Investigating the performance of snowmelt runoff model using temporally varying near-surface lapse rate in Western Himalayas

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The present study assesses the effect of accounting the temporal variation of near-surface lapse rate in the conceptual, degree-day snowmelt runoff model simulations in a cold-desert region of Himalayas. The near-surface lapse rate over Spiti basin shows seasonal variation during a year. The results obtained show that the inclusion of monthly variation of lapse rate in the hydrological modelling is able to capture the observed hydrograph more efficiently than when an annually constant value of lapse rate is employed. Based on our results and considering the available data, a monthly representation of near-surface lapse rates in the temperature index based models is recommended for Himalayan basins.

Keywords: Himalayas, lapse rate, snowmelt runoff model, temporal variation.

Introduction

SNOWMELT from the mountain snow packs is an important source of freshwater for human consumption, business and agriculture in many regions worldwide. The mountain snowpack functions as an ideal water reservoir system, storing winter precipitation as snow and then gradually releasing it to surrounding lowlands during the spring and summer when precipitation is low[1]. Himalayas are one such abode of snow and glaciers and are of crucial importance to South and Central Asia[2,3]. A comprehensive understanding of the snowmelt runoff system in Himalayas is important not just for better management of resources in these basins[4], but also to study the possible impacts associated with climate change[3]. Hence, in order to predict the timing and magnitude of snowmelt and to understand the associated physical processes, a number of conceptual and process-based hydrologic models have been employed[5]. Two widely adopted snowmelt computation approaches are the temperature-index based and energy-budget based methods. However, due to the large extent and difficult accessibility of high mountainous terrain in Himalayas, most studies in the Himalayan basins have focussed on the temperature-index (*T*-index) based methods[6–9].

The *T*-index based approach, also known as the degree-day approach is a simple approach that assumes empirical relationship between air temperature and snow or ice melting rates[10]. *T*-index based methods provide an easier and appropriate approach for quantifying daily snow-melt in comparison to energy-budget based methods, since they employ only temperature which is a relatively simple meteorological variable to monitor and is also relatively straightforward to extrapolate or interpolate on climatic and spatial time scales[11]. For stations where measurements do not exist, spatial extrapolation of temperature can be utilized. This spatial extrapolation requires computation of lapse rate[10].

'Lapse rate' is defined as 'the decrease of an atmospheric variable with height, the variable being temperature, unless otherwise specified'[12] and it often refers to the environmental lapse rate or free atmospheric lapse rate in a vertical profile of the atmosphere[13]. Lapse rate can also refer to reduction of temperature at the different elevations at the surface of a mountainous terrain where it is termed 'near-surface lapse rate'[14,15]. The employment of environmental lapse rates to estimate the surface conditions has an implicit assumption that the terrain and surface processes are insignificant in determining surface temperatures, which is not a good approximation for temperature estimations in mountainous basins[14,16]. The commonly used value of environmental lapse rate is 0.65°C/100 m, which is a spatially global and temporally climatic average of environmental lapse rates and therefore, may be problematic at short temporal and fine spatial scales[15]. Near-surface lapse rates are more variable than environmental lapse rates, both spatially and temporally[16,17].

The use of a constant value of lapse rate is not suitable for hydrological studies as they are usually subjected to

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local topography and climatic conditions[15]. As accurate estimates of spatially distributed near-surface temperature are critical to many *T*-index based hydrological models, this variability of lapse rate is crucial when using them to extrapolate air temperature. Near-surface lapse rates vary both diurnally and seasonally[10,15] and hence to prevent modelling complexity, Blandford *et al.*[15] recommended the use of monthly near-surface lapse rates as a practical combination of effective performance and ease of implementation.

