

Hydrological Modeling and Climate Change Impact Assessment Using HBV Light Model: A Case Study of Karnali River Basin

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Abstract: This study has simulated climate change impacts on the runoff processes of the Karnali River Basin of Nepal. Estimation of the variation of snowmelt contribution to streamflow in increased temperatures has been done. The semi-distributed HBV rainfall-runoff model has been calibrated using hydro-meteorological data available from 1986 to 1997. The model simulates runoff based on precipitation, air temperature and potential evapotranspiration. The calibrated model is fed with the climatic projections developed using the PRECIS Regional Climate Model to estimate future (2040s) streamflow. The study indicates that the growing temperatures will generally result in wetter flow regime in the future.

1. Introduction

Increase in the atmospheric contents of greenhouse gases (GHGs) due to rapid industrialization brings change in the radiative balance of the earth resulting in climate change, especially in terms of increase in temperature, change in precipitation pattern and rise in the frequencies of extreme events (Houghton, 2001). Extraordinary warming in the past two decades is believed to be due to the anthropogenic impact (Mann and Jones, 2003; Thorne et al., 2003; Trenberth et al., 2007). Meteorological data of the previous century suggest a global mean temperature rise of 0.07°C/decade (Folland et al., 2001; Jones and 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 intensity of extreme events has also increased worldwide (Sillmann and Roeckner, 2007). The frequency of severe floods in large river basins has increased during the 20th century (Milly et al., 2002).

Such climatic changes are likely to affect the hydrological processes of many parts of Nepal as well. Nepal's topography extends between the Himalayan ranges (with altitude upto 8848 masl) in the north to the lower southern planes (with altitude as low as around 300 masl). The country's climate is strongly affected by this variation. The lowland regions have a warm sub-tropical climate, with temperature varying around 22-27°C during summer and 10-15°C in the winter. The high altitude mountainous regions are considerably colder with temperatures around 5-15°C in summer and well below zero in the winter. Monsoon rainfall arrives in June and continues until August-September, bringing 250-450 mm of rain/month in most parts of the country but only 100-150 mm in the north-western mountain regions (UNDP, 2012).

Changes in flow patterns and magnitude in the major river systems of Nepal are likely to cause reduced water flows in the dry season and flood problems in the wet season. Frequency and magnitude of extreme events like floods and droughts have increased recently (WECS, 2011). Such adverse situations suggest a need to investigate the impacts of climate change on the water resources at present and in the future in order to conceptualize better strategies for water resource management. Prediction of snow and glacier melt runoff from the Himalayas is of great importance for effective water resources management in the country. Direct field observations needed for such studies are difficult to carry out due to difficulties in reaching remote locations. This necessitates the formulation of a snow and glacier melt runoff model (Higuchi et al, 1977). Very few hydrological studies have been carried out in the Karnali region of far-western Nepal.

This study has assessed the climate change impact on the streamflow processes in the Karnali River Basin (KRB). To achieve this, fine scaled climate change scenarios developed using the Providing Regional Climate for Impact Studies Regional Climate Model (PRECIS RCM) have been used (Jones et al., 2003). Projections from PRECIS RCM are fed into the Hydrologiska Byråns Vattenbalansavdelning (HBV) hydrological model to estimate the river discharge in the present and future climate scenarios. Such projections depend on the future changes in emissions of GHGs, which are related to future socioeconomic developments. The Special Report on Emission Scenarios (SRES) (IPCC, 2000) include six scenario groups; A1B, A2, B1, B2, A1T and A1F1 (Nakicenovic et al., 2000). In this study, the A1B scenario of the HadCM3 climate change model has been used to predict changes in the runoff regime in KRB for the time period between 2030 and 2060. Contribution of snowmelt to the total discharge has also been calculated.

2. Study Area

Karnali River Basin (KRB) located in far-western Nepal is the second largest basin of the country. The perennial Karnali River originating from the Mansarovar Lake in China is the longest river in Nepal with a length of 507 km. The 202 Km long, Seti River drains the western part of the catchment and the 264 Km long Bheri River drains the eastern part. The geographical location of the basin is shown in Figure 1.

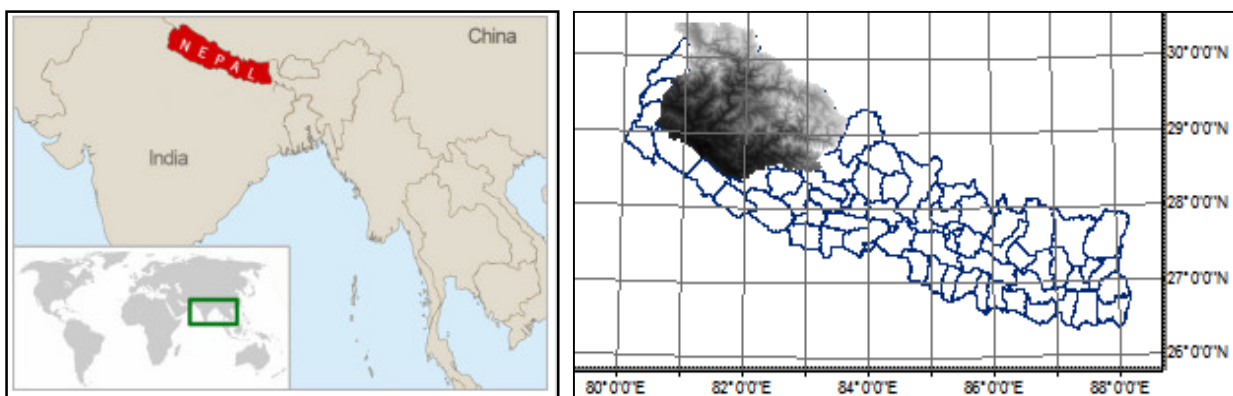


Figure 1: Geographical Location of the study area

The basin extends from latitudes 30.4° north to 28.2° south and longitudes 80.6° west to 83.7° east. The catchment extending between the mountain ranges of Dhaulagiri in Nepal

and Nanda Devi hills in India has an area of 127,950 km². The area falling within Nepal is around 41,058 km² at the outlet of the basin at Chisapani (Acharya, 2011). The watershed's elevation ranges from 140 m to 7498 m. The topography of the basin is characterized by high mountain ranges, steep slopes, terraces and flat valleys. Streamflow is characterized by seasonal variability. Major portion of the total yield occurs in August- September.

