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Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal

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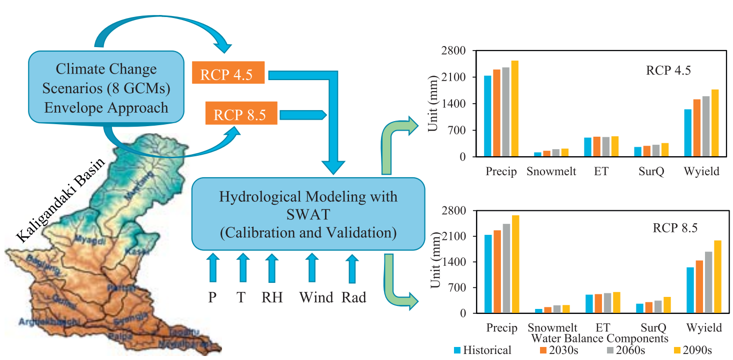
HIGHLIGHTS

- The rise in temperature and increase in precipitation is projected in future in Kaligandaki River basin.
- The water availability in the basin is not likely to decrease during this century.
- The change in water balance in the upper sub-basins of Kaligandaki River is higher.
- The output from this research could be beneficial for water resources management.

GRAPHICAL ABSTRACT



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ABSTRACT

The Hindu Kush-Himalayan region is an important global freshwater resource. The hydrological regime of the region is vulnerable to climatic variations, especially precipitation and temperature. In our study, we modelled the impact of climate change on the water balance and hydrological regime of the snow dominated Kaligandaki Basin. The Soil and Water Assessment Tool (SWAT) was used for a future projection of changes in the hydrological regime of the Kaligandaki basin based on Representative Concentration Pathways Scenarios (RCP 4.5 and RCP 8.5) of ensemble downscaled Coupled Model Intercomparison Project's (CMIP5) General Circulation Model (GCM) outputs. It is predicted to be a rise in the average annual temperature of over 4 °C, and an increase in the average annual precipitation of over 26% by the end of the 21st century under RCP 8.5 scenario. Modeling results show these will lead to significant changes in the basin's water balance and hydrological regime. In particular, a 50% increase in discharge is expected at the outlet of the basin. Snowmelt contribution will largely be affected by climate change, and it is projected to increase by 90% by 2090.Water availability in the basin is not likely to decrease during the 21st century. The study demonstrates that the important water balance components of snowmelt, evapotranspiration, and water yield at higher elevations in the upper and middle sub-basins of the Kaligandaki Basin will be most affected by the increasing temperatures and precipitation.

1. Introduction

The impact of climate change and adaptation measures is perceived as a major contemporary global concern (IPCC, 2014). Increases in global

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surface temperatures, variability of rainfall patterns both spatially and over time, as well changes in the predictability of this variance are all likely to occur over the next century (Trenberth et al., 2003; Alexander et al., 2006; Kharin et al., 2013). The Intergovernmental Panel on Climate Change has defined a series of Representative Concentration Pathways (RCP) scenarios for future climate projection, based on the Coupled Model Intercomparison Project (CMIP5) (van Vuuren et al., 2011). These suggest an average global rise in surface temperature of over 2 °C by the end of the century, compared to the reference period of 30 years from 1986 to 2005. More specifically, the average temperature is projected to increase over 1 °C under a low-emission scenario (RCP 2.6), and over 4 °C under an extreme scenario (RCP 8.5) (Knutti and Sedlácek, 2013). Increase in temperature and precipitation changes can alter regional water balances and hydrological regimes (Poitras et al., 2011; Bolch et al., 2012).

The potential impact of climate change will be more evident in the Himalayan region, where the runoff is dominated, largely, by glacier melt and snowmelt (Viviroli et al., 2007; Immerzeel et al., 2013; Lutz et al., 2014). The average contribution of snowmelt to the annual stream flow across the Hindu Kush-Himalayan region is nearly 20%, with a maximum contribution of >65% in the Indus catchment (Bookhagen and Burbank, 2010). In addition, glacier melt in the Upper Indus region is approximately 32% (Immerzeel et al., 2009). Whereas mean temperatures in the Indus, Ganges, and Brahmaputra (IGB) basin are projected to rise up to 3.5 °C for an RCP 4.5 scenario and 6.3 °C for an RCP 8.5 scenario. Similarly, the projected precipitation of this region is expected to vary between 3% to 37% under RCP 4.5, and RCP 8.5 scenario respectively (Lutz et al., 2016).

The Hindu Kush Himalayan region is one of the most vulnerable regions in the worlds with respect to climate change because of its highly diverse climatic and topographical variations (IPCC, 2007; Kundzewicz et al., 2007). Climate changes are expected to influence millions of people living in the region (Immerzeel et al., 2010). Many researchers have quantified the impact of climate change on the water availability in the snow and glacier dominated catchment of the Himalayan region in Nepal using hydrological and glacier mass balance models (Bharati et al., 2014; Khadka et al., 2014; Shea et al., 2014). Most of this research has used coarse-resolution, General Circulation Model (GCM) or Regional Circulation Model (RCM) based data. GCM resolutions may vary from 300 to 400 km and are not preferred for hydrological modeling in a mountainous catchment (Babel et al., 2014). However, the GCM data can be downscaled to catchment level using observed meteorological data. The downscaled GCM climate data can be used as a forcing data for hydrological models to project stream flow. A fine resolution data-set can significantly improve the projection of stream flow, thereby providing more reliable results.

In this study, we used 10-km resolution data-set developed by Lutz et al. (2016) for the IGB basin, constructed with a particular focus on the improved representation of high-altitude precipitation and temperature. The climate data were then used in a SWAT model to generate future outflows in the basin. The SWAT model was well tested and implemented for different catchments in the Himalayan region yielding good simulation (Bharati et al., 2012; Palazzoli et al., 2015; Dahal et al., 2016).

This study considers the individual contribution of precipitation, snowmelt, evapotranspiration and water yield within the water balance for the Kaligandaki basin, which could help to understand future hydro-climate variability. Previous research had mainly focused on a time-based stream flow in the basin only, often missing out on the other water balance components for instance water yield and evapotranspiration. This paper outlines the impacts of projected temperature and precipitation on different components of water balance in the Kaligandaki Basin in Nepal.

2. Materials and methods

2.1. Study area

The Kaligandaki Basin (Fig. 1) is an important sub-basin of the Narayani Basin in Nepal, which is a major tributary of the Ganges River Basin. It has a catchment area of approximately 11,830 km^2 and is located between 27° 43′N to 29° 19′N and 82° 53′E to 84° 26′E. Elevations within the Kaligandaki Basin varies from 188 to 8143 m, thus marked topographic variations is a feature. The upper region of the Kaligandaki Basin is characterized by high altitudes, low temperatures, and some glacier coverage. Permanent snow covers about 33% of the basin, while over 50% of this snow cover occurs above 5200 m (Mishra et al., 2014). The middle region of the basin is mostly hilly with high altitude terrain; the plains in the South have a sub-tropical climate and high precipitation.

Climate data (precipitation, relative humidity, solar radiation, wind speed, and temperature) collected at Department of Hydrology and Meteorology (DHM) stations throughout the basin were used as input to the SWAT model. In addition, land use data at a 300-m resolution were obtained from the European Space Agency. Global land cover data for 2000, 2005, and 2010 periods were also used in developing the hydrological model. The Soil and Terrain Database Programme (SOTER) provided a soil map at 1:1 million scale for Nepal and China. Separate soil maps were merged for the soil map of the Kaligandaki basin.

2.2. Hydro-meteorological stations in the Kaligandaki basin

The network of hydrological, precipitation and temperature stations used in the SWAT model are given in Fig. 1. Overall, daily data from 14 precipitations, 9 temperature, and 1 hydrological station were used in this analysis from 1995 to 2004.The hydro-meteorological station data for the Kaligandaki Basin were obtained from the Department of Hydrology and Meteorology, Nepal.

