Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
e-ISSN: 2395-3454

Vol. 17 No. 3 pp.691-702 2018

Original Research Paper Open Access

Hydrological Modelling and Climate Change Impact Assessment Using HBV Light Model: A Case Study of Narayani River Basin, Nepal

Santosh Bhattarai*†, Yihong Zhou*†, Narendra Man Shakya and Chunju Zhao***

*College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang, 443002, China

**Department of Civil Engineering, Water Resource Engineering, Tribhuvan University, Pulchowk Lalitpur, Nepal

†Corresponding authors: Santosh Bhattarai and Yihong Zhou

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 16-06-2017
Accepted: 21-08-2017

Key Words:
Hydrological modelling
Climate change
HBV light model
Narayani river basin

ABSTRACT

In this study, a semi-distributed conceptual hydrological model "HBV-Light" is applied to one of the snow fed basins "Narayani River Basin" in Nepal to estimate runoff at several gauging stations and to analyse the changes in catchment hydrology and future flood magnitude due to climate change. The model was calibrated for the period 1995-2005 and validated for the period 2006-2008 with satisfactory results producing values of Nash-Sutcliffe coefficient between 75.2% and 82.6% during calibration and 56.3% and 87.2% during validation for all the four sub-basins. The value of coefficient of determination (R^2) during calibration is between 0.789 and 0.844 and during validation is between 0.629 and 0.893. Due to the structural complexity, the model underestimates the low flows, whereas the peaks were correctly estimated except for some sharp peaks due to isolated precipitation events. Further, the volumetric error during the calibration period is acceptable. Contribution of snowmelt to annual, summer (March-July, MAMJJ) and winter (November-February, NDJF) runoff at the final outlet gauging station (Narayani River at Narayanghat) is 15.72% (avg.), 26.22% (maximum in year 2002) and 0.42% (minimum in year 1996) respectively. Sensitivity analysis (increased temperature) indicates that global warming leading to increase in average basin temperature will significantly lead to higher contributions to runoff from snowmelt. The model simulates an overall increase in monthly stream flow from January to June (34% to 51%) and November-December (10% to 15%) with the output of HADCM3 GCM, A1B scenario.

INTRODUCTION

Nepal is one of the richest countries of the world in water resources (Aryal 2011). Its climate is strongly influenced by its topography, which varies greatly between the north-western border, at very high altitudes (above 8000m) in the Himalayan mountain range and the south-eastern edge of the country which sits in the northern rim of the Gangetic plain at only around 300m above sea level. The lowland regions of Nepal have a warm and humid sub-tropical climate, with temperature around 22-27°C in summer months, and dropping to 10-15°C in the winter. The high altitude mountainous regions are considerably colder, at 5-15°C in summer months, and remaining well below zero in the winter. Monsoon rainfall arrive in June and continue until August or September, bringing 250-450mm of rainfall per month in most parts of the country, but only 100-150mm in the north-western mountain regions whereas, the winter months are very dry and all regions receive less than 50mm of rainfall per month (UNDP 2012). A recent climate classification of Nepal was carried out by Karki et al. (2015).

Nepal has a dense network of more than 6,000 rivers flowing from the Himalayan Mountains to the hills and plains. Most of these rivers are glacier-fed and provide sustained flow during the dry season to fulfil the water requirement downstream. Global warming has a significant effect on the runoff from such glaciarized and snow fed catchments. The changes in the runoff characteristics triggered by global warming has an impact over large areas. Glaciarized catchments are characterized by temporarily storing precipitation and releasing it with a time delay. Winter precipitation is stored as snow and ice and released during the spring and summer seasons.

According to Aryal (2011) and Eriksson et al. (2009), water resource sector (hydropower production, irrigation facility) was heavily affected with the global warming and temperature rise at an annual rate of 0.04-0.06°C per year over Nepal, especially in Himalayan region. The main cause of the increase in the frequency and magnitude of extreme events like floods and droughts are triggered from climate change (Sillmann & Roeckner 2007) worldwide. The effect of climate change on snow water equivalent, snowmelt runoff, glacial melt runoff and total stream flow is examined in many Himalayan rivers. Vavrus (2007) stated that climate change impacts on hydrological systems are severe, especially in mountain regions as it causes significant altera-

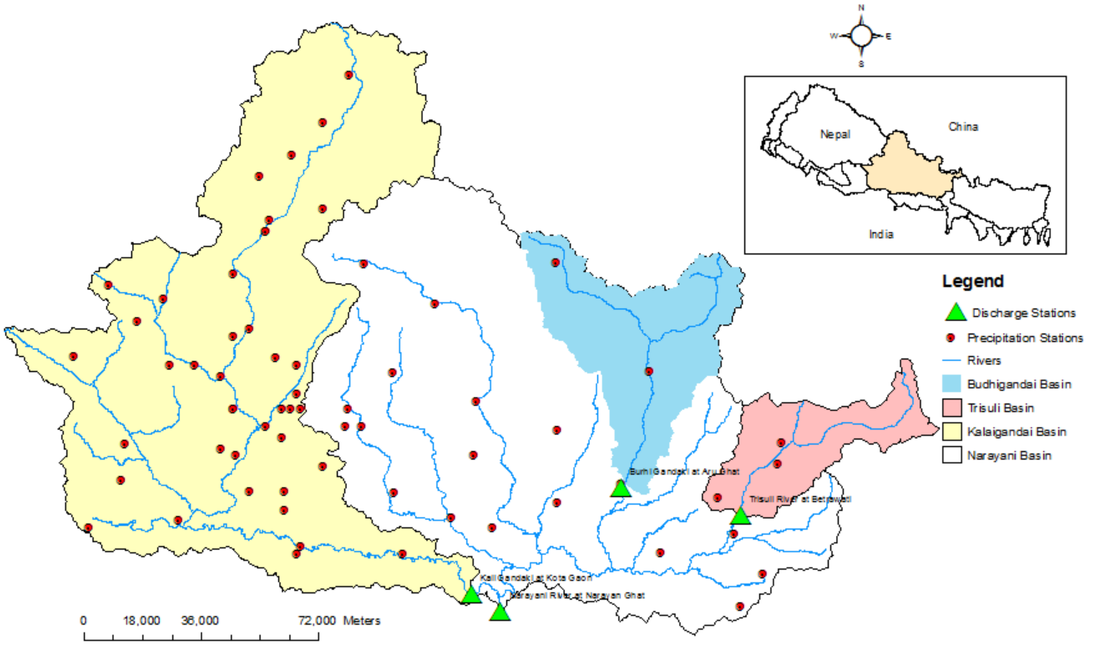


Fig. 1: Location of study area.

tions in the annual cycle of runoff (found that with an increase of 1.3°C in temperature, the annual snowmelt runoff, glacial melt runoff and the total stream flow also increases). Meteorological data of the previous century also suggest a global mean temperature rise of 0.07°C per decade (Folland et al. 2001, Jones & Moberg 2003). Globally observed annual precipitation has reportedly increased by up to 0.98% per decade in the twentieth century (New et al. 2001). The frequency of severe floods in large river basins has increased during the 20th century (Milly et al. 2002).