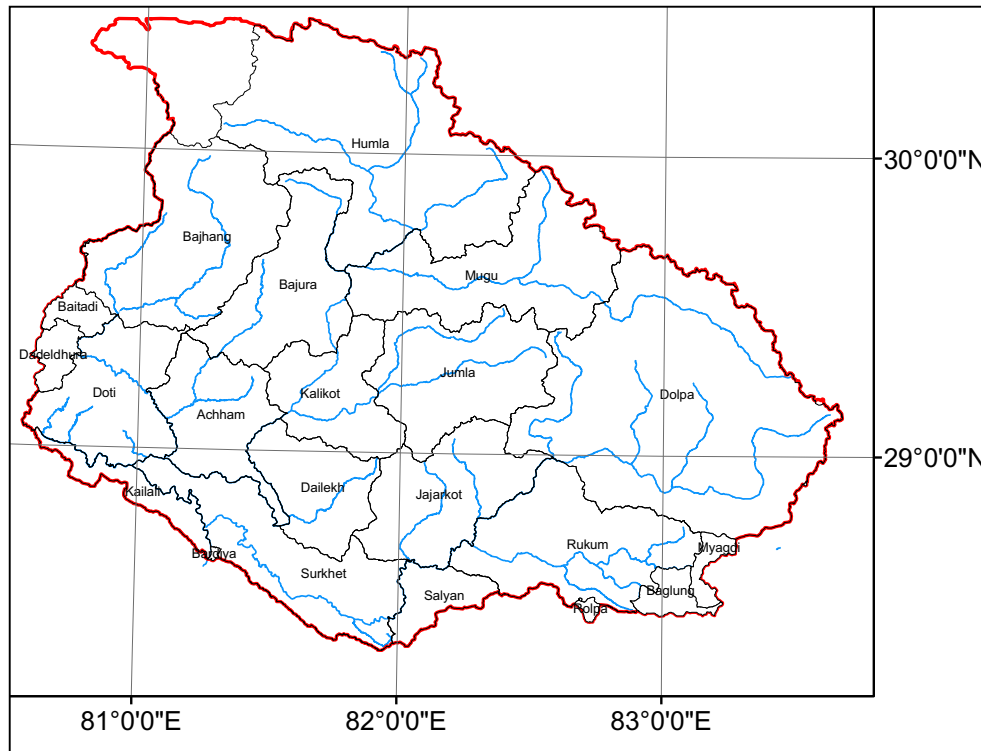


Figure 2: The study area and districts within the basin

Snowmelt is the main contributor to streamflow, which increases during summer. The basin consists of 1,361 glaciers with an area of 1740 km² and an estimated ice reserve of 127.72 km³ (Shakya).

3. The HBV Model

The HBV model is a semi-distributed conceptual rainfall-runoff model. It simulates streamflow using rainfall, temperature and potential evapotranspiration (PET) as input (Bergström, 1976). Mean catchment elevation and elevation of precipitation and temperature stations are also specified. HBV-Light (Seibert, 2005), a recent version of the model has been employed in several studies evaluating the effects of climate change on river basins (e.g., Wang *et al.*, 2006; Steele-Dunne *et al.*, 2008). The model has 12 parameters that need to be parameterized for calibration. Monte-Carlo (MC) simulations can be performed using random numbers from a uniform distribution within the set ranges for each parameter. The model is subdivided into three routines; snow and glacier routine, soil moisture routine and runoff generation routine.

The snow and glacier routine uses a temperature-index method to calculate snow and ice melt. Input data are daily air temperature and precipitation. Changes in precipitation and

temperature with elevation are calculated using the two parameters PCALT [%/100 m] and TCALT [°C/100 m]. The output is the effective precipitation as rainfall and snowmelt which is fed as input into the soil moisture routine. The liquid and solid precipitations are separated using the parameter, threshold temperature (TT). Snowmelt amount in any time step is calculated as the product of the degree-day factor (Cfmax) and the difference between air temperature and TT, if the air temperature is above TT.

Output of the snow and glacier routine is the input into the soil moisture routine (Bergström, 1976) which calculates soil moisture storage, infiltration and percolation through the soil. The maximum storage capacity of the soil is determined by the parameter FC (field capacity). Infiltration is calculated as a function of the ratio between actual soil moisture and FC. Parameter BETA accounts for different infiltration characteristics of soils. The smaller the BETA, the more water is sent to the next routine even when soil moisture is small as compared to FC. The routine calculates actual evaporation as a function of the parameter LP (fraction of soil moisture storage above which actual evaporation is supposed to be equal to the potential evaporation).

The model of a single linear reservoir is used for runoff generation. It is a simple catchment description where runoff at any time is assumed to be proportional to the soil water storage at that time step.

Inputs into the model are precipitation, air temperature, runoff, PET and catchment description. Precipitation and temperature data from meteorological stations need to be corrected for measurement errors. Runoff is taken from the selected gauging stations. Catchments can be separated into different elevation/vegetation zones and sub-catchments. HBV-Light uses a warming-up period to set variable values according to the preceding meteorological conditions.

4. Methodology

4.1. Data Acquisition

The existing streamflow data of various hydrological stations within the basin are obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal. Daily runoff data at these stations for the study period (1986 to 2004) have been analyzed. There are altogether 20 stations in the basin among which eight have been considered. Details of these stations are shown in Table 1. Filling gaps in the dataset is a necessary step to obtain a longer period of continuous data. It was done by a simple approach of arithmetic averaging of the flows during same day of the same months of the preceding and succeeding two years of the year with missing data.