2.3. Climate change data for the basin

Lutz et al. (2016)'s climate dataset for the entire IGB basin was based on selected CMIP5 GCMs with a 10 × 10 km spatial resolution and daily time steps. In the IGB dataset, the best GCMs were selected for the region using the 'Envelope' approach, and downscaled by Quantile mapping. In the envelope approach, suitable GCMs are selected from the universal sets of GCMs available covering different range of temperature and precipitation projection. Since the Kaligandaki basin is part of the Ganges basin, their dataset was used for our climate change analysis. Table 1 shows the selected climate model used for this study.

SWAT is a semi-distributed model that does not allow the use of meteorological data in a grid format, hence these were converted to point data in SWAT format. For this purpose, climate data located at the centroid of the unit grid were extracted (Price et al., 2014). To simplify the analysis, only virtual points representing the climatology of the basin were used for the model. Since the stations measuring precipitation and temperature adequately represent the spatial and topographical variation of the basin, only the gridded pixel stations were used for our analysis. This method enabled us also to compare the climate datasets with observed historical datasets for validation. We used GCM climate dataset 1990s (1981–2010) as a reference data and 2030s (Present-2040), 2060s (2041–2070), and 2090s (2071–2100) as a projected future data to see the change in climate between the reference and future projection in the Kaligandaki River Basin.

2.4. Hydrological modeling

Hydrological modeling plays an important role in the analysis of water resources subjected to climate change, especially when attempting to understand its consequences (Praskievicz and Chang, 2009). The hydrological model SWAT was used in this study to simulate future discharge and assess different water balance components in the context of climate change.

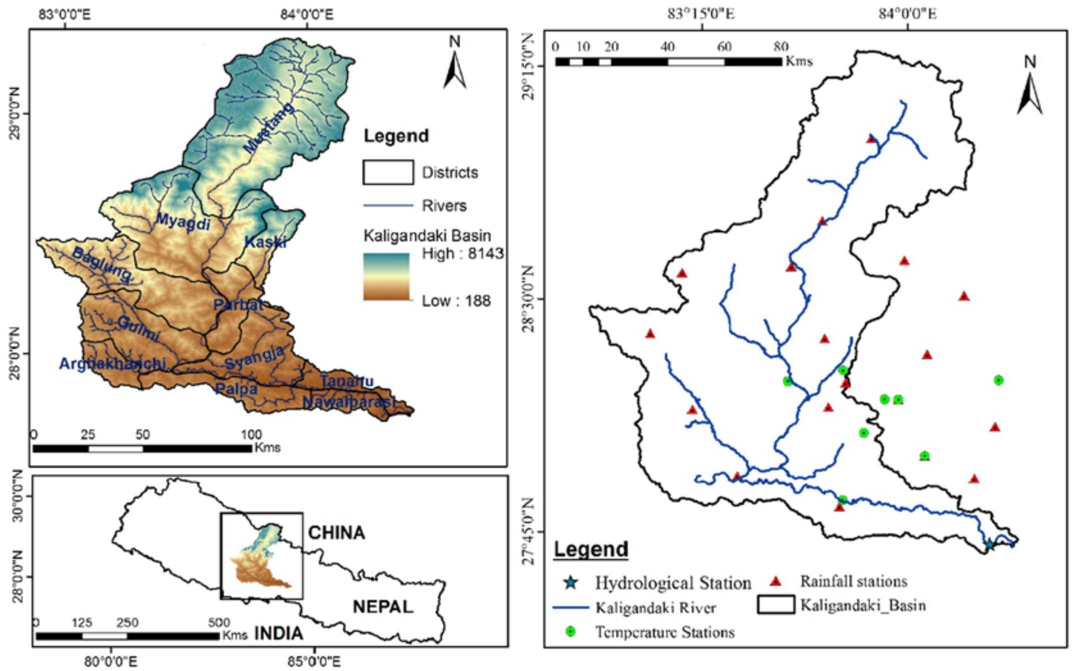

Fig. 1. Location map of Kaligandaki basin in Nepal (left) and Spatial distribution of Hydrological, Precipitation, and Temperature Stations (right).

The hydrological cycle in SWAT is governed by the following water balance equation (Arnold et al., 1998):

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

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

Snowmelt was included with rainfall in the calculations of runoff and percolation. The snowmelt in SWAT is a linear function of the difference between the average snow pack-maximum air temperature and the base of threshold temperature for snow melt. It can be represented by the following equation (Neitsch et al., 2009):

$$\mathrm{SNOW}_{\mathrm{melt}} = \mathrm{b}_{\mathrm{melt}} * \mathrm{snow}_{\mathrm{cov.}} \left(\left(\frac{T_{snow} + T_{max}}{2} \right) - \mathrm{T}_{\mathrm{melt}} \right) \quad (2)$$

$\mathrm{SNOW}_{\mathrm{melt}}$: daily snowmelt amount (mm), b_{melt}: daily melt factor (mm/daẙ C), $T_{max:}$ daily maximum air temperature, $snow_{cov:}$ fraction of HRU area covered by snow, T_{snow}: daily snowpack temperature (°C) and T_{melt}: optimum temperature for snow melt (̊C).

Arc SWAT 2012 was used to simulate the hydrological process under present and future climatic conditions. SRTM DEM of 90 m × 90 m resolution was used to delineate the watershed in the model. The DEM was used after the projection of coordinates to UTM Zone 44 N. A threshold area of 280,000 km^2 was defined to create the river networks. Defining a large threshold area leads to the delineation of larger sub-watersheds, whereas a smaller threshold area leads to the creation of too many sub-watersheds and finer streams. Manual outlets were generated automatically at the intersection of the stream by the SWAT model, based on the threshold area defined. To delineate the watershed, the outlet was defined at the Kota Gaon station. This resulted in the creation of 29 sub-basins.

A Hydrological Response Unit (HRU) is the smallest unit of the model. HRU is the combination of unique land features, soil type, and slope classification within a sub-basin based upon user-defined thresholds. For the creation of an HRU a land use map, soil map, and slope classes were used as input in SWAT. Look up tables were used to reclassify the land use map and soil map according to the SWAT database. The slope was first classified into four classes (0–25%, 25–50%, 50–70%, and >70%). However, five classes of slope can be defined in the SWAT model. A broader classification may be applicable for mountainous watersheds. To create fewer HRU units, a 10% threshold for land use, soil type, and the slope was set. Each HRU is based on a unique combination of these three elements.

To model the process of snowmelt and orographic distribution of temperature and precipitation in SWAT, elevation bands were created. An elevation band assists in discretizing the topographic effect of temperature and precipitation on snowmelt and discharge (Hartman et al., 1999). Each sub-basin in the model was divided into five elevation bands, and each band was assigned a mean elevation and area coverage percentage. A sub-basin with a less orographic difference was assigned only one elevation band. Up to 10 elevation bands may be assigned to each sub-basin in the SWAT model.

Table 1
Selected climate model and scenarios for IGB basin (Lutz et al., 2016).

RCP projection	RCP 4.5	RCP 8.5
Warm, dry	CMCC_CMS_r1i1p1	CMCC_CMS_r1i1p1
Warm, wet	CSIRO-MK3–6.0_r4i1p1	CanESM2_r3i1p1
Cold, wet	BNU_ESM_r1i1p1	bcc-csm1-1_r1i1p1
Cold, dry	inmcm4_r1i1p1	inmcm4_r1i1p1

2.5. Evaluation of the performance of SWAT model

Model evaluation is necessary to quantify the reliability of its output. Such outputs are considered reliable if the evaluation statistics fall within a permissible limit (Moriasi et al., 2007). According to Moriasi et al. (2007), a model is deemed good for monthly stream flow simulation, if PBIAS is within ±15% and NSE is above 0.75. We calculated the Nash-Sutcliffe Simulation Efficiency (NSE), Coefficient of Determination (R^2), and Percent Bias (PBIAS) to verify our SWAT results. Details of these methods are available in Nash and Sutcliffe (1970), Gupta et al. (1999), Singh et al. (2004), and Moriasi et al. (2007).