Most *T*-index based studies in Himalayan basins[6–9] have employed an annually constant value of 0.65°C/100 m as the lapse rate parameter, which is, as mentioned earlier, a spatio-temporally average value of environmental lapse rate and not representative of the local terrain and climatic conditions. Such simplistic employment of models with constant parameters may lead to lower accuracy and larger uncertainties of the results[18,19]. No study till date has looked into the implications of such simplistic lapse rate parameter specification for the snowmelt related hydrological simulations in Himalayas. Minder *et al.*[14] studied such an implication for Cascade Mountains (Washington), where they found that the lapse rates in that region substantially differed from the constant value and had appreciable implications to hydrological modelling. Kattel *et al.*[20] looked into the near-surface lapse rate variation on the southern slope of the central Himalayas and found that there was a temporal variation associated with the annual cycle of temperature lapse rates. Such a variation over a year is found to be a characteristic of Himalayas and is different from other mountainous regions[20]. Considering the unique characteristics of annual lapse rate in Himalayan region, it is necessary to understand its implication in terms of parametrization while performing snowmelt related hydrological simulations of Himalayas.

In this regard, an attempt has been made in the present study to quantify the variations in hydrological simulations arising from the use of seasonally varying and annually constant near-surface lapse rates (LR). Hereafter, LR corresponds to the near-surface lapse rate. Accordingly, a remote sensing and GIS-based distributed *T*-index based hydrological modelling has been carried out using snowmelt runoff model (SRM) to simulate snowmelt runoff contributions in Spiti river basin, located in western Himalayas.

Study area and datasets

The area chosen for this study is the Spiti river basin that lies in the cold desert region of the Himalayas and is a sub-basin of the Satluj river basin (Figure 1). The watershed is extracted from the high-resolution ASTER GLOBAL DEM using ArcGIS tools. The total area of the basin up to Khab is 12471.79 sq. km and extends from 33°8′47.01″N to 31°44′55.01″N and from 77°35′49.56″E to 78°59′54.563″E. The elevation of the Spiti river watershed varies from 2653 m to 6751 m with an arithmetic mean elevation of 4982.23 m above mean sea level (m amsl).

Meteorological data

There are three meteorological stations, of which two lie in the lower part of the Spiti basin and the third at Kalpa lies the basin as shown in Figure 1. The low density of meteorological stations is a major challenge for hydrological simulations in the basin. These meteorological stations are monitored by Bhakra Beas Management Board (BBMB) and Irrigation and Public Health (IPH) Himachal Pradesh. A summary of all three meteorological stations is given in Table 1.

Satellite data

The daily snow cover area (SCA) information was obtained from MODIS Terra 8-day snow-cover product (MOD10A2) for the simulation periods 2001, 2002, 2004 and 2005 (refs 21 and 22). The obtained satellite data was then re-projected from hierarchical data format (HDF) to universal transverse mercator (UTM) coordinates using MODIS re-projection tool (MRT) for snowmelt runoff modelling using SRM. Further, for SRM modelling, a linear interpolation of 8-day SCA has been done for estimation of daily snow cover area for each elevation zone of the study area, by following Abudu *et al.*[23].

Methodology

The methodology employed for this study aims to evaluate the significance of temporal variation of LR for *T*-index based SRM model simulations. For this purpose, monthly temporal variations have been considered as recommended by Blandford *et al.*[15]. Figure 2 shows the flow-diagram of the followed approach. SRM simulations are carried out in two ways: (i) with the annually constant value of LR taken as 0.65°C/100 m, the most commonly used value of LR[6–9] and (ii) with the monthly varying values of near surface LR. For both runs, calibration has been done for 2001 and 2002 and the validation done for 2004 and 2005. Inputs such as daily temperature, precipitation and SCA are obtained from the available ground based measurements and satellite-based products. Since the elevation range for the watershed is approximately 4000 m, its area has been divided into ten elevation zones (each covering around 400 m elevation) and the precipitation is distributed uniformly over the basin for the employment of SRM[24].

