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Impacts of climate change on the hydrological regime of the Koshi river basin in the Himalayan region

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Abstract

Understanding the potential impact of climate change on the hydrological regime in the Himalayan region is of great importance for sustainable water resources management. This study assessed the historic and projected climate trends in the Koshi river basin using statistical analysis. The hydrological characteristics and the contribution of different runoff components under present and projected future conditions were investigated in the Dudh Koshi sub-basin using the J2000 model. Data for 1995 to 2096 from the Providing REgional Climates for Impacts Studies (PRECIS) regional climate model were used in the J2000 model to project the impact of climate change under the A1B climate scenario in mid-century (2040–2050) and late-century (2086–2096), compared to baseline (2000–2010). Present climate showed an increase in average temperature in the river basin at a rate of 0.058 °C/year for maximum temperature and 0.014 °C/year for minimum temperature over the past forty years. The model simulation of the hydrological regime from 1985 to1997 was satisfactory. The average annual contribution of snow and glacier melt to total discharge was about 34%, whereas it was 63% in the pre-monsoon season (March to May). The projected future results from the model indicate a 13% increase in annual discharge by mid-century followed by a slight decrease; and a 16% increase in evapotranspiration by the end of the century. Snowfall is projected to decrease substantially due to the rise in temperature, the basin will lose snow storage capacity, and there will be a marked decrease in snowmelt runoff from non-glaciated areas. In contrast, melt from glaciated areas will increase up to mid-century and start decreasing thereafter. The model results suggest that snowfall pattern, snowmelt, discharge, and evaporation are all sensitive to the effects of climate change.

Keywords: Trend analysis; J2000 hydrological model; Climate change; Snow and glacier melt; Himalayan region; Dudh Koshi basin

1. Introduction

The mountains of the Himalayan region play a vital role in the regulation and distribution of water resources. These mountains contain the headwaters of ten major river systems – the Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze, and Yellow – that provide services to 1.3 billion people downstream (Eriksson et al., 2009). Many of the people in the river basins depend directly on these water resources as a basis for their livelihoods, including for food production, hydropower, industry, and domestic supply (Mirza et al., 2001). The snow and ice stored in the headwater regions of the major rivers sustains seasonal water availability in the downstream areas through melt runoff (Immerzeel et al., 2010; Nepal et al., 2014b). The potential impact of global climate change on the hydrological regime of the region (Eriksson et al., 2009; Immerzeel et al., 2010; IPCC, 2007a; Nepal, 2012; Nepal and Shrestha, 2015) and the distribution of water resources in both upstream and downstream areas (Nepal et al., 2014a) has been discussed widely in recent years, but the likely impact on water resources availability remains unclear for different sectors (such as agriculture) (Immerzeel et al., 2010).

The temperature in the Himalayan region has been reported to be increasing faster than the global average. The maximum temperature in Nepal increased at a rate of 0.06 °C per year between 1978 and 1994, with higher rates at higher elevations (Shrestha et al., 1999); temperatures on the Tibetan Plateau increased at a rate of 0.16 °C per decade between 1955 and 1996 (Liu and Chen, 2000). Sharma et al., (2000a) found an increasing temperature trend across the Koshi river basin in eastern Nepal, which was homogenous with respect to seasons, but heterogeneous with respect to sites. Many climate models, on both global and regional scales, indicate that the temperature of the region will rise by 2.5 to 5 °C by 2100 (Immerzeel et al., 2012; Kumar et al., 2011). The results for precipitation changes

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are less clear. Shrestha et al. (2000) did not identify any significant trends in the Nepal Himalayas, while Sharma et al. (2000a) found localized trends in precipitation in the Koshi river basin which lacked basin-wide significance. Indian summer monsoon rainfall has been projected to increase by 20% by the end of this century (Kumar et al., 2011), but the rate of change identified varied with the input from the different general circulation models (GCMs) and regional climate models (RCMs) and scenarios adopted in the study. Overall, the various studies suggest that the intensity of precipitation is likely to increase in the coming decades (Immerzeel et al., 2012; Kumar et al., 2011).

It is likely that under these projected scenarios, the water balance of the region will change, which could affect water availability downstream (Akhtar et al., 2008; Nepal et al., 2014a). Recent studies on climate change and water resources in the Himalayan region have mainly focused on the impact of global climate change on the glacier regime (Akhtar et al., 2008; Immerzeel et al., 2012; Lutz et al., 2014), but the combination of lack of data from these remote and inaccessible areas, and the complex response of glaciers to warming, means that there is considerable uncertainty in the results. Studies by Immerzeel et al. (2013) and Lutz et al. (2014) on the Himalayan watersheds indicate that overall annual runoff will increase with a change in climate as a result of an increase in precipitation as well as an increase in net glacier melt. The results suggest that the annual total water availability will be maintained until the middle of the century, but the impact of an increase in extreme hydrological events such as drought and floods associated with climate change (IPCC, 2007b) might seriously affect seasonal water availability in the downstream areas. However, all these studies have focused on the large domain of the Himalayan region and forced the models with climate projections applicable to the whole region. But there is considerable variation within the Himalayan region as a result of marked differences in topography, geology, and terrain which affect the climate system and the generation of runoff. Thus it is important to investigate the potential impacts of climate change in smaller scale catchments where the conditions can be modeled more precisely. There have been very few studies at this scale in the Himalayan region. The present study looked at the impact of climate change on future hydrology at a meso-scale by applying the regional climate model data to a meso-scale catchment.

The study had two objectives: (1) to identify the present climatic trends from historic data, and (2) to assess the projected impact of climate change on the hydrological regime. An integrated systems analysis approach was used to analyze hydro-climatic trends and to assess the impact of projected climate change on the hydrological regime in the Koshi river basin (KRB) – a large river basin in the Himalayan region dominated by glaciers in the high-altitude area. The mountain and hill part of the KRB (up to Chatara) is shared between China (to the north) and Nepal to the south, and has a distinctive climate as a result of its location across the northern and southern flanks of the Himalayas. The historic (observed) and projected trends in temperature and precipitation were calculated using statistical analysis. The hydrological system dynamics were analyzed in the Dudh Koshi (sometimes written Kosi) sub-basin using the process-oriented distributed J2000 hydrological model, which includes both hydrological and cryospheric processes (snow and glacier melt). Finally, the projected meteorological data from the PRECIS RCM A1B scenario (research period 1995 to 2096; baseline 2000–2010) were used as an input in the hydrological model to assess the impact on the hydrological regime. This type of systematic approach contributes to improved understanding of the effect of projected climate change on different watershed components, and the potential influence on water distribution in the basin, including future water availability downstream.

2. Materials and methods

2.1. The study area

The study area comprised the northern part of the Koshi river basin (KRB) from the Tibetan Plateau in China to Chatara in Nepal, where the river leaves the hills and enters the Indo-Gangetic flood plains (Fig. 1) before flowing through Bihar (India) to join the Ganges at Kursela. This part of the basin has a total area of 57,000 km^2; it is characterized by steep topography and high mountain peaks, and is dominated by glaciers in the high altitude areas. The elevation ranges from 8848 (Mt Everest) to 140 masl. The river has seven tributaries, six of which originate in the high altitude areas of the basin. North of the main Himalayan range, the basin is characterized by a dry alpine climate with low precipitation, whereas the southern part, which extends from the high mountains to the mid-hills, has a humid climate with relatively high precipitation. According to Sharma et al. 2000b, average annual precipitation in the southern part of the basin (1931 mm) is four times higher than that in the northern part (536 mm). Similarly, average annual evapotranspiration in the southern part (507 mm) is far higher than in the northern part (178 mm).