Prediction of snow and glacier melt runoff from high Himalayas is of great importance for the planning and design of hydropower project, flood warning system, irrigation projects, dry season water management, climate change foresight and inventory of water resources potential in local as well as regional scale. But the direct field observations are very difficult to carry out because of rugged and remote mountain terrain. The quantitative assessment of snow and glacier melt contribution to the river flow has been limited since melting process is very complicated and not well understood. In the Himalayan basins, where most parts are inaccessible and snow cover data from conventional methods are nonexistent, satellite remote-sensed observations provide the only viable alternative for acquiring snow cover data necessary for hydrologic forecasting of snowmelt runoff. A precise, comprehensive database of climate change impact is needed in order to conceptualize better strategies for water resource planning and management and policy formulations regarding irrigation, agriculture, hydropower production and flood protection. In this scenario, the necessity of formulating snow and glacier melt runoff model is reflected. Different kinds of hydrological models like, HBV (Normand et al. 2010, Shrestha & Alfredsen 2011), SRM model (Immerzeel et al. 2010, Khadka et al. 2014), SPHY model (Lutz et al. 2014) and J2000 model (Nepal et al. 2014) were used to evaluate the scenarios of climate change impact on hydrological regime and on river catchments. Hock (2003) stated that the snow and glacier melt process in the Himalayan region can be conceptualized by simple or complex approaches depending upon the data availability. Understanding the hydrologic response of the basin to physical (land use) and climatic (rainfall and air temperature) change is an important component of water resource planning and management (Vorosmarty et al. 2000).

In this study, an attempt has been made to assess the climate change impact on the future river discharge in Narayani River basin with the help of semi-distributed conceptual hydrological model (HBV-Light Model; Hydrologiska Byråns Vattenbalansavdelning). To achieve this end, outputs from climate change scenarios [HadCM3 A1B scenario achieved from PRECIS (2002) developed using the Providing Regional Climate for Impact Studies Regional Climate Model (PRECIS RCM)], are used as in-

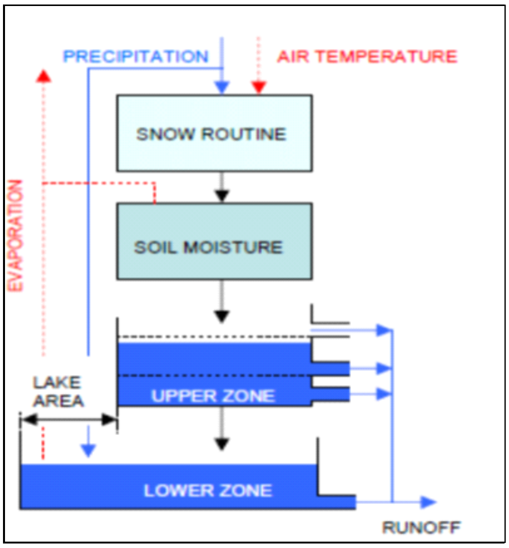


Fig. 2: Main structure of the HBV-light model (Killingtveit & Sælthun 1995).

put into the HBV hydrological model to estimate the river discharge in the present and future climate.

STUDY AREA

The study area is Narayani River basin (Fig. 1) situated in Nepal. It extends from Lat. 27°21’ to 29°20’ and Lon. 82°53’ to Lon. 86°13’ covering an area of 26800 sq.km (in Nepal only). The Narayani Basin includes the Himalayan range to the plains of Terai, with the elevation varying from 8200m to 185m. Narayani River is a perennial, torrential, turbulent and undisturbed river that originates from the Himalayas and carries snow fed flows with significant discharge even in the dry period. Its final outlet point is gauged at Narayanghat. The main contribution of the flow of the Narayani Basin is from Kaligandaki River, originated from Mustang district and from Trisuli, Madi Khola, Marsyangdi, and Budhigandaki rivers. The river is being used for irrigation at various locations and its major tributaries are also being used for hydropower, water supply and irrigation purpose (Fig. 1).

MATERIALS AND METHODS

Brief description of HBV-light model: The precipitation runoff model HBV (HBV is an acronym formed from Hydrologiske Byrån avdeling for Vattenbalans at SMHI, Sweden), like most of the hydrological models, especially for estimation of snowmelt, is based on the degree day method. The HBV model is a conceptual precipitation-runoff model which is used to simulate the runoff process in a catchment based on the data of precipitation, air temperature and potential evapo-transpiration. The model computes snow accumulation, snow melt, and storage in soil moisture and groundwater and runoff from the catchment. The model consists of different routines representing snowmelt by a degree-day method, soil water and evaporation, groundwater described by three linear reservoir equations and channel routing by a triangular weighting function (Seibert 1997). Descriptions of the model can be found in (Bergstrom 1976, 1992, Harlin & Kung 1992).

HBV-Light (Seibert 2005) is a recent version of the HBV model. HBV-Light version 3 employed in this project corresponds to the SMHI version 6 developed by Bergstrom. This model has been successfully employed in several studies evaluating the effects of climate change on river catchments around the world. Within HBV-Light, there are process parameters which do not necessarily have a physical correspondence within a catchment. Reasonable ranges for the parameter values are first estimated and then calculated through calibration. The only physical features to be specified within the model are mean catchment elevation and elevation of precipitation and temperature gauges. An advantage of the HBV-Light model is that Monte-Carlo simulations can be performed using random numbers from a uniform distribution within the set ranges for each parameter. A “warming up” period has been included in HBV-Light. The main structure of the HBV-Light model is shown in Fig. 2.