The SRM model requires seven input parameters such as runoff coefficients for snow (C_S) and rain (C_R), degree-day factor (DDF), temperature lapse rate (TLR), critical

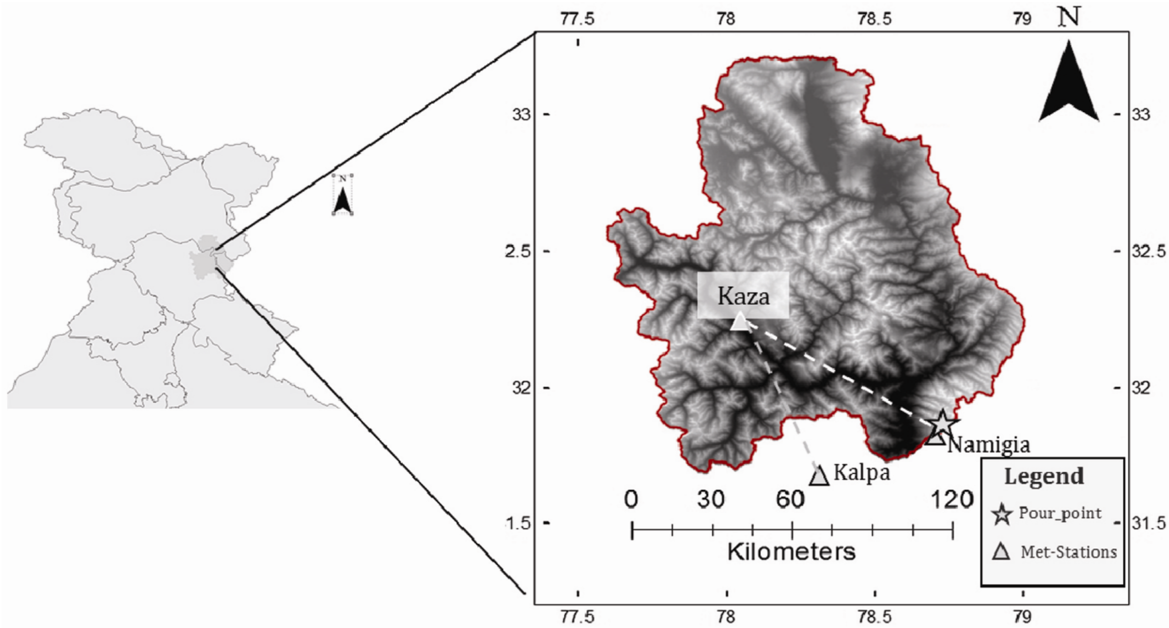

Figure 1. Spiti river basin up to Namigia. The map shows the locations of the meteorological stations and the pour point at Namigia used in order to delineate the basin.

Table 1. Summary of the available meteorological records of the three stations in the Spiti basin

				Temperature			Precipitation		
Station	Latitude	Longitude	Elevation (m amsl)	Period	Average minimum *T* (°C)	Average maximum T (°C)	Period	Average rainfall (mm/year)	Average snowfall (mm/year)
Kaza	32°13′25″	78°04′11″	3616	1984–2005	–3	8.82	1983–2005	103.8	458.4
Namigia	31°48′35″	78°39′22″	2910	1984–2005	–4.79	17.3	1983–2000	123.7	164.6
Kalpa	31°32′38″	78°15′19″	2731	1984	4.95	20.88	–	–	–

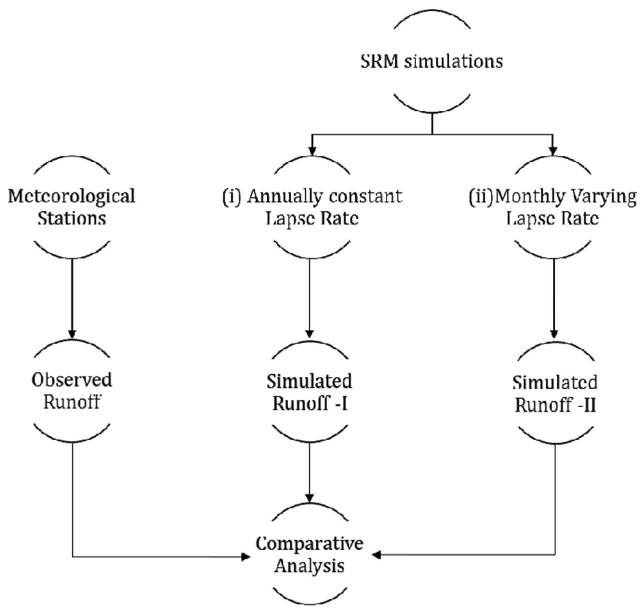

Figure 2. Flow-diagram showing the scenarios employed for SRM simulations.