The Dudh Koshi sub-basin was selected for hydrological modeling and impact analysis of climate change (Fig. 2). The sub-basin has a total area of 3712 km^2 with an elevation range from 8848 masl (Mt. Everest) to 465 masl (Rabuwa Bazaar gauging station) and average elevation of 3800 masl. The basin physiography ranges from the High Himalayas above 3000 masl, dominated by high mountains, glaciers (13% of the basin area), and permafrost and with a sub-alpine to alpine climate, to the Lesser Himalayas below 3000 masl, with a sub-tropical climate, where most of the anthropogenic activities such as agriculture and human settlements are found.

2.2. Data description

The historic trend in precipitation was analyzed using data from 36 precipitation stations in the Koshi basin. Details of the stations and data availability are given in Table 1. The 36 precipitation stations were located along four river corridors in the Koshi basin; the location is shown in Fig. 1. The precipitation data from different stations were available for different periods; stations were selected within a corridor that had the same time length of data (Table 1).

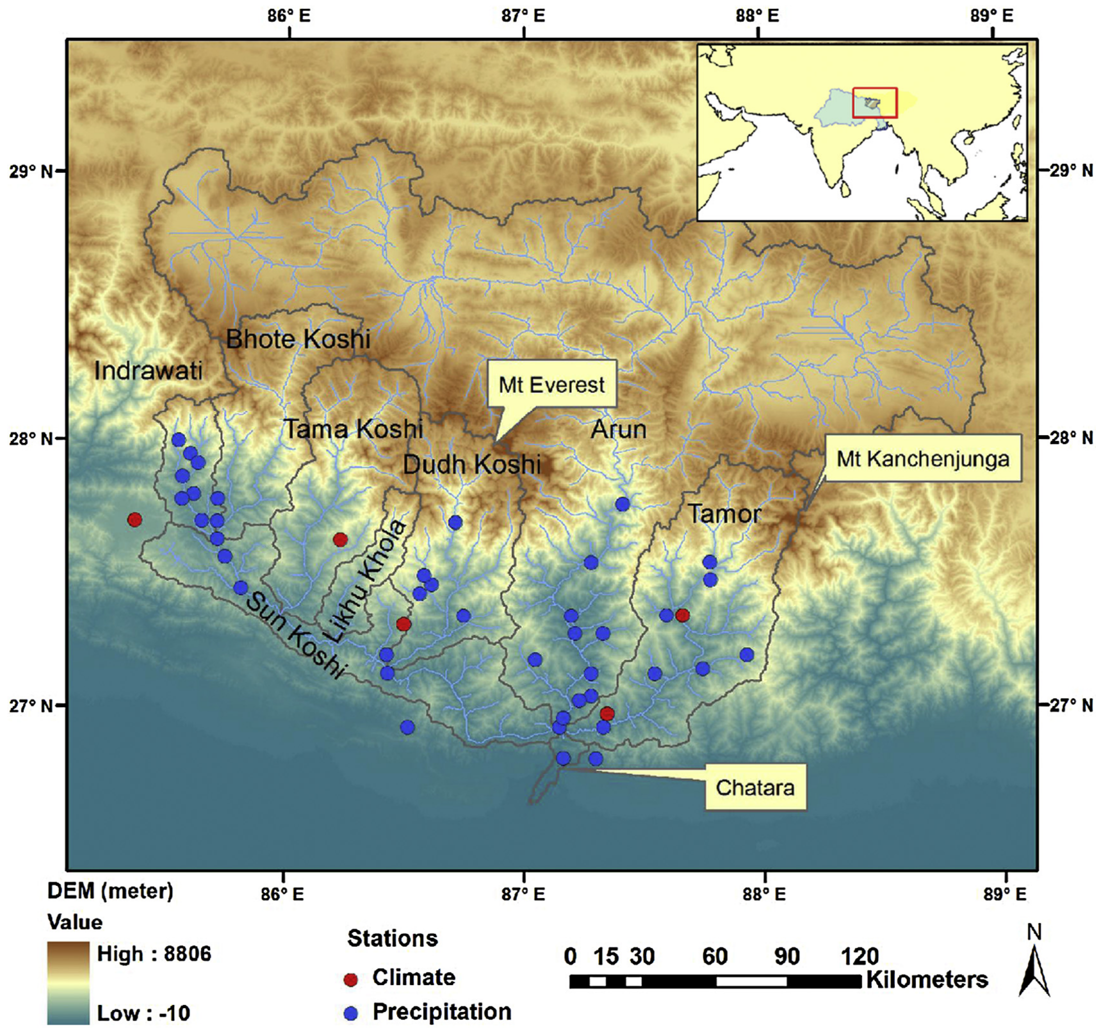


Fig. 1. The Koshi river basin (up to Chatara) showing tributaries and sub-basins, and position of precipitation (blue circles) and temperature (red circles) stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The historic temperature trend was analyzed using data from five temperature stations located at different points across the Koshi sub-basin. Details of the stations and data availability are given in Table 2, the location is shown in Fig. 1. The stations included one in Kathmandu, about 10 km to the south of the basin, due to its long-term data availability. All other temperature stations in the basin were excluded because the data had missing values (in some cases as long as five years) and/or only very short duration time series. Data from two stations in the part of KRB in China were not publicly available and could not be analyzed.

Table 1
Data used for analyzing precipitation trends in the Koshi river basin up to 2007; number of stations in the four river corridors and period for which data are available.

River corridor	Period for which data are available (years)	No. of stations
Indrawati	1973–2007 (35 years)	11
Dudh Koshi	1952–2007 (56 years)	6
Arun	1974–2007 (34 years)	11
Tamor	1952–2007 (56 years)	8

Hydrological modeling was performed using the data for 1985–1997 from five precipitation stations, one climate station and one discharge station in the Dudh Koshi sub-basin (Fig. 2). Details of the stations and mean annual precipitation are shown in Table 3. Data generated from the PRECIS RCM under the A1 B scenario with grid 50 × 50 km were applied in the model to project the future hydrology.