Model input data: The model requires basic spatial input datasets i.e., digital elevation model (DEM), evaporation data and meteorological data. The brief methodology for preparation of the data is described as below.

***Digital elevation model*:** The main applications of GIS in the hydrological models are delineating watersheds and streams, and defining slope, aspect, area, flow direction and flow length of catchment (Shrestha 2012). The GIS used for this study is mainly shape file of point networks for observation of temperature, precipitation, evaporation and runoff, catchment area and DEM of catchment. The required shape files including that of the rivers are collected from the Department of Hydrology and Meteorology (DHM). The

Table 1: List of temperature stations used in the study.

Index No.	Name	Elevation (m)	Mean daily temperature (°C)
604	ThakMarpha	2566	12.6
804	Pokhara Airport	827	21.3
814	Lumle	1740	15.9
816	Chame	2680	10.6
1038	DhuniBesi	1058	22.0

Source: DHM Nepal

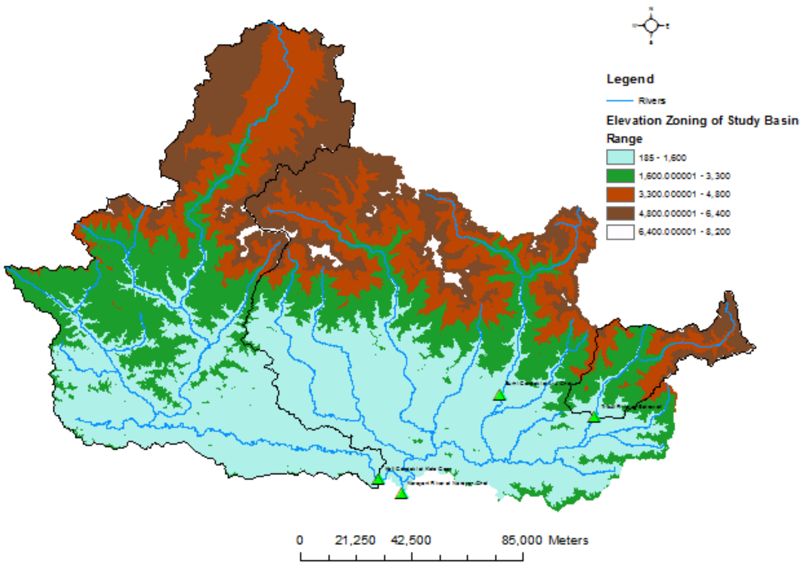


Fig. 3: Elevation zoning of the Narayani river basin.

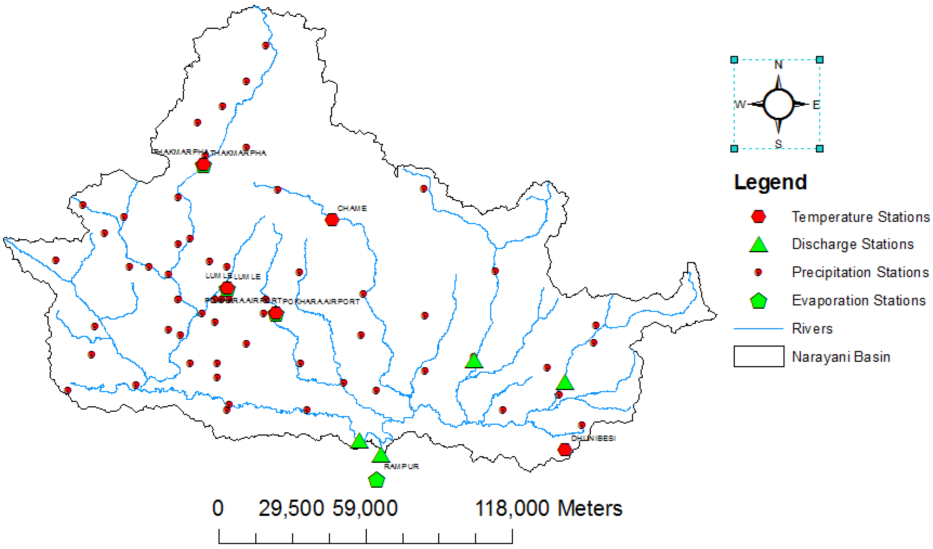


Fig. 4: Location of the different selected meteorological stations.

catchment delineation is performed in Arc Map 10.0 using the hydrology extension in the spatial analyst tool within Arc Toolbox (ESRI). The grid projection used for all the raster files and shape files employed in this study is the Everest_Adj_1937_Transverse_Mercator projected coordinate system. The Narayani River basin is divided into 4 sub basins (Fig. 1) to carry out the study at different points in the basin. Fig. 3 shows the elevation zoning of the Narayani River basin.

Meteorological data: Meteorological data required as an input of HBV-Light model for this type of analysis consist of daily precipitation, temperature and evaporation. These data were collected from DHM, Government of Nepal. Similarly, other hydrological parameter discharge data were collected for the gauzed stations within the study basin for calibration and validation of the model.

Evaporation data: Four evaporation stations index no: 604, 804, 814 and 902 (Fig. 4) exist in the entire Narayani River basin. For the purpose of this study, evaporation data from 814 (Lumle) obtained from the DHM were assumed to ap-