temperature (T_{CRIT}), rainfall contributing area (RCA), recession coefficient (k) and time lag (T_L). All the parameters except the DDF have been estimated as monthly average values from the historical dataset of input variables obtained from the previously mentioned meteorological stations. DDF is represented as an annually constant value, obtained from an experimental study done in a snow and glacier fed basin in western Himalayas[25]. The initial LR value has been approximated to the mean monthly near-surface LR between two meteorological stations, Kaza and Kalpa (Figure 1), since LR between Kaza and Namigia has been found to have exceptionally high values (of the order of 2.4°C/100 m).

The near-surface LR between these stations is calculated monthly by dividing the difference in average temperatures at two stations by the difference in their elevations. It is to be noted that only the daily maximum and minimum temperatures were available for the given stations from the meteorological data, which have been averaged to find the daily average temperature at these stations. Using the obtained LR, daily temperatures at the hypsometric mean elevation of each elevation zone is extrapolated from the reference station with known temperature values. Here, Kaza station has been taken as the reference station since it is located in the middle of the study region and would be more representative for the basin as suggested by Richard and Gratton[19].

Accuracy assessment

Accuracy assessment for the SRM model results is performed as per the WinSRM manual specification (Martinec *et al.*[10]) by utilizing two criteria: (i) the coefficient of determination (R^2) and (ii) the volume difference (D_v), for a more objective appraisal of how well the simulations have been done. The coefficient of determination is given by the eq. (1).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2}, \tag{1}$$

where Q_i is the measured daily discharge, Q_i' the computed daily discharge, $\bar{Q}$ the average measured discharge of the given year or snowmelt season and n is the number of daily discharge values.

The volume difference, D_v, is computed by eq. (2), Martinec *et al.*[10]:

$$D_v(\%) = \frac{V_R' - V_R}{V_R} \times 100, \tag{2}$$

where V_R is the measured yearly or seasonal runoff volume and V_R' is the computed yearly or seasonal runoff volume.

Results and discussion

The monthly mean variation of observed LR obtained from the available temperature record for 1984 along with standard deviation for all the months is shown in Figure 3 *a*. As anticipated, huge seasonal variation is associated with the observed near-surface lapse rates which might not be accurately represented when using an annual LR value while employing any snow melt hydrological model. The observed monthly mean lapse rates vary from 0.05°C/100 m for September to 1.4°C/100 m for March. The lower values of lapse rate during August and September can be explained by the increased moisture content in the atmosphere during monsoon season[15,20]. The higher lapse rate in March corresponds to the pre-monsoon (summer) season associated with clear weather and significant sensible heat flux[20].

Following this, the implications of this observed variability of LR for hydrological modelling using SRM have been analysed. For this purpose, a modelling was carried out using the manually calibrated input parameters for 2001 and 2002, and validation was done for 2004 and 2005. The most sensitive parameters, like LR, DDF, T_{CRIT}, C_S and C_R were calibrated within the physically realistic values to match the computed hydrographs with the observations in order to maximize the R^2 value and to minimize the volume difference (D_v). Figure 3 *b* shows the monthly calibrated values of LR. Figure 4 shows three hydrographs each for 2001, 2002, 2004 and 2005. The three hydrographs are associated with (i) observed runoff, (ii) runoff observed with SRM simulations with annually constant values of LR and (iii) runoff observed with SRM simulations with monthly LR. It is noticed that the shape of the observed hydrographs aligned more with the simulated hydrographs based on monthly lapse rate parametrization for both calibration and validation periods. For the months with higher lapse rates (Figure 3 *b*) such as May and June (which represents the onset of ablation period and pre-monsoon), the employment of annually constant value of LR (0.65°C/100 m) results in an overestimation of runoff. This overestimation is observed because of the lower annual LR value (compared to the calibrated LR), which results in lesser reduction in temperature with increasing elevation. This causes more melting there by resulting in high runoff while using the *T*-index approach. For the months with annual LR value more than the calibrated LR, like in July (Figure 3 *b*), the annual LR based simulations underestimates the runoff. Here, the higher annual LR (compared to the calibrated LR) leads to higher reduction in temperature with increasing elevation which causes low melt runoff generation. The October months (representing the onset of snow accumulation) show overestimation due to