2.3. Statistical analysis of precipitation and temperature

The precipitation and temperature data were tested for homogeneity as a measure of quality. The homogeneity of the dataset was checked using double sum analysis (Raghunath, 2006); for this, the station data were compared with data from another station in the same corridor which had long-term data with only a few missing values. Precipitation data from 4 stations were excluded as they failed the double-mass analysis test; data from the remaining 36 stations were used in the analysis. Data gaps were analyzed carefully before analyzing trends over the longer period. Availability of long-term data with only a few missing values indicated that the station had operated with a minimum of problems over a longer time. If the data gaps were

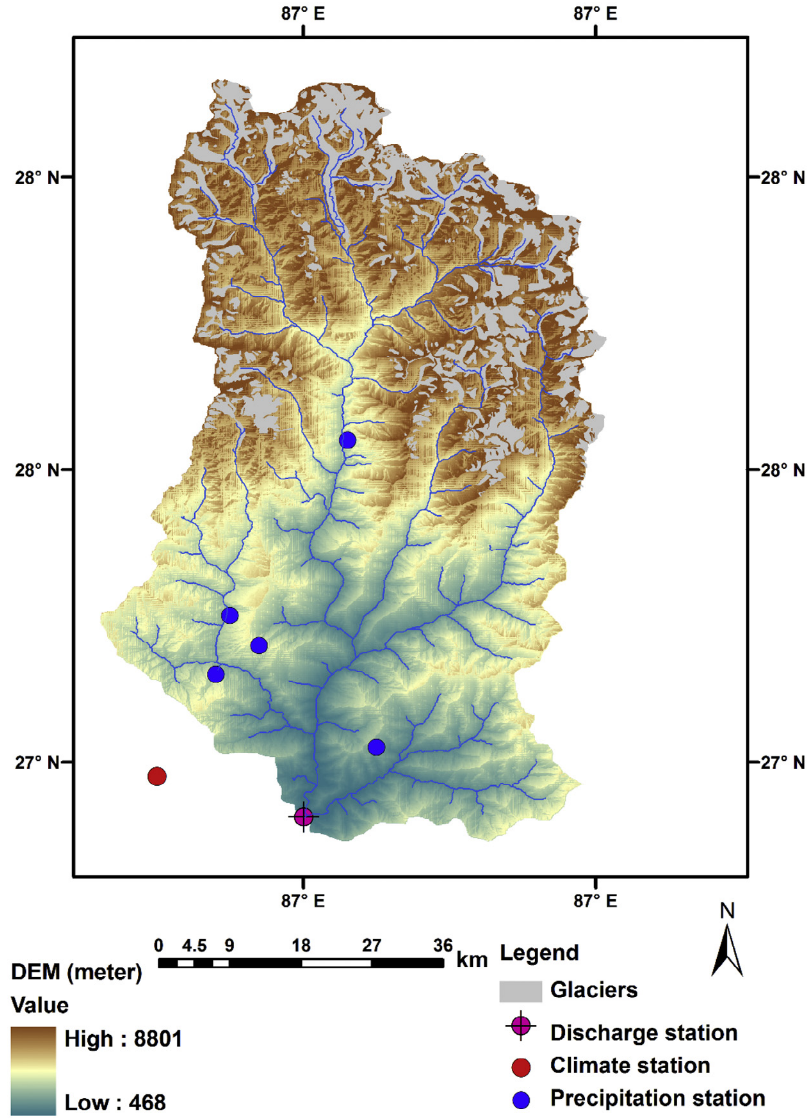


Fig. 2. The Dudh Koshi sub-basin showing the position of the stations that provided the data used to calibrate and validate the hydrological model. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

for less than one month during the monsoon season (which has around 80% of rainfall), or three months outside the monsoon season, the missing precipitation data were filled using IDW (inverse distance weighting) with elevation correction. Only nearby stations were used to fill missing values because the precipitation pattern varied substantially with position, in some cases over very short distances. The temperature data had considerably fewer gaps than the precipitation data. Gaps of less than four days were filled using linear interpolation with the average from the days before and after the gaps; longer gaps of up to two months were filled using linear regression with data from nearby stations. The coefficients of determination (r^2) for

Table 2
Data used for analyzing temperature trends in the Koshi river basin; details of stations and trends in maximum and minimum temperatures (°C/year).

Station	Elevation (masl)	Data period (year)	Maximum temperature		Minimum temperature	
			Trend (°C)	Significance	Trend (°C)	Significance
Jiri	2003	1967–2009	+0.044	***	−0.013	–
Okhaldhunga	1720	1963–2009	+0.053	***	+0.023	***
Dhankuta	1210	1987–2009	+0.219	***	+0.029	*
Kathmandu airport	1336	1968–2009	+0.073	***	+0.032	***
Taplejung	1732	1987–2009	+0.077	***	+0.024	–

Note: *Z = 0.05; ***Z = 0.001.

Table 3
Data used for hydrological modeling in the Dudh Koshi sub-basin; details of stations and annual mean precipitation (data period 1985–1997).

Station	Data type[a]	Latitude (deg.)	Longitude (deg.)	Elevation (m) asl	Annual mean (mm)
Aiselukhark	P	27.21	86.45	2143	2417
Pakarnas	P	27.26	86.34	1982	1885
Chialsa	P	27.46	86.61	2770	1806
Sallery	P	27.3	86.35	2378	1592
Chaurikark	P	27.42	86.43	2660	2096
Okhaldhunga	P,T and climate parameters	27.19	27.19	1,720	1805
Rabuwabazaar	D	27.26	86.65	670	1602[b]

[a] P = precipitation, C = climate, D = discharge.
[b] Average discharge value.

nearby stations to fill the missing gaps were in the range 0.8 to 0.95.

Precipitation and temperature trends were analyzed using the non-parametric rank-based Mann–Kendall (MK) test (Kendall, 1975; Mann, 1945). Non-parametric tests make no assumptions about the distribution of data and are useful for detecting monotonic trends. In addition, the MK test is based on sign differences rather than value, and is thus robust to the effect of extreme values and outliers (Helsel and Hirsch, 2002). It is widely used for trend analysis (Gemmer et al., 2004; Hamed, 2008; Sharma et al., 2000a; Shrestha et al., 1999; Souvignet, 2011).

The MK test statistics (S) were calculated using the formula:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k)$$

where x_j and x_k are the annual values in years j and k, ($j > k$), respectively.

The presence of a statistically significance trend was estimated using the Z value, with a positive or negative value of Z indicating an upward or downward trend, respectively. Z has a normal distribution (Salmi et al., 2002). The significance level increases with the number of successive identical signs. Three different significance levels were used: 0.001 or 99.9% confidence level (***), 0.01 or 99% confidence level (**), and 0.05 or 95% confidence level (*). A significance level of 0.001 means that there is only a 0.1% probability that the values x_i are from a random distribution, and thus that a monotonic trend is very likely (Helsel and Hirsch, 2002).

The non-parametric Sen's method was used to estimate the true slope of the identified trends (quantitative value as change per time step) (Sen, 1968). The method can be used in cases where the trend can be assumed to be linear. It calculates the median of all possible pairwise slopes and is particularly useful since missing values are allowed during the analysis. A positive value indicates an upward trend (i.e. increasing with time), whereas a negative value indicates a downward trend (i.e. decreasing with time). The widely-used excel template application MAKESENS developed by the Finnish Meteorological Institute was used to estimate trends (Salmi et al., 2002).