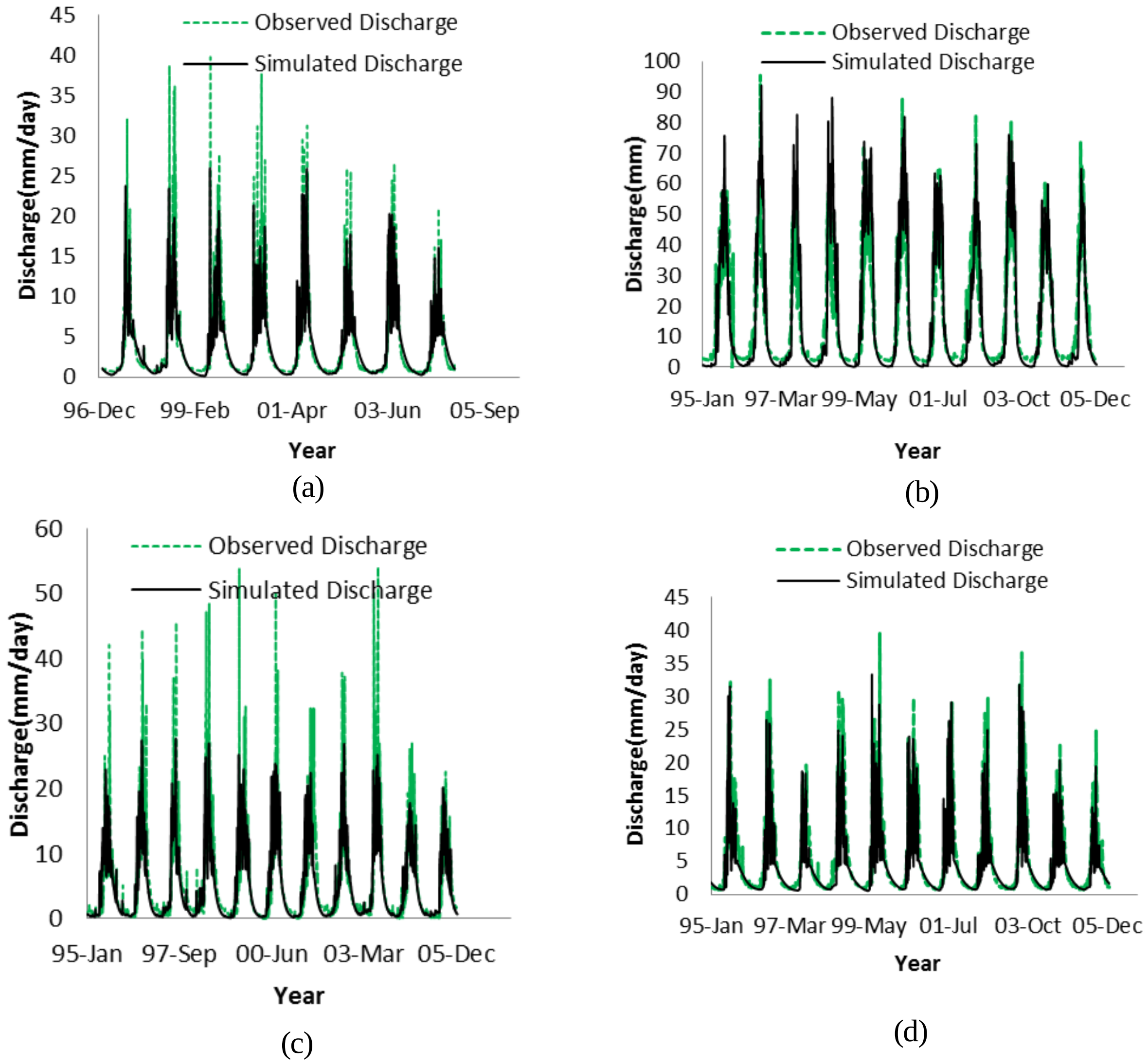


Fig. 5: Observed and simulated discharge (mm/day) during calibration period: (a) Kaligandaki River at Kumalgaon, (b) Trisuli River at Betrawati, (c) Budhigandaki at Arughat (d) Narayani River at Narayanghat.

proximately reflect the evaporation scenario of the Narayani basin as whole due to lack of good quality data in other stations.

***Precipitation data*:** For a satisfactory calibration and validation of rainfall-runoff modelling using the HBV model, data for at least 10 years is required to increase the possibility of including both dry and wet years. Rainfall data were collected for 69 meteorological stations (Fig. 4) within the basin. The period of data (1994 to 2008) was selected taking into consideration the availability of continuous observations. This continuity is important to compare the average monthly rainfall over the same period and to evaluate the quality of observations. The consistency and continuity of precipitation data are very important in statistical analyses such as time series analyses (Silva et al. 2007). In this study, generally accepted interpolation techniques (arithmetic mean method) are used to fill the gaps (missing observations).

***Temperature data*:** Air temperature data (maximum and minimum temperature) were available from 5 meteorological stations (Fig. 4) within the basin at different elevation ranging from 825m asl to 2680m asl. The details of the available temperature stations are listed in Table 1. The mean air temperature for each day is used as input to the HBV model for the differentiation of the precipitation as snowfall or rainfall and for the computation of snow melt and potential