3. Results

3.1. Model development

Calibration and validation of the model are required for further use of its outputs (e.g., discharge). The observed daily discharge data available from DHM were from 1995 to 2004. SWAT was calibrated from 2000 to 2004 and validated from 1995 to 1999 at the outlet of the Kaligandaki Basin (Figs. 2 and 3). We used a warm-up period of 2 years (1998–1999) for calibration to develop appropriate soil and groundwater conditions (Fontaine et al., 2002). Altogether, over 50 parameters in SWAT may be used for calibration.

The model was calibrated manually by changing the parameters for runoff, evapotranspiration, snowmelt, groundwater, and soil. Calibration parameters were based on literature review, adjustment of peak flows, base flow, and volume. The temperature lapse rate was adjusted to 5.6 °C/km. Khadka et al. (2014) used a seasonal lapse rate of 5.3°–5.8 °C/km to analyse the impact of climate change on snowmelt runoff in the Tamakoshi basin in Nepal. The SCS curve number (dependent on land use type) varied from 40 to 90. The Manning N value for the main channel was calibrated from 0.03 to 0.066. Snowmelt parameters, such as snowfall temperature and minimum snowmelt rate, were adjusted to the values of 0 °C and 7 mm/°C-day, respectively.

The simulated discharge from the model shows a good result with the observed data. Hence, it shows that SWAT model is able to simulate the discharge at the outlet of the catchment realistically and with reasonably high accuracy. The calibration and validation output value of NSE, R^2 and PBIAS is provided in Table 2.

The calibrated and validated SWAT model was forced with historical ensemble climate variables from different GCMs used in this study from 1980 to 2010. The water balance components such as evapotranspiration and discharge obtained from simulated SWAT model were treated as baseline data for the reference period of 1980 to 2010. The water balance components hence obtained from the reference period were compared with the future simulated water balance components for an ensemble of 4 GCMs with RCP 4.5 scenario and 4 GCMs with RCP 8.5 scenario.

3.2. Climate change analysis

3.2.1. Projected precipitation

Data (downscaled) on the IGB basin at 10 km ∗ 10 km resolution were used for an analysis of projected precipitation and temperature. The future timeline was categorized into three periods: 2030s, 2060s, and 2090s. Each timeline period would have 30 years of data to compare with the reference period the 1990s.

The warm-dry projection by CMCC-CMS models shows a decreased precipitation for both RCP 4.5 and RCP 8.5 scenarios for all time periods. The projection from the RCP 8.5 scenario shows less annual average precipitation of over 13% during the 2090s. The least decrease in precipitation was projected during the 2060s, about 0.5% and 0.8% for RCP 4.5 and RCP 8.5 scenarios. In contrast, GCMs under cold-wet and warm-wet projection show an increase in annual average precipitation.

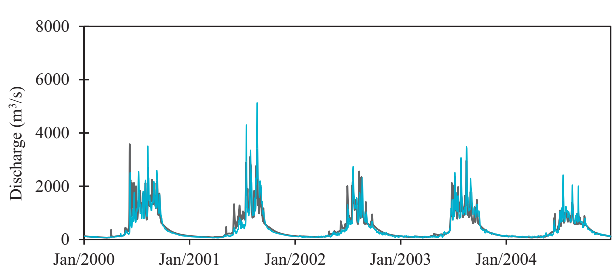

Fig. 2. Calibration of SWAT model of Kaligandaki basin at Kota Gaon from 2000 to 2004.

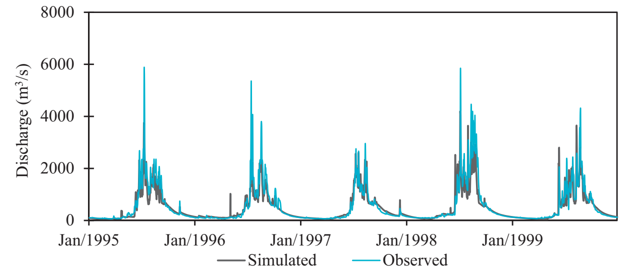

Fig. 3. Validation of SWAT model of Kaligandaki basin at Kota Gaon from 1995 to 1999.

There is a maximum increase of up to 24% during the 2090s compared to the baseline average annual precipitation. The cold-dry projection of inmcm4 shows an initial decrease of −5.38% in average annual precipitation during the 2030s under an RCP 4.5 scenario. Our finding is consistent with the study carried out by Lutz et al. (2016) which shows that the projected precipitation varied by −3.1% under an RCP 4.5 scenario, with an increase precipitation of +37.4% under an RCP 8.5 scenario for the IGB basin.

Our projections further showed a higher annual average precipitation of 2.3% and 12.5% during the 2060s and 2090s, under the RCP 8.5 scenario. It is projected to increase by 0.5%, and about 14% and 31% during the 2030s, 2060s, and 2090s respectively. The selected GCM projections in this study mostly show an increase in precipitation and its intensity, especially during the monsoon season. However, during the winter and dry season, most GCMs project decreased annual average precipitation. December, January, and February (dry/winter season) are the driest, receiving the least rainfall. The uncertainty range is expected to be small in this period. June, July, August, and September (monsoon season) are the wettest with the maximum rainfall.

The range of uncertainty for the change in future projected precipitation is presented in Fig. 4.The higher range of uncertainty may be judged by the large difference in the 5th percentile and 95th percentile value of the precipitation change. The winter season shows the least uncertainty, as it receives only around 3–5% of total rainfall. The range is expected to be highest during the 2090s under both RCP scenarios, more during the monsoon obviously. The higher uncertainty range indicates a more erratic behaviour of rainfall and its intensity. It could aggravate rainfall-induced disasters such as landslides and floods. Changes in the frequencies of extreme rainfall events might impinge on land degradation processes such as mass movements, soil erosions, and removal of top fertile soil as well as sand casting, which might reduce agriculture land. Ultimately, change will impact the lives and livelihood of the poor people who are residing in the Kaligandaki basin.

3.2.2. Projected temperature

Temperature is one of the crucial factor and also the most sensitive parameter in climate science. All GCMs in this research show an increase in both minimum and maximum temperatures on the future timeline. The increase in temperature appears progressive for all GCMs on a temporal basis, unlike precipitation that showed no particular trend of increase or decrease across time.

The projected maximum temperature shows uncertainty for different seasons which can be analyzed from Fig. 5. Projections show higher temperatures throughout all seasons. The positive median value for all

Table 2
Model performance of daily stream flow during calibration and validation at Kota Gaon outlet.

