

Article

Hydro-Climatic Variability in the Karnali River Basin of Nepal Himalaya

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Abstract: Global climate change has local implications. Focusing on datasets from the topographically-challenging Karnali river basin in Western Nepal, this research provides an overview of hydro-climatic parameters that have been observed during 1981–2012. The spatial and temporal variability of temperature and precipitation were analyzed in the basin considering the seven available climate stations and 20 precipitation stations distributed in the basin. The non-parametric Mann–Kendall test and Sen’s method were used to study the trends in climate data. Results show that the average precipitation in the basin is heterogeneous, and more of the stations trend are decreasing. The precipitation shows decreasing trend by 4.91 mm/year, *i.e.*, around 10% on average. Though the increasing trends were observed in both minimum and maximum temperature, maximum temperature trend is higher than the minimum temperature and the maximum temperature trend during the pre-monsoon season is significantly higher (0.08 °C/year). River discharge and precipitation observations were analyzed to understand the rainfall-runoff relationship. The peak discharge (August) is found to be a month late than the peak precipitation (July) over the basin. Although the annual precipitation in most of the stations shows a decreasing trend, there is constant river discharge during the period 1981–2010.

Keywords: monsoon; spatial_temporal trend; Mann-Kendall test; Sen’s slope; climate change

1. Introduction

Global climate change is now unequivocal and it is acting locally upon us [1]. Studies show that the Earth’s surface has been successively getting warmer [2] and available observations suggest that the Himalayan region, which is more sensitive than other land surfaces of the same latitude [1,3], is experiencing warming [4] with greater magnitude than the global average [5,6]. The Himalayan region, also known as the water tower of Asia, plays an important role in regional climate, most particularly with respect to monsoon circulation [6]. The climate and hydrological cycles in the area are significantly influenced by the summer monsoon system [7], which, in turn, has already been affected by climate change [8–10]. The Himalayan region data indicates a statistically significant decreasing trend in summer precipitation [11–13] and the rate of increasing temperature is projected to be two to three times higher than that recorded during the 20th century [14]. This rise in temperature in combination with changes in precipitation pattern are affecting livelihood of the people [15] in the Himalayan region with profound influence on both upstream and downstream communities [12,16,17] including many sectors of water uses, namely, hydropower, agriculture, and biodiversity, with far-reaching implications

to the people of the region and the Earth's environment as a whole [18,19]. Similarly, changing glacier and negative mass balance may be the manifestation of warming in the region [5,12].

Intergovernmental Panel on Climate Change (IPCC) has identified the Himalayan region as the place devoid of meaningful data because of the lack of adequate climate data and impacts information [20,21]. In Nepal Himalaya, meteorological, and hydrological stations are not enough because of the complex and rugged topography and the study on the recent climate trends from the Himalayan range are limited [13]. The climatic gradient of the Himalayan region demands for a dense network of stations, but because of the inaccessibility and expense factor it has always been a difficult task.

The Karnali River Basin (KRB) in the western region of Nepal has an acute problem in having a good enough network of stations and, therefore, lacks specific ground observations [22] of important climatic variables like precipitation and temperature. In addition, some of the available stations have missing data [23]. The assessment of hydrological and climatic parameters is important but challenging in mountains [16] because of its sensitive enactment to hydro-climatic variations [24] which can result to the overall variability [25] of basin and livelihood of the people living there in. Therefore, there is a significant gap of knowledge regarding the effect of global climate change in this part of the Himalayan region [26].

Few studies carried out in Nepal in reference to the hydro-meteorological trend suggest that the trend is apparent in the case of the temperature whereas, for precipitation, it is not clear. The analyses of maximum temperature data from 49 stations (1971–1994) of Nepal reveal warming trends after 1977 ranging from 0.068 to 0.128 °C per year in most of the stations [6]. Similarly, Shrestha *et al.* [7] examined the spatial and inter-annual variability in precipitation using data for 78 stations (1959–1994) of Nepal showed large inter-annual and decadal variability and there is no clear trend. Recent study by Salerno [13] in the southern slopes of the Mt. Everest, in the eastern part of Nepal, shows that the annual rate of decrease in precipitation with almost similar value in both higher and lower elevations. This research also shows that pre-monsoon temperature is increasing slightly but it is insignificant while the rate is higher and significant during the post-monsoon months.

Nepal, with its location in the central part of the Great Himalayan range, has unique physiographic and topographic features, which gives rise to varied climatic and ecological diversities within a north-south span of about 130–260 km. In KRB, both Indian monsoons and westerlies play active roles to bring precipitation into the region [27]. Recent study shows that the Indian monsoon is becoming weaker and westerlies are becoming stronger in the region [12], thus it can influence the precipitation pattern of the region. Due to anticipated climate change, significant local impacts can be expected [10] which calls for more in situ measurements of hydro-climatic parameters, as well as their analysis in the region. Such information is important for implementing effective measures to help the poor communities to cope and adapt to the impacts of climate change and focus on the climate compatible developmental programs.

