Perennial to ephemeral transformation of a Lesser Himalayan watershed

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Under a changing climate, the Sub-Himalayan ecosystems are likely to experience marked transformations in hydrological, biogeochemical and biophysical processes. To explore this, we have been observing various hydrometeorological parameters in a completely rain-fed sub-Himalayan watershed (Salla Rauetella Watershed) since 1991. We noted a changing trend for some of the hydrometeorological parameters over the 22-yr period. While the annual air temperature has increased significantly, the annual rainfall also shows an increasing trend with a higher probability of increased rainfall intensity. The run-off data show a peculiar trend that the watershed has been transforming itself from a perennial to an ephemeral system, despite an increasing trend of rainfall magnitudes. This is primarily attributed to the increasing trends of rainfall intensities exceeding the infiltration capacities of the soil which trigger large but high-intensity run-off events with dry spells in other periods, which makes the river ephemeral. We infer a likely dynamic change in the run-off-generation mechanism which warrants the need for a more precise and rigorous observation-cum-measurement strategy of ecohydrological processes in Himalayan ecosystems, supported with modelling and remote sensing approaches. This will help identify the optimal headwater treatment measures for augmenting groundwater to sustain the rainfed streams of the Himalaya under a changing climate.

Keywords: Climate change, ecosystem transformation, precipitation trends, run-off generation, watersheds.

THE Himalayan watersheds are among the most vulnerable regions to climate change owing to their higher altitudes and abundance of freshwater resources in the form of lakes, rivers, snow and glaciers, similar to other mountainous ecosystems[1–5]. As such, climate change in these regions affects many of the ecosystem services such as regional hydrology[6], carbon cycle[7,8], agriculture[9–11], animal husbandry[12], biodiversity[13], agro-based industry, etc. The Himalayan regions are also subjected to higher anthropogenic pressures[14], as this mountain system houses one of the most densely populated regions. However, research on the impact of climate change on hydrometeorological and ecohydrological processes in the Himalayan regions is still in its infancy[2,14], compared to other ecosystems of the world.

Recent studies have shown that many climate change-induced ecohydrological phenomena in the Northwestern Himalaya are already active[15,16]. Most of these phenomena are directly or indirectly related to perturbations in the local hydrological cycle[15,17]. These effects include increasing monsoon rainfall[18]; increasing temperature[19,20], changes in rainfall pattern[11,21], increased frequency of extreme events[15,22,23], steady recession of glaciers[24–26], rapid depletion of tributary glaciers[27], shrinking of snow cover[17], decreased contribution of glacier-melt water to river discharge[27], shifting of natural vegetation and fruit belts to higher elevation[28], changes in agricultural patterns[10,29,30], emergence of new pests[31], decrease in the length of perennial river network and summer run-off due to depletion of ground water[2,32], etc.

In this article, based on historical records of hydrometeorological data, we demonstrate how a perennial stream in the rainfed (i.e. non-glacial fed) regime in the Sub-Himalayan region is being transformed from a perennial to an ephemeral system due to changes in the rainfall characteristics, probably due to a changing climate.

Experimental watershed

The current study area (Figure 1) is located in the central region of the Lesser Himalayan terrain in Almora district, Uttarakhand, India. The experimental watershed, Salla Rautella Watershed (SRW) encompasses an area of 0.296 km^2 and is located between 29°35′9.133″–29°35′29.636″N lat. and 79°33′8.46″–79°33′29.636″E long. The elevation of SRW ranges from 1640 to 1989 m amsl. The long-term mean annual temperature is