Timeline	Evaluation criteria		
	NSE	R^2	PBIAS
Calibration Period	0.78	0.78	−4.01
Validation Period	0.8	0.82	+9.6

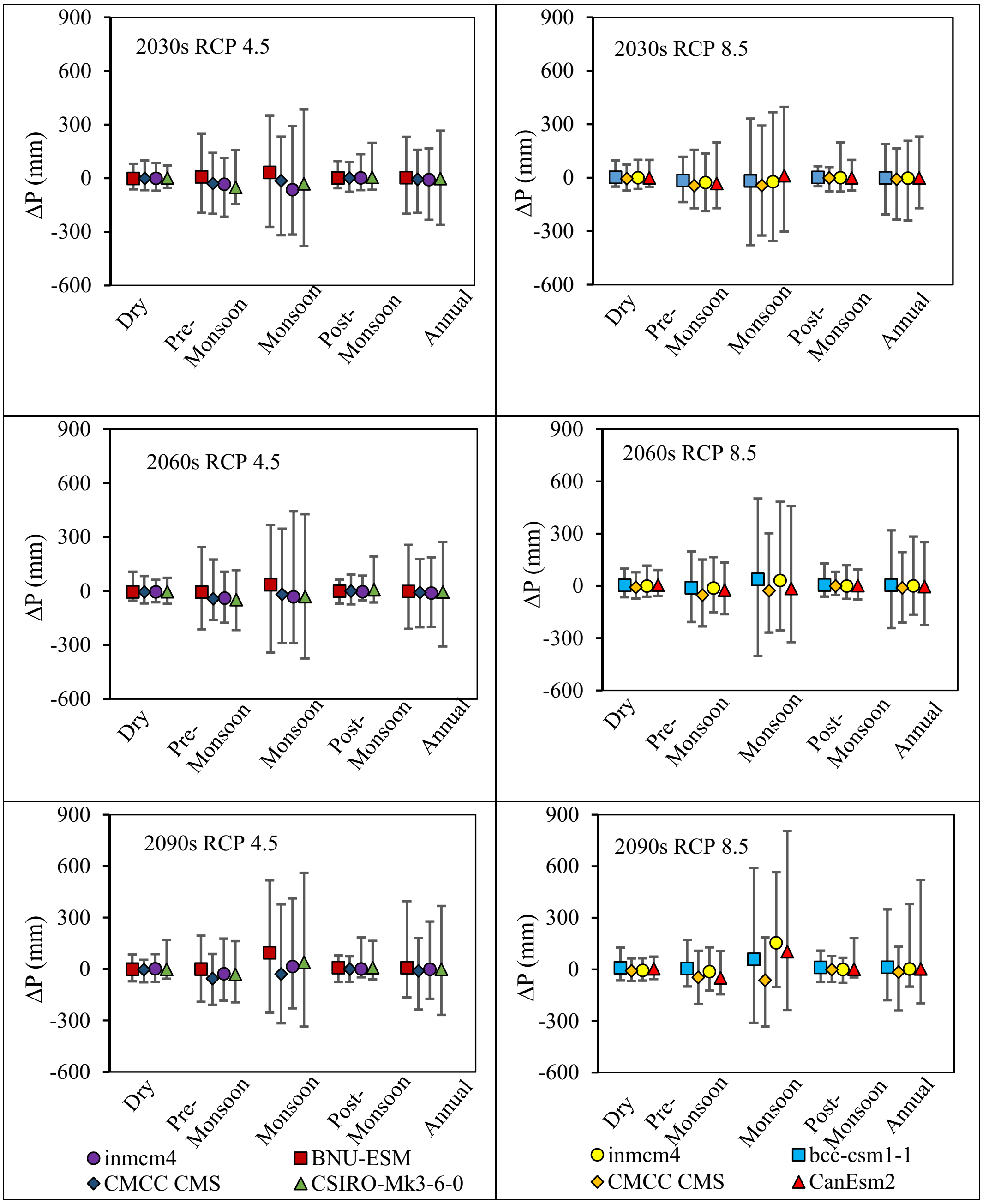

Fig. 4. Range of change in seasonal mean precipitation for different scenarios and GCMs for Kaligandaki basin. The lower end of the bar represents the 5th percentile, the upper end represents the 95th percentile, and the marker represents the 50th percentile intervals of the uncertainty range.

periods and scenarios indicate an increase in maximum temperatures, according to all GCMs with a variation of 0.1 °C–6 °C. The maximum range of uncertainty in the change of maximum temperature is observed during the 2090s under the RCP 8.5 scenario, whereas it is the least during the 2030s under the RCP 4.5 scenario. The CMCC-CMS GCM under RCP 8.5 projects a maximum rise in temperature during the 2090s by 5.5 °C. A similar study on the Koshi basin of Nepal showed higher mean temperatures by at least 4 °C by the end of the century, with a decadal increment of almost 0.5 °C (Nepal, 2016).

All our GCMs under the RCP 8.5 scenario show at least a 3 °C rise in maximum temperature by the end of the century. Significantly, under the RCP 4.5 scenario, the maximum temperature is also expected to rise, by about 2.8 °C. This finding is similar to that of Immerzeel et al. (2013), which projected that the upper part of the Ganges basin will be warmed by 2.2 °C in 2021–2050. All this clearly indicates no sign of a decrease in annual average temperature. This aligns with the trend of global projections for the northern hemisphere (Rangwala et al., 2013). Immerzeel et al. (2012) reported that higher temperature will increase evapotranspiration and increased melt of ice and snow. Similarly, the fraction of precipitation that falls in the form of liquid precipitation will increase instead of snow and net effect on the total discharge, glacier area and its composition.

The range of uncertainty in temperature is not expected to vary much, unlike precipitation, but is expected to increase as we progress in time. Notably, the uncertainty in temperature increase is significantly less during the post-monsoon period, compared to the other seasons.

3.2.3. Impact on discharge

Discharge of a river may be affected by various water balance components. Under both RCP scenarios, the discharge at the outlet of the