Table 1: Hydrological stations used

No.	St. No.	River	Location	Latitude	Longitude	Elev. (m)	Area (km ²)
1	215	Humla Karnali	Lalighat	29.15	81.60	590	15200
2	250	Karnali	Benighat	28.96	81.12	320	21240
3	256.5	Budhi Ganga	Mangalsen	29.16	81.21	506	1576
4	259.2	Seti River	Gopaghat	29.30	80.78	750	4420
5	260	West Seti	Banga	28.98	81.14	328	7460

6	265	Thulo Bheri	Rimna	28.71	82.29	772	7084
7	270	Bheri	Jamu	28.76	81.35	246	12290
8	280	Karnali River	Chisapani	28.64	81.29	191	42290

Precipitation data from 30 Meteorological stations for the period from 1986 to 2004 were collected as shown in Table 2. Precipitation data from the stations were used to derive a time series of mean areal daily precipitation using Thiessen polygons. Arithmetic Mean Method and Normal Ratio Method have been used to fill the gaps in the data series to assure data consistency and continuity. Figure 3 shows the selected meteorological and hydrological stations.

Table 2: Meteorological stations used

S.N.	Station name	Index No.	District	Latitude (deg)	Longitude (deg)	Elevation (m)
1	Dadeldhura	104	Dadeldhura	29.3	80.58	1848
2	Chainpur(West)	202*	Bajhang	29.55	81.22	1304
3	Silgadhi Doti	203	Doti	29.27	80.98	1360
4	Bajura	204	Bajura	29.38	81.32	1400
5	Katai	205	Doti	29	81.13	1388
6	Asara Ghat	206	Achham	28.95	81.45	650
7	Bangga Camp	210	Achham	28.97	81.12	340
8	Khaptad	211	Doti	29.38	81.2	3430
9	Kola Gaun	214	Doti	29.12	80.68	1304
10	Godavari(West)	215	Kailali	28.87	80.63	288
11	Mangalsen	217	Achham	29.15	81.28	1345
12	Thirpu	302	Kalikot	29.32	81.77	1006
13	Jumla	303*	jumla	29.28	82.17	2300
14	Guthi Chaur	304	Jumla	29.28	82.32	3080
15	Sheri Ghat	305	Kalikot	29.13	81.6	1210
16	Gam Shree Nagar	306	Mugu	29.55	82.15	2133
17	Rara	307	Mugu	29.55	82.12	3048
18	Nagma	308	Kalikot	29.2	81.9	1905
19	Bijayapur (Raskot)	309	Kalikot	29.23	81.63	1814
20	Dipal Gaun	310	Jumla	29.27	82.22	2310
21	Simikot	311	Humla	29.97	81.83	2800
22	Dunai	312*	Dolpa	28.93	82.92	2058
23	Pusma Camp	401	Surkhet	28.88	81.25	950
24	Dailekh	402	Dailekh	28.85	81.72	1402
25	Jamu (Tikuwa Kuna)	403	Surkhet	28.78	81.33	260
26	Jajarkot	404	Jajarkot	28.7	82.2	1231
27	Chisapani(Karnali)	405	Bardiya	28.65	81.27	225

28	Surkhet	406*	Surkhet	28.6	81.62	720
29	Bale Budha	410	Dailekh	28.78	81.58	610
30	Shyano Shree	413	Bardiya	28.35	81.7	510

Daily maximum and minimum temperatures at four stations (marked with an asterisk in Table 2) for the period ranging from 1986 to 2004 were also obtained. Daily temperature has been calculated as the simple average of the maximum and minimum temperatures. Lapse rate of $-0.6^{\circ}\text{C}/100\text{ m}$ is used to compute temperature at elevations different from the measuring stations. Average monthly PET data in mm/day have also been obtained.

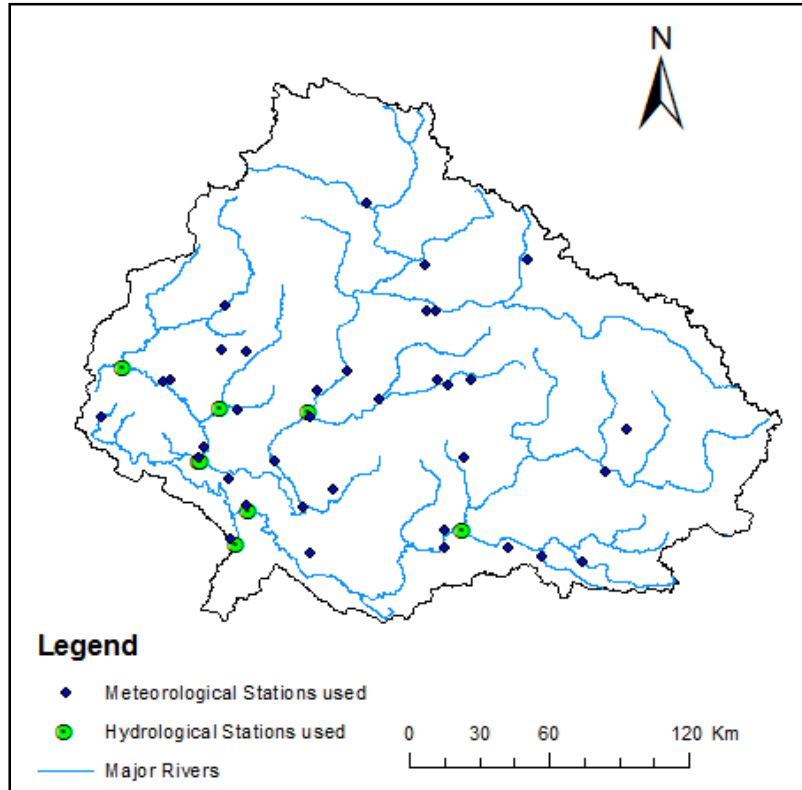


Figure 3: Meteorological and discharge stations in the area

4.2. Elevation Zoning

Basin elevation ranges from 185 masl to 7731 masl. The basin has been divided into 10 elevation zones. Table 3 shows the areal extent and average elevation of each zone. Forcing this information into the model gives the accumulation and melting of snow in each zone for each sub-catchment.