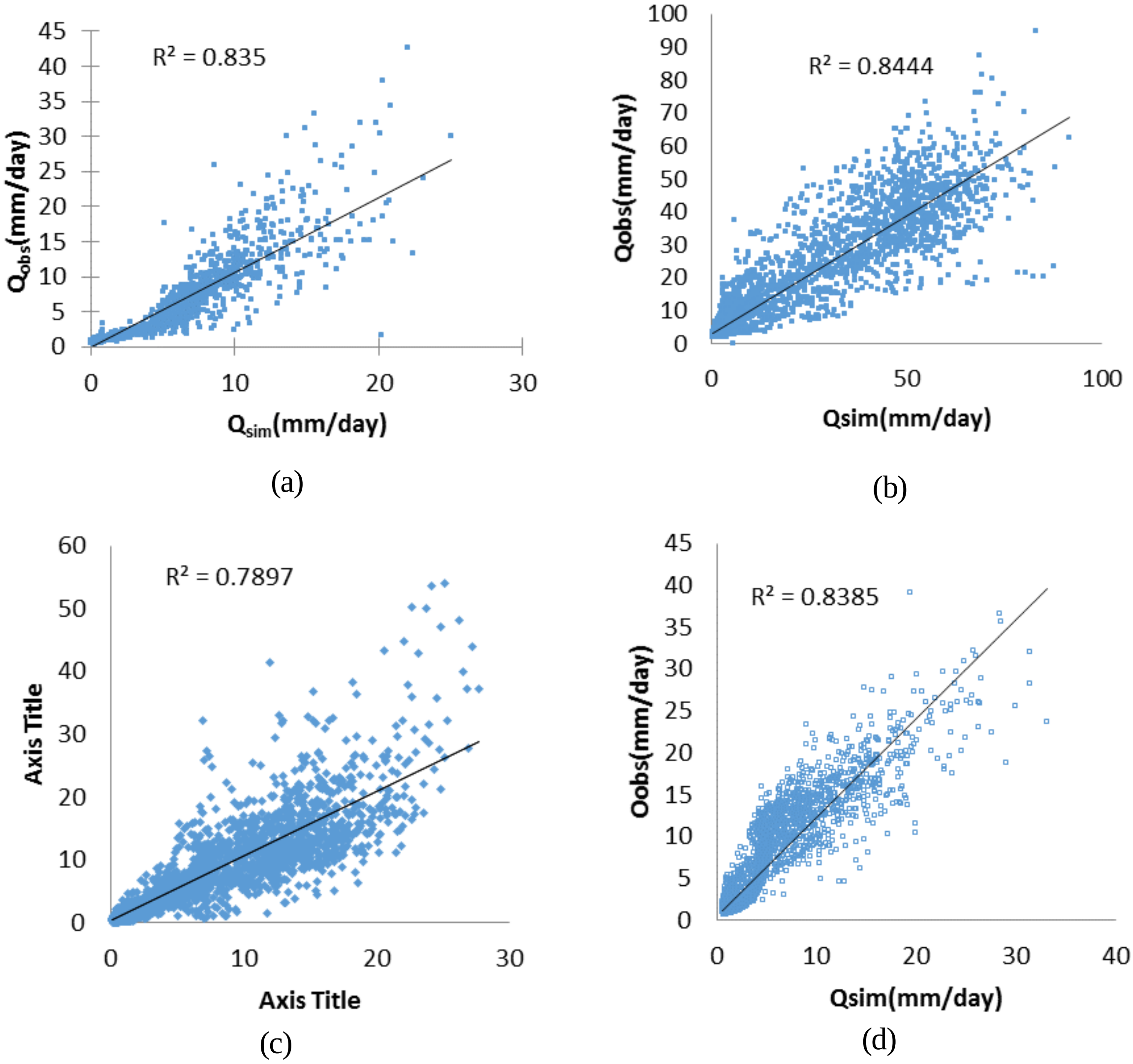


Fig. 6: Scatter plots: (a) Kaligandaki River at Kumalgaon, (b) Trisuli River at Betrawati, (c) Budhigandaki River at Arughat, (d) Narayani River at Narayanghat.

evapo-transpiration. In this study, an average value of lapse rate -0.6°C/100m is used to compute the temperature at elevations different from the temperature at the measuring station.

Model calibration and validation: The calibration and validation were carried out at monthly time period using gauged discharge data available from DHM of Nepal for the years from 1994 to 2008. The data from 1994 to 1995 was used for warming up and initialization of the model variables and this period was not used for evaluation of the model predictions. The data from 1995 to 2005 were used for actual calibration. Similarly, data from 2006 to 2008 were used for validation of the model. The HBV-light model includes a large number of parameters that describe different hydrological conditions and characteristics across the watershed. These parameters need to be calibrated to adequately simulate the stream discharge.

Parameterization of HBV-light model: The parameters in HBV-light model are process parameters i.e., they are not physically measurable and thus must be calibrated. Physical interpretations of the parameters of a conceptual model are normally very vague and should be regarded with sound skepticism (Bergstrom 1992). As, there is no established best method to estimate the model parameters, a variety of different methods have been used for this purpose in previous studies. Harlin & Kung (1992) estimated reasonable ranges of the parameter values by selecting the minimum and maximum values of each parameter from eight autono-