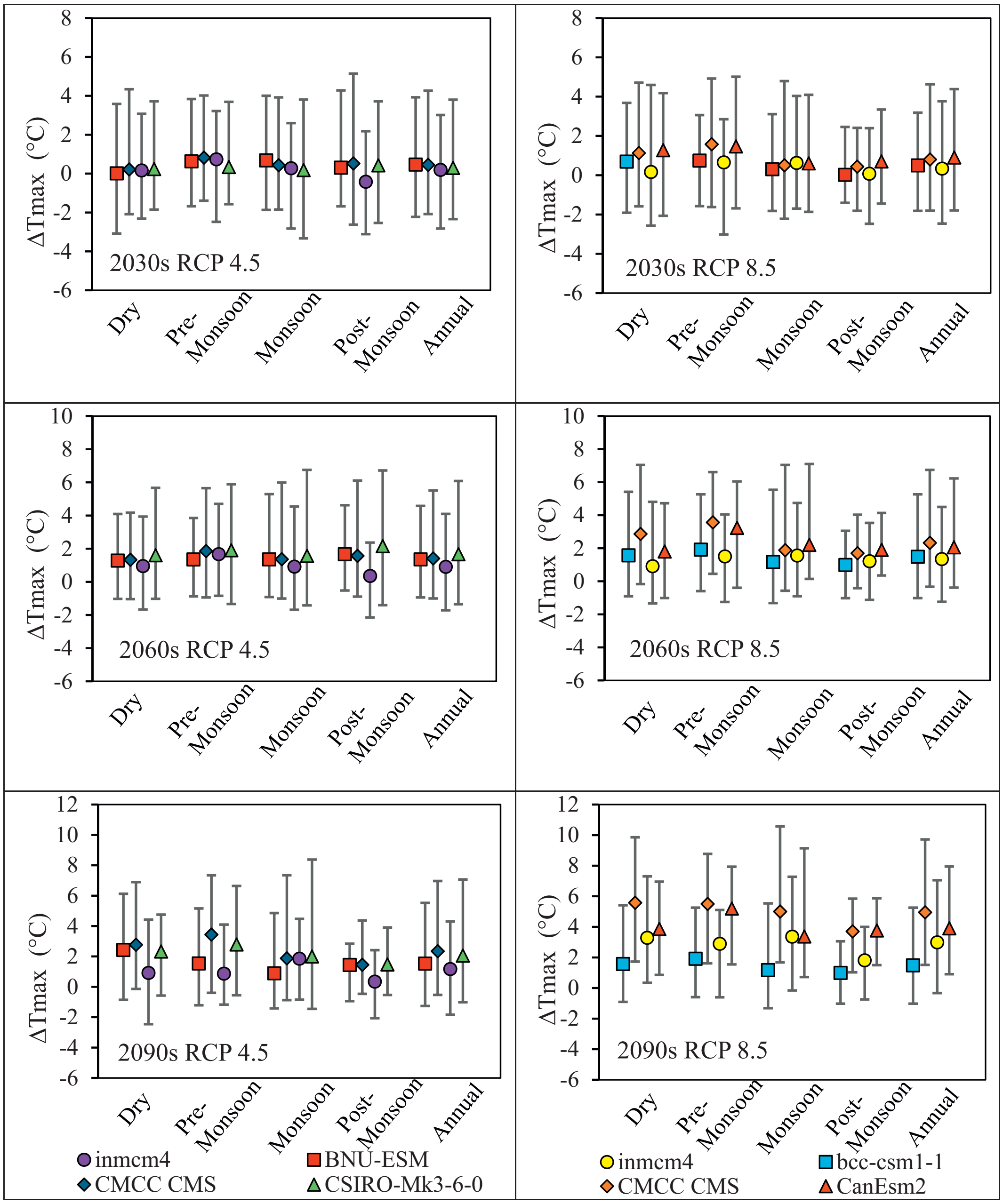

Fig. 5. Range of change in seasonal mean maximum temperature for different scenarios and GCMs for Kaligandaki basin. The lower end of the bar represents the 5th percentile, the upper end represents the 95th percentile, and the marker represents the 50th percentile intervals of the uncertainty range.

Kaligandaki River is expected to increase significantly in future. Increase in discharge is projected to be maximal during the pre-monsoon under RCP 4.5 and the monsoon under RCP 8.5. There would be a maximum increase during the 2090s, of 41% under RCP 4.5, and over 50% under RCP 8.5. Such a significant increase was also reported by Immerzeel et al., 2012 and Bhattarai and Regmi (2016) in a study of the Langtang basin in Nepal. The increase in discharge is mostly contributed by increases in precipitation and temperature. The latter contribute to more snowmelt runoff, which, in turn, causes higher discharge of the river.

The projected discharge in the Himalayan catchment as a whole is expected to increase by 32% (RCP 4.5) and 88% (RCP 8.5) by the end of the century (Immerzeel et al., 2013). The peak is expected to be similar during the 2030s and 2060s under both RCP scenarios. But in the 2090s, it is expected to shift earlier under RCP 4.5, but to be delayed under RCP 8.5, both by a few days (Fig. 6). This might be due to shifting precipitation and snowmelt timing but a shift in the timing and magnitude of water flows in the river are of particular crucial for the water management.

The rate of increase in discharge is significantly higher than the percentage of increase in precipitation, as snowmelt is expected to increase by over 90% late century. These results are similar to research findings by Immerzeel et al. (2012 and (2013) and Khadka et al. (2014 and 2015) in the Langtang and Koshi river basins in Nepal. They, too, had projected an increase in river flow in the basins due to climate change.

3.2.4. Impact on water balance components

Water balance components contribute to the discharge of the river and overall hydrological cycle of the basin. In our research, we tried to analyse the impact of climate change on several water balance components in the basin - precipitation, snowmelt, evapotranspiration, and water yield - for different seasons (Fig. 7).

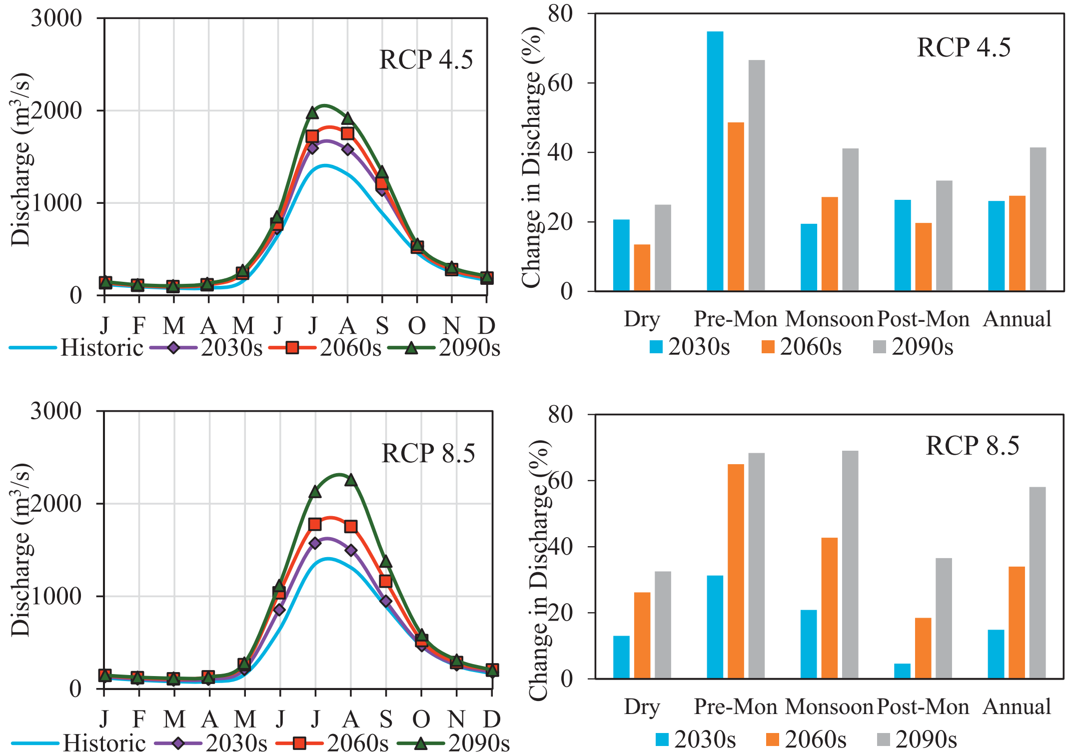

Fig. 6. Impact of climate change on the discharge at the outlet of the Kaligandaki basin during the 2030s, 2060s, and 2090s under RCP 4.5 (top) and RCP 8.5 (bottom) scenarios.

Water yield here refers to the net amount of water contributed by the sub-basins and HRUs to the stream flow. Basically, it is the combination of surface runoff, lateral flow, and groundwater flow, with any deduction in transmission losses and pond abstractions (Arnold et al., 1998).

The water balance components in this research for the future period were compared to the reference simulated water balance components (from 1980 to 2010: 1990s) obtained from the SWAT model, after the calibration and validation of the model with the observed data.

Since we did not have the observed data of the different water balance components for the basin, it is justifiable to use the output from the SWAT model as the baseline or reference data to compare the water balance components for future scenarios.

In terms of percentage change, snowmelt is mostly affected by an increase in precipitation and temperature. It occurs mostly during the monsoon for all timelines under RCP 4.5.This result is consistent with the findings of a study in the Tamakoshi basin in Nepal (Khadka et al., 2014). They projected an increase in snowmelt of over 80% during the 2090s under RCP 4.5. Singh and Kumar (1997) had projected an increase in snowmelt of 41% in the western Himalayan catchment, considering a scenario of a temperature increase by 3 °C and precipitation increase by 10%.

After snowmelt, water yield is the most affected water balance component in the basin. It is expected to increase throughout all the seasons under RCP 4.5 scenarios. An increase is projected of over 20% during the 2030s, whereas during the 2060s it is just below 30%. A maximum increase could be expected during the 2090s, of over 45%, under RCP 4.5. Climate change has a moderate impact on evapotranspiration. It could increase by 10% under an RCP 4.5 scenario during the early (2030s) and mid-century periods (2060s).

Under the RCP 8.5 scenario snowmelt is also the most affected water balance component of the basin in future. The average annual snowmelt is expected to increase by 45% during the 2030s and by as much as 90% in amid and late century. Both winter and monsoon precipitation are projected to increase, at maximum during the 2090s under the RCP 8.5 scenario.

Notably, an increase in water yield is projected with a maximum in the dry season, that too, by over 50% during the 2090s under RCP 8.5. However, not unexpectedly, the amount of water yield increment (mm) is higher during the monsoon.