2.4. Hydrological modeling

The J2000 hydrological model (Krause, 2001, 2002) was used to investigate the hydrological characteristics of the Dudh Koshi sub-basin. The J2000 is a process-based hydrological model in which catchment properties are distributed using the concept of hydrological response units (HRUs) (Flügel, 1995). The model receives spatially distributed information about the catchment (such as soil, land use, geology, elevation, slope and aspect) from the HRU parameter file in which hydrological processes are controlled by calibration parameters. The principal layout of the model is shown in Fig. 3. A glacier module is integrated into the standard J2000 hydrological model to simulate the snow and glacier melt from glacier areas of the basin (Nepal et al., 2014b). The glacier melt is a function of enhanced degree day factor taking into account temperature, radiation, slope, aspect, and a debris-covered factor (for details see Nepal, 2012; Nepal et al., 2014b). The glacier runoff is defined as total runoff from the glacier area (i.e HRU), including seasonal snowmelt, glacier ice melt, and rain runoff (rain

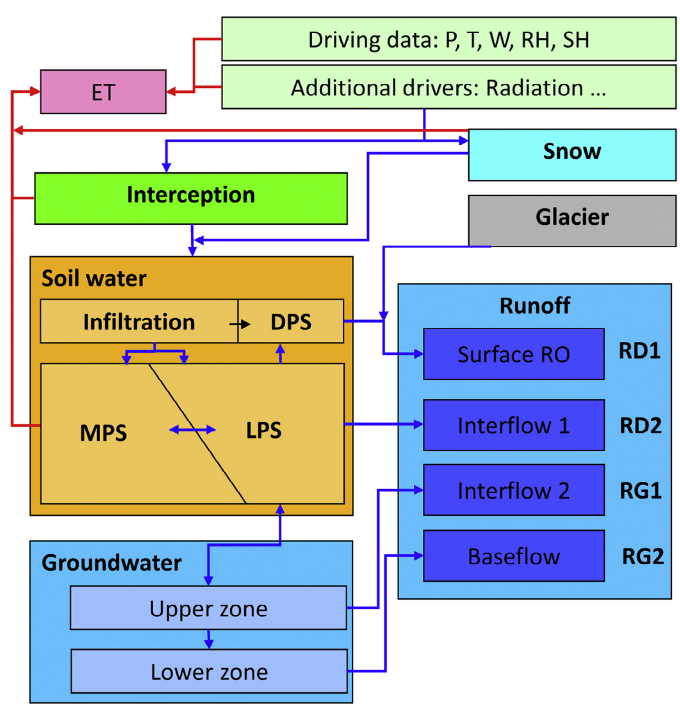


Fig. 3. The principal layout of the JAMS/J2000 hydrological model (adapted from Krause, 2001). Note: ET = evapotranspiration, P = precipitation, T = air temperature, W = wind speed, RH = relative humidity, SH = sunshine hours, LPS = large pore storage, MPS = middle pore storage, DPS = depression storage.

falling on the glacier surface). In the model, ice melt is triggered when snow storage is zero in the glacier HRU. The snowmelt (non-glacier snowmelt) is taken as the runoff from snow outside the glacier and also includes rain-on-snow, which is high in the lower elevation areas and low in higher elevation areas.

The model takes into account the important hydrological processes such as interception, evapotranspiration, snow and glacier melt, soil water, groundwater, and routing. For details of model input data, modeling application, and calibration parameters for the J2000 model, see Nepal (2012). Briefly, in the model, the precipitation is first distributed between rain and snow depending upon the threshold air temperature. The interception modules take into account the rain and snow stored in vegetation by considering the leaf area index of the vegetation types. The snowmelt is calculated by considering the external energy, supplied in the form of temperature, and rain and soil, which are provided as calibration parameters. The meltwater is stored in a snow pack as liquid water which is released only when the snow density is higher than a threshold provided by the user. The snowmelt is then supplied to the soil water module. The input to the soil water module is distributed in soil storage, which is divided into large pore storage (LPS) and middle pore storage (MPS) depending on the soil texture of a particular soil type. When the soil storage is filled (i.e. soil is saturated), the saturation excess runoff dominates. The model also considers the infiltration excess runoff (summer and winter seasons and snowmelt runoff), which is controlled by a threshold in the form of calibration parameters. These are taken together as surface runoff (RD1). The water stored in the MPS is reduced by plant transpiration and is determined by actual evapotranspiration (actET). The model first calculates the potential evapotranspiration (potET) which is the maximum amount of water evaporated under the given climatic conditions using the Penman–Monteith approach as described in Allen et al. (1998). Later, the actET is estimated based on the available water storage in the snowpack, interception, and MPS. The soil moisture zone provides sub-surface runoff (RD2), which is the excess water outflow from the LPS zone, which corresponds to the lateral runoff within the soil zone and reacts more slowly than RD1. The excess water from the soil water module is supplied to groundwater and thereby distributed between upper and lower groundwater storage compartments. The outflow from the upper groundwater storage, represented as a shallow aquifer, is taken as the interflow (RG1) and is slower than the sub-surface outflow. The lower groundwater storage, represented as deep aquifer, is responsible for base flow production (RG2), and is the slowest of all outflows. The J2000 model has two routing components: the lateral routing describes the water flowing from the upper HRU to the lower HRU (in a hill slope) until it reaches the stream network. The routing in the stream network is described by kinematic flood routing in which the runtime of runoff waves is controlled by calibration parameters. The model has altogether 36 calibration parameters, of which 16 were found to have greater influence and were used for sensitivity and uncertainty analysis as described in Nepal et al. (2014b).

The J2000 model was applied in the Dudh Koshi sub-basin from 1985 to 1997; the calibration period was taken as 1986 to 1991 and the validation period from 1992 to 1997. The first year was taken as the initialization period. Precipitation data were taken from six stations (Fig. 2 and Table 3). The discharge data from Rabuwabazar gauging station were used for model validation (Fig. 3). The model performance was assessed using the Nash-Sutcliffe efficiency coefficient (ENS) (Nash and Sutcliffe, 1970), log Nash-Sutcliffe (LNS), and the co-efficient of determination (r2) (Krause et al. 2005). The results of the calibration and validation, including sensitivity and uncertainty analysis, are described in detail in Nepal et al. (2014b).

2.5. Climate change impact analysis

Climate projection data from the PRECIS (Providing REgional Climates for Impact Studies) regional climate model were used to investigate the impact of climate change on the hydrological regime. PRECIS is a regional climate modeling system developed by the Hadley Centre, UK, and was run at the Indian Institute of Tropical Meteorology (IITM), Pune, India, at a horizontal resolution of 50×50 km over the South Asian domain (Kumar et al., 2011). The PRECIS data were provided by IITM, Pune. PRECIS is based on the atmospheric component of the Hadley Centre Coupled Model (HadCM3) GCM (Gordon et al., 2000) which is described in Jones et al. (2004). The PRECIS simulations correspond to the IPCC SRES A1B emission scenario (Kumar et al., 2011). The A1B storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in the mid-21st century and declines thereafter, and the rapid introduction of new and more efficient technologies.

The PRECIS RCM is widely used to project data for climate change related studies in the monsoon-dominated Himalayan region (for example, Akhtar et al., 2008; Rajbhandari et al. 2014; Forsythe et al. 2014). The PRECIS output is described in detail in Kumar et al. (2011). There are three simulation outputs; the different parameter sets are provided as a part of the quantification of uncertainties in climate projection. The standard parameter setting, Q0, was used in the present study as it has shown better results in simulating seasonal monsoon rainfall (Kumar et al., 2011).

