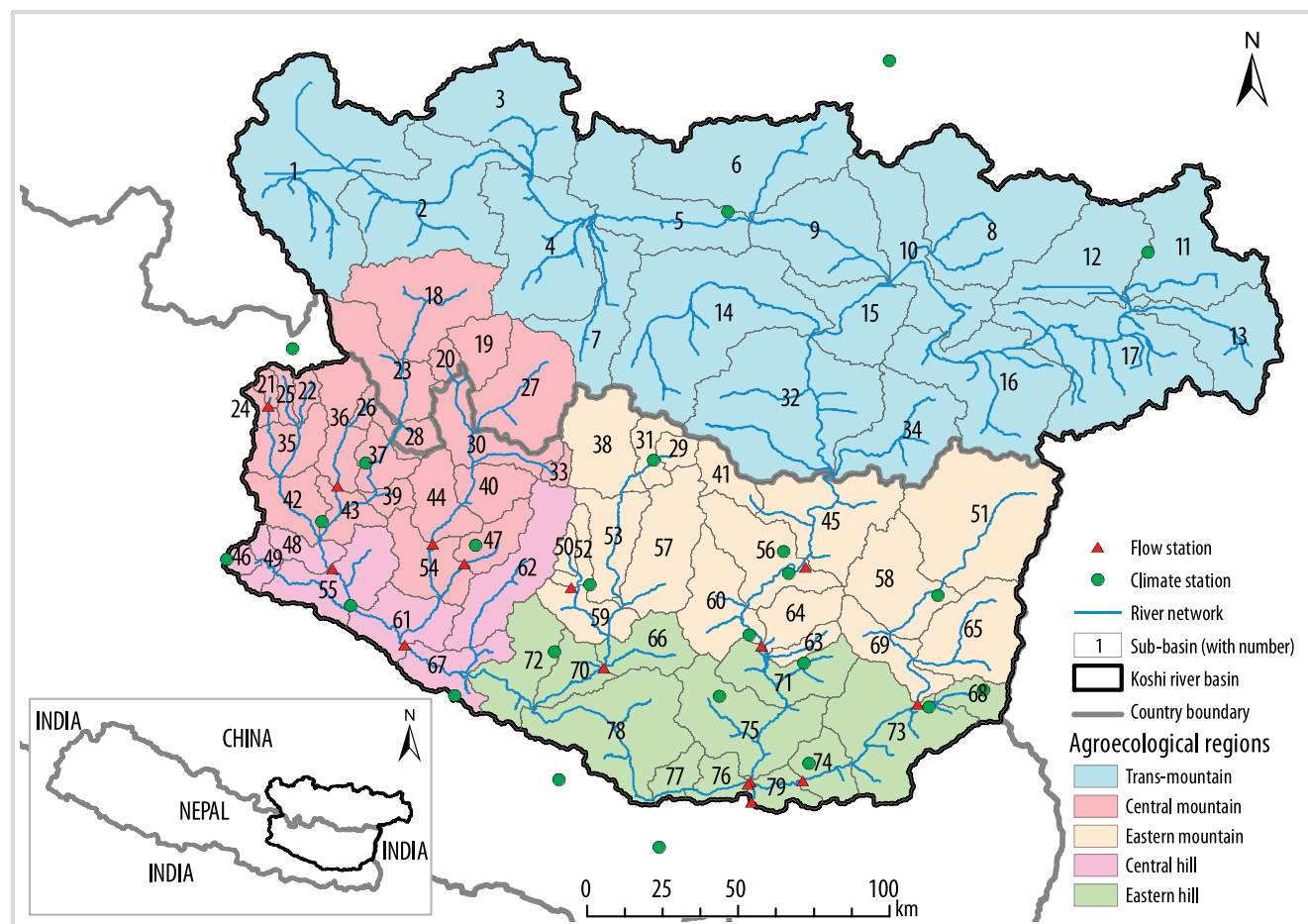
Water has been identified as a key resource for development and economic growth in Nepal (GoN-WECS 2011). Although the country has 225 billion cubic meters of water available annually, only an estimated 15 billion cubic meters (less than 7%) has so far been utilized for economic and social purposes (GoN-WECS 2005). Nepal's national water plan (GoN-WECS 2005) indicated that only 72% of the population has access to safe drinking water and only 562 MW of hydropower capacity is exploited (out of an economically feasible potential of about 42,000 MW). Over 80% of Nepal's population depends on subsistence agriculture for livelihoods (World Bank 2009), and agriculture consumes around 99% of all water used in the country (FAO (2012). Yet only 24% of arable land is irrigated, crop productivity is significantly lower than in the rest of South Asia, and the country relies heavily on food imports from India. Thus, the issue of water resources development and management looms large for Nepal. The general perception is that if this resource is properly

harnessed, it would be the ticket out of poverty through economic growth, mainly in the hydropower and agriculture sectors.

Climate change is a frequent topic in national development discussions in part because of its possible impact on future water availability (Dixit et al 2009; NCVST 2009; GoN-WECS 2011). Climate change impacts in the Himalayan region are reported to encompass changes in both precipitation and temperature and to have wide-ranging consequences—including glacier retreat, loss or functional change of wetlands, increased flow variability, and change in flow timing and amounts—that affect agriculture, rural livelihoods, and the overall economy (Bates et al 2008; UNEP 2008).

A recent report by the Intergovernmental Panel on Climate Change (Stocker et al 2013) predicted with high confidence a rise in temperature and with medium confidence a rise in summer monsoon precipitation across South Asia. Model projections diverge on smaller regional scales (Stocker et al 2013), however, generating

FIGURE 1 Map of Koshi basin showing the location of climate and flow stations, agroecological regions, and sub-basins. (Map by the authors)



uncertainty about climate change projections for the region. Different global circulation models have not agreed even on the direction, let alone magnitude, of climate change impacts for the region (Annamalai et al 2007; Kripalani et al 2007). Hydrological systems would respond differently to these different projected changes.

The combination of variability and uncertainty regarding future changes due to climate change is perceived to make water resources planning very challenging. Yet certain questions can be asked for underdeveloped areas such as the Himalayan region: To what extent do the above constraints matter, and should they impede the immediate implementation of development objectives? If they matter, then to what sectors of economy, in which parts of the basin, and with what implications? This study attempted to answer these questions for the Koshi River basin in the Himalayas by assessing the likely impact of climate change on future water resource availability there. The analysis presented here used the IPCC 2007 scenarios (Solomon et al 2007), because the 2013 report (Stocker et al 2013) had not yet

been published. This paper looks at projected changes in bulk water resources due to climate change.

### Study area

The Koshi River basin, which extends into China and India as well as Nepal, is the largest river basin in Nepal, reaching from 26°54'47" N to 25°24'43" N and 87°09'25" E to 87°15'32" E, and serves as a smaller model of the larger physiographic region. The massive water resources in the basin (48 billion cubic meters) remain largely untapped (only 14% of the total flow is estimated to be withdrawn), with a hydropower potential of almost 30,000 MW and irrigable land of nearly 500,000 hectares (GoN-WECS 1999). The portion of the basin considered in this study is upstream of Chatara in the mountainous region of eastern Nepal and the southern part of the Tibetan Autonomous Region, China (Figure 1) and covers a catchment area of 57,760 km<sup>2</sup>. It includes the entire hill and mountainous region in the Koshi basin and is characterized by high climatic and geographical variability (Sharma 2000).

Elevation ranges from 140 m at Chatara to more than 8000 m in the Great Himalayan Range including Mt. Everest (8848 m). The basin can be divided into a transmountain region, central and eastern mountain regions, and central and eastern hill regions. Transmountain, mountain, and hill regions are physiographic categories, and central and eastern are administrative categories.

### Studies of climate-change impacts on water resources

Information on climate and hydrology is said to be lacking for the Himalayan region as a whole (Solomon et al 2007) and for the Koshi basin in particular (Sharma et al 2000a, b; Bhutiyani et al 2008; Dixit et al 2009; Krishnamurthy et al 2009; NCVST 2009; Karki et al 2011). The few published findings are summarized in the following paragraphs.