Compared to the baseline period (1990s), the average annual precipitation in the basin will increase most, by about 20%, during the 2090s under RCP 4.5. Snowmelt is projected to increase to the

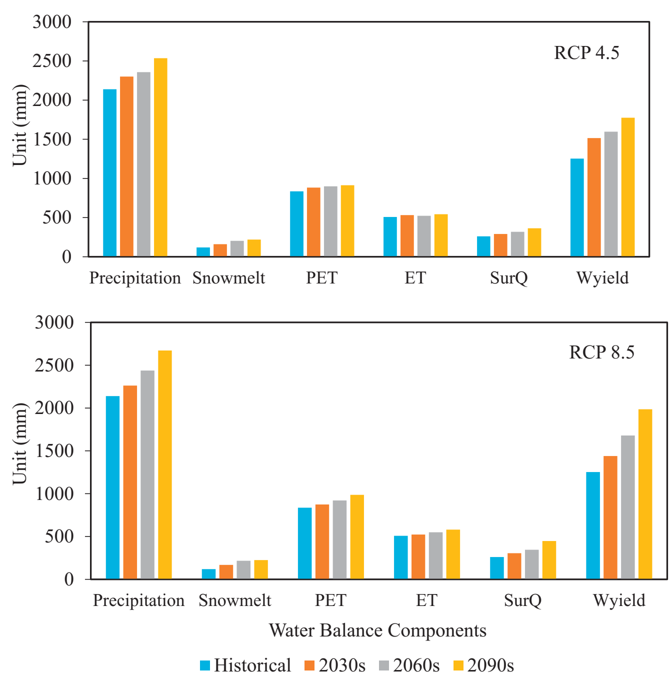

Fig. 7. Climate change impacts on annual average water balance components in the Kaligandaki basin during the 2030s, 2060s, and 2090s under RCP 4.5 and RCP 8.5 scenarios, compared to the simulated historical (1990s) period.

maximum level by the end of the century by >80% under an RCP 8.5 scenario. Likewise, evapotranspiration is expected to increase approximately by 7% and 14% during the late century under RCP 4.5 and RCP 8.5 scenarios, respectively. Nepal (2016) also expected more evapotranspiration in the Koshi basin (16%) by then. Water yield would most increase during the 2090s, by 41% and 51% under RCP 4.5 and RCP 8.5, respectively.

3.2.5. Impact on snowmelt

Snowfall and snowmelt from a frequent annual cycle at higher elevation of the basin and are an integral part of the overall hydrological cycle. Since temperature is their major driving factor, higher temperatures are expected to influence their annual cycle. The combination of expected, erratic rainfall behaviour and higher maximum and minimum temperatures in the basin, will bring about changes in snowfall and snowmelt significantly. In our study, we analyzed the impact of climate change on the future spatial distribution of snowmelt that was contributing to the stream flow of the Kaligandaki River, under both RCP 4.5 and RCP 8.5 scenarios.

Fig. 8 shows a spatial increase in the amount of snowmelt (mm) during the 2030s, 2060s, and 2090s compared to the reference period (1990s) under RCP 4.5 and RCP 8.5 scenario. The spatial distribution shows very little or no snowmelt at lower elevations; it is not affected by climate change under RCP 4.5. The lower basins are located at lower elevations, so the temperature is relatively higher there and no snowfall is observed. Obviously, snowmelt is most at the higher elevation sub-basins, and it is expected to increase over time. The highest increase (up to 30 mm) is projected during the 2090s under RCP 4.5.

The lower basin shows a minimum effect of climate change on snowmelt under the RCP 8.5 scenario as well. There is a significant increase in future scenarios for individual sub-basins at higher altitudes. The maximum increase (ranging 20–40 mm) was projected in the mid and upper basins. A progressive increase in the amount of snowmelt (mm) was observed at higher elevations, with expected maxima during the 2090s under this scenario.

3.2.6. Impact on evapotranspiration

Higher temperatures are expected to increase the evapotranspiration of the basin temporally and spatially. This increase is projected higher at upper and mid-basins during the 2090s, by 10–15% under RCP 4.5 and 25–45% under RCP 8.5 compared to 1990s reference period. Evapotranspiration is more pronounced at the upper and middle basins at higher elevations than the lower basins at lower elevations. Bharati et al. (2014) concluded similar results for the Koshi basin in Nepal.

Fig. 9 shows the change in spatial distribution of evapotranspiration for different sub-basins during the 2030s, 2060s, and 2090s under RCP 4.5 and RCP 8.5 scenarios compared to 1990s reference period. The increase in the rate of evapotranspiration is progressive in a future period, as it is crucially affected by the increase in temperature in the basin. The gradual increase in the future projected temperature will eventually cause the evapotranspiration to rise as well. Combining the effect of a change in precipitation with the increase in temperature will significantly influence the evapotranspiration of the basin. A mild increase was observed during the 2030s under the RCP scenarios, ranging from 0 to 15%. A moderate increase (up to 20%) is projected during the 2060s. Maximum evapotranspiration is projected in a late century (2090s) - up to 45% at the uppermost sub-basin of the study area. This might be the influence of a projected increase in minimum and maximum temperatures, which causes a shortening of the snow-cover season in the sub-basins at a higher elevation and causes the largest