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~17°C and the annual rainfall is ~1004 mm. Approximately 77% of the total annual rainfall is contributed by the southwest monsoon and ~2% occurs during the post-monsoon season. The remaining ~11% and ~10% of the influxes are contributed by summer and winter rainfall respectively. This region falls under the Cwb Köppen climate class (subtropical highland), and is entirely rain-fed as the snowline lies almost 4300 m amsl in the region and SRW is not part of any glacial-melt water-fed (i.e. snow-fed) rivers. Figure 2 shows the seasonal characteristics of various hydrometeorological indicators (long-term mean) of the study area. SRW is entirely covered by pristine forests, predominantly comprising chir pine (*Pinus roxburghii*) as the overstorey. Species found in the crest and mid-crest areas of the watershed include oak (*Quercus leucotrichophora*), Burash (*Rhododendron arboretum)* and Utish (*Alnus nepalensis*). The leaf area index (LAI) of SRW is around 4–5 cm^2. The Salla river that flows through the watershed is among the thousands of first-order perennial streams of the non-glacial-fed Kosi River system in the Lesser Himalayan terrain.

The local geology comprises fractured granite and gneiss of the Syahidevi formation[33]. A small section of the watershed near its mouth comprises garnetiferous sericite–chlorite schist and muscovite–schist alternating with micaceous quartzite, locally called Sitalakhet Schist[34]. Considering the mountainous nature of the terrain and the local geology, soil depth is shallow, implying relatively young soils. A soil survey[35] conducted at 20 different sites indicates that the average soil depth is around 1 m. The topsoil is covered by an organic litter layer with varying degrees of decomposition.

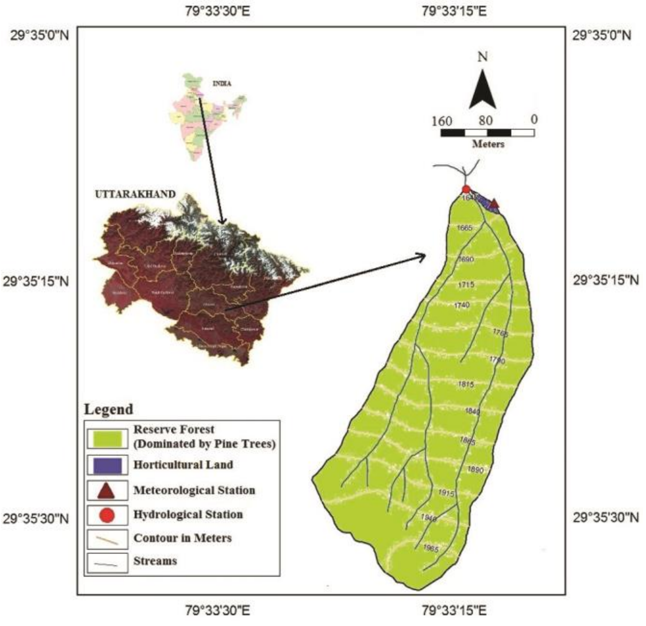

Figure 1. Location of the Salla Ratella Watershed (SRW) in the sub-Himalayan terrain in India.

Data collection

For monitoring of hydrometeorological processes, the first monitoring station was set up in the region in 1987 (ref. 36). In 1991, a network of six other micro-watersheds having diverse ecohydrological characteristics was identified to monitor a set of hydrometeorological variables[37]. The operational monitoring of these watersheds was carried out under different sponsored research projects. SRW is important among the seven watersheds.