Sharma (2000a) tested the sensitivity of hydrology to changes in climatic conditions and projected that with current precipitation levels and a rise in temperature of 4°C, runoff would decrease by 2–8%. Climatic trend analysis has suggested an increasing trend in temperature and precipitation but a negative trend in discharge, especially during low-flow months (Sharma 2000a). More recently, Dixit et al (2009) and NCVST (2009) looked at the impact of climate change projections and adaptation strategies and projected that wet seasons in the Koshi basin are likely to become wetter and the dry seasons are likely to become drier, with an increasing likelihood of both droughts and floods (Dixit et al 2009; NCVST 2009). Gosain et al (2011) evaluated average annual water balance components simulated for the upper Koshi River basin using the Soil and Water Assessment Tool (SWAT), the Hadley Centre Regional Model, and the IPCC Special Report on Emissions Scenarios and projected increases in precipitation, snowmelt, surface runoff, and actual and potential evaporation. That study did not, however, assess seasonal and spatial variations at sub-basin levels or projections from other climate models.

Immerzeel et al (2013) studied the Langtang watershed of the Ganges River and the Baltoro watershed of the Indus River and concluded that, due to a rise in net glacier melt runoff as well as a positive change in precipitation, water availability during this century is not likely to decline. They suggested that the conclusions could be similar for other Himalayan catchments. That study focused on upper mountain areas, so it might not be possible to generalize its findings for the downstream areas of the Himalayan basins; nor did it address the scale issue when assessing climate change impacts. Other modeling studies (eg Singh et al 2008) examined the hydrological regime of individual glaciers in the Upper Ganges basin, rather than the impacts of water use and climate change on basin-wide water resources. Seidel et al (2000) modeled the runoff regime of the Ganges and

Brahmaputra basins, accounting for precipitation, remotely sensed snow cover, and temperatures using the Snowmelt Runoff Model. They projected that the already high risk of floods from July to September will increase slightly with climate change.

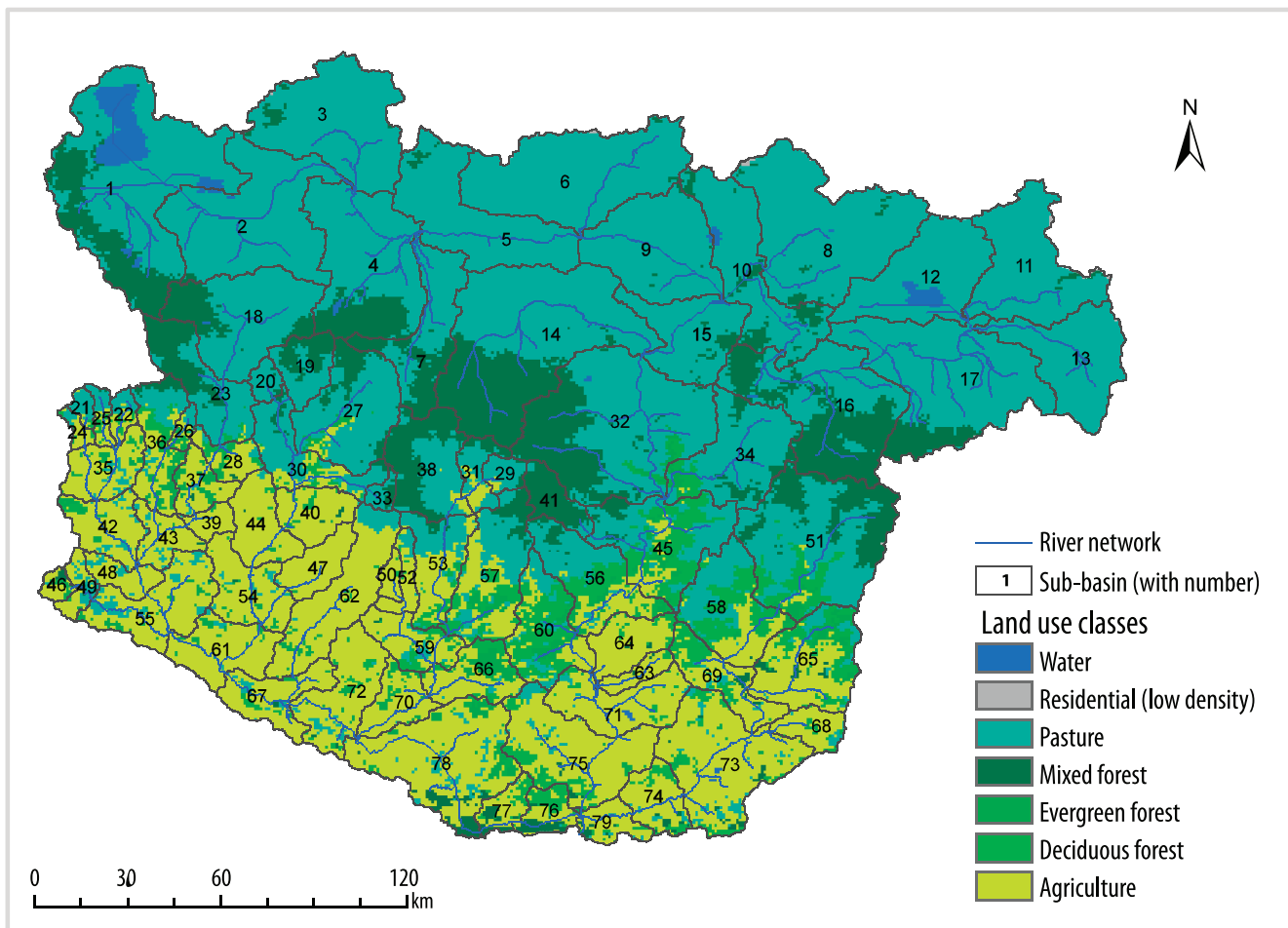
Bharati et al (2014), which looked at past spatial and temporal variability and compared it to climate change projections in the Koshi basin, found that seasonal and interannual variability as well as spatial variability in climate and flow are already high in the basin, and that future projections were outside the boundary of the past data ranges in the following cases: (1) higher maximum precipitation during monsoon and postmonsoon seasons and lower maximum precipitation during winter, (2) increased precipitation and flows in the transmountain region during all seasons except for flows during the monsoon, (3) increased postmonsoon precipitation and flow volumes in the whole basin, (4) decreased winter precipitation and routed flow volumes in all except the transmountain region, and (5) increased frequency of high flow peaks and decreased base flow. The scope of that study was, however, limited to assessing variability in the hydrological system and not bulk water availability, which is one of the main bases for planning future development.

### Methods and data

#### Soil and water assessment tool

The Soil and Water Assessment Tool (SWAT) is a process-based continuous hydrological model that predicts the impact of land management practices on water, sediment, and agricultural chemical yields in complex basins with varying soil, land use, and management conditions (Arnold et al 1998; Srinivasan et al 1998). It divides a basin into sub-basins, each of which is connected through a stream channel. Sub-basins are further divided into hydrologic response units, unique combinations of soil and vegetation types in a subwatershed; they constitute the level at which SWAT simulates hydrology, vegetation growth, and management practices. Since the model maintains a continuous water balance, subdivision of the basin enables the model to reflect differences in evapotranspiration (ET) for different crops and soils. Thus, runoff is predicted separately for each sub-basin and routed to obtain the total runoff for the basin. This increases accuracy and gives a much better physical description of the water balance. The soil profile can contain several layers. Soil water processes include infiltration, percolation, evaporation, plant uptake, and lateral flow. Potential evaporation can be calculated using the Hargreaves, Priestley-Taylor, or Penman-Monteith method (Arnold et al 1998). In this study, the Penman-Monteith method was used. More detailed descriptions of the model can be found in Arnold et al (1998) and Srinivasan et al (1998).