Table 3: Division of the basin into elevation zones

Elev Zone	Elevation Range (masl)		Average Elevation	% of Total Area	Area Covered (Km ²)
	Min	Max			
1	120	875	60	6.17	2720.03
2	875	1800	900	13.72	6044.54

3	1800	2500	2150	12.31	5423.21
4	2500	3200	2850	11.89	5240.44
5	3200	4000	3600	14.11	6215.28
6	4000	4700	4350	13.26	5840.54
7	4700	5500	5100	20.72	9129.23
8	5500	6200	5850	7.32	3224.60
9	6200	7100	6650	0.45	197.43
10	7100	8200	7650	0.05	22.80

4.3. Watershed Delineation

The basin has been delineated into eight sub-basins to carry out the modeling at different points as shown in Figure 4 and Table 1.

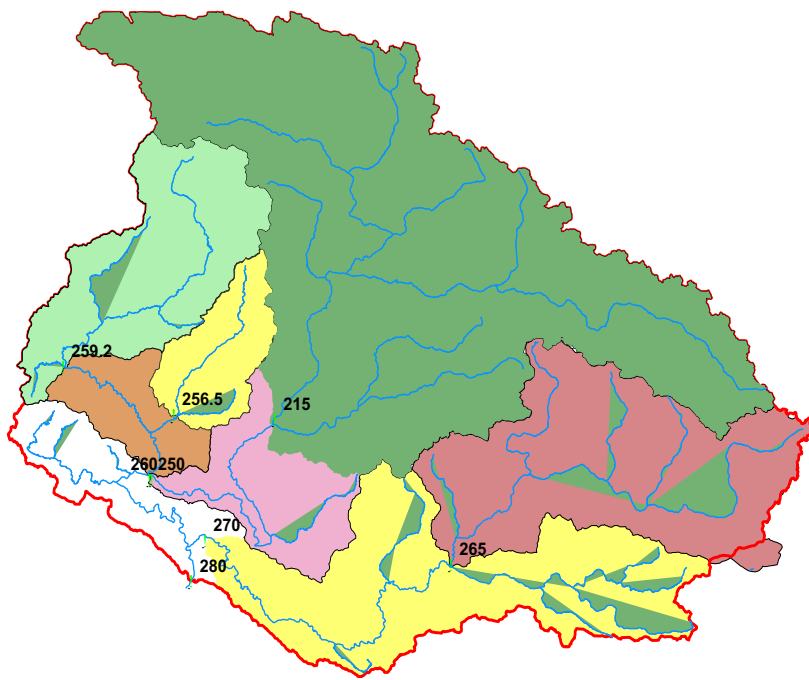


Figure 4: Sub-basins delineated at selected gauging stations

4.4. Model Execution

Daily records of mean flow, temperature, precipitation and PET from 1986 to 1997 were used as input for model calibration and records from 1998 to 2004 have been used for model validation. Warming-up period from 1986 to 1987 has been used to allow for adjustments to the initial and boundary conditions. Calibration has been done to obtain the best process parameters for each sub-basin.

Then, assessment of snowmelt is done, which helps in computation of snowmelt contribution to the streamflow. Finally, the calibrated model is run to simulate the future runoff processes in the basin and change in flow regime as compared to a historic base period. The model has been forced with the statistically downscaled climate data of the Had CM3 GCM and the A1B climate scenario to simulate the streamflow processes for

the control period (1970 to 2000) and the future period (2030 to 2060). Temperature and precipitation from the control period of the scenario has been input into the calibrated model. Similar procedure has been carried out to obtain runoff for the future period. Hydrological behavior of the basin has been compared over the two time periods.

4.4.1. Calibration

The Nash Sutcliffe (NS) efficiency criterion has been employed as the likelihood measurement for calibration of the parameter sets. NS score for a perfect fit between observed and modeled flows is 1. The criteria is biased towards higher flows because the largest residuals tend to be found near the hydrograph peaks, and as the errors are squared, greater weight is given to prediction of the peaks of the hydrograph. (Legates and McCabe, 1999; Krause *et al.*, 2005).

The range of the parameter values was initially specified and sampling was done by 5000 Monte-Carlo (MC) runs specifying 0.6 as the threshold value for each sub-catchment. Table 4 shows the number of sets of parameters yielded that gave acceptable NS scores and also the minimum, mean and maximum values of NS scores from all simulations.

Table 4: Summary of the MC simulations

Sub catchment	Threshold value of NS	No. of NS values above Threshold	Min	Mean	Max
Humla Karnlai	0.6	223	0.615	0.643	0.72
Karnali at Benighat	0.75	376	0.75	0.799	0.875
Thulo Bheri, Rimna	0.65	123	0.67	0.71	0.77
Bheri at Jamu	0.75	220	0.75	0.82	0.86
Budhi Ganga	0.6	287	0.63	0.66	0.73
Seti at Gopaghat	0.6	62	0.6	0.64	0.69
Seti at Bel Gaon	0.7	361	0.7	0.76	0.798
Karnali, Chisapani	0.8	166	0.81	0.84	0.87

Parameter values obtained from the simulations are optimized manually for the best NS scores, Coefficient of Determination (CoD) and Mean Difference (MD) between observed and simulated flows. Table 5 shows the calibrated parameter values for all sub-catchments.

Table 5: Optimized model parameters

Parameter	PERC	UZL	K0	K1	K2	MAXBAS
Catchment						
Humla Karnali	6.43	69.76	0.64	0.37	0.03	1.68
Karnali, Benighat	4.01	20.34	0.26	0.18	0.02	1.46
Thulo Bheri, Rimna	8.50	20.00	0.01	0.10	0.05	1.35
Bheri, Jamu	7.53	47.86	0.41	0.13	0.03	2.30
Budhi Ganga	4.64	37.95	0.12	0.02	0.01	2.17

Seti, Gopaghat	5.54	96.59	0.11	0.05	0.01	1.53
Seti, Bel Gaon	3.06	68.92	0.26	0.19	0.01	1.71
Chisapani	4.46	12.47	0.11	0.02	0.03	1.52

Parameter	TT	CFMAX	SFCF	FC	LP	BETA
Catchment						
Humla Karnali	-3.27	2.26	1.28	295.50	0.95	1.68
Karnali, Benighat	-3.00	3.17	0.26	130.68	0.99	1.46
Thulo Bheri, Rimna	-4.50	3.22	1.36	550.68	0.75	1.35
Bheri, Jamu	-6.78	2.95	0.11	650.00	0.51	2.30
Budhi Ganga	-5.41	0.55	0.09	92.01	0.95	2.17
Seti, Gopaghat	-4.83	2.89	0.16	90.11	0.40	1.53
Seti, Bel Gaon	-3.04	1.27	0.67	442.03	1.00	1.71
Chisapani	-2.58	3.97	0.15	275.46	1.00	1.52

4.4.2. Validation

The calibrated set of the parameters was then tested against the observed flow of the validation period.