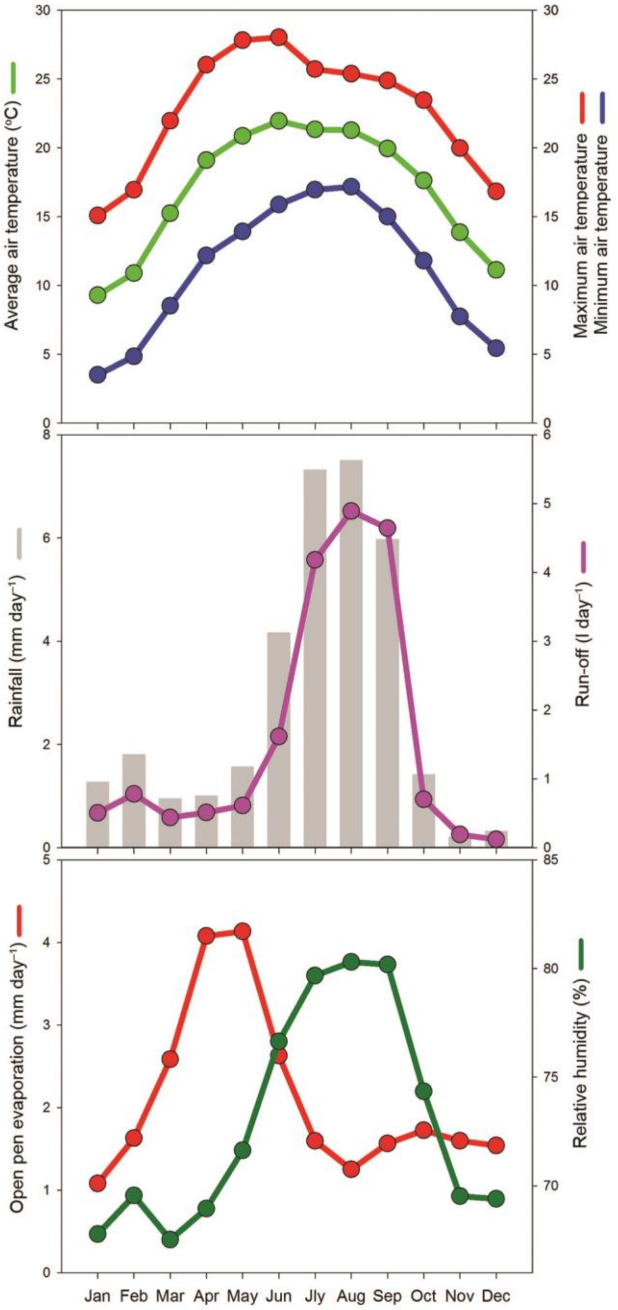

Figure 2. Seasonal variability of different hydrometeorological parameters (average of all the years) in SRW.

This study is based on long-term data collected from SRW, the most important in-house observatory. At SRW, the daily watershed discharge is being measured using a compound 90°V notch and rectangular weir. A meteorological station located near the mouth of the watershed has been recording various meteorological variables such as rainfall (rain gauge, Hindusthan Clock Works® IS5235-1969), air temperature (maximum and minimum thermometer, Zeal®, UK), humidity (wet and dry bulb thermometer, Zeal®, UK), potential evaporation (Arslar® Open Pan Evaporimeter IS5973) and wind velocity (Arslar® Cup Counter Anemometer IS9512-1970). However, watershed monitoring was interrupted during 1994 and 1995. Being an important in-house research facility, various types of biometric, hydraulic and ecohydrological investigations are being conducted over the years at different locations spread across the SRW.

Admittedly, the World Meteorological Organization (WMO) practice is to employ the average of a climate variable (e.g. temperature) over a 30-yr period for climate change-related issues, but a dataset spanning about 75% of that length assumes salience particularly in view of a significant hydrological event, viz. conversion of a perennial stream to a seasonal one. We designed some indicators that could efficiently summarize and explain the nature of inter-annual variability (IAV) of various hydrometeorological parameters. In this context, we calculated three indicators: (1) the annual rainfall intensity (ARFI) calculated as annual precipitation divided by the number of rainy days in a given year; (2) the annual run-off intensity (AROI) calculated as annual run-off divided by the number of days when the average run-off is more than 0.02 l $\sec^{-1}$, and (3) the number of zero discharge days (ZDD) for a given year by cumulating the number of days in a year when the river discharge is 0 or not measurable (i.e. <0.02 l $\sec^{-1}$).