**FIGURE 2** Land use map of Koshi basin used in hydrological simulations. (Source: Advanced Very High Resolution Radiometer [AVHRR] 1992/93)



### Downscaled climate data

For this study, downscaled climate data were obtained from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CGIAR n.d.). The global circulation models used to generate daily climate data were Centre National de Recherches Météorologiques Coupled Global Climate Model, version 3 (CNRM-CM3), Commonwealth Scientific and Industrial Research Organization—Mark 3.5 (CSIRO-Mk3.5), ECMWF Hamburg, version 5 (ECHam5), and Model for Interdisciplinary Research on Climate, version 3.2 (MIROC3.2); the projected data are averages of these four models. For the downscaling process, the MarkSim weather generator (Jones et al 2002) was used. Baseline data used in the projections are from 1971–2000. The period of future simulations are from the near to midrange future—2030s (average for 2016–2045) and 2050s (average for 2036–2065)—the time horizons for which water management decisions have to be made. Further information on the downscaling methods can be found in Jones et al (2009). Future scenarios considered for this study are the IPCC SRES A2 and B1. The A2

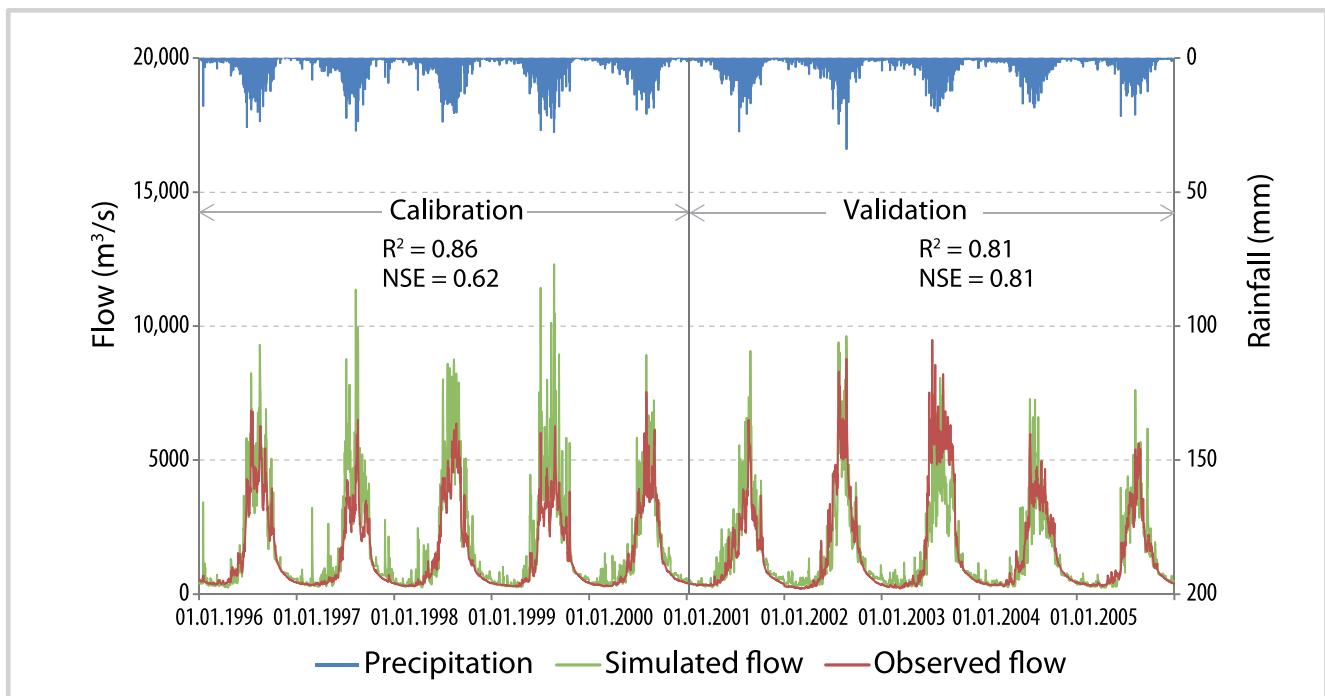
scenarios represent regionally oriented economic development with increases in temperature of 2.0–5.4°C, and the B1 scenarios represent global environmental sustainability—a more integrated and more ecologically friendly world—with temperature increases of 1.1–2.9°C (Solomon et al 2007).

The study also compared the downscaled baseline climate data from MarkSim with observed climate data, and corrections were carried out on both the baseline and the projections. The adjustments were based on matching the mean and standard deviation in the baseline and historical/observed data. The specific adjustment techniques and statistical downscaling approaches are described in Bouwer et al (2004) and Bharati et al (2011).

### SWAT model setup for the Koshi basin

The SWAT model works with spatial and temporal data. Spatial data include elevation, soil type, and land use/land cover. For this study 90 m Shuttle Radar Topography Mission was used for the digital elevation model. Figure 2 shows land use with sub-basin delineation (Hansen et al 2003). As can be seen from Figure 2, forest and pasture

**FIGURE 3** Observed and simulated daily flows at the Chatara-Kothu station, Sapta Koshi river, with coefficient of determination ( $R^2$ ) and Nash-Sutcliffe efficiency (NSE) values.



dominate the upper reaches, while lowland areas are used for agriculture. The source of the soil data was FAO (1995). Major soil types in the basin are lithosols in upper areas and dystric cambisols at lower elevations, where agricultural is predominant. Lithosols are shallow soils found in steep mountainous regions where erodible material is so rapidly removed by erosion that a permanent covering of deep soil cannot establish itself. Cambisols are developed in medium and fine-textured materials derived from a wide range of rocks. Most of these soils make good agricultural land and are intensively used. The dystric cambisols, though less fertile, are used for mixed arable farming and grazing.

The temporal input data for the model are climate data. In this study, climate data from 17 stations were used (Figure 1). Most of the available data are from the lower part of the basin in Nepal. However, data from three stations in the Tibetan Autonomous Region, China, were useful in representing the trans-Himalayan part of the basin. The nearest-neighbor method was used to interpolate climate data. The SWAT model classifies precipitation as rain or freezing rain/snow based on daily air temperature, with a boundary temperature defined by the user. (If the mean daily air temperature is less than the boundary temperature, then the precipitation within the hydrological response unit is classified as snow and the water equivalent is added to the snow pack. Snowmelt is then included with rainfall in the calculations of runoff and percolation.)

The model calibration and validation period was from 1996 till 2005, with calibration from January 1996 to December 2000 and validation from January 2001 to

December 2005 (Figure 3). Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing prediction uncertainty. It was carried out in three steps: sensitivity analysis, auto-calibration, and manual calibration. Sensitivity analysis was performed using the inbuilt sensitivity analysis tool of SWAT, changing the values one at a time, from which the 11 most sensitive parameters were identified. Table 1 lists the sensitive parameters. An inbuilt SWAT tool was used to autocalibrate using these parameters. The model was run for 1000 iterations during this step. Sensitivity analysis and autocalibration in SWAT are limited to the use of observed data from a single gauging station at a time. Thus, observed flow data from the Chatara outlet of the Koshi basin were used for this purpose.

Although the range of values for the sensitive parameters was narrowed down, the simulated and observed hydrographs did not match well. One reason could be the large size of the basin and hence the inability to fit the parameters to the entire basin based on the results from one flow gauging station. Thus, it was decided to improve the results from the autocalibration process with manual calibration based on expert judgment. Manual calibration was done simultaneously using daily flow data from five gauging stations in Nepal. Unfortunately, flow data from China were not available. An iterative approach was used for manual calculation consisting of (1) simulation, (2) comparison of observed and simulated values, (3) checking whether the output was reasonable, (4) if not, adjusting the parameters based on expert judgment and other guidance, and (5) repetition of

**TABLE 1** Calibrated SWAT parameters based on observed flow data from the Chatara outlet of the Koshi basin.<sup>a)</sup>

Parameters	File	Level	Calibrated values	Allowable range
SURLAG	.bsn	Basin	4	1 to 10
SFTMP	.bsn	Basin	1	-5 to 5
SMTMP	.bsn	Basin	0.5	-5 to 5
GW_DELAY	.gw	HRU	31	0 to 50
ALPHA_BF	.gw	HRU	0.048	0 to 1
GW_REVAP	.gw	HRU	0.05	0.02 to 0.2
CN_2	.mgt	HRU	49–72	35 to 98
CH_N2	.rte	Reach	0.014	0 to 1
SOL_K	.sol	HRU	66–88	0 to 100
SOL_Z	.sol	HRU	1000	0 to 3000
SOL_AWC	.sol	HRU	0.2–0.22	0 to 1

<sup>a)</sup>HRU, hydrologic response unit. For a detailed explanation of the parameters, refer to Arnold et al (2011).

the process until best results were obtained (Arnold et al 2012).