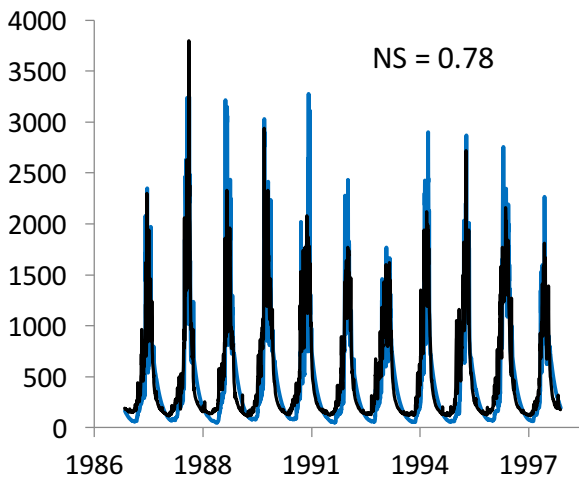
5. Results and Discussion

5.1. Model Performance

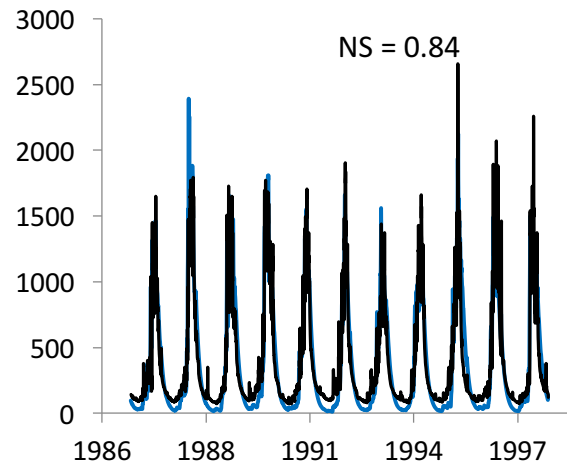
The threshold temperature (TT) is a critical model parameter because simulations show that most of the precipitation under freezing conditions occurs as snow. On the other hand, most of the runoff is generated in summer when temperature is above freezing point. Table 6 shows the NS scores, CoD, observed and simulated discharge during the calibration period and their MD. The NS values are within acceptable range. Figure 5 shows the observed and simulated discharge during the calibration period for selected sub-basins (Bheri, Seti and Karnali River at Benighat and Chisapani). It is seen that the model generally underestimates the peak values while the low flow is better simulated.

Table 6: Model performance during calibration

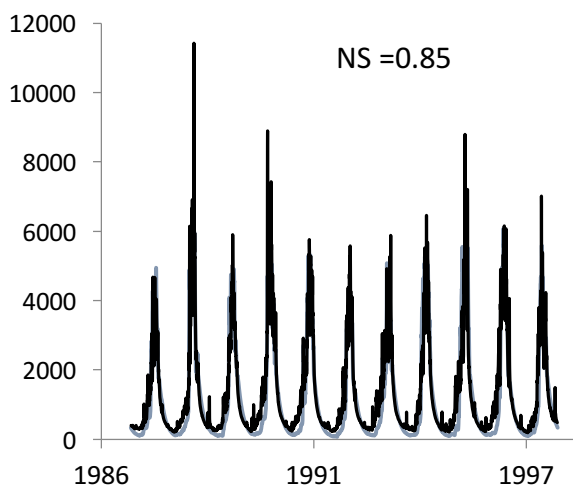
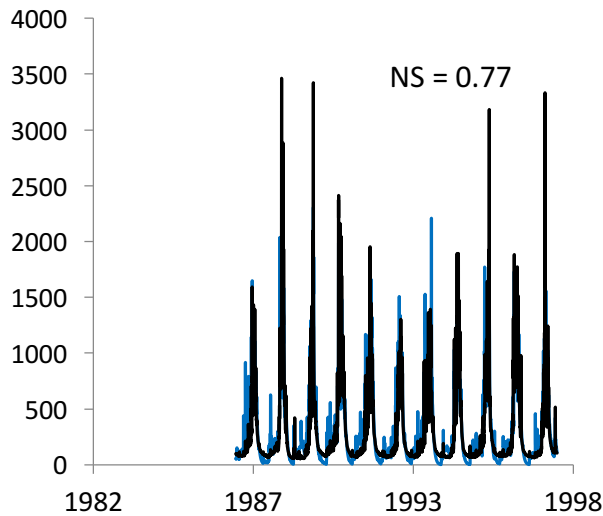
Basin	Water Balance [mm/year]		Goodness of fit		
	Sum Qsim	Sum Qobs	CoD	NS	MD
Humla Karnali	528.23	573.89	0.64	0.63	45.65
Karnali, Benighat	772.37	809.59	0.81	0.77	37.22
Thulo Bheri, Rimna	731.83	773.72	0.77	0.71	41.89
Bheri, Jamu	853.26	890.56	0.86	0.84	37.29
Budhi Ganga	1374.24	1386.22	0.73	0.67	11.98
Seti, Gopaghat	1706.22	1727.83	0.67	0.63	21.61
Seti, Bel Gaon	1173.27	1191.01	0.77	0.77	17.73
Chisapani	904.23	965.44	0.87	0.82	61.15



(a)



(b)



(c)

(d)

Figure 5: Observed and simulated discharge (mm/day) during calibration for (a) Karnali at Benighat, (b) Bheri at Jamu, (c) Seti at Bel Gaon, (d) Karnali at Chisapani. Observed hydrograph in black and simulated hydrograph in blue. Discharge in the ordinate, time (year) in the abscissa.