The calibrated and validated J2000 hydrological model was run with PRECIS input data from 1995 to 2096 to analyze the impact of projected climate change on future hydrology. The initial five years (1995–1999) was used as the initialization period and the next decade from 2000 to 2010 as the baseline period. The continuous 100 years of data from the RCM enabled future hydrology to be projected for two time slices representing mid century (2040–2050) and late century (2086–2096). Looking at two future time slices rather than trends is useful in terms of the implications for policy (Rajbhandari et al., 2014). A similar approach using the average over a decade to provide a single future time slice has been used in a number of studies (e.g., Lutz et al., 2014). However, uncertainty remains as the future projections represent only a 10-year period. The various levels of uncertainty in projections of climate change impact are discussed in the results section.

The PRECIS RCM data were used directly in the J2000 model to compare the baseline hydrology with future hydrology. The bias behavior of the climate projection data is consistent in the past and future time periods. Also, bias correction could have an impact on the climate change signal for specific locations and months and thereby create another level of uncertainty in the model results (Hagemann et al., 2011). In the present study, a direct approach was used in which the future simulated precipitation and temperature from the PRECIS RCM was directly applied in the hydrological model. Some studies of future scenarios like delta change (Hay et al., 2002) estimate the expected change in climate variables, and add the differences to the observed data to create a future dataset. In this study the direct approach was sufficient, as the analysis of future hydrology focused on change with reference to the baseline, not on absolute values, and both the baseline and future scenarios were derived from the PRECIS dataset. The same approach was also used by Akhtar et al. (2008).

The PRECIS precipitation grid data that were compared with the observed station data (1985–1997: model run period) for monthly precipitation shows coefficient of determination (r^2) was 0.69; PRECIS underestimates in July and August (monsoon season) and overestimates in the dry, non-monsoon, season. Overall, PRECIS overestimates by 17%. The monthly temperature showed a coefficient of determination (r^2) of 0.99. The results corresponded closely in the summer, and PRECIS slightly underestimated temperatures in the winter. As the eight grids contained only a few monitoring precipitation stations, and no high altitude data, the results can be considered satisfactory.

2.5.1. Assumptions and limitations

The following assumptions were made while assessing the impact of climate change on the hydrological regime using the climate projected data.

1. A few adjustments were made to adapt the conditions of the PRECIS data to the J2000 model. First, PRECIS provides 50 km grid resolution data, and the Dudh Koshi sub-basin has six grids. For the modeling exercise, the center of the grid was considered as a station, and the value of the grid cells was then regionalized into the surrounding HRUs. The model was calibrated and validated from 1985 to 1997 using observed data. As this only included one temperature station so the lapse rate was used for temperature distribution. However, in PRECIS, there were six temperature stations for the projected climate data, thus inverse distance weighting (IDW) was used instead.
2. In the glacier area, the modeling application with the PRECIS data was carried out with snowmelt only; glacier icemelt was not included because the glacier area and related ice storage is time invariant in the J2000 modeling system. In the model, the contribution from ice melt increases in the future hydrology assessment if the air temperature rises (and vice versa) because the ice melt is a function of the degree-day factor, but in reality the glacier area will be reduced with increase in temperature (Immerzeel et al., 2012), which would reduce the actual amount of glacier melt. Rees and Collins (2006) discussed these shortcomings in studies in which the future glacier area is time variant (Sharma et al., 2000b; Singh and Bengtsson, 2003; Singh and Kumar, 1997).

3. Results and discussion

3.1. Precipitation and temperature trend analysis

The precipitation trend for each station is shown in Fig. 4 (period range 1952–2007 to 1974–2007 depending on station). Altogether, 22 of the 36 stations showed an increasing trend in precipitation, which was only statistically significant in two cases, and 14 stations showed a decreasing trend, which was only statistically significant in one case. These results are similar to those reported elsewhere which indicate that trends in precipitation tend to be inhomogeneous (Sharma et al., 2000a; Shrestha et al., 2000).

The trends for maximum and minimum temperature for each of the five stations are shown in Fig. 5; and the rates of change are given in Table 2. All stations showed a statistically significant increasing trend for maximum temperature; all except Jiri showed an increasing trend for minimum temperature, but only three were statistically significant. At Dhankuta, Kathmandu, and Taplejung, 2009 was the warmest year. The average rate of change was calculated using data from the three stations with longer-term (>40 years) data series (Jiri, Kathmandu, and Okhaldunga). Based on these, the maximum temperature in the Koshi region increased at a rate of 0.058 °C/year, and the minimum temperature at a rate of 0.014 °C/year for the forty years up to 2009 (statistically significant at 0.001 level of significance). This confirms the results reported by Shrestha et al. (1999), among others, of increasing temperature trends for the whole of Nepal.

The PRECIS RCM data projected a gradual increase in temperature at a rate of 0.46 °C per decade for both the mid-century and late-century study periods, resulting in an overall increase in mean temperature of about 4 °C by the end of the century. This is similar to the results reported by Immerzeel et al. (2012), who estimated future precipitation and temperature in a glaciated alpine catchment in central Nepal based on five GCMs (CGCM3.1, CM2.0, ECHAM5, MIROC3.2, HADGEM1) and projected a temperature increase of 0.6 °C/decade. It is also in line with the observed historical trend in the KRB which shows a gradual increase in temperature over the past half century. However, there is some uncertainty associated with the result because of the limited number of climate stations in the basin that could provide data for the analysis, which thus represent point data. Also, as in many mountainous regions (Barry, 2008; Nepal et al., 2014b), the majority of stations in high altitude areas were located along the river valleys (Fig. 2), and the overall density was low at only one station per 618 km^2. Only one PRECIS RCM scenario – A1B – was considered for future scenarios; thus it was not possible to assess the uncertainty associated with the future scenario by comparing results

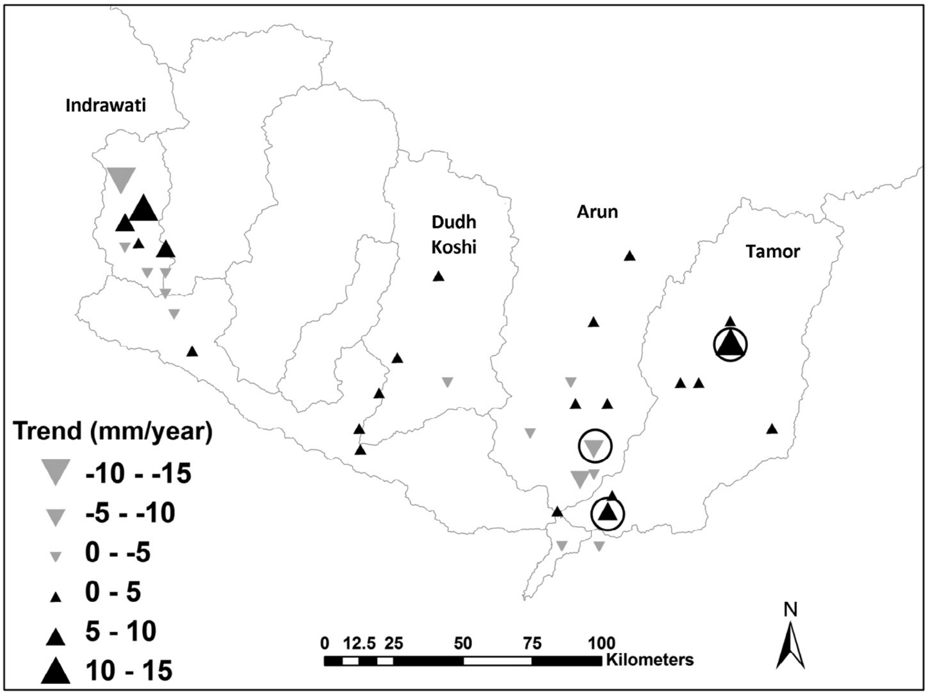


Fig. 4. Precipitation trends in the Koshi river basin; black triangles represent increasing trends, grey triangles decreasing trends, circled symbols are statistically significant.

from a range of scenarios or GCMs as discussed in Rajbhandari et al. 2014; Kumar et al. 2006; Lutz et al., 2014.