During manual calibration, adjustments were made first to the more sensitive parameters and then to the less sensitive ones. At times, it was also found that parameters other than those identified during the sensitivity analysis also needed to be adjusted for better performance of the model. The basis for evaluating model prediction during manual calibration consisted of visual inspection of the hydrographs (peak, time to peak, shape of the hydrograph, and baseflow), statistics (mean, standard deviation, coefficient of determination [ $R^2$ ], Nash-Sutcliffe efficiency), and comparison of the simulated water balance with the observed values. Care was taken throughout the calibration process to ensure that the physically based parameter values remained within an acceptable range (Table 1).

Figure 3 presents the observed and simulated hydrographs. When comparing model simulated flows to observed flows at the basin outlet, the coefficient of determination ( $R^2$ ) for the monthly simulations was 0.96 during calibration and 0.91 during validation.  $R^2$  for daily simulations was 0.86 during calibration and 0.81 during validation. The daily simulation results showed that the peaks were underestimated during model calibration but improved during model validation.

Following satisfactory model calibration and validation, the SWAT model was run with climate data from the MarkSim weather generator for the baseline (1971–2000), 2030s (average for 2016–2045), and 2050s (average for 2036–2065) to simulate water balances and runoff from the basin. The impact of climate change was estimated by comparing the baseline with the projected data.

## Results

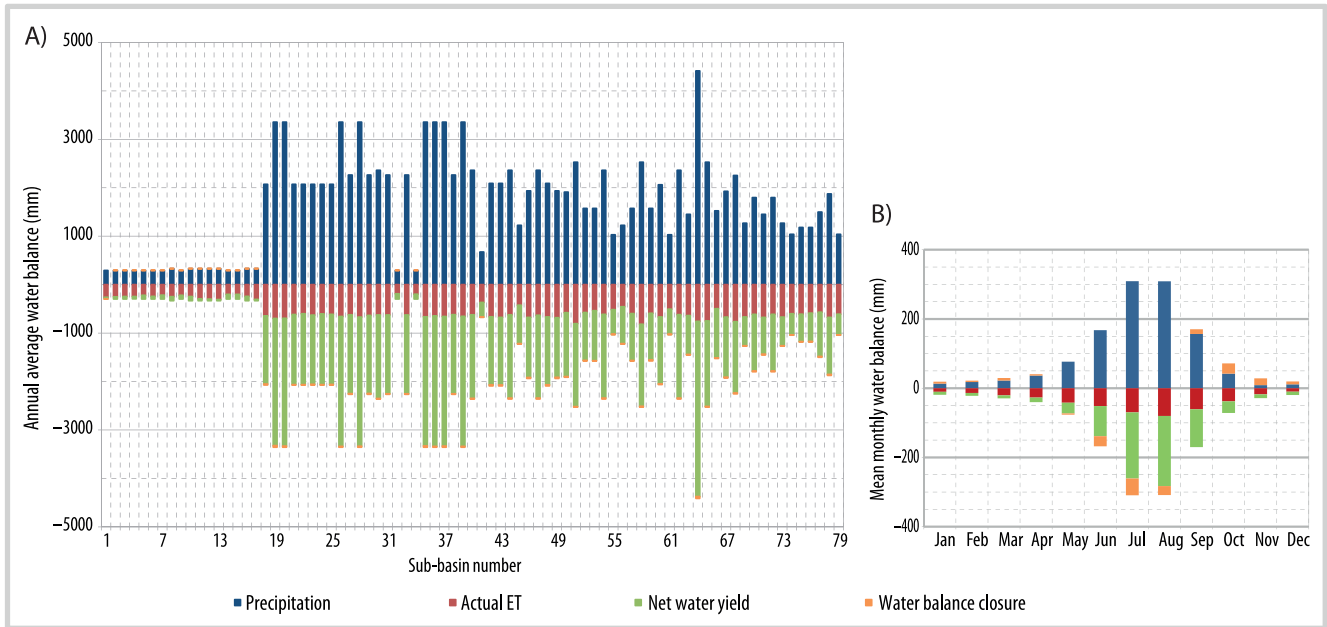
### Current and future water balances throughout the Koshi basin

Figure 4A presents annual water balance components at sub-basin scale, including average annual precipitation, actual ET, and water yield generated using the SWAT model. Mean annual precipitation in the whole basin was 1234 mm from 1976 to 2005. Mean seasonal distribution of precipitation was 223 mm, 856 mm, 59 mm, and 96 mm in premonsoon, monsoon, postmonsoon, and winter seasons, respectively. As can be seen from Figure 4A, the southern part of the basin is wetter than the trans-Himalayan northern part. Average annual precipitation was highest in the central mountain (1775 mm) and eastern mountain regions (1418 mm). The lowest precipitation during both dry season (premonsoon, postmonsoon, and winter) and wet season (monsoon) was in the transmountain region, where mean precipitation was 113 mm during the dry season and 307 mm during the wet season.

Actual ET is related to precipitation as well as land cover. During both the dry and wet seasons, average actual ET was highest in the central and eastern mountain regions and lowest in the transmountain region. Runoff was higher than ET in the lower sub-basins. The highest ET values were from sub-basin 58 (817 mm), which has deciduous forests, pasture, and agricultural fields. ET was higher than runoff in the upper sub-basins; however, in the lower part of the basin, runoff was higher than ET, which also indicates that the basin is rich in water resources.

Figure 5 presents the spatial distribution of net water yield for each sub-basin. Net water yield is a sum of the

**FIGURE 4** (A) Annual water balance values (precipitation, actual ET, and net water yield) for sub-basins in the Koshi basin, averages for 1976–2005. The numbered sub-basin locations can be seen in Figure 1. (B) Monthly water balance values for the entire Koshi basin, means for 1976–2005.

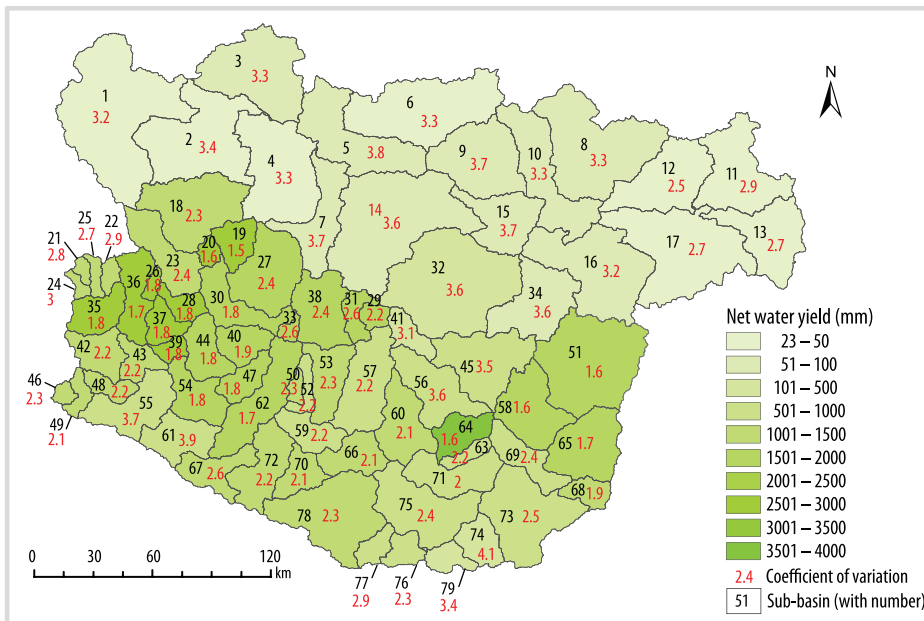


snow melt, runoff from rain, base flow, and lateral flow. It does not always mirror precipitation patterns, because it is also affected by rainfall intensity, soil properties, and land cover. For example, rain falling with high intensity on bare and compacted soils will produce higher runoff than longer rainfall events on deep soils and cropped areas. The analysis found water yield to be highest in the mountain regions and lowest in the transmountain

region. The range was, however, quite big, from 5 mm during the dry season in the transmountain region to 1629 mm in the central mountains.