Figure 6 shows the scatter plots of observed discharge versus simulated discharge values at the selected four locations of the basin. The figure also gives the corresponding R^2 values. Observation of the scatter plots indicates that the model performance is satisfactory. Thus, it can be inferred that the model satisfactorily simulates the runoff processes of the basin with the help of the optimized parameters.

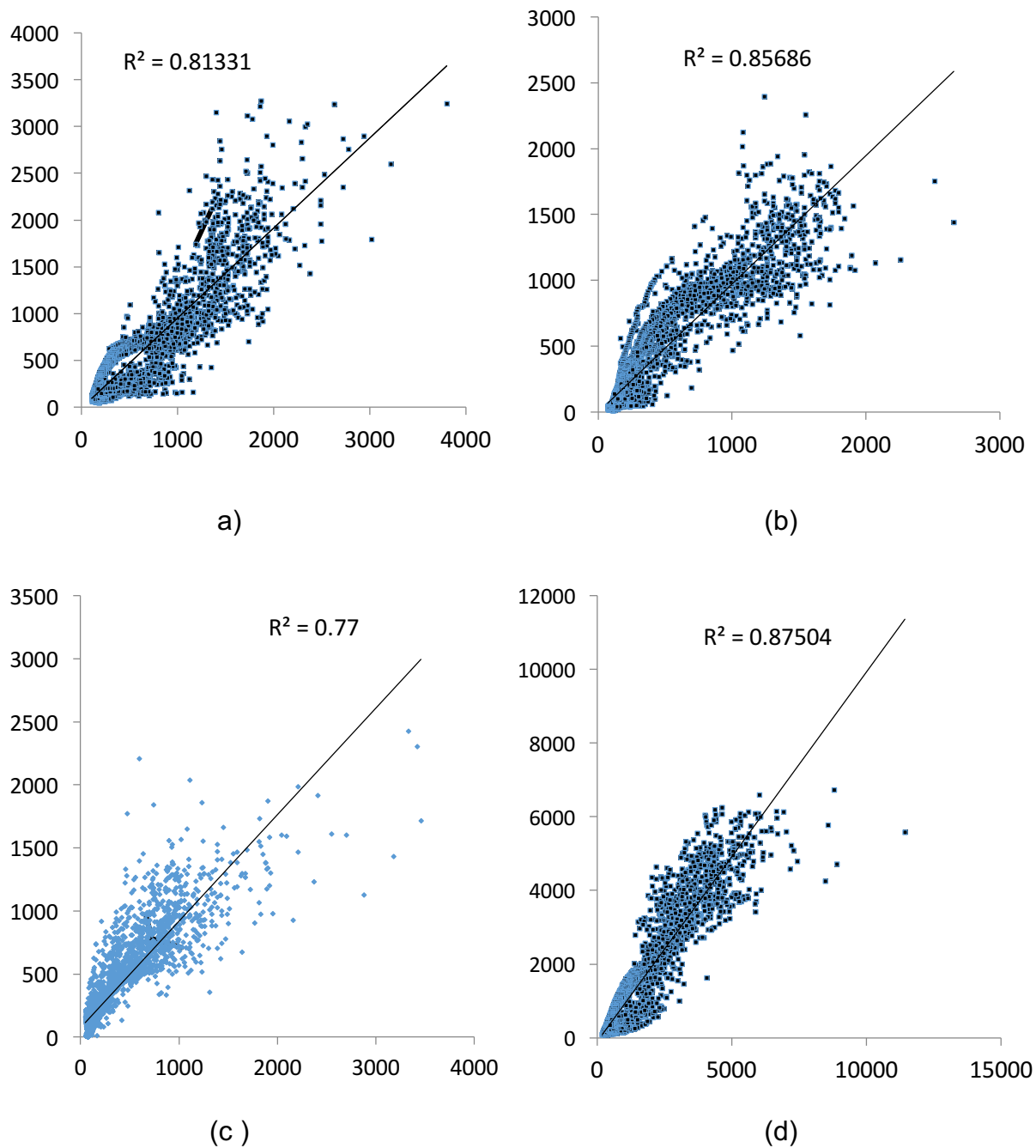


Figure 6: Scatter plots of observed vs. simulated discharge at: Top-left (Karnali at Benighat), Top-right (Bheri at Jamu), Bottom-left (Seti at Bel Gaon), Bottom-right (Karnali at Chisapani). Observed discharge in cumecs in the ordinate and simulated discharge in cumec in the abscissa

Table 7 shows the model performance for the validation period. Acceptable range of NS scores and CoD indicates the robustness of the model.

Table 7: Model performance during validation

Basin	Water Balance [mm/year]		Goodness of fit		
	Sum Qsim	Sum Qobs	CoD	NS	MD
Humla Karnali	592.52	533.84	0.78	0.71	-58.68
Karnali, Benighat	781.35	890.92	0.80	0.79	109.56
Thulo Bheri, Rimna	883.76	870.56	0.74	0.61	-13.20
Bheri, Jamu	983.97	990.07	0.78	0.78	6.10
Budhi Ganga	1581.03	1845.63	0.72	0.72	264.61
Seti, Gopaghat	1383.85	1466.22	0.66	0.66	82.37
Seti, Bel Gaon	1293.19	1272.21	0.75	0.75	-20.97
Chisapani	919.97	1117.19	0.87	0.87	197.21

Results indicate close proximity between observed and simulated runoff at different locations. This demonstrates that the calibrated parameters are satisfactory and can be used to simulate the streamflow for any independent time period.

5.2. Snowmelt contribution to total runoff

The model has been used to assess the contribution of snowmelt to total discharge at the selected locations. Results show that the contribution of snowmelt to annual flow at the basin outlet is about 11% with a maximum monthly contribution of 30% in May and a minimum of 2% in January. Results show that in almost all sub-catchments, the maximum contribution is maximum from March to July and minimum from November to February. Figure 7 shows the snowmelt contribution in percentage to annual streamflow in various sub-catchments.