Research based on a vulnerability assessment framework of the IPCC indicates that the KRB and its watersheds are more vulnerable to climate change than other major basins of Nepal [28]. At the same time, scientifically, it is the least explored area, and even the basic climatic parameter's status is devoid in the area. Therefore, this research has been focused in the western part of Nepal that will contribute to a better interpretation of the hydro-climatic (temperature, precipitation, river discharge) status, which ultimately helps to understand the changes in the climate system in this region and, at the same time, it will also contribute to generating climate information in this part of the data-sparse Himalayan region.

2. Study Area

The Karnali River, the longest river flowing inside Nepal, originates from south of Mansarovar and Rokas lakes located in China (Tibet). The KRB in Figure 1 is one of the three major basins of Nepal; the other two are Gandaki and Koshi basins in Central and Eastern Nepal, respectively. The Karnali

River enters Nepal as Humla-Karnali near Khojarnath with many snow-fed rivers as its tributaries. The KRB extends from Dhaulagiri Mountain in the east to Nanda Devi Mountain in the west with total spatial coverage of 45,269 km². It has six major watersheds (West Seti, Kawadi, Humla Karnali, Mugu Karnali, Tila, and Bheri) of which all others originate in Nepal except Humla Karnali, which originates in China. Interestingly, unlike most of the rivers in Nepal, which generally flow from north to south, Mugu Karnali flows from east to west, and the Humla Karnali from west to east. The Karnali River flows through the western part of Nepal and joins the Mahakali River in India, which is called the Ghaghara in lower reaches of India. Though a small portion of the KRB lies in the Tibetan region, this research has focused only the basin that lies within Nepal due to inaccessibility of transboundary data.

In KRB it is evident that more meteorological stations are located in the lower elevation areas compared to the sparse station network in the higher altitudes (Figures 1 and 2).

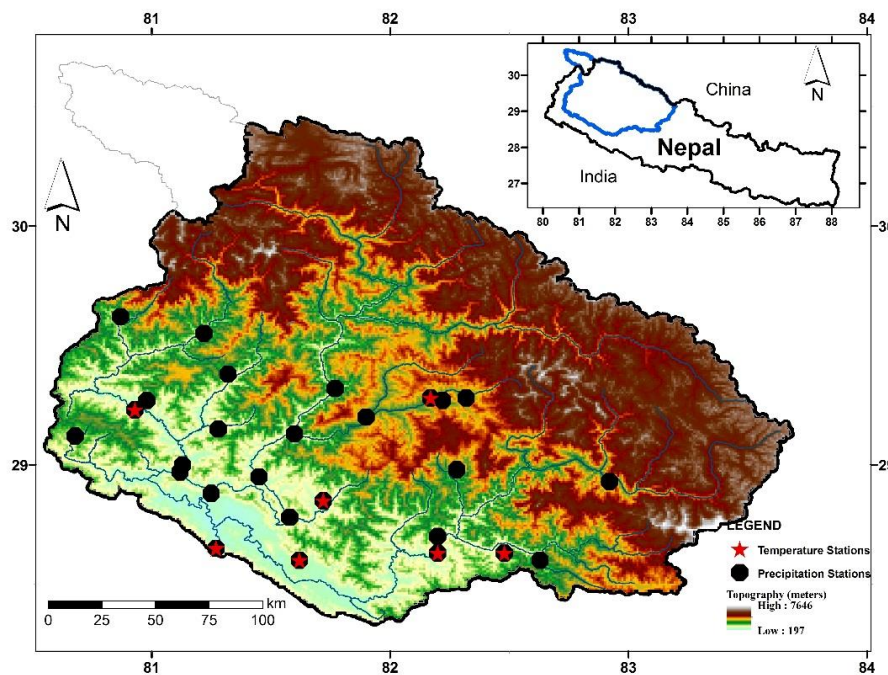


Figure 1. Karnali River Basin in western Nepal showing the precipitation and temperature measuring stations used in the study.

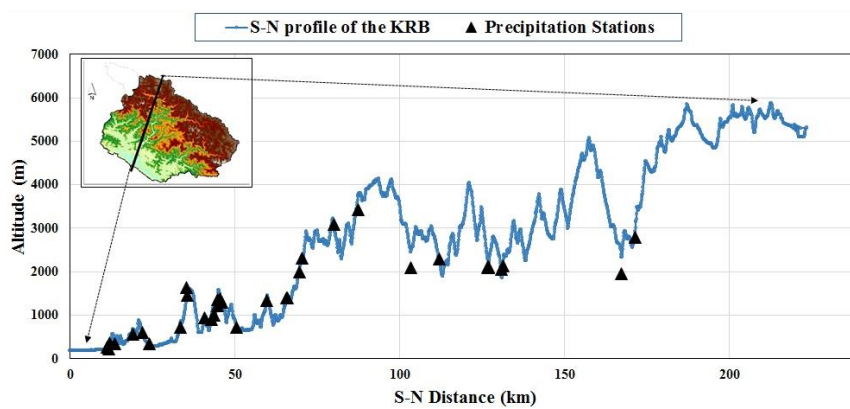


Figure 2. South-North gradient along the transect shown by dark line and the location of stations in the KRB.