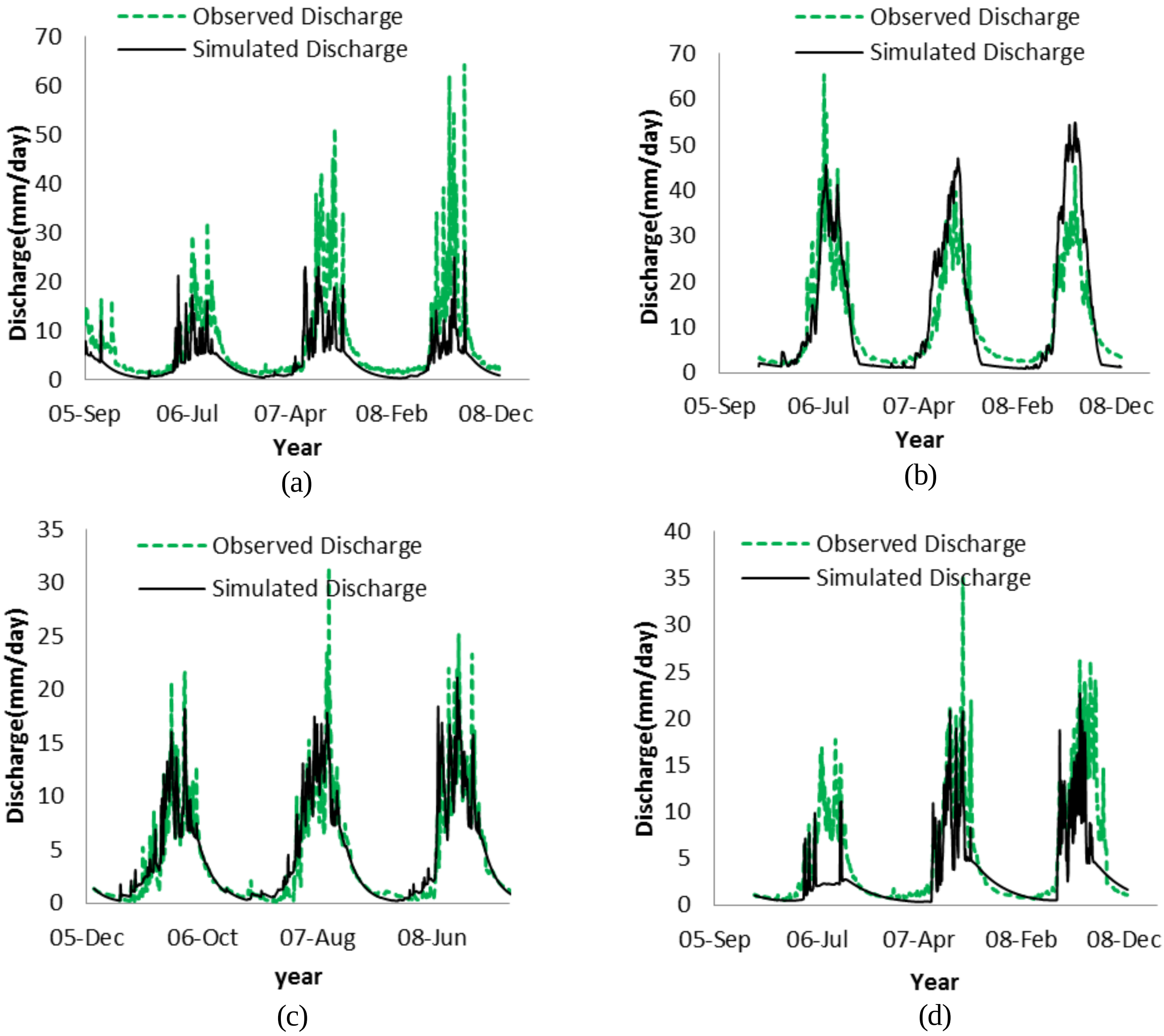


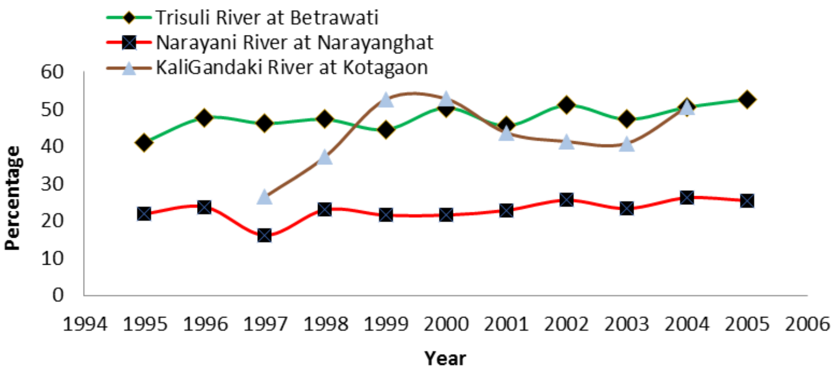
Fig. 7: Observed and simulated discharge vs time (validation): (a) Kaligandaki river at Kumalgaon, (b) Trisuli River at Betrawati, (c) Budhigandaki at Arughat and (d) Narayani River at Narayanghat.

mous calibrations of two catchments. Seibert (1999) used 300,000 Monte Carlo runs to estimate parameter values based on three objective function scores. Booij (2005) used the experience of previous researchers to identify the best parameters.

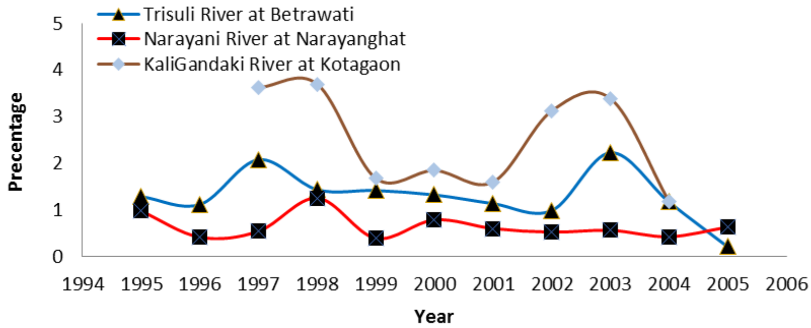
Criteria for model evaluation: NSE and R^2 are the most frequently used efficiency criteria for hydrological applications and flow comparisons (Krause et al. 2005). In this study both the above mentioned criteria and mean difference error were used to evaluate the performance of the model.

Nash-Sutcliffe efficiency (NSE) and Coefficient of determination (R^2): The efficiency E proposed by (Nash & Sutcliffe 1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation, whereas, the coefficient of determination (R^2) is defined as the squared value of the coefficient of correlation (Rodgers & Nicewander 1988). NSE and R^2 are calculated as:

$$NSE = 1 - \frac{\sum_{t=1}^{T} (Q^t_o - Q^t_m)^2}{\sum_{t=1}^{T} (Q^t_o - \bar{O}_o)^2} \quad ...(1)$$



(a)



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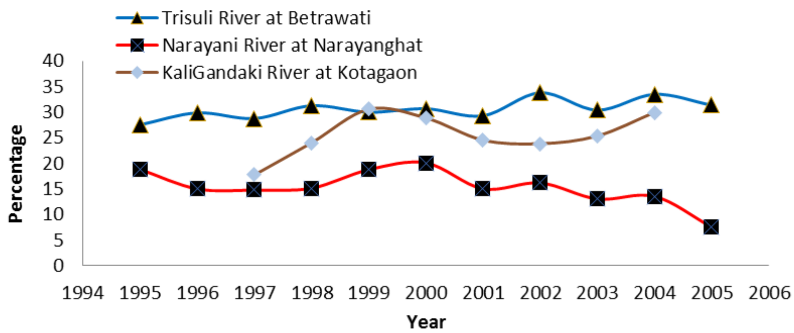


(c)

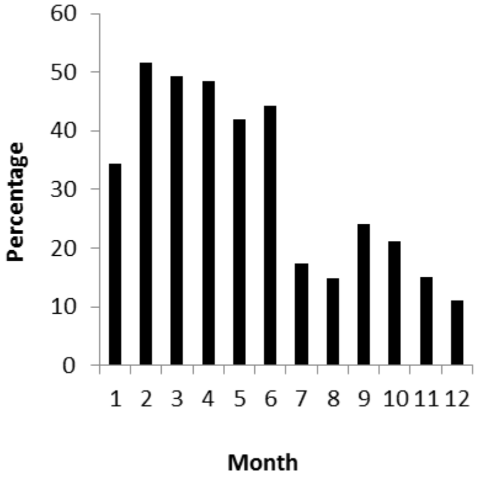
Fig. 8: Snowmelt contribution in percentage to stream flow: (a) March-July, (b) November-February and (c) annual.

$$R^2 = \left(\frac{\sum_{i=1}^{N} (Q_{oi} - \bar{O}_o)(Q_{mi} - \bar{Q}_m)}{\sqrt{\sum_{i=1}^{N} (Q_{oi} - \bar{O}_o)^2 \sum_{i=1}^{N} (Q_{mi} - \bar{Q}_m)^2}} \right)^2 \quad ...(2)$$

Where, Q_o is the observed discharge, Q_m is the modelled discharge and Q_{ot} is the discharge at time *t*. The efficiency varies from 0 to 100, where 100 denoting perfect fit. Generally, NSE is very good when NSE is more than 75%, satisfactory when between 75% and 36%, and unsatisfactory when it is less than 36% (Nash & Sutcliffe 1970).