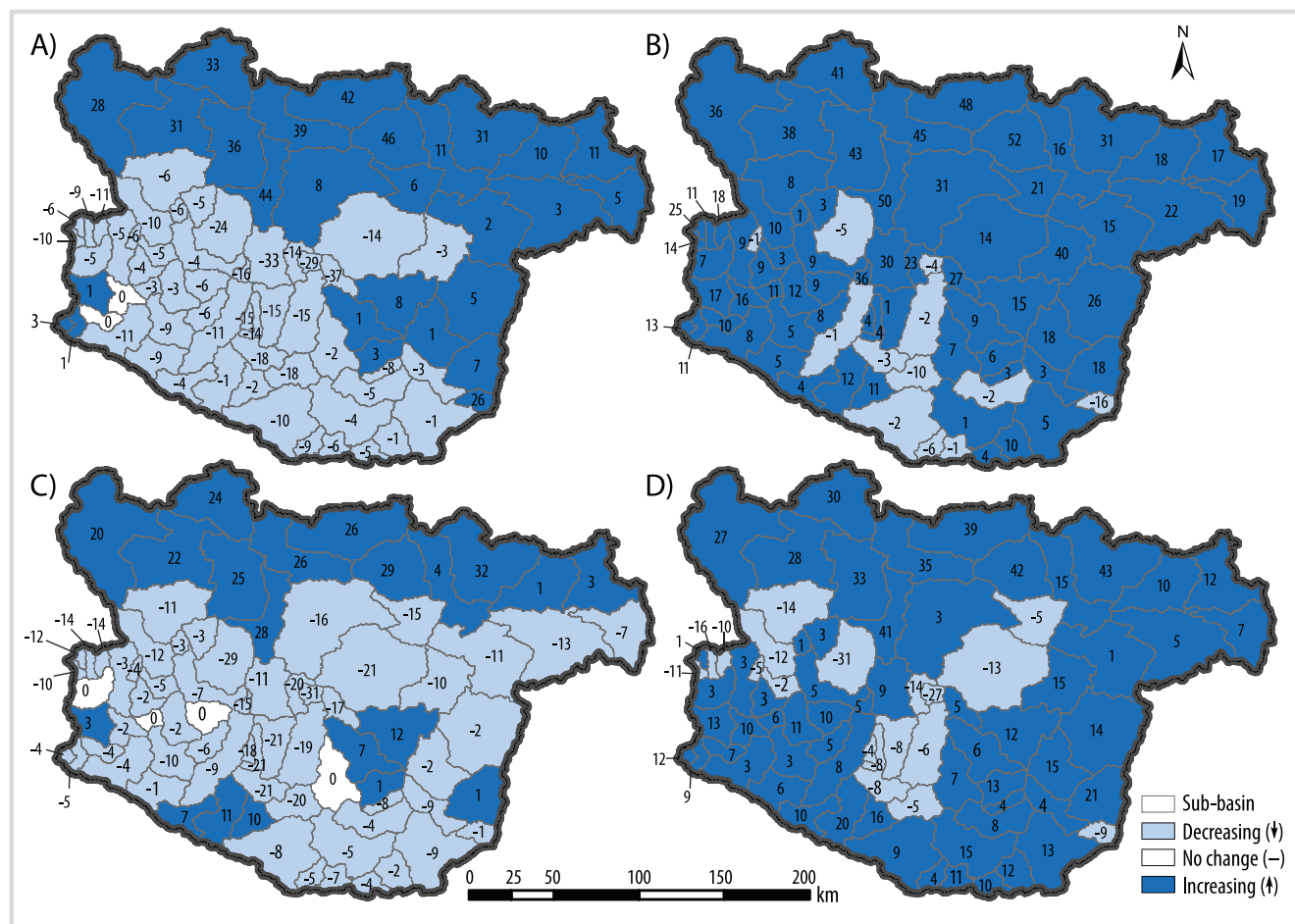
Model simulations also yielded an annual flow volume of about 52,731 million cubic meters in the whole basin under the current climate scenario; however, water availability was very seasonal, with 70.8% of annual flow occurring during the monsoon (June–September), 13.2%

**FIGURE 5** Net water yield by sub-basin, 1976–2005. Numbers indicate the coefficient of variation for each sub-basin.





**FIGURE 6** Percentage of projected annual change in precipitation by sub-basin. (A) A2 scenario, 2030s; (B) A2 scenario, 2050s; (C) B1 scenario, 2030s; (D) B1 scenario, 2050s.



during the postmonsoon season (October–November), 8.1% in winter (December–February), and 7.9% in the premonsoon season (March–May). Figure 4B also shows the mean monthly water balances for the modeling period, again reinforcing the importance of the monsoon season. In Figure 5, each sub-basin is also labeled with the coefficient of variation, which is a normalized measure of dispersion of a probability distribution or frequency distribution. The coefficient of variation values, which were based on daily outputs, were high in all the sub-basins. Therefore, the Koshi basin exhibits both strong spatial gradients in annual runoff between sub-basins and an extremely pronounced annual cycle. The spatial and seasonal variations are driven by the spatial patterns and timing of the precipitation regime, respectively.

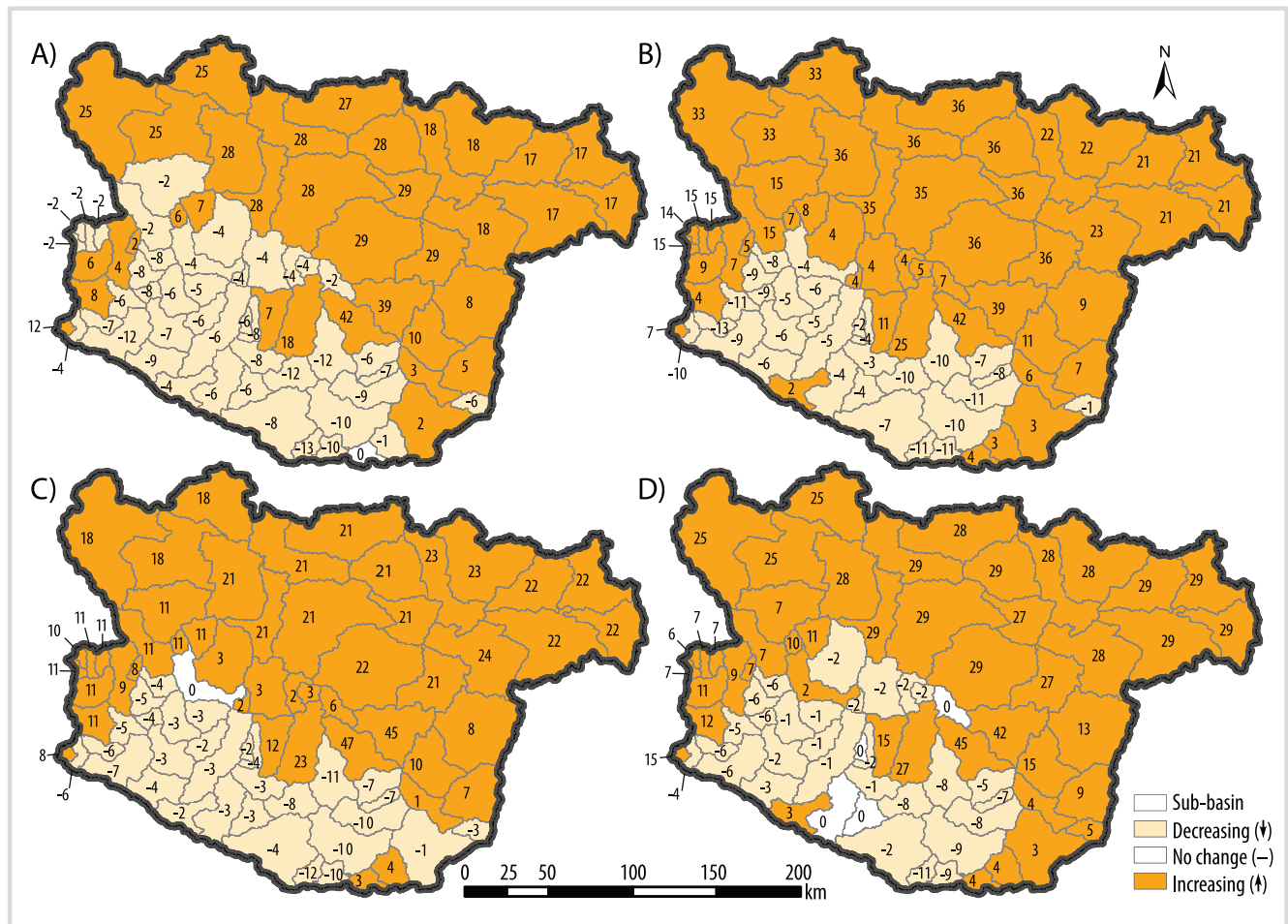
Under current climate conditions, the average mean annual maximum temperature in the basin ranged from 8.0°C to 31.4°C, whereas the mean annual minimum temperature ranged from -12.4°C to +8.8°C. With climate change, annual maximum temperature is projected to increase by 0.3°C per decade under both the A2 and B1 scenarios. Similarly, annual minimum

temperature is projected to increase by 0.3°C and 0.2°C per decade under the A2 and B1 scenarios, respectively.