3. Data and Methodology

In this study precipitation observations from 27 stations and temperature observations from seven stations in the KRB for the period of 32 years (1981–2012) have been used (Figure 1), which were acquired from the Department of Hydrology and Meteorology (DHM), Nepal. Prior to analyses, screening of daily data was conducted by visual comparison and homogeneity was checked using double-mass curve analysis from neighboring stations. Among 27 precipitation stations, eight of them had less than 1% missing data, 14 stations had 2% to 5% of missing data, while five of the stations located in the high altitude region had 7% to 10% of missing data. Daily data was converted to monthly, and the missing rainfall data was filled up by using a spatial (Kriging) interpolation technique. Kriging is an advanced geo-statistical procedure for interpolation which generates values at grid points based on the available station data observed at known locations. It is considered to be one of the suitable interpolation algorithms in the Himalayan region [6]. This method uses variograms to express the spatial variation and minimizes the error of generated values which are estimated by spatial distribution of the generated values [29]. However due to a lack of adequate measurement stations there may be some uncertainty in interpolations. Temperature gaps of less than five days were filled using linear interpolation while longer gaps of maximum up to four months were filled using linear regression with data from nearby stations. The discharge data of Chisapani (Karnali) at the lower reaches of the KRB for the period of 30 years (1981–2010) were used for the analysis.

For the purpose of climatic trend, the basin has been divided into four agro-ecological zones: Terai (<500 m.a.s.l.), Hills (500–2500 m.a.s.l.), Mountain (>2500 m.a.s.l.), and Trans-Himalaya (Dolpa and some portion of Mugu districts which shows distinct climatic characteristics) regions. Seasons were defined, namely, as winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to November). For the trend analysis, non-parametric Mann–Kendall test [30,31] were taken into consideration for the analysis of climate data as it can evade the problem arising from the skewness of the data [32,33]. The associated Sen's Nonparametric Estimator of Slope [34] was used to determine the magnitude of trends. For the purpose of this study, four different significance levels were used: $p < 0.001$ or 99.9% confidence level (***), $p < 0.01$ or 99% confidence level (**), $p < 0.05$ or 95% confidence level (*), $p < 0.1$ or 90% confidence level (*). A significance level of 0.001 means that there is only a 0.1% probability that the values are from a random distribution, and thus that a monotonic trend is very likely [35]. These tests have been extensively used [6,32,36–38] for studying the spatial variation and temporal trends of environmental and hydro-climatic datasets. For the analysis of the trend Microsoft Excel spreadsheet template application called MAKESENS, developed by the Finnish Meteorological Institute [39] and applied by Keuser *et al.* [40], Panthi *et al.* [32], and Nepal [38] was used.

4. Results and Discussions

4.1. Precipitation Pattern and Trend

The climate in the KRB is mainly influenced by the monsoonal system, physiography of the region, and westerlies [27]. The summer monsoon which originates from the Indian Ocean [41] is the main cause of precipitation in Nepal and as the KRB lies in the western part of Nepal its influence is weaker than in eastern part of Nepal [42]. During the summer monsoon season (June–September) Nepal receives substantial portion (80%) of the annual precipitation of 1530 mm [27,43]. The average monthly precipitation of KRB was calculated on the basis of average of all the stations from the years 1981–2012. The distribution of the monthly average rainfall in the KRB (Figure 3) shows that highest precipitation occurs in July (377 mm) and lowest in November (10 mm which is less than 1% of total precipitation). In the KRB the precipitation amount peaks in the month of July–August (~26% of total precipitation in each month) month while a study by Kansakar *et al.* [44] show peaks in July in the eastern part of Nepal.

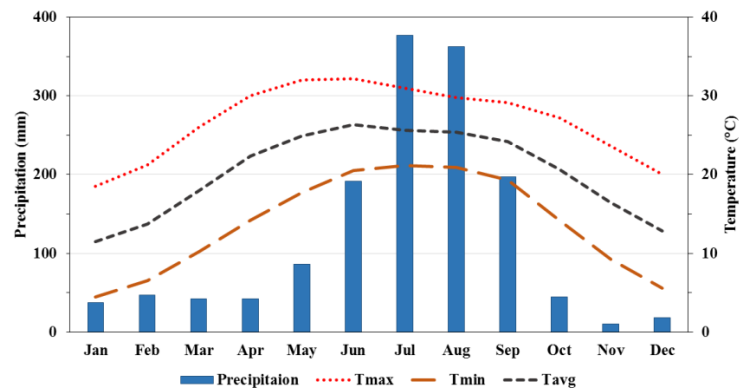


Figure 3. Average monthly precipitation and temperature (minimum, maximum, and average) in the KRB from 1981 to 2012.

The annual average precipitation in the basin is 1479 mm and 77% of this rainfall occurs during the summer monsoon season, whereas only 7% occurs in winter. Pre-monsoon precipitation accounts for 12% of the annual total while in post-monsoon there is only 4%. The spatial average annual precipitation distribution is shown in Figure 4. The northern part of the basin with higher altitude receives less precipitation (<1000 mm per year) but the southern part receives comparatively higher precipitation. The rainfall seems to be induced by topography as the moist air masses sweeps towards Himalayan mountains however the specific controls are not fully understood [45]. The KRB contains the Mahabharata range (1500–2700 m.a.s.l), a barrier to monsoon circulation which helps to uplift the moisture laden air from lowland to high altitude areas leading rainfall in some areas [45]. This results very high precipitation in several pocket area [46] and local orographic effects are seen in the spatial precipitation pattern (Figure 4). Though precipitation amount is comparatively less in the higher altitude but some stations like Maina Gaun present at altitude 2000 m.a.s.l (~2000 mm/year) and Musikot at 2100 m.a.s.l (~2200 mm/year) have comparatively higher precipitation than surrounding stations due to their unique locations.