Results and discussion

Seasonal trends in run-off and rainfall

We analysed the long-term trends in various hydrometeorological parameters during the 22-yr period (1992–2013). We found that there is a statistically significant trend in some of the variables: mean temperature ($R = 0.68$, $P < 0.001$), maximum temperature ($R = 0.49$, $P = 0.042$), minimum temperature ($R = 0.45$, $P = 0.033$), evaporation ($R = –0.55$, $P = 0.015$), ARFI ($R = 0.51$, $P = 0.023$), annual run-off ($R = 0.45$, $P = 0.048$), ZDD ($R = 0.94$, $P < 0.001$) and AROI ($R = 0.67$, $P = 0.001$). A detailed discussion of the IAV of hydrometeorological variables is provided in the Supplementary Material (online). After observing the nature of IAV of different hydrometeorological variables, the seasonal hydrographs and the corresponding hyetographs were analysed for three milestone years (1992, 2001 and 2013). These represent the (i) initial year when ZDD = 0, (ii) year when ZDD > 0 for the first time and (iii) the present year respectively (Figure 3). Considering the increasing gaps in the grey panels in the figure (that correspond to the occurrences of ZDD), the transition of SRW from perennial to seasonal is distinctly evident. It is clear from the figure that the nature of the SRW was perennial in 1992 with ZDD = 0. It continued to be perennial until the end of 2000 (not visible in the figure, but the lowest discharge during this period was 0.020 l $\sec^{-1}$, as evident from the data). During 1992–2000, in general, rainfall was moderate and well-distributed. In 2001, however, the stream acquired a seasonal characteristic because there was no flow for almost 64 days (i.e. $\mathrm{ZDD}_{2001} = 64$). Since then, the number of ZDD has been showing an increasing trend (e.g. ZDD_{2013} was 187). From these observations, it can be deduced that despite the increasing annual rainfall, the process of transformation of SRW from a perennial to an intermittent system has been initiated. The classical rainfall intensity–infiltration rate relationship can be evoked to explain the rainfall intensity–run-off mechanism that is observed in this study[38,39]. High-intensity short-duration rainfall is much more likely to exceed the capacity of the soil to infiltrate water and result in overland flow than a longer, less-intense rainfall. We analysed the infiltration rates (I_R) of soils in the SRW at 20 different places that are spatially distributed widely using a ring infiltometer. We also studied the soil profiles at these sites to understand its depth and other hydraulic characteristics. Figure 4 shows the watershed-averaged I_R–time characteristics. The watershed average constant rate of infiltration (I_c) is around 70 mm h^{-1}. Hence, it can be reasoned that when the rainfall intensity is comparable to the I_c values, the probability of ponding can be higher, which necessarily kick-starts the surface run-off[38,39]. From the 2013 daily precipitation patterns, we can observe that on Day of the Year (DOY) 167 and 168, the rainfall flux peaked as high as 124 and 74 and mm day^{-1} respectively. Based on our local knowledge, we know that during these days, a huge storm event occurred that lasted up to 30 min with a rainfall intensity of the order ~130 mm h^{-1} (i.e. 70 mm downpour within a period of half an hour). Thus a large amount of waterflux occurred within a short period of time. As India Meteorological Department (IMD) considers rainfall intensities over 100 mm h^{-1} as 'cloudburst', this event could also be classified as one[40,41]. Cloudburst takes place when moist and thermodynamically unstable atmosphere rapidly uplifts along a steep topography (e.g. the cloudburst of Uttarkasi, Uttarakhand in 2012 and the one in Shillagarh, Himachal Pradesh in 2003). Any intense rainfall event such as a cloudburst has high probability of triggering a run-off mechanism, as these rainfall intensities are much larger than the infiltration capacity of the soil. Similar to this Himalayan region, climate change-induced alteration of the watershed hydrological

