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ORIGINAL PAPER

Hydro-climatic extremes in the Himalayan watersheds: a case of the Marshyangdi Watershed, Nepal

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Abstract

Climate change/variability and subsequent exacerbation of extremes are affecting human and ecological health across the globe. This study aims at unpacking hydro-climatic extremes in a snow-fed *Marshyangdi* watershed, which has a potential for water infrastructure development, located in Central Nepal. Bias-corrected projected future climate for near (2014–2033) and mid-future (2034–2053) under moderate and pessimistic scenarios were developed based on multiple regional climate models. Historical (1983–2013) and future trends of selected climatic extreme indices were calculated using RClimDex and hydrological extremes using Indicators of Hydrologic Alteration tool. Results show that historical trends in precipitation extremes such as number of heavy and very heavy precipitation days and maximum 1-day precipitation are decreasing while the temperature-related extremes have both increasing and decreasing trends (e.g., warm spell duration index, warm days and summer days are increasing whereas cold spell duration index, cool days and warm nights are decreasing). These results indicate drier and hotter conditions over the historical period. The projected future temperature indices (hot nights, warm days) reveal increasing trend for both the scenarios in contrast with decreasing trends in some of the extreme precipitation indices such as consecutive dry and wet days and maximum 5-day precipitation. Furthermore, the watershed has low mean hydrological alterations (27.9%) in the natural flow regime. These results indicate continuation of wetter and hotter future in the *Marshyangdi* watershed with likely impacts on future water availability and associated conflicts for water allocation, and therefore affect the river health conditions.

Abbreviations

CD	Coefficient of dispersion
CPA	Change-point analysis
DHM	Department of Hydrology and Meteorology
H	High
HA	Hydrologic alteration
IHA	Indicators of Hydrologic Alteration
IPCC	International Panel for Climate Change
L	Low
M	Moderate
masl	mean above sea level
MF	Mid-future
NF	Near future
OD	Overall degree
P	Percentage of deviation
PPT	Precipitation
Q	Discharge
RCM	Regional climate model
RCP	Representative concentration pathway
RVA	Range of variability approach
Tmax	Maximum temperature
Tmin	Minimum temperature

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1 Introduction

Climate change and variability is recognized as a major threat for the environment and sustainable development (Lal et al. 2012). It is evident that a change in the climate, depending upon location, may cause disastrous consequences on the socioeconomic survival of millions of people (Bhutiyani et al. 2007). Therefore, studies on climate change, hydro-climatic extremes, and potential impacts on various sectors have gained momentum in recent years (Chen et al. 2007). In the last few decades, hydro-climatic variations became more prominent and were studied widely at global, regional, and local scales. These extreme climatic events like heat waves, floods, and drought induced by the hydro-climatic variability are expected to exacerbate in the future potentially due to climate change thus posing a major challenge to various sectors such as agriculture, biodiversity, and related ecosystem services that support livelihoods (Shrestha et al. 2017). The socioeconomic impacts of those changes are significant in all countries; however, low- and middle-income countries are especially vulnerable (IPCC 2013). Such countries experience higher fatalities even when exposed to hazards of similar magnitude and further with the 1 °C additional warming, risks associated with such types of extreme events increases progressively (IPCC 2013).

A warmer world is projected to bring more precipitation across the world as well as in Nepal; most models project a wetter and warmer future (2040–2059) mostly in the range of 2–3 °C, depending on the location and scenarios considered (Agrawala et al. 2003). Baidya et al. (2008) observed the general increasing trend in the temperature and precipitation extremes all over Nepal indicating more weather-related extreme events like flood and landslides in the future. Similarly, Manandhar et al. (2012) revealed a warming trend in the Kali Gandaki River Basin at higher altitudes with variable trends in precipitation indices. Bastakoti et al. (2016) also showed an increasing trend of climatic extreme in the recent past. Shrestha and Nepal (2016) observed changes in temperature and rainfall patterns at Makwanpur district of Nepal. Furthermore, Shrestha et al. (2017) found an increasing trend of extreme climatic events in Koshi river basin though long-term trend was not observed in rainfall pattern. In Western Nepal too, warmer and wetter future is projected in Chamelia watershed of Mahakali river basin (Pandey et al. 2019). The warming trends observed over the past several decades exacerbate the hydrological cycle and hydrological systems in many ways. Some of them include change in precipitation patterns, widespread melting of snow and ice; increase in atmospheric water vapor; increase in evaporation; and changes in soil moisture and runoff causing natural variability on inter-annual to decadal time-scales (Bates et al. 2008). Therefore, increased climate variability, could have influence on extreme climatic events like floods and droughts, both in frequency and intensity, affecting Nepal in various ways (Agrawala et al. 2003; Chaulagain 2006; Society of Hydrologists and Meteorologist 2012). Thus, understanding the historical as well as projected future trends in hydro-climatic variables, especially amount and significance of the trends in the extremes, are useful for informed climate-resilient development planning and decision-making.