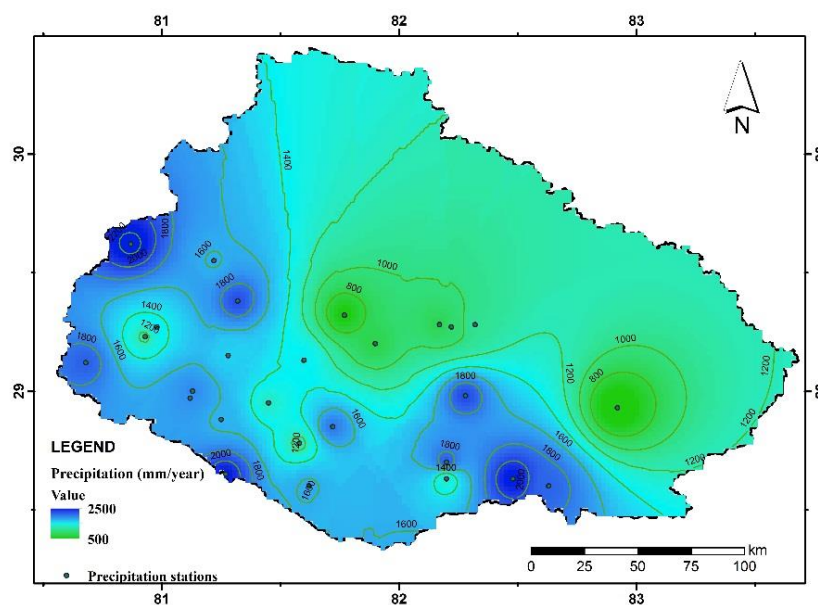


Figure 4. Spatial distribution of average annual precipitation (mm) in KRB for the period of 1981–2012.

Due to the remoteness and extremely difficult terrain, the establishment of the stations itself is a significant challenge, as is the data collection [46]. This condition dictates the network of a number

of stations; therefore, we have sparse meteorological data in high altitude areas. At the same time, the summer monsoon system or any rain-producing system is influenced by the aspect, wind, and topography, which give rise to unique precipitation pattern.

The annual average precipitation of the basin is heterogeneous and most of the stations show decreasing at the rate of 4.91 mm/year (10% in the analyzed period 1981–2012) and significant at 95% level (Table 1). Two stations in the lower elevation shows decreasing trend by 2% per year along with other six stations by more than 1%, and 11 stations by less than 1% per year, among them five stations are significant while, in stations like Seri Ghata and Nagma, which are located in the valley of the high altitude mountains, and six other stations show the increasing precipitation by nearly 1% annually.

Table 1. Precipitation trend (mm/year) in KRB at different seasons and agro-ecological zones.

	Terai	Hill	Mountain	Trans-Himalaya	Basin Average
Winter	−1.23	−1.28	0.18	−1.2 *	−1.21
Pre-monsoon	−2.13	−1.34	−0.88	−3.89 ***	−1.54
Monsoon	−1.6	−1.12	3.5	−3.27	−1.58
Post-monsoon	−0.82	−0.69	−0.35	−0.91 **	−0.74
Annual Average	−4.12 *	−5.45 +	2.76	−12.12 **	−4.91 *

$p < 0.1$ (+), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

On the basis of agro-ecological zones (Table 1), precipitation in the mountains of the KRB is increasing while, in other regions, it is decreasing, and it is higher in Hills and Trans-Himalayan regions. During the monsoon season, the precipitation trend is found to be increasing over the mountain region, with a decreasing trend in other parts. As the summer monsoon is the main rainy season and such characteristics with increasing precipitation trend may cause more floods in the monsoon season, subsequently affecting the downstream region.

The individual stations show that the precipitation trend is not uniform across the basin (Figure 5). There is an increasing precipitation trend in some stations in the northern side of the basin while, in the southern side, there is a mostly decreasing trend. Among the 27 stations, 19 stations show decreasing trends and five of them are significant, while eight station show an increasing trend and one of them is significant. Most of the stations in KRB show a decreasing trend mainly in winter and the post-monsoon season (Figure 5) and eight different stations in both seasons are significant. In winter only two stations, and in the post-monsoon only one station, show increasing trends and none of them are significant. The unique topography of the basin may be the cause for a lack of uniform trend. More number of station are showing significantly decreasing trend than increasing in all the season. Likewise, Nepal [38] also suggested lack of clear trend for the precipitation in the Koshi River basin of Eastern Nepal. However, unlike to the KRB, most of the stations (22 stations out of 36) shows increasing trend with two of them statistically significant and only one station shows a significant decreasing trend.