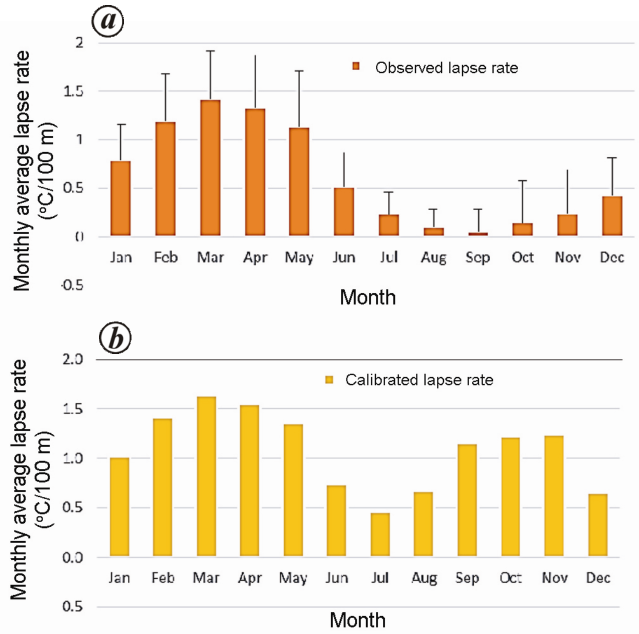

Figure 3. Monthly mean variation of near surface lapse rates between Kaza and Kalpa meteorological stations for 1984. ***a***, Observed monthly average lapse rates. ***b***, Calibrated monthly average lapse rates.