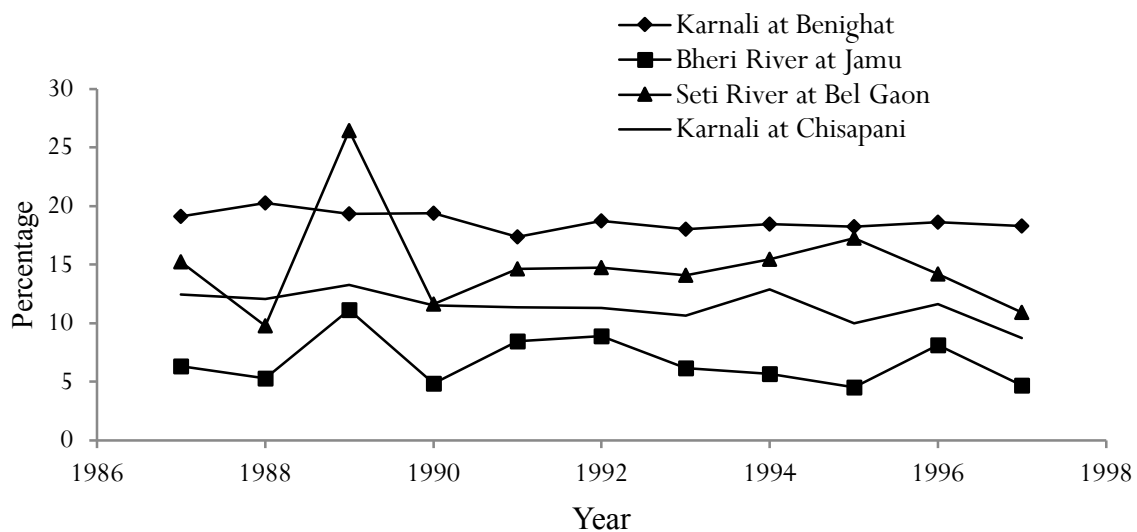


Figure 7: Snowmelt contribution to annual flow

Contribution to annual streamflow is highest at Benighat (16% to 18%) and is least in Bheri at Jamu (almost 5%). Snowmelt contribution to annual runoff at Seti River at Bel Gaon shows a varying trend; up to 27% in 1987 and as low as 11% in 1997. As we move further downstream, the contribution is lowest at the outlet at Chisapani.

5.3. Sensitivity Test

Contribution of snowmelt is estimated for increasing temperature scenarios for which the calibration period is taken as the base period. The model is run for estimating snowmelt by increasing the mean daily temperature by 0.5°C, 1°C and 1.5°C. This sensitivity test has been done for selected stations as shown in Table 8.

Table 8: Snowmelt contribution (%) to total runoff in increased temperatures

Station		Increase in temperature (°C)			
		0	0.5	1	1.5
Karnali at Benighat	MAMJJ	28.07	38.18	39.65	40.59
	NDJF	2.78	2.75	2.89	3.26
	Annual	19.2	21.21	22.07	22.75
Bheri at Jamu	MAMJJ	14.87	8.25	7.37	6.43
	NDJF	5.04	5.15	5.05	5.74
	Annual	6.73	5.31	4.91	4.74
Seti at Belgaon	MAMJJ	28.06	28.73	28.04	27.37
	NDJF	9.78	10.16	10.72	10.78
	Annual	15.3	15.38	15.54	15.02
Karnali at Chisapani	MAMJJ	21.75	25.31	28.39	29.49
	NDJF	2.69	2.84	3.49	3.8
	Annual	11.44	13.61	15.63	16.57

MAMJJ: March-May, NDJF: November-February

Results indicate no definite pattern of the increment of snowmelt contribution with increase in temperature. The maximum rate of this increment is observed at Benighat where the contribution is seen to increase at a very high rate from March-July. With an increase of 1.5°C, the snowmelt contribution is seen to increase from 22% to 30% at different seasons at the basin outlet. Contribution during the winter in all stations is increasing at a much lesser rate. Annual contribution of snowmelt is seen to be most extreme at Benighat and Chisapani with increased temperatures.

5.4. Simulation of future flows

The model has been forced with the downscaled climate data of the HadCM3 GCM and the A1B climate scenario to simulate streamflow processes for the control period (1970-2000) and the future period (2030-2060). Figure 8 shows the percentage change in monthly streamflow over the two periods. The model simulates an overall increase in monthly streamflow. In Benighat, the model simulates a high increase in streamflow from January to June (up to 170% of the control values). However, in July-December, the model simulates a conservative increase (about 20%).