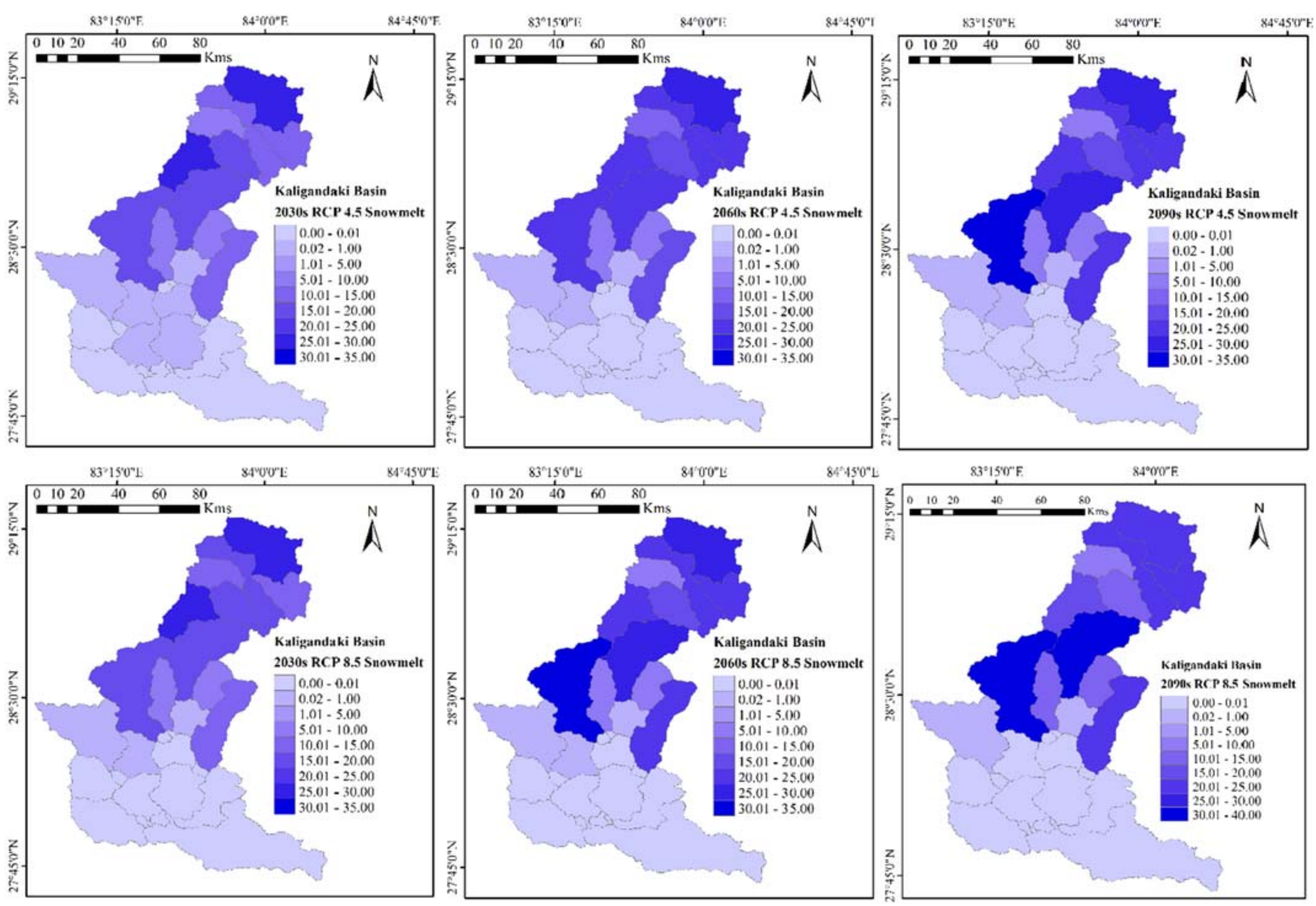

Fig. 8. Spatial distribution of projected change in snowmelt (mm) of Kaligandaki basin for RCP 4.5 (top) and RCP 8.5 (bottom) compared to 1990s reference period.

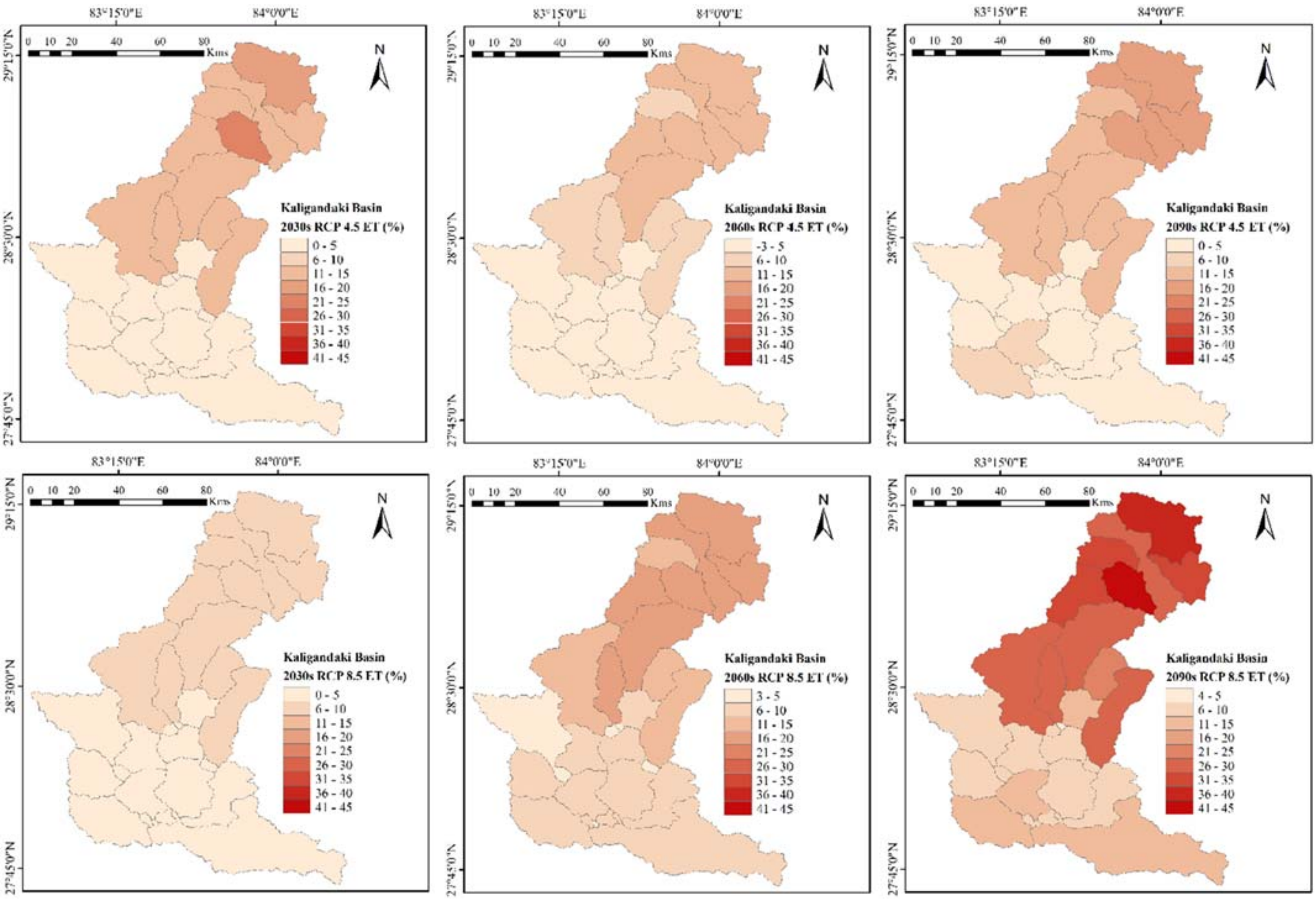

Fig. 9. Spatial distribution of projected change in evapotranspiration (%) of Kaligandaki basin for RCP 4.5 (top) and RCP 8.5 (bottom) compared to 1990s reference period.

increase in evapotranspiration (Dankers and Christensen, 2005). Higher evaporation might decline natural grassland coverage and the grass yield in the upper part of the Kaligandaki basin.

3.2.7. Impact on water yield

Water yield takes into account the surface runoff, lateral flow, groundwater flow, transmission losses, and pond abstraction. The increase in water yield is relatively higher in the upper and mid basins. It is expected to increase by no >30% in lower basins over time. The maximum increase was observed in the upper basin (60–100%).

The maximum increase in water yield at higher basins indicates that the high mountain regions are more vulnerable to climate change than the flatlands in the lower basins. The lower basins are snow-free throughout the whole year and are not affected by the snowmelt if the analysis is considered individually for sub-basins. However, snowmelt plays a crucial role in the water yield of the upper basins. The contribution of snowmelt is most in the upper basins and hence is responsible for the largest percentage increase in water yield in that region (Fig. 10).

In addition, the increase in precipitation yields more water. In comparison to temperature and precipitation, other input variables such as radiation, relative humidity, and wind speed have a less significant effect on water yield (Stonefelt et al., 2000).

The water yield is projected to increase by 8–60% during the 2030s. This increase is aggravated and expected to increase up to as much as 100% at a higher altitude during the 2090s. The increase in water yield for the middle basin, however, is expected to be about 80% and up to 40% at the lower basins during the late century.

4. Discussion

Water balance components and the influence of climate change have significant implications for water resource planning and management. The increase in discharge can have both a positive and negative influence in the future period for water resource management and planning.

The Kaligandaki basin is being developed as a major hub for hydropower electric generation. It also houses the nation's largest hydropower plant, the Kaligandaki 'A' hydropower plant with an installed capacity of 144 MW.

All hydropower plants currently under operation are based on a Run of the River (ROR) design. The amount of electricity generated from this design is heavily dependent on the daily discharge. As the future discharge is expected to increase, a ROR type of hydropower plant like the Kaligandaki 'A' can hugely benefit from climate change.

Although the increase in discharge in the monsoon does not affect hydropower production efficiency, the production can benefit from an increase in discharge during the dry season. In that season, an ROR hydropower plant always generates less electricity than its designed capacity. Projections show an increase in discharge around 20% (RCP 4.5, 2030s) during the dry season. The average increase in dry season discharge during the late century (RCP 8.5, 2090s) can reach as much as 35%. This might be advantageous for the hydropower plant since more energy can be produced.