Under climate change, mean annual precipitation for the whole basin is projected to decrease by 1–3% in the 2030s and increase by 8–12% in 2050s. Projected changes in annual precipitation are presented in Figure 6; under both scenarios, precipitation is predicted to increase in the upper transmountain region in the 2030s and in most of the basin in the 2050s, but it is expected to decrease in the lower sub-basins in the 2030s. Actual ET is also projected to increase in the upper transmountain and parts of the central and eastern mountain regions and decrease in parts of the central and eastern mountains (Figure 7). Water yield is projected to increase in most of the basin, except under the A2 scenario for the 2030s, where positive changes are projected mainly in the transmountain, eastern mountain, and hill regions (Figure 8).

Thus, projected climate change impacts are more pronounced at the sub-basin scale than at the full-basin scale. For example, changes in mean precipitation under scenarios A2 and B1 for the full basin are projected to be,

**FIGURE 7** Percentage of projected annual change in actual ET by sub-basin. (A) A2 scenario, 2030s; (B) A2 scenario, 2050s; (C) B1 scenario, 2030s; (D) B1 scenario, 2050s.



respectively,  $-1\%$  and  $-3\%$  for the 2030s, and  $+12\%$  and  $-8\%$  for the 2050s. However, at sub-basin scale, the change in mean annual precipitation is projected to range from  $-37\%$  to  $+46\%$  under A2 and  $-31\%$  to  $+32\%$  under B1 for the 2030s, and from  $-16\%$  to  $+52\%$  under A2 and  $-31\%$  to  $+43\%$  under B1 for the 2050s.

#### Changes in water availability under future climate-change scenarios

Simulation results showed an annual flow volume of about 52,731 million cubic meters in the Koshi basin under the baseline climate scenario (Figure 9), with 70.8% of total annual flow occurring during the monsoon and 13.2% in the postmonsoon season, 8.1% in winter, and 7.9% in the premonsoon season. Projections revealed no significant changes in the seasonal distribution of flows, with the monsoon remaining the dominant hydrological driver.

Projected changes in flow volumes at the basin outlet are presented in Table 2. Flow volumes in the 2030s are projected to show the greatest reduction in the premonsoon season (16%) under the A2 scenario and the greatest increase in the postmonsoon season (15%) under

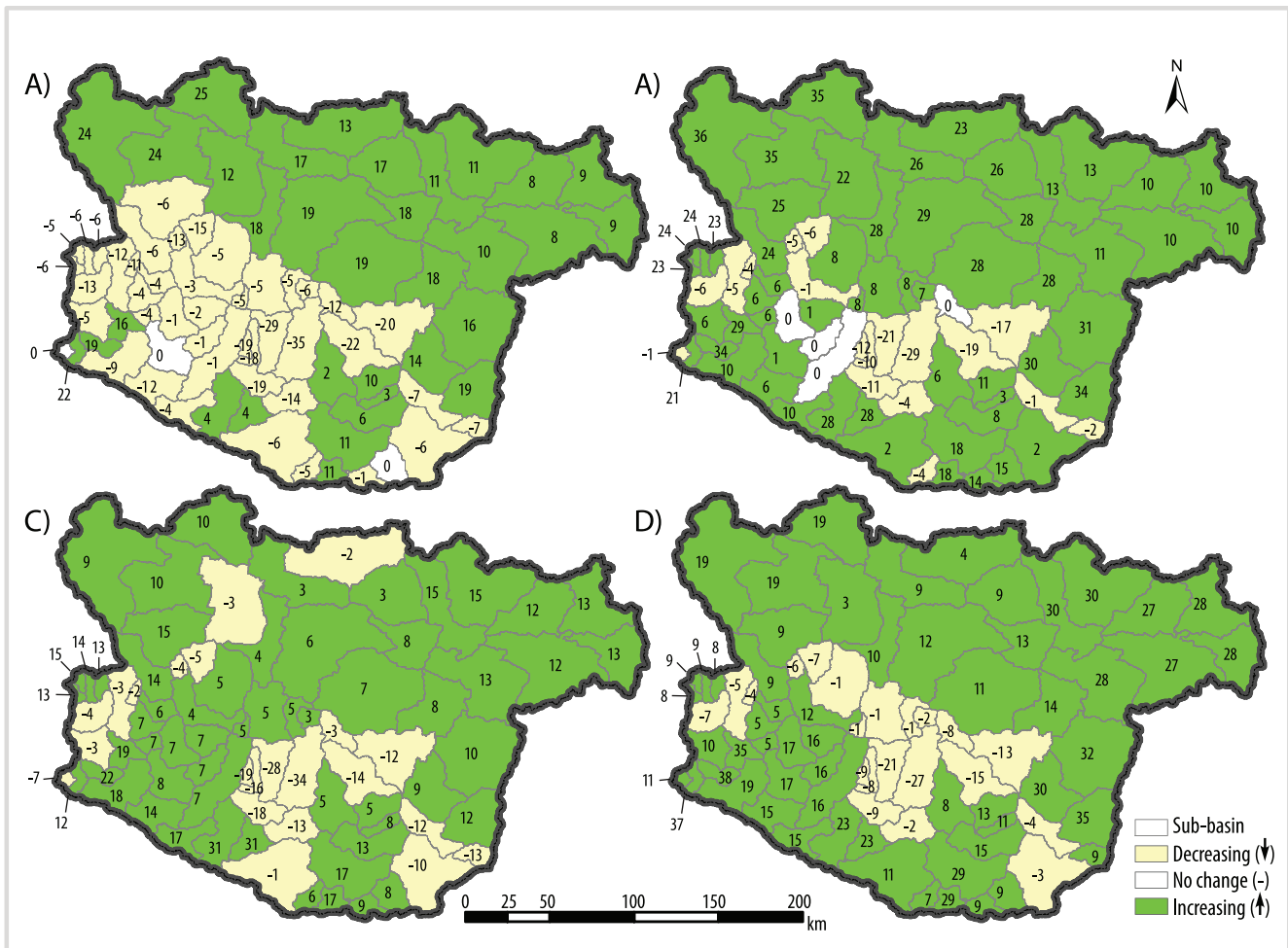
the B1 scenario. Similarly, annual flow volumes in the 2050s are projected to show the maximum reduction during the premonsoon season (16%) under A2 and the maximum increase in the postmonsoon season (25%) under B1. Meanwhile, all four annual flow changes are projected at less than 5%. Thus, climate change is expected to significantly affect seasonal changes but not annual changes.

Overall, few drastic changes in annual flow volume are likely. Figure 10 shows the extent of change in flow volume projected for different sub-basins. For both scenarios, in both time frames, only a few sub-basins were projected to undergo a (positive or negative) change in flow of more than 30%.

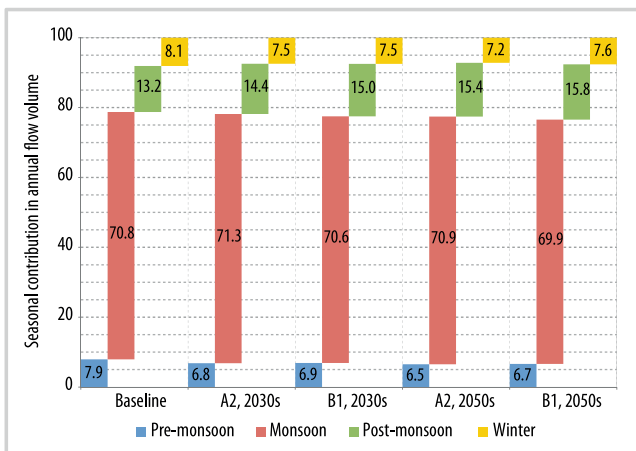
#### Discussion: Implications of climate change for water resources development

Most previous studies of the hydrological implications of climate change in the Himalayan region focus on one particular scale—for example, the entire Ganges basin

**FIGURE 8** Percentage of projected annual change in water yield by sub-basin. (A) A2 scenario, 2030s; (B) A2 scenario, 2050s; (C) B1 scenario, 2030s; (D) B1 scenario, 2050s.