RESULTS AND DISCUSSION

Model calibration: Table 2 shows the optimized sets of parameters used in calibration period for the study area. In the HBV-light model, some adjustments on the range of the parameter values (obtained from previous studies) were initially specified and sampling was done by 5000 Monte Carlo runs specifying certain threshold efficiency. The model was



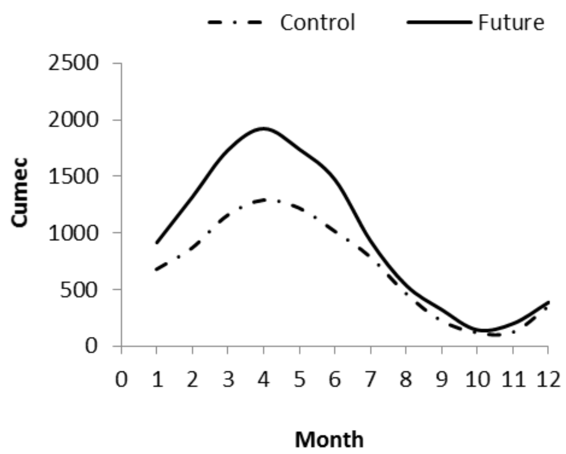


Fig. 9: Simulation of future flow for Trisuli River at Betrawati: (a) Percentage change in future stream flow as compared to the control period and (b) Absolute changes in stream flow for the 2040s using the HadCM3 A1B scenario.

calibrated with the number of sets of parameters yielded after the Monte Carlo runs, those giving acceptable Nash-Sutcliffe efficiency (NSE). The optimized parameter values are those which give the best values of NS efficiency, coefficient of determination (R^2) and mean difference between the observed and the simulated stream flow values.

Fig. 5 shows the observed and simulated discharge during the calibration period (1995-2005) for four outlet stations of the study basin one of which is the final outlet point (Narayani River at Narayanghat). From the observed simulations, it is seen that HBV-light model generally underestimates the peak values and the low flow period is better simulated.

Table 3 shows the NSE, R^2, mean observed and simulated discharge and their difference for the different river basins during the calibration period under the study. It has been observed that the average simulated and observed discharges are close to each other. In addition, NSE values obtained for the gauging stations: Kaligandaki River at Kotagaon, Trisuli River at Betrawati, and Budhigandaki River at Arughat and Narayani River at Narayanghat are 82.6%, 70.5%, 76.5% and 78.9% respectively. No generally agreed absolute threshold exists for the performance indicators; however, based on the previous published studies, hydrological simulation of monthly values with NSE above 75% can be considered good, satisfactory when between 75 and 36%, and unsatisfactory when they are less than 36% (Moriasi et al. 2007, Nash & Sutcliffe 1970). Further, during the calibration period the value of R^2 for the basin is between 0.789 and 0.844. The mean difference of water balance (volumetric error) during calibration is very less with value from -54.0mm to +414.8mm for Kaligandaki basin and Narayani basin respectively.

The scatter plots shown in Fig. 6 indicate the similar behaviour of the observed and HBV-light simulated discharges during the calibration. The efficiency values and the visual inspection of the hydrographs demonstrate that the performance of the HBV-light model is satisfactory. During calibration it is noted that for the river basins under study, threshold temperature is the most critical parameter because the simulations generally show that most of the precipitation occurs under freezing conditions when the precipitation is in the form of snow. On the other hand, most of the runoff is generated in summer when temperature is above the freezing point.

Model validation: The calibrated parameter sets were used for the representation of the catchment behaviour using an independent data set for the validation period from 1st January 2006 to 31st December 2008. Performance of the validation results are shown in Table 3 and Fig. 7. The acceptable range of the NS score given in Table 3 over the validation period indicates the robustness of the model as a reliable simulator of catchment behaviour. One out of thirteen catchments show a higher NS efficiency in the validation period compared to the calibration period. The efficiency range during the validation period (0.563 to 0.872) is somewhat better than that in the calibration period (0.705 to 0.826). The efficiency is highest for Kaligandaki River at Kotagaon compared to the other basins in the calibration period. However, comparison of this value between different river basins needs to be done carefully as this measure is highly influenced by runoff variability (Akhtar 2008). Dur-

Table 2: Optimized Values of the different model parameters during calibration.

Gauging stations	Parameters PERC	UZL	K0	K1	K2	MAXBAS	TT	CFMAX	SFCF	CFR	CWH	FC	LP	BETA
Arughat	11.05	0.19	0.03	0.14	0.02	1.35	-4.57	2.03	0.50	0.04	0.15	399.76	0.82	0.57
Betrawati	7.72	76.44	0.06	0.07	0.03	1.00	-1.23	1.72	0.01	0.47	0.35	122.68	0.48	0.11
Kotagaon	8.91	23.18	0.09	0.20	0.03	1.44	-1.09	2.26	0.15	0.54	0.74	99.75	0.79	1.34
Narayan-ghat	7.10	67.85	0.45	0.70	0.01	1.51	-0.36	0.59	0.09	0.53	0.30	496.43	0.95	1.50

Table 3: Performance of the HBV model during calibration and validation period in different river basins.

Catchments	R_{eff}		R^2		Log R_{eff}		Water Balance (mm/yr) Calibration			Validation		
	Calibr-ation	Valida-tion	Calibr-ation	Valida-tion	Calibr-ation	Valida-tion	Qsim	Qobs	Mean Diff	Qsim	Qobs	Mean Diff
Budhigandaki	0.765	0.872	0.789	0.893	0.851	0.876	2533.50	2452.90	-80.6	2157.37	2165.37	8.23
Betrawati	0.705	0.589	0.844	0.845	0.219	0.428	5825.10	5333.70	-491.40	4698.69	4025.44	-673.14
Kotagaon	0.826	0.844	0.829	0.893	0.312	0.344	1224.00	1170.00	-54.0	916.82	910.83	-5.99
Narayanghat	0.781	0.563	0.838	0.629	0.805	0.643	1493.80	1908.60	414.8	1153.48	1702.57	549.14

Reff: Nash Efficiency, R^2: Coefficient of Determination

Table 4: Snowmelt contribution (%) for increased temperature conditions.