3.2. Hydrological modeling

The J2000 was applied at a daily timescale. The plots for calibration and validation (Nepal et al. 2014b) show that the model is able to represent the overall hydrological dynamics. The base flow and medium range flows are well represented, although some underpredictions were seen in the initial years. The flood peaks are also well represented, which can be seen especially in the years 1991, 1996, and 1997. Overall, the modeling results indicate that the J2000 model is able to simulate the hydrological dynamics of the monsoon-dominated alpine catchment of the Dudh Koshi sub-basin. The Nash–Sutcliffe (ENS) efficiency was 0.84 and 0.87 for the calibration and validation periods, respectively. The efficiency results for three objective functions (ENS, LNS, and r^2) are shown in Table 4. The model efficiency results also indicate that the simulations were equally good for high and low flows.

The modeling application provides important information about the hydrological processes in the catchment. The glacier melt runoff contributes about 17% of the catchment discharge, including 5% from glacier icemelt; while snowmelt from outside the glacier area (non-glacier HRU) also contributes about 17%. Thus snow and glacier melt are an important source of streamflow, together contributing about 34% of annual discharge. The melt runoff contribution is particularly significant during the premonsoon season (March to May), providing 63% of streamflow when water is otherwise scarce (Table 5), compared to 10% during winter (November to February) and around 39% in the monsoon season (June to September). This suggests that the seasonal contribution of melt runoff is more important than the annual average, and highlights the importance of considering seasonal variation when looking at the potential impact of any change.

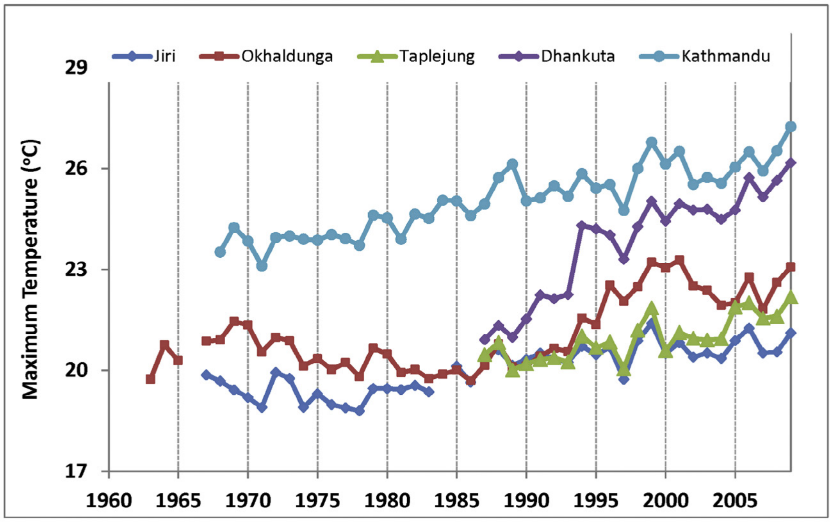
Similarly, the model is able to distinguish different runoff components. Overland flow was the major component in the

Table 4
Model efficiency results for the calibration and validation periods.

Efficiency criteria	Calibration	Validation
Nash–Sutcliffe (ENS)	0.84	0.87
Log Nash–Sutcliffe (LNS)	0.90	0.95
Coefficient of determination (r^2)	0.85	0.88

Table 5
Monthly contribution of glacier melt (from glacier area) and snowmelt (from non-glacier area) to discharge. (The glacier melt is defined as seasonal snowmelt, glacier icemelt, and rain-on-snow from the glacier area (glacier HRUs)).

Months	Glacier melt (%)	Snowmelt (%)
January	0	10
February	0	16
March	2	38
April	23	47
May	36	43
June	30	29
July	19	16
August	17	16
September	17	15
October	10	6
November	4	4
December	0.4	5



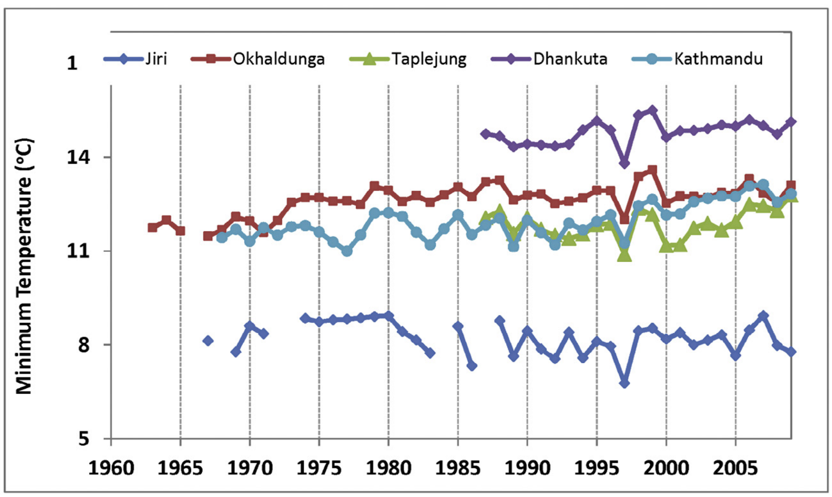


Fig. 5. Maximum (top) and minimum (bottom) temperatures at the five Koshi river basin temperature stations from 1960 to 2009. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

hydrograph and contributed nearly 50% of total discharge, the interflows (RD2 and RG1) contributed about 30%, and base flow about 20%. Thus base flow is an important part of the hydrograph; it also plays a major role in sustaining streamflow during the dry season.

The application of hydrological models is associated with uncertainty at various levels including model conceptualization (which is a simple representation of the real world), model forcing data, and model parameters (Beven, 2001). The model forcing data in this study also had limitations due to the low number of stations in high altitude areas. These sources of uncertainty in model input need to be considered when analyzing the model output data.

3.3. Impact of projected climate change on hydrology

The model was run with PRECIS input data from 1995 to 2096 to analyze the impact of projected climate change on future hydrology. The baseline and projected future precipitation and snowfall in the basin are shown in Fig. 6. Compared to the baseline (2000–2010), the annual precipitation is projected to increase by 13 and 14% (1.58 mm/year) in the mid- and late-century, respectively, with the increase more prominent in lowland areas than at higher elevations. Immerzeel et al. (2012) projected an increase in precipitation at a similar rate (1.9 mm/year) in Central Nepal using five GCMs. June is the wettest month in all periods. Snowfall is projected to decrease by 20 and 43% in the mid- and late-century periods, respectively, compared to the baseline period. This is mainly the result of the increase in temperature, which causes the snowline to shift upward and more precipitation to fall as rain instead of snow, which will also decrease the snow storage capacity of the basin.