The number of the rainy days (Figure 6) calculated from the representative stations selected on the basis of the least missing data inside the KRB shows decreasing trend in the KRB. In this paper rainy days are defined as the days with more than 1 mm of precipitation. Station at Jumla (altitude: 2300 m.a.s.l) represents the Mountain region, the Hilly region is represented by Jajarkot (Maina Gaun; altitude: 1231 m.a.s.l) and Terai by Surkhet (Chisapani-Karnali; altitude: 225 m.a.s.l), and Achham (Asara Ghat; altitude: 650 m.a.s.l) represents the valley in the Mountainous region. In all of the selected stations the number of rainfall days are decreasing, while it is higher in the mountain valley (1 day/year) and it is statistically significant at the 99% level. Similarly, in Terai and Hills the rainy days are decreasing by 3 days/decade and the trend of Terai is significant at the 90% level. However the rainfall days are decreasing by only (7 days/century) in mountains (higher altitude). The analysis shows that the rainy days are decreasing at all stations in the basin and the rate is highest in valley of the mountainous region where the average total number of rainy days in a year is the least.

Increasing total rainfall amounts and decreasing rainy days, particularly in the mountainous region indicates the extreme rainfall events are increasing, which might cause higher amount of rainfall when it rains and flooding events in the downstream area.

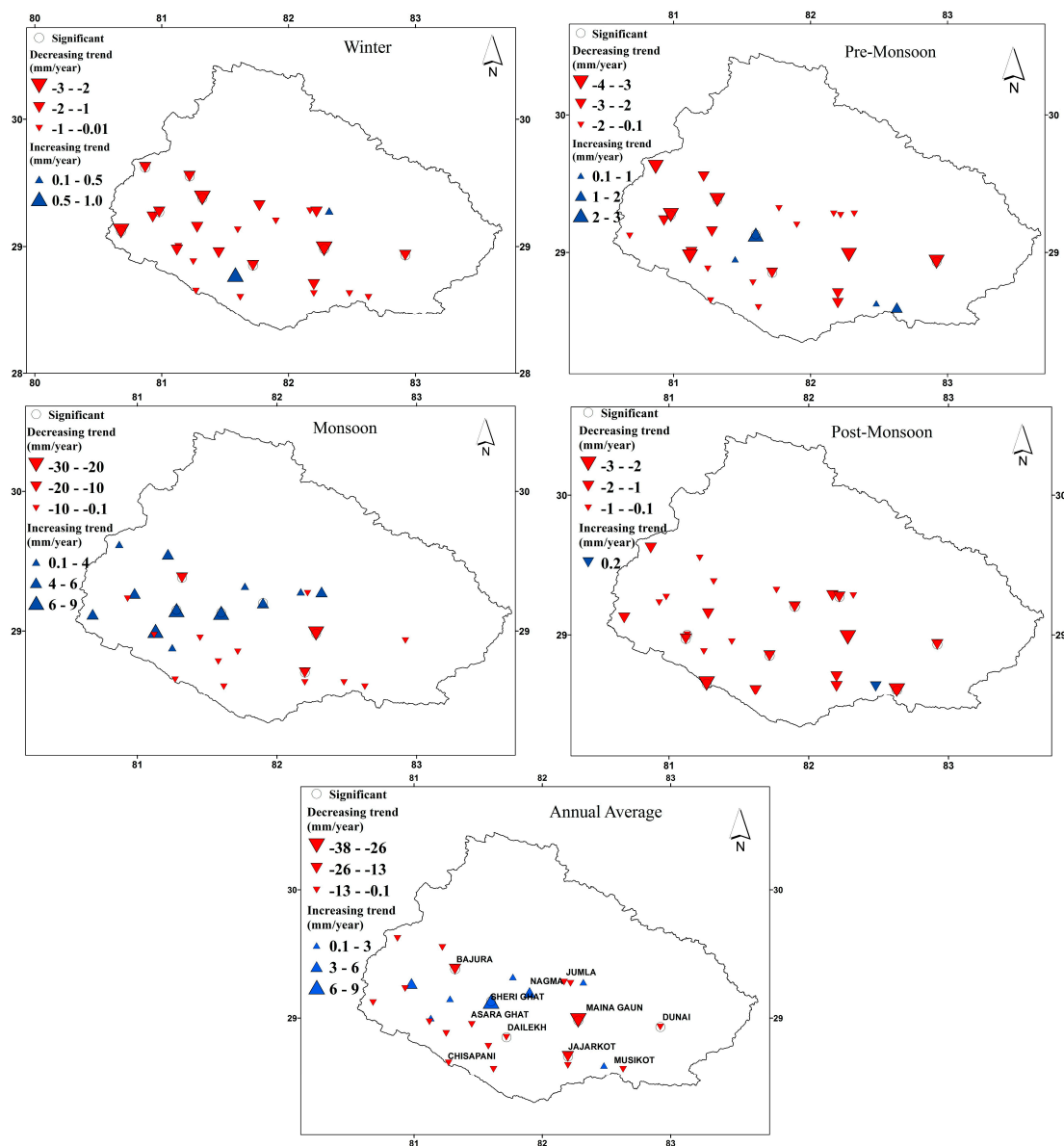


Figure 5. Station-wise precipitation trend at different season in KRB; red symbols represent the decreasing trend whereas the blue indicates the increasing trend.