**FIGURE 9** Seasonal simulated flow volumes at basin outlet Chatara-Kothu, under baseline and future climate projections (A2 and B1 scenarios, 2030s and 2050s).



(Gosain et al 2006; Moors et al 2011), smaller sub-basins (eg Dixit et al 2009; Bharati et al 2011; Immerzeel et al 2013), or the headwater catchments with a focus on glaciers and snow (eg Singh and Bengtsson 2005; Bajracharya and Mool 2009). This study compared projected changes at both temporal and spatial scales in water balance components (precipitation, actual ET, and water yields) as well as flow volumes. Its findings indicate that the impacts of climate change are likely to be higher at smaller (seasonal and sub-basin) scales than at larger (annual and full-basin) scales. This conclusion has significant implications for planning. For example, if infrastructure is in place to store and transfer water, then the problem of water deficit due to any changes in rainfall patterns over space or time could be managed.

Another important factor to consider is current water use. According to the National Water Plan (GoN-WECS 2005), Nepal currently utilizes only 7% of its annual water availability (14% in the Koshi basin). Water yield at both full basin and sub-basin level, especially for the upper sub-

TABLE 2 Projected changes in flow volume at basin outlet Chatara-Kothu.

Period	Scenario	Premonsoon	Monsoon	Postmonsoon	Winter	Annual
2030s	A2	-16%	-1%	7%	-9%	-2%
	B1	-12%	1%	15%	-7%	1%
2050s	A2	-16%	3%	20%	-9%	2%
	B1	-13%	3%	25%	-2%	4%

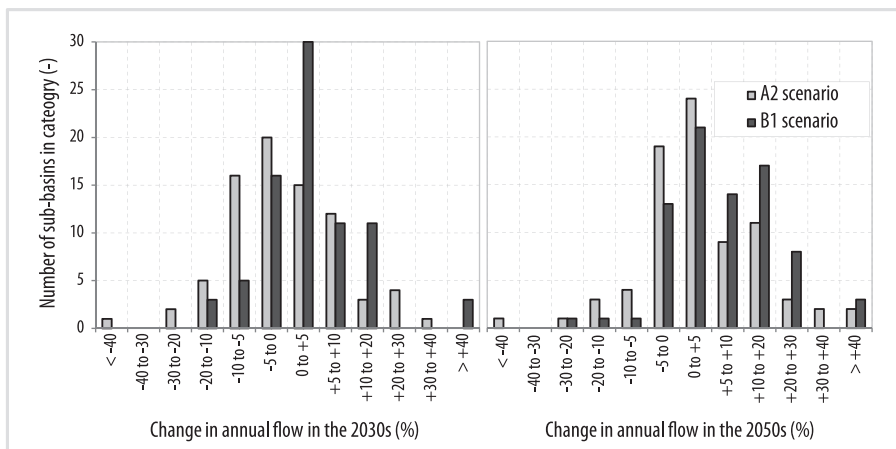
basins, is high (Figure 4A). Even under significant climate change, Nepal can make significant progress in water resources development with relatively simple improvements to retain water in upland catchments through watershed management, rainwater harvesting, irrigation that lessens reliance on rain-fed agriculture, small storage systems such as ponds, small dams, and infrastructure to store and distribute water. A recent paper (Immerzeel et al 2013) also stressed this point. Therefore, infrastructure and resource management systems must be designed for the full range of conditions that could occur, even if their performance is optimized only for the most common occurrences, and projected changes in seasonal variability should be taken into account by development projects to remedy possible seasonal water scarcity.

In this analysis, the main focus was to assess climate change implications for water resources development in general, and hence the emphasis was on bulk water balance component values (means and volumes). Variability in the hydrological regime, however, is another factor that will affect water management. Bharati et al (2014) evaluated past and future variability and found that the system is already quite variable and that this variability is likely to increase in the future. For example, the Koshi River is also prone to extreme floods, erosion, and transport of large sediment loads, with

devastating impacts on rural communities. Other recent climate change analyses (Dixit et al 2009; Bharati et al 2012) suggest that the frequency of high-flow events is likely to increase, thus making the basin even more vulnerable to flooding.

Furthermore, recent evidence suggests that extremes of water shortages interspersed by devastating floods, as a result of climate variability, are becoming more frequent. In 2008/2009, winter droughts caused barley and wheat crop yields to drop, and nearly 2 million people were placed in danger of food insecurity (WFP 2009). In the same year, monsoon floods destroyed significant amounts of cultivated land. Similarly, in spring 2013, western Nepal was hit by a severe drought, leading to crop failures; in June, the same region was devastated by its worst floods in 50 years, caused by intense monsoon rains, which killed at least 5700 people in the Indian states of Uttarkhand and Himanchal Pradesh and caused an estimated loss of US\$2 billion (Qiu 2013). The risks associated with such extremes will also affect the development of water resources. Therefore, although changes in flow volumes or water balance components from climate change might not affect development plans, if managed properly, increases in variability, including extreme events such as floods and droughts, will increase risks and need to be taken into consideration.

FIGURE 10 Projected changes in annual flow volume under A2 and B1 scenarios for the 2030s and 2050s.



## Conclusion

Assessment of the Koshi basin water balance showed that there is large temporal and spatial variability in precipitation, actual ET, and water yield in the basin. In the upper parts of basin, runoff is greater than ET, whereas in the lower parts, ET is greater than runoff. Climate change analysis shows that the impacts are very scale dependent. There is likely to be little impact at annual, full-basin scales. At sub-basin scale, however, under both projections used in this study, precipitation is likely to increase in the upper transmountain region in the 2030s and in most of the basin in the 2050s, and to decrease in the lower sub-basins in the 2030s. Actual ET is also likely to increase in the upper transmountain and parts of the central and eastern mountain regions and decrease in certain parts of the central and eastern mountain and hill regions. Furthermore, water yield is likely to increase in most of the basin except for one scenario (A2, 2030s) in which positive changes are projected mainly for the transmountain, eastern mountain, and hill regions. Flow volumes are likely to increase during the monsoon and postmonsoon but decrease during the winter and premonsoon seasons.

As water use in the basin is estimated to be only 14% of annual availability, the main conclusion of this study is that temporal and spatial water scarcity issues at the sub-basin scale, for the present as well as the future, can be

effectively managed with water storage and distribution infrastructure. Therefore, it is recommended that the focus be shifted from projecting whether climate change will increase or decrease mean flows in the basin to storing and distributing water from times and areas of abundance to those of need. The monsoon season is likely to remain the main source of precipitation and the main hydrological driver. Water yields in the monsoon are much higher than current and expected water use. Therefore, proper storage and utilization of monsoon flows is a sound strategy for both present and future. However, the risks associated with extreme events leading to floods and droughts should also be considered in planning.

This study assessed the implications of climate change only from a water resource perspective; it mainly proposes technological solutions. An effective system is, however, not just an accumulation of good physical capital. Physical systems do not run effectively unless there is a buildup of social capital among those operating them. Therefore, any storage and distribution systems that are built need to be incorporated within local social and institutional contexts. Environmental impacts should also be considered in order to make sure that any development is sustainable. In the water resources context, proper assessment of environmental flows will need to be carried out and incorporated into the operationalization of any water infrastructure scheme.