There are various statistical methods and tools available for evaluating climatic trend as described in literatures (Helsel and Hirsch 2002; Khon et al. 2007; Some'e et al. 2012; Duhan and Pandey 2013). The knowledge on amount of the long-term trends, change points (if any), their position in the time series, and statistical significance of the trends are very important as they allow the interpretation of its possible causes (Moraes et al. 1998). There are many parametric and nonparametric methods suitable for detection and attribution of trends and breaks in hydro-climatic series. Nonparametric tests are widely used as they will work with independent data and can accommodate outliers. One of the widely used nonparametric tests for detecting a trend in hydro-climatic time series is the Mann–Kendall (Mann 1945; Kendall 1975; Shrestha et al. 1999; Nepal 2016; Khatiwada et al. 2016). RClimDex (Zhang and Yang 2004), a R-based tool, is also available in public domain for calculating trends in climatic variables (i.e., temperature and precipitation) and their statistical significance. RClimDex has been used by many studies over the years. They include but not limited to Manton et al. (2001), Kiktev et al. (2003), Alexander et al. (2006), Tank et al. (2006), Baidya et al. (2008), Islam (2009), Donat et al. (2013), and Shrestha et al. (2017). The tool can calculate 27 indices related to temperature and precipitation as defined by Expert Team on Climate Change Detection and Indices (ETCCDI) (WMO 2009).

In addition to determining the historical climatic trend, projecting future climatic extreme plays a vital role for the climate impact studies. Future climate of an area is generally projected using General Circulation Models (GCMs) or Regional Circulation Models (RCMs). However, RCM has been widely used for the climate impact studies due to its higher resolution and better capturing of regional conditions. Many recent studies have used RCMs in climate projection and impact studies (Kulkarni et al. 2013; Fang et al. 2015; Devkota and Gyawali 2015; Khadka et al. 2016; Magar et al. 2016; Rajbhandari et al. 2017; Bhattarai et al. 2018; Pandey et al. 2019). RCM projections can further be downscaled using approaches such as linear scaling (Teutschbein and Seibert 2012), quantile mapping (Gudmundsson et al. 2012), local intensity scaling (Fang et al. 2015), power transformation (Fang et al. 2015), variance scaling (Teutschbein and Seibert 2012; Fang et al. 2015), and delta change (Ruiter 2012) to make RCM projections usable for a watershed level.

Similarly, a large number of studies (Wang et al. 2012; IPCC 2013; Panda et al. 2013; Kundzewicz et al. 2015; Asadieh et al. 2016; Dery et al. 2016) have examined potential trends in observed streamflow during the twentieth century, at scales ranging from catchment to global. Some studies have detected significant trends in selected indicators of flow and demonstrated statistically significant links with trends in temperature or precipitation (Bates et al. 2008). Trends in various indicators of streamflow, one of the important hydrological components that can be altered by both climatic and nonclimatic factors, can be analyzed by various statistical approaches. Indicators of Hydrological Alteration (IHA) (Richter et al.

1996; Ritcher et al. 1997) is a tool that has a capability to analyze 33 indices related to hydrological extremes (Kiesling 2003; Bharati et al. 2016). The hydro-climatic time series may also have abrupt changes in addition to gradual changes (or trend). In such cases, one needs to calculate trends separately before and after such abrupt changes. Statistical tests such as Pettitt's Change Point (Pettitt 1979) and Mann-Kendall (Mann 1945; Kendall 1975) are widely used (Liu et al. 2012; Xia et al. 2014; Mallakpour and Villarini 2016) to detect a change point and statistical significance in hydro-climatic time series.