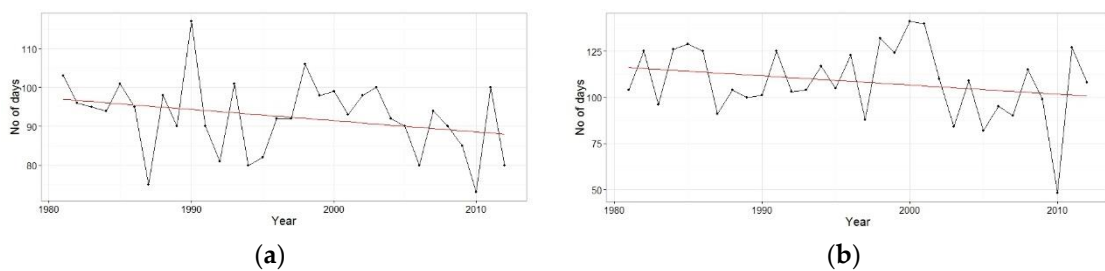


Figure 6. Cont.

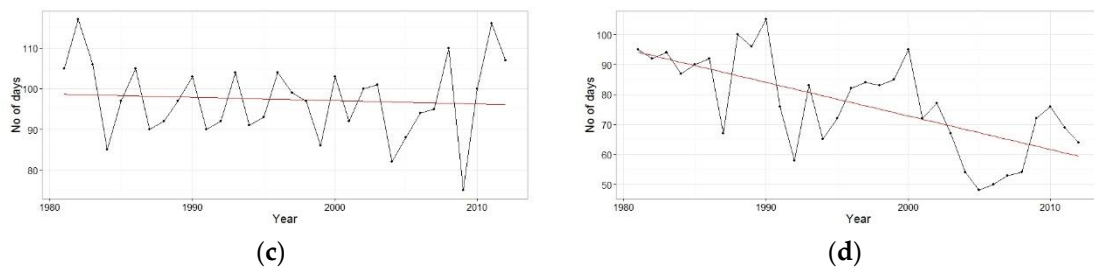


Figure 6. Number of rainfall days from the selected stations inside the KRB; (a) In Terai; (b) in hills; (c) in mountain; and (d) mountain valley.

4.2. Temperature

The average maximum temperature of the basin is 25 °C, while the average minimum temperature is only 13 °C. In the basin, temperature starts to increase from the last week of December or the first week of January and reaches at maximum in mid-June and then gradually decreases (Figure 3). Similarly, the temperature gradually decreases from south (Terai) towards the north (Mountains) as the altitude increases. It is as high as 40 °C in the Terai during the month of June while it is as low as −14 °C in the Mountain region during January. There are not enough meteorological stations in the higher altitude to show it spatially; the important stations present in higher altitude, like at Simikot (2800 m.a.s.l) and Rara (3048 m.a.s.l), are marked by several missing data and do not have enough years to show their climatic trends. The annual maximum, minimum, and average temperature anomaly of the basin is shown in Figure 7, which shows that the trends of minimum, maximum, and the average temperatures are positive, and more inter-annual variation has been seen in the minimum temperature.

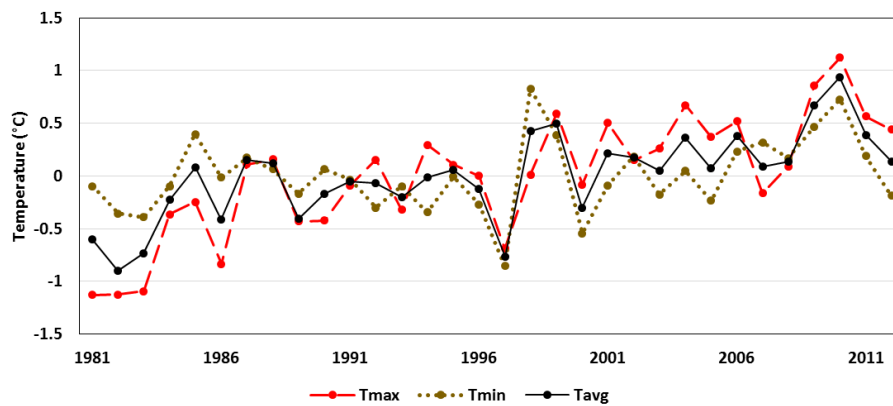


Figure 7. Average annual maximum, minimum, and mean temperature anomaly of the KRB.

Table 2 depicts that the maximum, minimum, and the average temperatures are increasing in most of the stations with statistical significant rate in mid- to high-altitude regions. The maximum and average temperature increase rate is higher in higher altitudes, whereas, the minimum temperature trend decreases with increasing altitude. An interesting result has been found that the station located at Dailekh (Station index: 402, altitude: 1402 m.a.s.l) has the highest positive trend for the maximum temperature in the pre-monsoon season and negative trend for the minimum temperature in the winter season, suggesting a reduction in snow cover or increasing rainfall in winter [1] with possible sensitivity of mountainous regions to climate changes.

Table 2. Temperature trend (°C/year) in different elevations of the KRB.