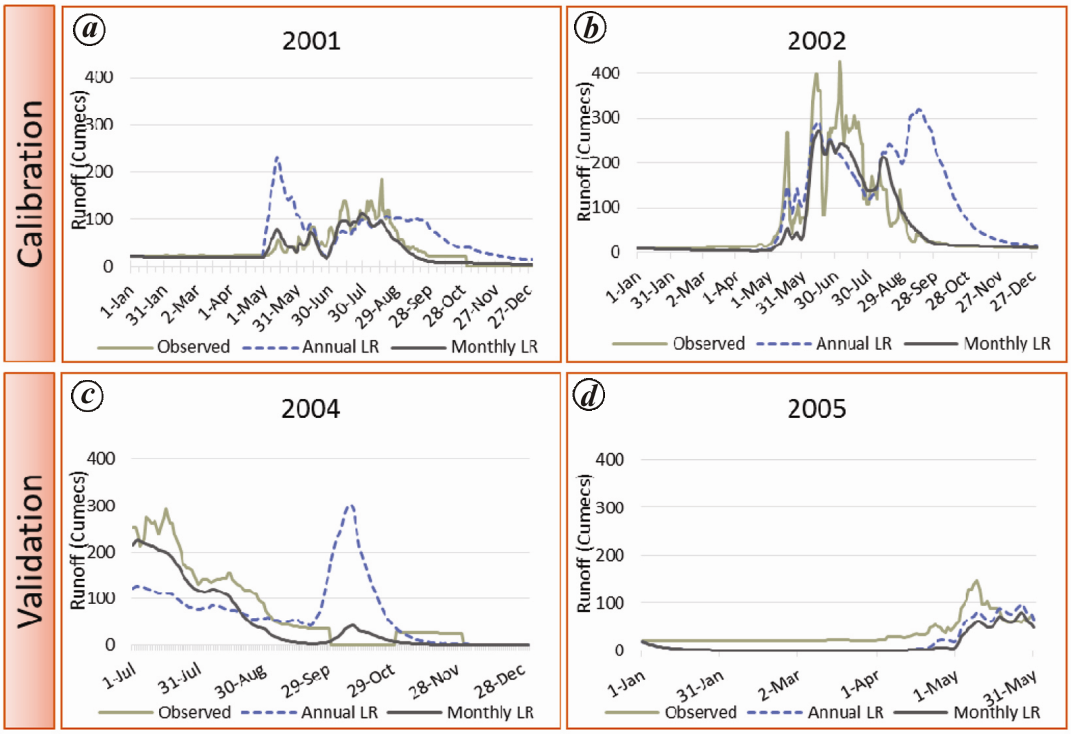

Figure 4. Hydrographs for observed, annual LR scenario and monthly varying LR simulations for the Spiti basin for the calibration years (***a***) 2001, (***b***) 2002 and validation years (***c***) 2004, (***d***) 2005.

Table 2. Characteristics of the observed and simulated hydrographs

	Hydrograph characteristics						Statistics			
	Observed		Computed (with Annual LR)		Computed (with monthly LR)		Volume difference (D_v) (%)		Coefficient of determination (R^2)	
Year	Runoff volume (10^6 m³)	Average runoff (m³/s)	Runoff volume (10^6 m³)	Average runoff (m³/s)	Runoff volume (10^6 m³)	Average runoff (m³/s)	With annual LR	With monthly LR	With annual LR	With monthly LR
2001	1181.89	37.48	1745.9	55.36	1025.52	32.52	–47.71	13.23	–0.63	0.80
2002	2148.72	68.135	3116.4	98.82	1860.55	58.99	–45.03	13.41	0.03	0.80
2004	1120.52	35.43	1120.5	35.43	1320.53	41.76	–97.50	–17.84	–0.127	0.64
2005	491.42	37.67	491.4	37.67	367.33	28.16	–12.07	25.25	–0.193	0.56

the low values of annual LR than the calibrated LR as shown in Figure 3 *b*.

Characteristics of the simulated hydrographs and their comparison with the observed hydrographs are summarized in Table 2. The simulations based on monthly varying LR resulted in improved statistics for all the years compared to the annually constant LR-based simulations. It is to be noted that the R^2 value is 80% and the D_v value is as low as 13.2% for monthly varying LR-based simulations for calibration years. For validation years (Figure 4 *c* and *d*), R^2 is 64% and 56% respectively, which is fairly good compared to the poor performance of annual LR-based simulations for the same period. As shown in Figure 4 *a* and *b*, the negative D_v corresponds to underestimation in runoff since the simulations are unable to capture the sharp peaks of the observed hydrographs. This inability to capture the peak could be due to the poor observation spatio-temporal variation of local precipitation events because of the sparse network of precipitation stations in the study area. It is observed that the annual LR-based simulations overestimate the runoff during most of the simulation periods and hence, overestimate the runoff by 48% for the year 2001, by 45% for 2002 and by 97% for 2004. In view of the above mentioned results, it is strongly recommended that caution be exercised while employing a constant value of near-surface LR over an entire year.

Summary and conclusions

In this study, the temporal variation of near-surface lapse rate for Spiti basin is analysed and found that it varies significantly across each months. Therefore, to understand the implication of such a variation in snowmelt runoff computations, *T*-index based snow melt runoff modelling using SRM model is carried out for Spiti basin using monthly varying and annually constant lapse rate values. The results obtained indicate that the assumption of an uniform and constant free air lapse rate of 0.65°C/100 m is not suitable for hydrological simulations in Himalayas. The study, therefore, highlights that the employment of a monthly variation of lapse rate is important for better hydrological simulations in Himalayan basins. However, future studies should look into the implications of interplay of other inputs such as degree-day factor, critical temperature, recession and runoff coefficients on the hydrological response of the basin.

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