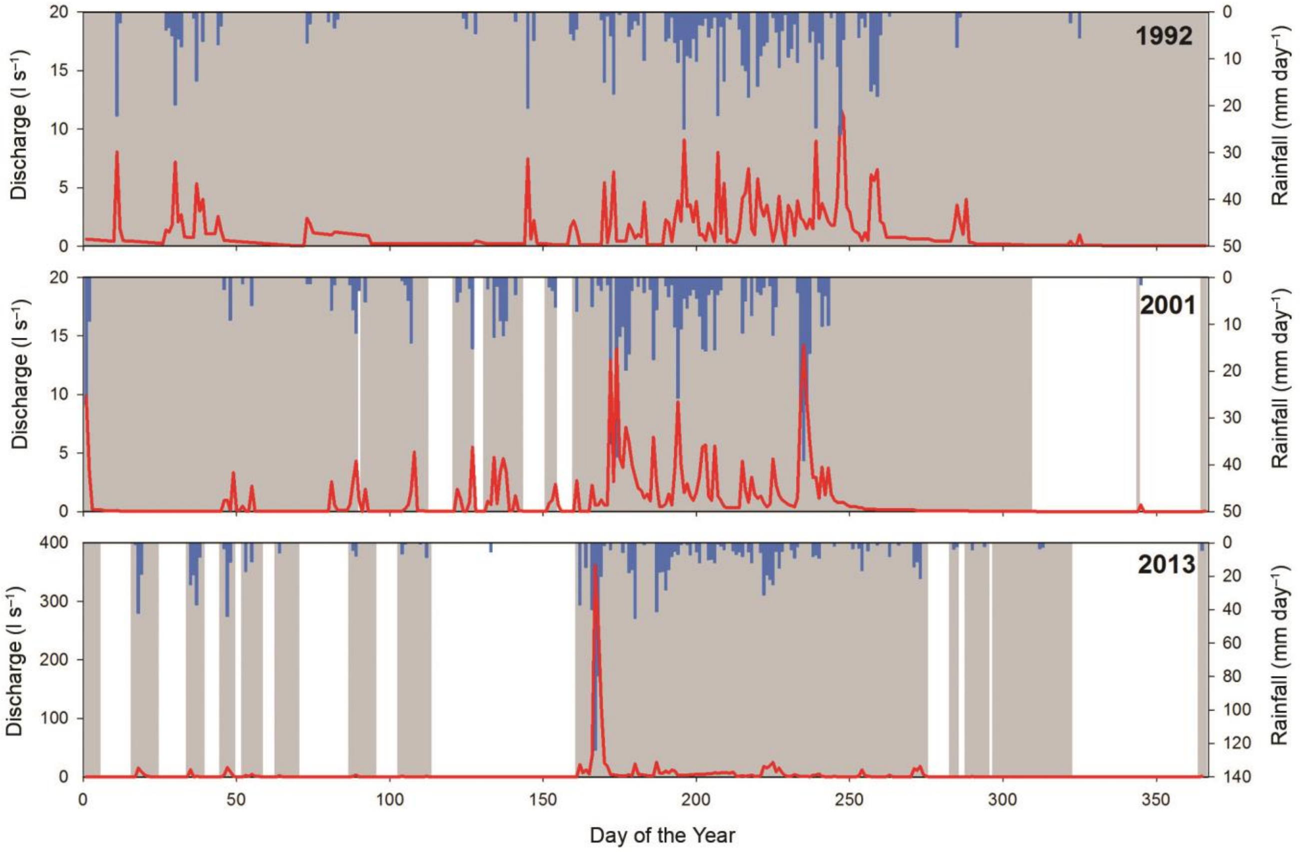

Figure 3. Seasonal variability of rainfall and run-off at SRW for the three milestone years. The grey background denotes days when the river was flowing. Note the gradual development of gaps in the grey region in 2001 and predominance of gaps in 2013.