Station		Increase in Temperature ^{0}C 0	0.5	1	1.5
Trisuli River at Betrawati	MAMJJ	47.7	48.8	49.7	50.5
	NDJF	1.3	1.3	1.3	1.4
	Annual	30.6	31.1	31.7	32.0
Kaligandaki River at Kotagaon	MAMJJ	43.2	44.6	46.9	47.7
	NDJF	4.3	4.0	3.7	4.2
	Annual	25.6	26.1	27.2	27.8
Narayani River at Narayanghat	MAMJJ	22.9	23.0	24.8	25.3
	NDJF	0.7	0.7	0.8	0.8
	Annual	15.3	15.8	16.2	16.9

MAMJJ: March to May, NDJF: November to February

ing the validation period, the mean difference values show that in most cases, the models underestimate the discharge. The acceptable value of R^2 during validation is between 0.629 and 0.893, which indicates that the calibration of the model was successful.

Snowmelt contribution to total runoff: Fig. 8 demonstrates the percentage contribution of snowmelt (calculated using a simple water balance equation assuming total incoming water flow to the basin is equal to the total outgoing water flow from the basin) to annual runoff and runoff at different seasons; season with less contribution (November to February) and that with maximum contribution (March to July) for the three main gauging station of the basin except Budhigandaki River at Arughat. It can be seen from Fig. 8 that the contribution of snowmelt to annual stream flow is (27.5% to 33.7%) at Trisuli River at Betrawati and (17.75% to 30.57%) at Kaligandaki River at Kotagaon. As we move further downstream, contribution has lesser values (almost 15%) annually with a maximum contribution to 26.22% in year 2004 of month MAMJJ and a minimum contribution of 0.42% in the year 1996 of month NDJF at Narayani River at Narayanghat in all the calibration years.

Further, results show that for all three basins, the maximum contribution of snowmelt to the stream flow is maximum from March to July, and minimum from November to February. This is the reason that, with the start of summer, the accumulated snow begins to melt and from November to February, when the snow accumulates and the snow pack rises, the contribution of snowmelt to stream flow is the least. During the summer season, this value ranges between 16.2% and 26.22% with an average of 22.87% at the Narayanghat station with increase in the range as we move upward (an average value of 47.66% at Trisuli River at Betrawati of summer flow and an average value of 43.21% at Kaligandaki River at Kotagaon). Contribution of snowmelt from November to February shows simultaneous decrease at the downstream outlets. At the most downstream outlet of the basin at Narayanghat, this value ranges between 0.42% and 1.26 %.

Sensitivity analysis: Sensitivity analysis was performed for increasing temperature scenarios to estimate the percentage contribution of snow and glacier melt discharge. The model is simulated for snow melt discharge estimated by increasing the temperature by 0.5°C, 1°C and 1.5°C and the calibration period (1995-2005) is taken as the base period for this analysis. Sensitivity test has been done for the three main gauging stations given in Table 4. The results indicate that the snowmelt contribution runoff increases along with an increased temperature.

Simulation of future flow using the validated model: In this study, future flow pattern was simulated at only one gauging station (Trisuli River at Betrawati) under the study. The HBV-light model was forced with the statistically downscaled data available from HadCM3 GCM for the A1B scenario. The model output was evaluated over two time slices; the base period from 1970 to 2000 and 2030 to 2060. Temperature and precipitation from the control period (1970 to 2000) with the HadCM3 A1B scenario were used as input to the model. The model was run with the best parameter set obtained during calibration. The output from the model is runoff in mm.

Fig. 9a shows the percentage change in monthly stream flow over the two time periods under study. The model shows an overall increase in monthly stream flow. In Trisuli at Betrawati the model simulates increase in stream flow in the months of January to June (34% to 51%). However, in the months with minimum stream flow (November-December), the model simulates a rather conservative increase in stream flow (10% to 15% of the control period values). Such a difference in stream flow can have large consequences for water abstraction activities in the basin. Fig. 9b shows the absolute changes in stream flow discharge in cumec in the monthly flow regime for the 2040s. By 2040s, the model simulates a significantly wetter monthly flow regime, particularly in the main season of flooding. This highlights the changes in flood magnitude due to climate change.

CONCLUSION

This study attempts to estimate the snow melt contribution in rainfall-runoff modelling of a watershed with significant coverage of snow, for which the snow melt discharge was estimated by application of general water balance method aided with a lumped runoff model (HBV-light model). Based on the analysis, the following conclusions have been drawn from the present study:

1. HBV-light model has been proven to be very effective to simulate stream flow and snowmelt effectively in the snow fed basin. The model was calibrated for the period 1995-2005 and validated for the period 2006-2008 with satisfactory results producing values of Nash-Sutcliffe coefficient between 75.2%-82.6% during calibration and 56.3%-87.2% during validation for all four sub-basins. The value of coefficient of determination (R^2) during the calibration is 0.789-0.844, and during validation is 0.629-0.893.
2. The model performance is highly sensitive on the choice of the values of the parameter sets. Different sets of parameters can give same efficiency. This leads to ambiguity in determining the best parameter set. So, the generation of a large number of parameter sets using the Monte Carlo method helps in prioritizing the important parameters to be used during calibration.
3. The contribution of snow melt discharge to the total flow decreases downstream. At the most downstream station Narayanghat, contribution of snowmelt to annual, summer (March-July, MAMJJ) and winter (November-February, NDJF) runoff at the final outlet gauging station (Narayani River at Narayanghat) is 15.72% (avg.), 26.22% (maximum in year 2002) and 0.42% (minimum in year 1996) respectively.
4. The result of sensitivity tests demonstrate that the impact of climate change (i.e., increase in temperature) to stream flow is significant. Increase in temperature causes an enhancement in the annual and seasonal stream flow along with the snowmelt contribution to the stream flow.
5. Running the model with climate change outputs of the HadCM3 RCM simulates a significantly wetter monthly flow regime in the 2040s, particularly in the main season of flooding. This highlights the changes in flood magnitude due to climate change.
6. To simulate the snowmelt more accurately (in our study, we use simple water balance approach) it is recommended that the model is run in hourly time steps. Besides, in order to attain the better results, it is recommended to consider the glacier melt by using satellite images to extract the glaciarized area and the use of spatially distributed hydrological models for snow and glacier melt.

Further, the use of two or more climate change scenarios is recommended to assess the uncertainty of climate change impact studies that arise due to the use of different future climate data.

ACKNOWLEDGEMENT

We are truly grateful to the Department of Hydrology and Meteorology (DHM) of Nepal for providing all the necessary data for this study.

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