SN	Station Name (Index, Altitude in Meter)	Pre-Monsoon			Monsoon			Post-Monsoon			Winter		
		Tmax	Tmin	Tavg	Tmax	Tmin	Tavg	Tmax	Tmin	Tavg	Tmax	Tmin	Tavg
1	Chisapani (405, 225)	0.05 *	0.04 *	0.05 *	0.02	0.01 *	0.02 ⁺	0.02	0.02	0.02 ⁺	−0.01	0.01	0
2	Dipayal (218, 652)	0.06 *	0.08 ***	0.07 **	−0.01	0.02 *	0.01	0.01	0.04 *	0.02	0.04	0.05 **	0.04 *
3	Surkhet (406, 720)	0.09 ***	0.03	0.06 **	0.05 **	0.01	0.03 **	0.07 ***	0.03 *	0.05 ***	0.08 ***	−0.01	0.03 **
4	Chaut Jhari (513, 910)	0.04	0.02	0.03 ⁺	0.01	0.04 ***	0.02	−0.12 ***	0.05 **	−0.03 ⁺	−0.04 *	0.02	−0.01
5	Dailekh (402, 1402)	0.22 ***	0.0013	0.11 ***	0.14 ***	−0.10 *	0.02	0.17 ***	−0.04	0.06 *	0.11 ***	−0.01	0.04 ⁺
6	Musikot (514, 2100)	0.05	0.009	0.04	0	−0.04 **	−0.02	0.07 ***	0	0.04 *	0.08 **	0.02	0.04 *
7	Jumla (303, 2300)	0.06 **	0.02 *	0.05 **	0.03 **	0.03 ***	0.03 ***	0.07 ***	0.02	0.05 **	0.05 *	0.01	0.03
	Average basin	0.08 **	0.03 *	0.05 ***	0.04 ***	−0.01	0.02 *	0.03 *	0.02	0.02 *	0.05 **	0.01	0.03 *

$p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), 0.1 (⁺).

On the basis of available data the temperature variation in the KRB depicts that the maximum temperature is increasing at a faster rate ($0.05\text{ }^{\circ}\text{C}$ per year) than the minimum temperature ($0.01\text{ }^{\circ}\text{C}$ per year), which is similar to the previous studies carried out across Nepal by Shrestha *et al.* [6], Bhutiyani *et al.* [47] and Nepal [38] in the eastern part of Nepal and the rate of increase is higher in higher altitude. However, study [13] in the eastern part of Nepal, the minimum temperature increased much more than the maximum temperature even in higher altitude. In KRB, during the pre-monsoon season, the maximum temperature trend is higher ($0.08\text{ }^{\circ}\text{C}/\text{year}$) than other seasons (Table 2) which may act as a driving factor in melting the snow and glaciers in the higher reaches [4]. Likewise, after the pre-monsoon the temperature trend is seen more in the winter season which implies the possibility of reduction of the snow in winter.

The station at elevation 225 m.a.s.l has a comparatively lower maximum temperature trend in all season than the station at higher elevation at 2300 m.a.s.l. Most of the stations show high altitude mountains regions have the higher positive maximum temperature trends in KRB. Similar to this result, high latitude regions in the Asia which are experiencing faster rates of warming than lower latitude regions [48]. Shrestha *et al.* [6], Collins *et al.* [23] and Rangwala and Miller [1] supports that temperature trends over Nepal found broad agreement with temperature trends found in the Northern Hemisphere and the Tibetan Plateau, while it differs from the Indian plains.

While KRB is full of natural resources [41], Human Poverty Indices of districts in KRB are the most impoverished in Nepal [49] and people do have very low adaptive capacity [50]. This region is suffering from the chronic food deficits [51] and, at the same time, some parts are highly exposed to natural disasters, like landslides [28,51]. This highly vulnerable region [28] will be more sensitive towards increasing temperature and decreasing precipitation trends that are being observed in KRB. This increasing temperature may have different implications and affect all major components of hydrological systems [52], including precipitation pattern change, alteration of soil moisture and evapotranspiration rates, and shrinkage in the overall glacier mass, providing short-term annual increases in meltwater contribution to downstream river flows [53].

4.3. Precipitation Versus River Discharge

The mean annual discharge at the outlet of the KRB at Chisapani is $1369\text{ m}^3/\text{s}$ with the highest runoff during the month of August ($4278\text{ m}^3/\text{s}$) and lowest during February ($302\text{ m}^3/\text{s}$). Likewise, during 1981–2010, the annual discharge ranged from $1013\text{ m}^3/\text{s}$ (lowest) in 1987 to $1790\text{ m}^3/\text{s}$ (highest) in 2000.

Monthly river discharge and precipitation in KRB show a positive correlation coefficient (0.7 and 0.5 in July and August, respectively) and the peak discharge is found to be lagged by a month to precipitation (Figure 8). This peculiar behavior in the basin may be due to the large size of the basin, meaning it takes some time for the rainwater to arrive at the outlet as surface and sub-surface runoff, or it is an indication that the melting of the snow and glacier in the region is contributing to such characteristics in discharge [4]. There is an indication that the river discharge at the KRB is much more sensitive to the change in pre-monsoon temperature in the basin, particularly in the northern parts. The discharge in KRB begins to increase in May and peaks in August. During the pre-monsoon season when the temperatures starts rising, the snow and glacier melt contribute to the stream flow [4]. The higher runoff time coincides with the monsoon season and continues until the post-monsoon period when temperatures are relatively high. Likewise, after August there is more discharge at its outlet Chisapani than the precipitation in the KRB where probably the groundwater contribution and glacial discharge may be playing a major role.