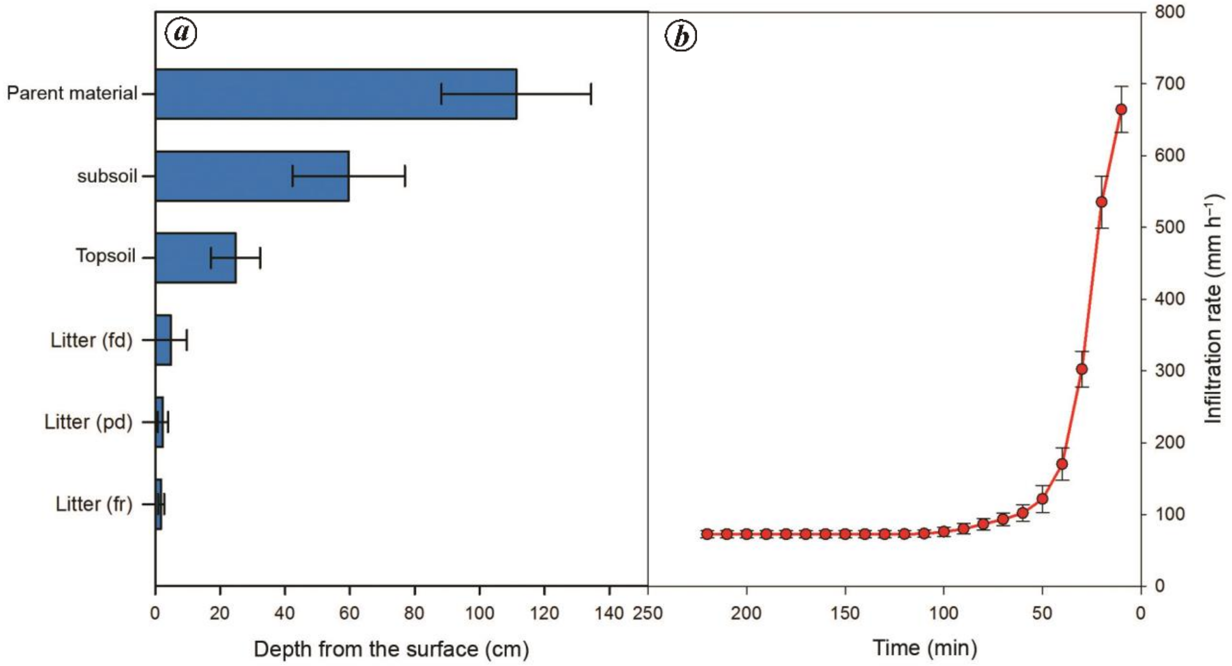

Figure 4. ***a***, Soil hydraulic characteristics measured from the surface. Note the position of bedrock at around 100 cm, reflecting the shallow soil characteristic. ***b***, The watershed average (average of 20 points) infiltration characteristics. Note the mean constant rate of infiltration is around 70 mm/h.

processes has been studied in other mountainous ecosystems of the world such as the Alps[42], Rockies[43] and Andes[44], all of which unanimously confirm the dominant role of rainfall intensities on the landscape hydrological processes. This is further worsened by the fact that the mountain soils are relatively shallow compared to other types of landscape. An analysis of the soil depth data reveals that the average soil depth is around 1 m (±0.5 m) throughout the watershed. The role of the bedrock depth and run-off characteristics under a changing climate has been vividly examined in the Cascades mountain ranges of the Rockies[45]. Thus, with a relatively shallow soil, the inherent storage capacity is not very large. If we consider soil porosity to be 45%, the total soil storage capacity will be ~450 mm, consisting of both phreatic (below the water table depth (WTD)) and vadose zones (above WTD). The phreatic zone may be of substantial proportion, implying that the saturation deficit could be very low. A high-magnitude rainfall event could markedly bring the water table to the soil surface, triggering a run-off event.

Thus, we can conclude that in 2013, a high-intensity storm event caused a large run-off event. There appears to be a reasonable correlation between rainfall intensity (AFRI) and ZDD, although the annual precipitation shows an increasing trend during the period of observation. It is evident from Figure 5 that AFRI and ZDD are significantly correlated with each other and the probability that this trend occurs by mere chance is negligible. Broadly speaking, a unit increment in the annual rainfall intensity increases the ZDD by about 10 days, which is a highly influential hydrometeorological effect. It can be seen that the recent years are represented close to the top-end of this scatter plot. This suggests that the process is escalating probably because of changing climate. Our field-based observation is congruent with some of the modelling works[44,46], which suggest that rainfall intensity is the key parameter that governs run-off loss in the short term. However, in the long term, there may be other mechanisms that operate. For example, climate change-driven precipitation patterns affect the quality and quantity of vegetation, which in turn affects the local water balance, via evapotranspiration and nature of groundwater recharge.