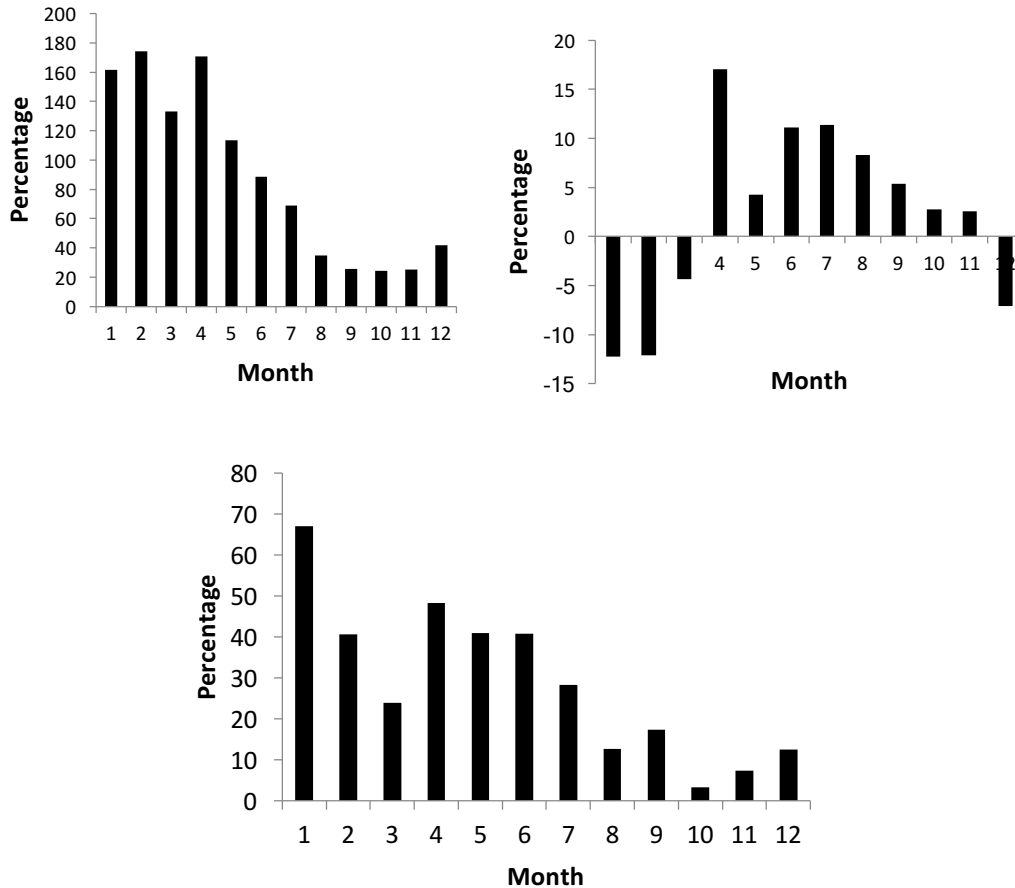


Figure 8: Percentage change in future streamflow as compared to the control period (Top-left: Karnali at Benighat, Top-right: Bheri at Jamu, Bottom: Seti at Bel Gaon)

At Jamu, the highest percentage increase in monthly streamflow is in April (17%). The largest reduction occurs in January-February. The streamflow from September-November are much nearer to the control values (-2%--7%). Figure 9 shows the absolute changes in streamflow in the 2040s. The model simulates a significantly wetter monthly regime, particularly in the main flooding season. This indicates that increasing temperatures will have significant effects in the overall hydrological regime of the basin.

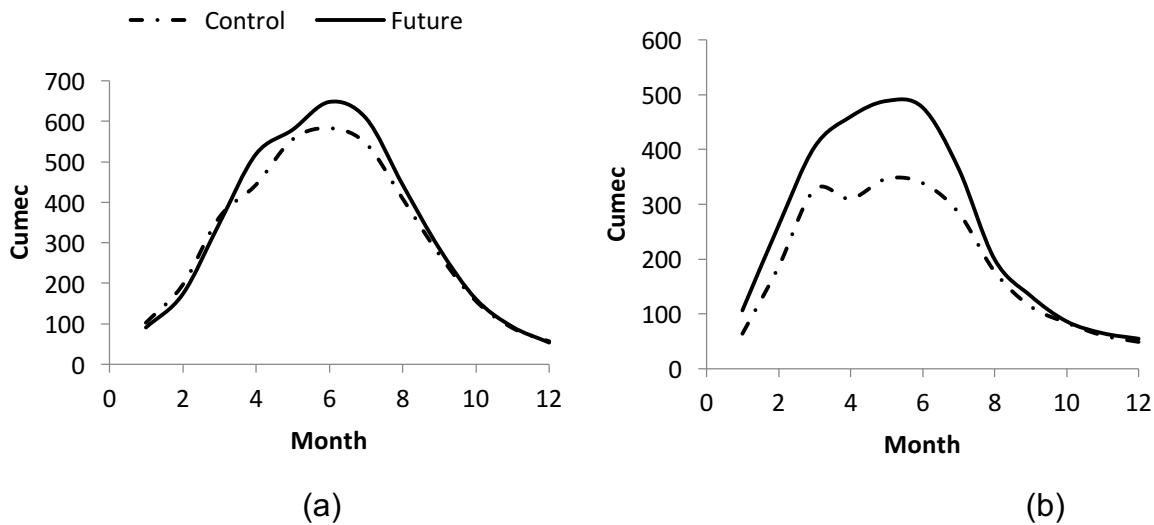


Figure 9: Absolute changes in streamflow in the 2040s (a) Bheri at Jamu, (b) Seti at Bel Gaon

6. Conclusion

Snowmelt is a major source of runoff in Karnali River Basin, especially from March to July. With the start of summer, snow accumulated in the previous winter begins to melt and feeds the mountainous rivers. Snowmelt occurs mostly from the elevation range between 3000 and 5000 masl. Snow accumulated above this range does not provide significant contribution to streamflow. Snowmelt contribution to the runoff in different seasons at different locations of the basin has been estimated in the study. Choice of the HBV-Light model for the purpose of simulating streamflow and snowmelt has been proven to be effective. The NS-efficiency criterion has shown the effectiveness of the model in simulating rainfall-runoff processes. Model performance is highly sensitive on the initial choice of parameter values. Generation of a large number of parameter sets using MC simulation is useful in prioritizing the important parameters to be used during calibration.

At the basin outlet at Chisapani, snowmelt contribution to annual flow is about 11%. This contribution increases as one moves upstream. It is seen that the maximum contribution is from March-July at different locations in the basin. Result of sensitivity tests demonstrate that increasing temperatures may cause enhancement in the annual and seasonal streamflow and also in the snowmelt contribution to streamflow. Running the calibrated model with outputs of the HadCM3 RCM simulated significantly wetter monthly regimes in the 2040s. The impact will be highly pronounced in the flooding season. This may have consequences on water abstraction activities, leading to changes in cropping patterns, electricity production and supply of drinking water in the basin, which will have impacts on the economy of the region.

There is a need of more hydro-meteorological stations in the mountainous catchments - where snowmelt forms the major source of annual runoff-for better hydrological simulations. The need of high quality data measurement and analysis becomes more vital during times of population growth and changing socioeconomic activities (Murphy, 2010).

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