3.3.1. Impact on water balance components

Fig. 7 shows the monthly hydrograph for the baseline and two future periods. The discharge is projected to increase overall during the monsoon (June to September) and post-monsoon (October to November) seasons for both the mid- and late-century periods compared to the baseline period. During the monsoon season, the discharge is increased by 26% and 18% in the mid- and late-century, respectively, with the change

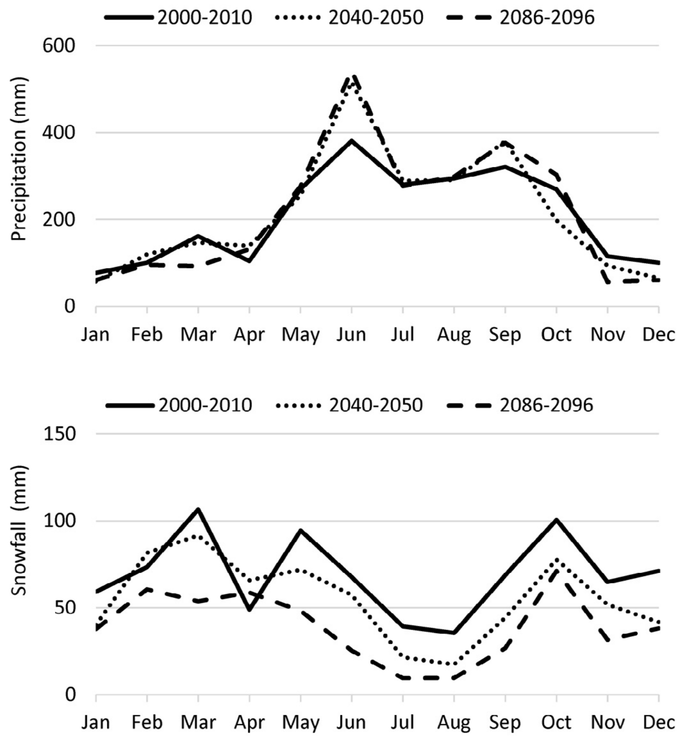


Fig. 6. Precipitation (top) and snowfall (bottom) in the Dudh Koshi river basin for baseline and future periods.

most pronounced at the start of the monsoon season, and a slight reduction in discharge in the latter part of the monsoon season, in the late-century scenario. The monsoon precipitation in mid and late century is virtually identical (Fig. 6: top), but the late century shows a slight increase in discharge in June, and a reduction in July to September, compared to the mid-century scenario. This variation may result from the reduction in snowfall (Fig. 6: bottom) and thus change in the amount of snow available to contribute to snowmelt, as well as changes in the snowmelt rate as a result of the increase in temperature. Increased evapotranspiration rates may also play a role.

Fig. 8 shows the projected impact of climate change on different components of water balance. The total discharge is projected to increase by 13% by mid-century, and decrease slightly thereafter. The increase in average annual discharge by mid century can be attributed to an increase in annual precipitation, and the slight decrease thereafter to increased evapotranspiration. The annual evapotranspiration is projected to increase by 7 and 16% in mid and late century, respectively, compared to the baseline period, as a result of the increased temperature (Fig. 8). Singh and Bengtsson (2005) projected a 12 and 24% increase in evapotranspiration with a 2 °C increase in temperature from rainfed and snowfed basins, respectively, in the western Himalayas using a snowmelt model (SNOWMOD). Similarly, Nepal et al. (2014b) estimated an increase in evapotranspiration by 25 or 53% with a 2 °C or 4 °C rise in temperature in the Dudh Koshi catchment using the J2000 model. The snowmelt outside the glacier area (non-glacier snowmelt) is

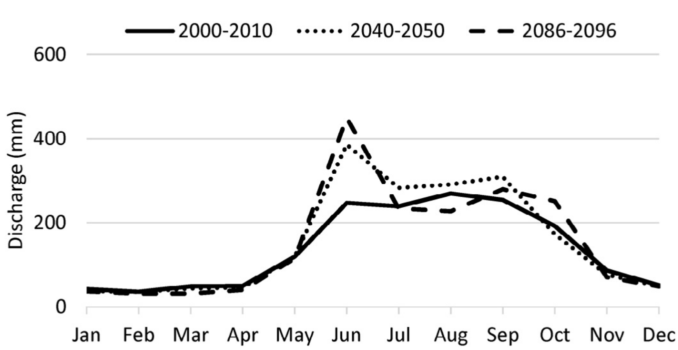


Fig. 7. Monthly discharge from the Koshi basin in the baseline and future periods.

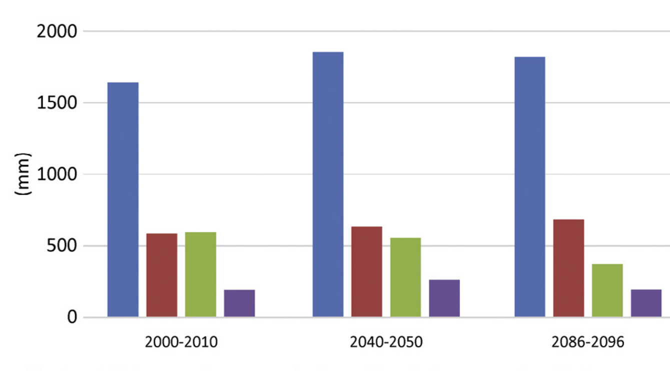


Fig. 8. Total discharge and individual water balance components in the baseline and future periods. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

projected to decrease by 7 and 38% in mid and late century, respectively, as a result of the reduced snowfall (Fig. 8); whereas snowmelt from the glacier area (glacier snowmelt) is projected to increase by 37% in mid century and then decrease almost to baseline levels by late century. In both study periods, the increase in temperature shifts the snowline upward causing more precipitation to fall as rain rather than snow, which decreases the snow storage capacity of the basin. Thus loss of snow storage, and reduction in snowmelt, is higher in the lower elevation areas outside the glaciers than on the glaciers themselves. Snowmelt from the glacier areas increases in mid-century as snow is still available from previous years, but the rate of melt is higher due to the higher temperature. By late century, the snow reserves on the glaciers have melted and snowmelt is reduced. Thus the total snowmelt contribution to basin discharge will decrease by late century, indicating a gradual change in basin streamflow from a ‘melt-dominated river’ to a ‘rain-dominated river’. However, as the main melt season coincides with the rainy season, the change in snowmelt will not greatly affect the overall hydrograph.

3.3.2. Glacier runoff

The precise dynamics of future glacier change and related melt runoff is still unknown. A number of authors suggest that glacier melt might accelerate up to mid century and decrease toward the end of the century (Immerzeel et al., 2010; Lutz et al., 2014). With increasing temperatures, the glacier area (above snowline) exposed to melt is likely to increase, leading to an initial increase in discharge; the increase in melt will lead to a decrease in glacier area, eventual loss of some glaciers at lower elevations, and subsequent reduction in glacier ice melt (Hock, 2005; Jansson et al., 2003). Lutz et al. (2014) suggest that the runoff will increase at least up to 2050 in the tributaries of the Ganges, after which, the glacier storage will be less and melt runoff might decrease. A study by Immerzeel et al. (2012) on the Langtang glacier in Central Nepal which used a high resolution distributed glacier dynamic model, projected a substantial decrease in glacier area (50% by 2055 and 75% by 2088), with glacier runoff remaining constant until 2040, as increased melt compensates for decreased area, and then decreasing markedly. An earlier study by Gitay et al. (1998) suggested that the extra runoff may persist for a century or more in areas with large glaciers and storage. All these processes depend upon how much ice is stored within a glacier as well as changes in rainfall and snowfall patterns.