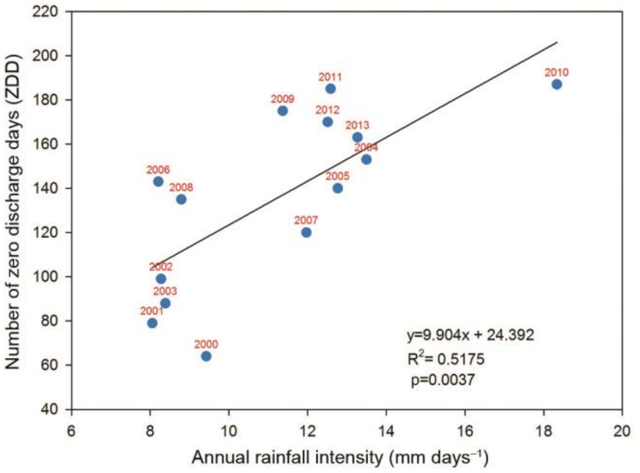

Figure 5. Relationship between mean annual rainfall intensity and zero discharge days.

The increased occurrences of high-intensity rainfall events are complex mesoscale atmospheric processes. Nevertheless, these mesoscale events may be perturbed by the variability of the surface energy balance under changes in land use and latent heat flux. Based on local knowledge, the Kumaun region in the past had a characteristic low intensity but continuous precipitation event that lasted for almost seven days (locally called 'Satjhar') during the first and second week of July[2]. These are extremely low-intensity week-long rainfall events. Most of the water that comes through these fluxes infiltrate and recharge the soil storage. In recent years, however, these low-intensity events have almost disappeared.

Thus, we conclude that the consistently declining lean season discharge for the last two decades is dangerously threatening the perennity of the Salla River. This might be due to climate change and the consequent alterations in the rainfall patterns, especially the increased frequency of extreme events. The rainfall data reveal the increasing tendency in annual rainfall amount. Despite the increasing trend of rainfall, the Salla Rautella is being transformed from a perennial to an intermittent stream and is perhaps on its way to becoming a seasonal or ephemeral stream.

Ecohydrological implications of increasing ZDD under climate change

From the analysis of historical hydrometeorological data, it is evident that SRW is transforming itself from a perennial to an ephemeral system and thus the number of ZDD is increasing. There are several ecohydrological implications of such transformation that we need to consider to better understand how this ecosystem might behave under a possibly changing climate.