A study carried out in the Upper Tamakoshi Hydropower Project in Nepal, which is in the Koshi basin, shows that a higher stream flow is expected which results in the average annual energy production in the project by about 4% during the late century (Shrestha et al., 2016). The higher energy production is mostly contributed by the increase in

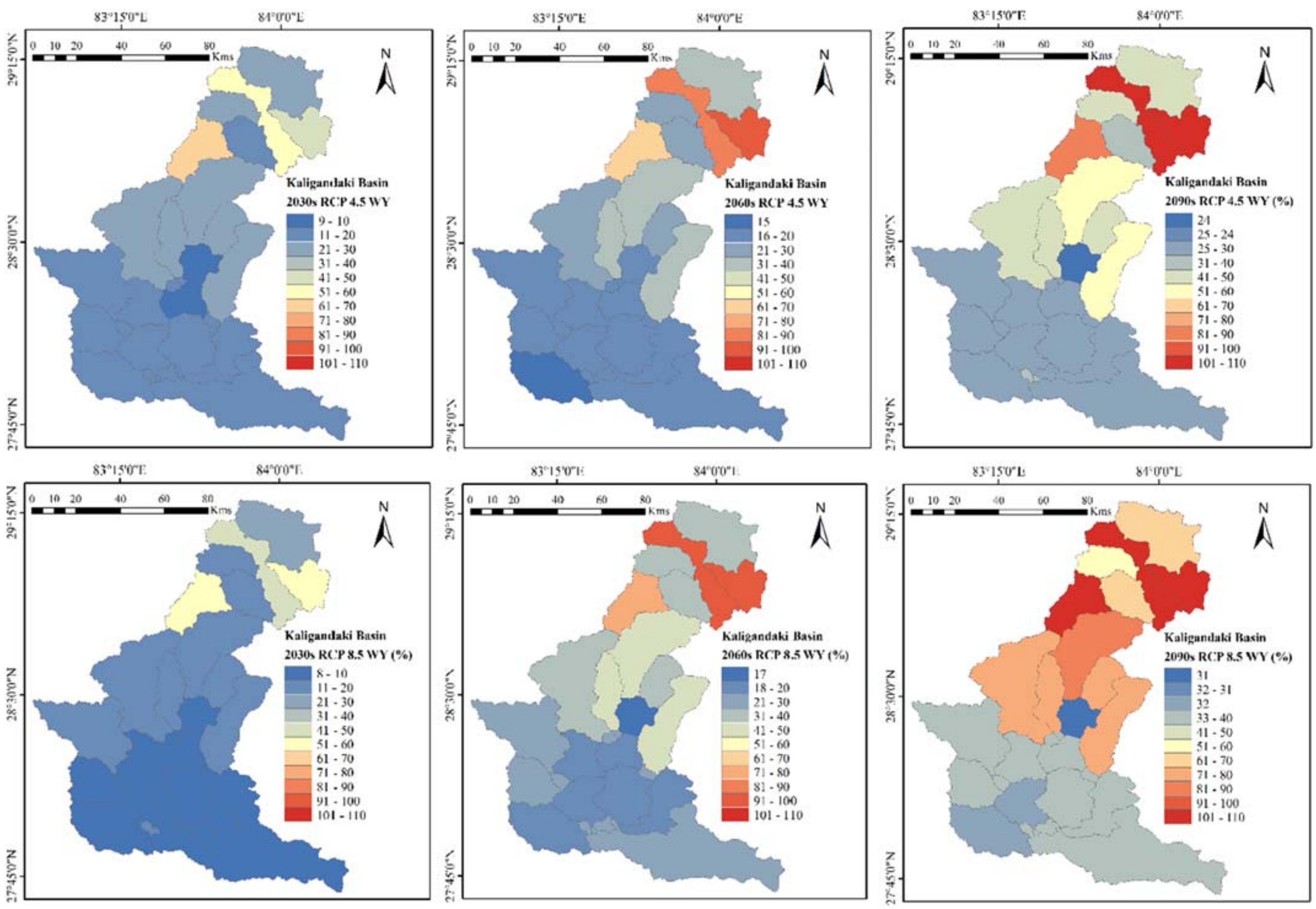

Fig. 10. Spatial distribution of projected change in water yield (%) of Kaligandaki basin for RCP 4.5 (top) and RCP 8.5 (bottom) compared to 1990s reference period.

discharge during the dry season and pre-monsoon season. The increase in discharge during the pre-monsoon season is mostly attributed by an increase in precipitation and earlier snowmelt because of higher, projected temperatures.

An increase in temperature in the Kaligandaki basin is more pronounced in upper elevation basins than lower elevation basins. This could be of serious concern because the glacier and glacier lakes are dominant features of high elevation zones in the Kaligandaki basin. There are >2300 glacier lakes in Nepal at an elevation above 3500 m (Mool et al., 2001). Glacier lakes are formed by the accumulation of runoff from the glacier and snowmelt in natural depressions.

The water level in these lakes is increasing at an alarming rate due to deglaciation caused by climate change. A higher lake level poses the serious threat of a glacier lake outburst flood (GLOF). A GLOF phenomenon occurs as a result of the failure of glacier lakes to retain the extra water, resulting in the release of a large amount of water downstream. Such an event has the potential of causing catastrophic damage to people and infrastructures downstream (Shrestha and Aryal, 2011). A GLOF event occurred in 1985 in the Bhote Koshi River in Nepal completely destroying the Namche Small Hydropower plant and resulted in the loss of five lives (ICIMOD, 2011). Bajracharya (2010) reported two unknown occurrences of GLOF in the Kaligandaki Basin.

More than 1000 glaciers have been identified in the Kaligandaki Basin covering an area of over 2000 km^2. A study carried out by ICIMOD, Nepal, reported 26 glacier lakes in the basin as of 2009, based on satellite images (Ives et al., 2010). Bajracharya (2010) observed: 'Warming temperature, 50 lakes are growing with the additional formation of 22 new glacier lakes at higher elevation in Nepal.'

As the increase in temperature results in glacier melt and an expansion of glacier lakes, planning necessary precautions and mitigation measures is essential to prevent any catastrophic disaster in future resulting from a GLOF.

5. Conclusion

The effect of climate change on water resources is discerned as one of the key challenges in the Hindu Kush Himalayan Region. Climate change has a prominent effect on the temporal and spatial variation of water balance components in the Kaligandaki basin of Nepal.

Future projected climate variables (precipitation and temperature) from downscaled CMIP5 GCM models were forced into a Soil and Water Assessment Tool (SWAT)-based hydrological model to study the impact of projected climate change on the hydrological regime of the Kaligandaki basin.

The extreme projection of an RCP 8.5 scenario shows that the average annual temperature of the basin is expected to increase by >4 °C. Likewise, the average annual precipitation in the basin is projected to increase by as much as 26% during the late century under an RCP 8.5 scenario. The synergetic effect of an increase in temperature and precipitation shows the aggravated effect on the discharge and water yield with an increase of >50% at the outlet of the basin. Snowmelt largely contributes to the increase in discharge, for snowmelt is anticipated to increase by as much as 90% during the 2090s.

In general, there does not seem to be a problem of water availability in the Kaligandaki basin in this century considering a projected increase in precipitation, snowmelt, water yield, and discharge. Our research further concluded that the water balance components at higher elevations of the upper and mid sub-basins of the Kaligandaki basin will be most affected compared to the basins at a lower elevation.

Our research findings could contribute to an effective management and planning of water supply and demand in the Kaligandaki basin considering the effect of climate change. Several hydropower projects under operation and prospective hydropower plants could benefit from this research. Particularly so, because they could help understand the future hydro-climate variability, which is important for designing hydropower plants.

In general, the effect of climate change could be beneficial for harnessing the maximum benefit from reliable water availability from the catchment, but its negative effects such as floods and GLOF will be hard to ignore.

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