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## REFERENCES

- Annamalai H, Hamilton K, Sperber KR.** 2007. The South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations. *Journal of Climate* 20:1071–1092.
- Arnold JG, Kiniry JR, Srinivasan R, Williams JR, Haney EB, Neitsch SL.** 2011. *Soil and Water Assessment Tool Input/Output File Documentation* (version 2009). Texas Water Resources Institute Technical Report No. 365, Texas A&M University System.
- Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, Van Griensven A, Van Liew MW, Kannan N, Jha MK.** 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE [American Society of Agricultural and Biological Engineers]* 55(4): 1491–1508.
- Arnold JG, Srinivasan R, Muttliah RS, Williams JR.** 1998. Large area hydrologic modeling and assessment, Part I: Model development. *Journal of the American Water Resources Association* 34(1):73–89.
- Bajracharya S, Mool P.** 2009. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology* 50(53): 81–86.
- Bates BC, Kundzewicz ZW, Wu S, Palutikof JP, editors.** 2008. *Climate Change and Water*. Technical paper of the Intergovernmental Panel on Climate Change. Geneva: IPCC Secretariat.
- Bharati L, Gurung P, Jayakody P.** 2012. Hydrologic characterization of the Koshi Basin and the impact of climate change. *Hydro Nepal: Journal of Water, Energy and Environment* 11(1):18–22.
- Bharati L, Lacombe G, Gurung P, Jayakody P, Hoanh CT, Smakhtin V.** 2011. *The Impacts of Water Infrastructure and Climate Change on the Hydrology of the Upper Ganges River Basin*. IWMI Research Report 142. Colombo, Sri Lanka: International Water Management Institute. <http://dx.doi.org/10.5337/2011.210>.
- Bhutiyan MR, Kale VS, Pawar NJ.** 2008. Changing streamflow patterns in the rivers of northwestern Himalaya: Implications of global warming in the 20th century. *Current Science* 95:618–626.
- Bouwer LM, Aerts JCJH, van de Coterlet GM, van de Giesen N, Gieske A, Mannaerts C.** 2004. Evaluating downscaling methods for preparing Global Circulation Model (GCM) data for hydrological impact modelling. In: Aerts JCJH, Droogers P, editors. *Climate Change in Contrasting River Basins*. Wallingford, UK: CAB International, pp 25–47.
- CGIAR.** n.d. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Montpellier, France: CGIAR. [www.cgiar.org/our-research/cgiar-research-programs/cgiar-research-program-on-climate-change-agriculture-and-food-security-ccafs/](http://www.cgiar.org/our-research/cgiar-research-programs/cgiar-research-program-on-climate-change-agriculture-and-food-security-ccafs/); accessed on 21 December 2011.
- Dixit A, Upadhyaya M, Dixit K, Pokhrel A, Rai DR.** 2009. *Living with Water Stress in the Hills of the Koshi Basin, Nepal*. Kathmandu, Nepal: International Centre for Integrated Mountain Development.
- FAO [Food and Agriculture Organization of the United Nations].** 1995. *The Digitized Soil Map of the World and Derived Soil Properties* (version 3.5). FAO Land and Water Digital Media Series 1. Rome: FAO.
- FAO [Food and Agriculture Organization of the United Nations].** 2012. *Aquastat*. Rome: FAO. [www.fao.org/nr/water/aquastat/main/index.stm](http://www.fao.org/nr/water/aquastat/main/index.stm); accessed on 10 January, 2012.

- GoN-WECS [Government of Nepal, Water and Energy Commission Secretariat].** 1999. *Basin Wise Water Resources and Water Utilization Study of the Koshi River Basin*. Kathmandu, Nepal: GoN-WECS.
- GoN-WECS [Government of Nepal, Water and Energy Commission Secretariat].** 2005. *National Water Plan, Nepal*. Kathmandu, Nepal: GoN-WECS.
- GoN-WECS [Government of Nepal, Water and Energy Commission Secretariat].** 2011. *Water Resources of Nepal in the Context of Climate Change*. Kathmandu, Nepal: GoN-WECS.
- Gosain AK, Rao S, Basuray D.** 2006. Climate change impact assessment on hydrology of Indian river basins. *Current Science* 90(3):346–353.
- Gosain AK, Rao S, Mani A.** 2011. *Hydrological Modelling: A Case Study of the Koshi Himalayan Basin Using SWAT*. Soil Hydrology, Land Use and Agriculture. Wallingford, United Kingdom: CAB International.
- Hansen M, DeFries RS, Townshend JRG, Sohlberg R.** 2003. *LBA Regional Land Cover from AVHRR, 1-km, 1992–1993*. Oak Ridge, TN: Oak Ridge National Laboratory Distributed Active Archive Center. <http://dx.doi.org/10.3334/ORNLDAAC/678>.
- Immerzeel WW, Pellicciotti F, Bierkens MFP.** 2013. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience* 6:742–745.
- Jones PG, Thornton PK, Diaz W, Wilkens PW, Jones AL.** 2002. *MarkSim: A Computer Tool that Generates Simulated Weather Data for Crop Modeling and Risk Assessment*. Cali, Colombia: Centro Internacional de Agricultura Tropical.
- Jones PG, Thornton PK, Heinke J.** 2009. *Generating Characteristic Daily Weather Data Using Downscaled Climate Model Data from the IPCC's Fourth Assessment*. Project report. <https://hc.app.box.com/shared/f2gk053td8>; accessed on 2 February 2012.
- Karki MB, Shrestha AB, Winiger M.** 2011. Enhancing knowledge management and adaptation capacity for integrated management of water resources in the Indus River Basin. *Mountain Research and Development* 31(3):242–251.
- Kripalani RH, Oh JH, Kulkarni A, Sabade SS, Chaudhari HS.** 2007. South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4. *Theoretical and Applied Climatology* 90:133–159.
- Krishnamurthy CKB, Lall U, Kwon HH.** 2009. Changing frequency and intensity of rainfall extremes over India from 1951 to 2003. *Journal of Climate* 22:4737–4746.
- Moors EJ, Groot A, Biemans H, van Scheltinga CT, Siderius C, Stoffel M, Huggel C, Wiltshire A, Mathison C, Ridley J, Jacob D, Kumar P, Bhadwal S, Gosain A, Collins DN.** 2011. Adaptation to changing water resources in the Ganges basin, northern India. *Environmental Science & Policy* 14(7):758–769.
- NCVST [Nepal Climate Vulnerability Study Team].** 2009. *Vulnerability through the Eyes of the Vulnerable: Climate Change Induced Uncertainties and Nepal's Development Predicaments*. Kathmandu, Nepal: Institute for Social and Environmental Transition, Nepal Climate Vulnerability Study Team.
- Qiu J.** 2013. Floods spur mountain study. *Nature News*, 4 September.
- Seidel K, Martinec J, Baumgartner MF.** 2000. Modelling runoff and impact of climate change in large Himalayan basins. International Conference on Integrated Water Resources Management (ICIWRM), 19–21 December, Roorkee, India.
- Sharma KP, Moore B, Vorosmarty CJ.** 2000a. Anthropogenic, climatic, and hydrologic trends in the Koshi basin, Himalaya. *Climatic Change* 47(1–2): 141–165.
- Sharma KP, Vorosmarty CJ, Moore B.** 2000b. Sensitivity of the Himalayan Hydrology to landuse and climatic changes. *Climate Change* 47:117–139.
- Singh P, Bengtsson L.** 2005. Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region. *Journal of Hydrology* 300(1–4):140–154.
- Singh P, Haritashya UK, Kumar N.** 2008. Modelling and estimation of different components of streamflow for Gangotri Glacier basin, Himalayas. *Journal of Geophysical Research* 53(2):309–322.
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors.** 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.
- Srinivasan R, Ramanarayanan TS, Arnold JG, Bednarz ST.** 1998. Large area hydrologic modeling and assessment, Part II: Model application. *Journal of the American Water Resources Association* 34(1):91–101.
- Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, editors.** 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.
- UNEP [United Nations Environment Programme].** 2008. Freshwater under threat South Asia: Vulnerability assessment of freshwater resources to environmental change. [www.roap.unep.org/pub/](http://www.roap.unep.org/pub/); accessed on 5 July 2009.
- WFP [World Food Programme].** 2009. Winter drought worsens food insecurity in Nepal. Rome: WFP. [www.wfp.org/news/news-release/winter-drought-worsens-food-insecurity-nepal](http://www.wfp.org/news/news-release/winter-drought-worsens-food-insecurity-nepal); accessed on 5 July 2009.
- World Bank.** 2009. *Nepal: Priorities for Agriculture and Rural Development*. Washington, DC: World Bank. <http://go.worldbank.org/D9M30RHVLO>; accessed on 2 July 2009.