The annual precipitation of KRB and annual discharge at its outlet Chisapani is shown in Figure 9 and it shows a decreasing trend in precipitation at $4\text{ mm}/\text{year}$ while at the same time (1981–2010) the discharge at Chisapani is nearly constant ($0.88\text{ m}^3/\text{s}$ per year) but both the trends are not significant. During this period of 1981–2010 the discharge and rainfall are well correlated (correlation coefficient = 0.73). The observed increased temperature could have increased the glacier

melting balancing the expected lower discharges. Similarly, the insignificant trend of discharge may be due to the different hydrological systems, like changing precipitation pattern or increasing rainfall variability or melting ice, affecting water resources, and sediment transport [26].

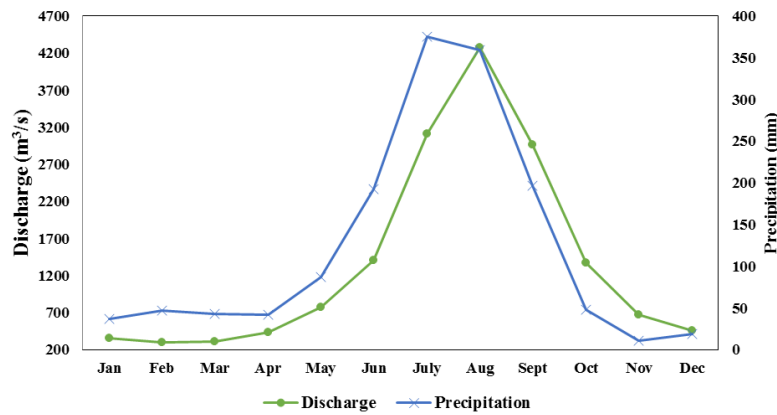


Figure 8. Monthly average precipitation and discharge relation in KRB.

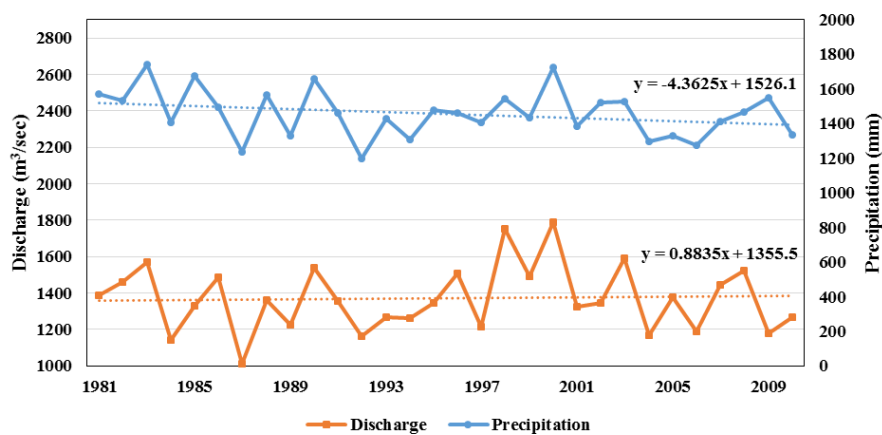


Figure 9. Annual average precipitation of KRB and river discharge at its outlet at Chisapani.

5. Conclusions

Nepal lies in the central part of the Great Himalayan range and the KRB region lies in the western part of Nepal, but was not considered well in previous research. This research contributes to the understanding and interpretation of the hydro-climatic variability. Along with the contribution to knowledge and information about the basin and its societal importance, this research has contributed to the application of scientific tools and methods in the remote and topographically-challenging Himalayan basin.

The results of this study showed that the average precipitation in the basin is decreasing by 4.91 mm/year with around 10% during the year 1981–2012 and both maximum and minimum temperatures are increasing. The rate of increase is greater for the maximum temperature (0.05 °C/year) than for the minimum temperature (0.01 °C/year) and the warming rate is faster in high elevation than in lowland areas. It has been observed that the maximum warming trend is highest during the pre-monsoon and winter season.

In general, there is a decreasing trend in precipitation, but there is significant spatial variation in KRB. The issue of decreasing precipitation is not just for the shortage of drinking water; it is tied up with the problems of food production, land development with increasing population, and importantly lifestyle changes. This decreasing trend of precipitation in most of the area of Terai, Hills,

and Trans-Himalaya, and increasing temperature trends in almost all areas of KRB will aggravate the situation leading the poor quality of livelihood [51] and towards greater vulnerability. It affects not only water and livelihood, but also to different developmental programs [54]. Though most precipitation station's trends were not statistically significant, reflecting high inter-annual and decadal variability, the decreasing trend of precipitation, nearly constant discharge, and almost a month of time lagging in the peak discharge needs further detailed study.

The KRB is mostly susceptible to drought and higher food prices; it will take longer for households in this region to recover from climatic shocks [51]. Therefore, along with the incorporation of the local indigenous knowledge and practices, regional cooperation with synchronized collective efforts [55] are vital to cope and adapt with this changing hydro-climatic variability in the basin.

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