There are many studies focused on various aspects of climate change in Nepal, ranging from climate change impact assessments (e.g., Pandey et al. 2019, 2020) to flood risk assessments in climate-change context (e.g., Devkota and Bhattarai 2015; Devkota and Maraseni 2018). A summary of selected studies related to climate change in Nepal are provided in Appendix Table 6. However, there are limited studies focusing on climate projection using RCMs and the most recent representative concentration pathways (RCP) scenarios in Central Nepal in general, and *Marshyangdi* watershed. Furthermore, studies focusing on both historical and future climatic extremes as well as hydrological extremes are almost non-existent. *Marshyangdi* is a snow-fed/Himalayan catchment having high potential for water infrastructure development, and it hosts a good number of hydropower projects. The watershed has a potential to generate at least 3251.8 MW of electricity (Jha 2010). Currently, three hydropower projects, namely, Marshyangdi (69 MW), Middle Marshyangdi (70 MW), and Upper Marshyangdi-A (50MW) are in operation and six more have got license. Therefore, understanding hydro-climatic extremes in that watershed is important for informed-adaptation planning. Thus, we aim to unpack hydro-climatic extremes in a *Marshyangdi*, located in Central Nepal which feds to Narayani river basin (Fig. 1). The objectives of this study are as follows: (i) to characterize historical and projected trends in climatic extremes and (ii) to characterize hydrological extremes in the watershed.

2 Materials and methods

Overall methodological framework is shown in Fig. 2. It consists of preparation of historical time series of climatic data (temperature and precipitation) at selected stations, projection of future climate, selection of suitable set of indices for climatic extremes, evaluation of trends in those indices, evaluation of hydrological indices related to extremes, and finally direction and magnitude of hydro-climatic trends with its significance obtained. All these aspects are elaborated in the following sub-sections.

2.1 Study area

Marshyangdi watershed is a sub-basin of one of the major river systems, the Gandaki River Basin, in Central Nepal. It is located between 27° 50′ 42″ and 28° 54′ 11″ N latitudes and 83° 47′ 24″ and 84° 48′ 04″ E longitudes (Fig. 1), covering an area of 4148 km^2. The elevation of this watershed varies between 274 and 8042 m above the mean sea level (masl). The major portion of the watershed lies above 45% slope and are covered by snow and glacier, i.e., most of the area lies between 4000 and 6000 masl.

Climate in the watershed varies from Tropical Savannah in the lower belt to Polar frost type in the higher altitudes (Karki et al. 2016). The mean slope of this basin is 29.42°. Average annual maximum and minimum temperatures are 26°°C (June) and − 6°°C (January), respectively (Sharma 2017). Population in the four districts covered by the study watershed is 0.77 million (CBS 2019). Major land use/cover pattern in the watershed is the Grassland, followed by Barren land and Agricultural land, respectively (Sharma 2017). This region is a part of the major Annapurna Trekking route from Besisahar (in Lamjung district) where the local economy also depends upon it.

The *Marshyangdi* River is perennial in nature and has a typical dendritic drainage system which begins at the confluence of two mountain rivers, the Khangsar and Jharsang, northwest of the Annapurna massif at an altitude of 3600 masl. Then it flows eastward through Manang district and southward through the Lamjung district covering other districts Gorkha and Tanahu. Finally, it joins the Trishuli river system at Mugling as one of the major tributaries of the Saptagandaki River system. Major tributaries of the Marshyangdi River includes *Khudi*, *Dordi*, *Chepe*, and *Daraudi*.

2.2 Historical trend analysis

Historical time series of daily observed temperature, both maximum and minimum, and precipitation at 12 climatic stations and observed river discharge data at 2 stations were collected for the period of 1970–2018 from the Department of Hydrology and Meteorology, Nepal. However, data at only 11 stations (Appendix Table 7), including one hydrological station, were selected for further use after an exploratory data analysis. Then suitable data length was selected (Appendix Table 7) considering the missing values calculated for each month per year for variables like maximum temperature (Tmax), minimum temperature (Tmin), precipitation, as well as for discharge.