In pristine ecosystems, a variety of run-off generation mechanisms are plausible. They can be broadly classified into Hortonian (infiltration excess) mechanism, subsurface return flow or Hewlitt (saturation excess) mechanisms[47,48]. These could operate alone or in combination. Rainfall events having intensities greater than the infiltration capacity of soils generate spontaneous run-off events based on the Hortonian mechanism[49–51]. However, under low-intensity rainfall events, run-off generation is primarily caused because of a saturation excess flow[52]. It is possible that under climate change, the dominant run-off generation mechanism might change from one form to another according to location-specific characteristics. For example, Hortonian mechanism might set in under high-intensity events replacing the saturation-excess run-off mechanism. There is evidence in the literature supporting that run-off generation mechanisms are spatially and temporally dynamic in different ecosystems and are governed by a variety of factors, including climate[46,51]. Nevertheless, the net result of the perturbed hydrological processes reflects a transformation in the nature of the local water balance mechanism. The hydrological processes are perhaps the best measure to evaluate the environmental degeneration or regeneration of a watershed[53]. An increase in ZDD can eventually result in a steady decline in the soil moisture regimes due to lower influx of water (due to lowered infiltration), accentuated by a higher outflux of water (due to evapotranspiration). Thus, the soil moisture and WTD might decline and consequently, there could be a sharp decline in storage change at the end of the year. This mechanism is highly likely to affect the nature of water balance in the following year as well. Even though the rainfall magnitude is higher with a lowered intensity in the following year, much of this water will be used to replenish the already depleted soil storage. This implies that a vicious cycle sets in, perturbing the original hydrological characteristics of the ecosystem, which, in the long term can affect the vegetation functioning (mostly via ecophysiologically controlled evapotranspiration demands), initially for the understorey vegetation with shallow root systems, and later for the overstorey vegetation. These ecohydrological processes comprise part of a feedback mechanism for local hydrological processes[54]. There is already some evidence in the Sikkim Himayala that climate change in the form of rising temperatures, and intense precipitation patterns have further reduced the natural groundwater recharge[45], which corroborates this study. The temporal patterns of the run-off affect the local or regional carbon balance by affecting the (i) nature of soil water balance that regulates the ecophysiological factors that controls photosynthesis; and biogeochemical processes that govern ecosystem respiration and also (ii) the export–import of dissolved organic carbon, which can be a significant form of carbon flux in this type of Lesser Himalayan ecosystems where coniferous litter prevails. The dynamics of the run-off variability may also affect: (1) the local biodiversity such as grasses, herbs, shrubs and trees, and wildlife and fish population in these watersheds in the downstream regions; (2) means of drinking water from natural springs – locally known as ‘Naulas’ and ‘Dharas’, gravity flow and lift schemes[15], and (3) means of irrigation and thus the agricultural productivity. Further studies that combine measurements and process-based modelling are warranted to better understand the ecohydrological complexities associated with climate change-induced run-off changes in this watershed. Aforesaid studies would enable better understanding of the fundamental mechanisms responsible for these unique dynamical systems. These climate change-induced effects that are primarily governed by regional hydrology, warrant the need to adopt site-specific mitigation measures that might be useful for rainwater harvesting and thereby add to rejuvenate these primarily rainfed headwater streams in the sub-Himalaya.

Conclusion

Under climate change, Himalayan ecosystems are being drastically transformed leading to various direct and indirect influences threatening the biogeophysical and biogeochemical dynamics and biodiversity in the region[55]. In order to explore the influence of climate on the hydrological processes, we have been monitoring various hydrometeorological parameters in an experimental watershed since 1991. Our data, even with their limitations, suggest that the local climate has indeed changed in the region with air temperature significantly increasing over the past 22 years. Precipitation also shows an increasing trend, but there is significant increase in the precipitation intensity rather than the magnitude itself. The run-off magnitudes and intensities of the watershed also show an increasing trend. Ironically, the number of days the watershed remains dry for a given year (ZDD) also shows an increasing trend. This suggests that although the magnitude of precipitation increases, the watershed has transformed itself to an ephemeral system. This has numerous implications on various ecohydrological processes of the region that need to be further explored using a set of coordinated experiments and modelling at multiple scales. The dynamics of the run-off generation mechanism under a changing climate needs to be further investigated employing strategically designed measurements (or observations) and modelling approaches. We acknowledge that there are some data limitations in our study, which could be improved in future. For this, we could have a network of spatially distributed measurements of different hydrometeorological, biophysical and edaphic variables in this watershed. These include the dynamics of hydrometeorological variables such as soil moisture, water table depth and actual evapotranspiration (including radiation components). In order to quantify the role of vegetation in landscape hydrology, it may be useful to quantify the vegetation phenology using biophysical indicators such as LAI with a combination of field measurements and modelling of the canopy radiative transfer mechanism. This information on phenology can be linked with remote sensing and modelling of ecohydrological processes. In order to precisely parameterize the role of soil in watershed hydrology, we need to have a clear idea on the spatial distribution of soil texture and soil organic matter content so that efficient, spatially explicit pedotransfer functions could be generated to map soil hydraulic properties in order to better quantify the influence of soil storage capacity. It is also important to have a clear idea of the spatial variability of bedrock depth to aid in hydrogeological mapping[15]. The information is important to understand the watershed dynamics for data-driven or modelling-based approach at multiple spatial and temporal scales.

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