In the J2000 hydrological model, the glacier melt runoff includes glacier snowmelt, glacier ice melt, and runoff from rainfall on the glacier. In the analysis of two future periods, the impact of climate change on glacier ice melt was omitted due to the inability of the model to deal with changing glacier area and its effect on related melt runoff in the context of a warming climate. Thus in the projections, glacier melt runoff is composed of glacier snowmelt and rain runoff only. Snow storage in glacier areas is developed in the model for more than 100 years. Glacier snowmelt was projected to accelerate up to 2046 (by 1.78 mm/year on average) and decrease thereafter (by 0.68 mm/year on average) (Fig. 9). Thus overall, the present study showed similar results to those in previous publications in terms of total discharge from glacier areas. As glacier ice melt comprised just over a quarter of total glacier runoff, and only 5% of total annual discharge, its omission is unlikely to have had a marked impact on the final discharge projections; however, the importance of the seasonal contribution should not be ignored. The fluctuations in glacier discharge under a warming climate are complex, and replicating the response in a model system is challenging (Hock, 2005; Singh and Kumar, 1997). As suggested by Hock (2005), the response of glacier runoff to climate warming depends on the timescale.

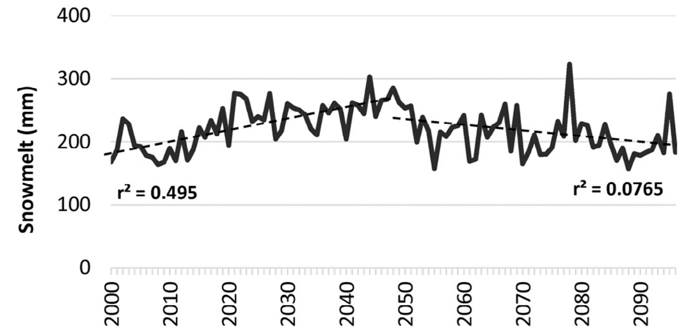


Fig. 9. Snowmelt runoff from glacier area (from baseline through mid century to late century).

3.3.3. Impact on runoff components

The impact of projected climate change on different components of runoff is shown in Fig. 10. The most visible impact is on surface runoff (RD1), which is increased by 27% in mid-century and 25% in late-century with respect to baseline. There are two possible reasons: (a) increased precipitation in the monsoon season when the rainfall–runoff coefficient is high due to the saturated soil conditions and (b) increased number of extreme precipitation events which also result in higher runoff. The interflow is also increased slightly, by about 5%, for both future study periods. In contrast, the base flow is projected to decrease by 2 and 5% in mid and late century, respectively. The

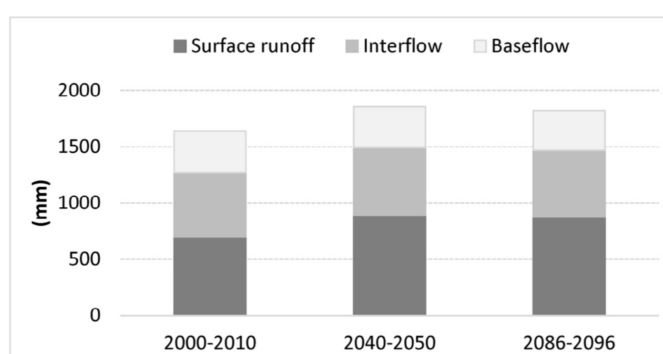


Fig. 10. Runoff components in the baseline and future periods (see J2000 layout in Fig. 3).

decrease in base flow can be explained by the increase in surface runoff, which implies reduced infiltration.

Snowfall pattern, snowmelt, runoff, and annual evapotranspiration were all found to be sensitive to climate change, which will affect water availability (timing and quantity). The glacier ice melt contribution to total discharge in the model calibration and validation periods (1985–1997) was only 5%, thus any impact of changes in glacier ice melt contribution to discharge resulting from climate change is likely to be low in terms of overall hydrology, but their importance in terms of seasonal contribution should not be overlooked. The projected increase in precipitation is likely to lead to an increase in discharge volume (and related water availability) up to mid century.

An analysis of hydrological impact due to climate change contains different levels of uncertainty. The primary uncertainty lies in the climate projections, which have a strong influence on the projected future hydrology. As suggested by Doblas-Reyes et al. (2003), multi-model climate models help to assess uncertainty and have been used in many studies (such as e.g. Lutz et al., 2014). In this study, only one scenario was considered from one climate model; thus the uncertainty arising from the climate projections cannot be assessed.

4. Conclusions

This study looked at the climate trends in the Koshi river basin (KRB) in the Himalayan region, and applied a hydrological model to simulate the hydrological regime of a glaciated alpine catchment within the basin and investigate projected future trends under the A1B climate scenario. The analysis both confirmed observations by other studies and provided some fresh conclusions. The main findings can be summarized as follows.

- All five temperature stations showed a consistent and statistically significant increasing trend in temperature in the KRB over the past 45 years, at an average rate of 0.058 °C/year (maximum temperature) and 0.014 °C/year (minimum temperature).
- Changes in precipitation were spatially less homogeneous and more variable than the change in temperature, with two-thirds of the precipitation stations showing an increasing trend, and the remainder a decreasing trend, while only three of the 36 values were statistically significant.
- The regional climate model data suggest that the average annual temperature will increase by nearly 4 °C by the end of the century and precipitation will increase by 14%. Snowfall is likely to decrease continuously, and the increase in temperature will result in an upward shift of the snowline, resulting in decreased snow storage capacity in the basin.
- The J2000 hydrological model provides important insights into the hydrological dynamics of the river basin. The average annual contribution of snow and glacier melt to total discharge was 34%. The melt runoff contribution was more significant at the seasonal time scale than at the annual, with a contribution of 63% in the pre-monsoon season (March–May).
- Running the model with PRECIS climate model data to project future patterns suggests that the hydrological regime of the Dudh Koshi sub-basin might change, and that this could affect water distribution (timing and quantity) in the downstream region. The model results suggest that annual discharge will increase, but the increase will be mostly during the monsoon season, which could lead to more flood events. Snowfall will decrease substantially as will snowmelt from outside the glacier area, whereas snowmelt from the glacier area will increase up to mid century and decrease thereafter. Evapotranspiration is likely to increase by 16% toward the late century. The results suggested that snowfall pattern, snowmelt, total discharge, and evapotranspiration are all sensitive to climate change.

Considering the potential sources of uncertainty as discussed in previous sections, the results should be taken as indicative of how the hydrological regime might change in future rather than definitive. By incorporating high resolution data and replicating studies in reference catchments in the Himalayan region, analyses of this type can be made more reliable and used to support decision-making, for example in developing strategies for adaptation to the rapidly changing environmental conditions.

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