Data quality control (QC) was carried out using RClimDex statistical tool, with the purpose of identifying errors in data processing, such as errors in manual keying (Alexander et al. 2006). Months with missing values of

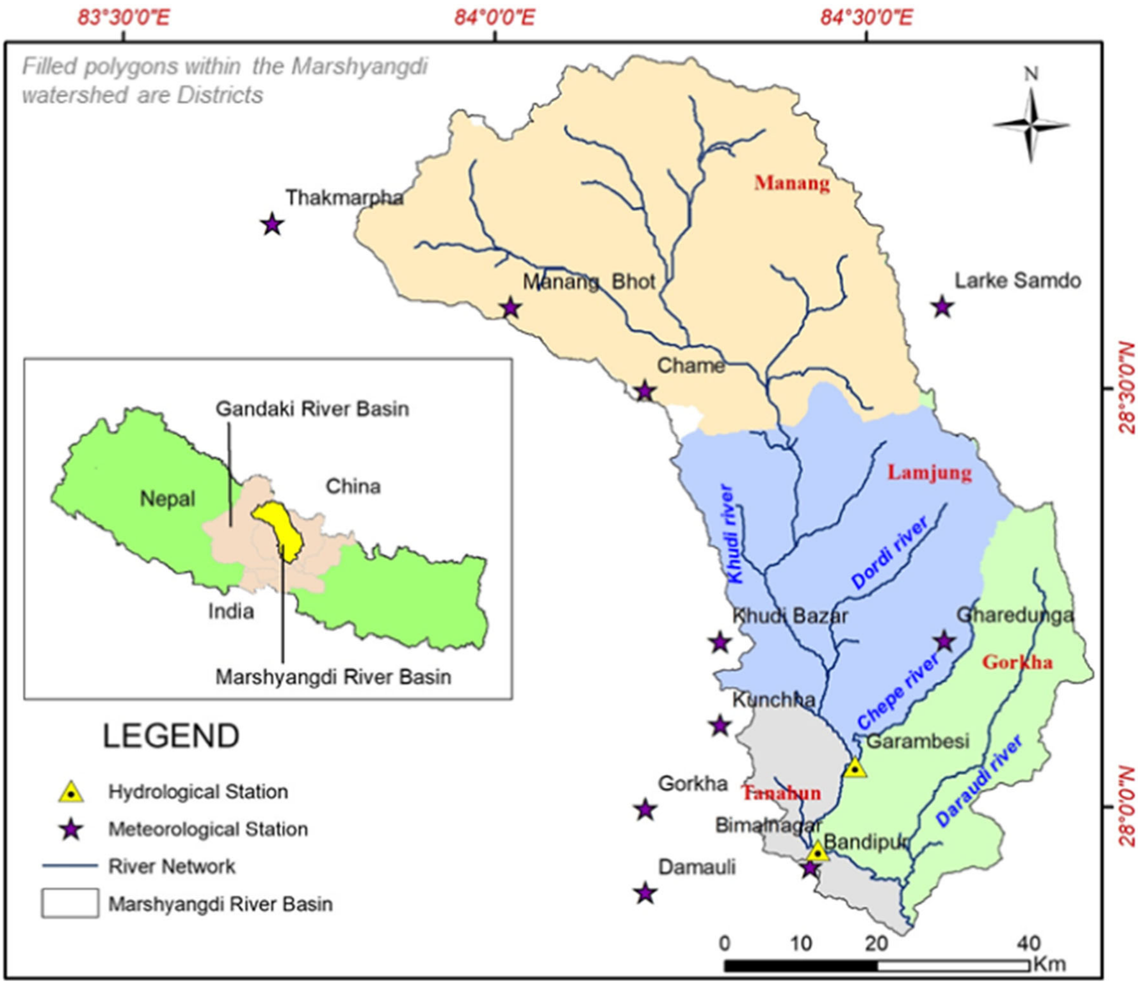

Fig. 1 Location and topographical details of the Marshyangdi watershed in Nepal

more than 10 days were considered month with missing data and coded accordingly while preparing data for RClimDex. We defined outliers in daily maximum and minimum temperatures as the values beyond the range of three standard deviations (SD) of the mean (i.e., mean ± 3*SD)) (Zhang and Yang 2004; Vincent et al. 2005). Similarly, 25 and 0 °C were defined as upper and lower thresholds of daily maximum temperature and 25 mm as the threshold of daily precipitation. A set of indices used in this analysis are based on the 27 indices related to daily

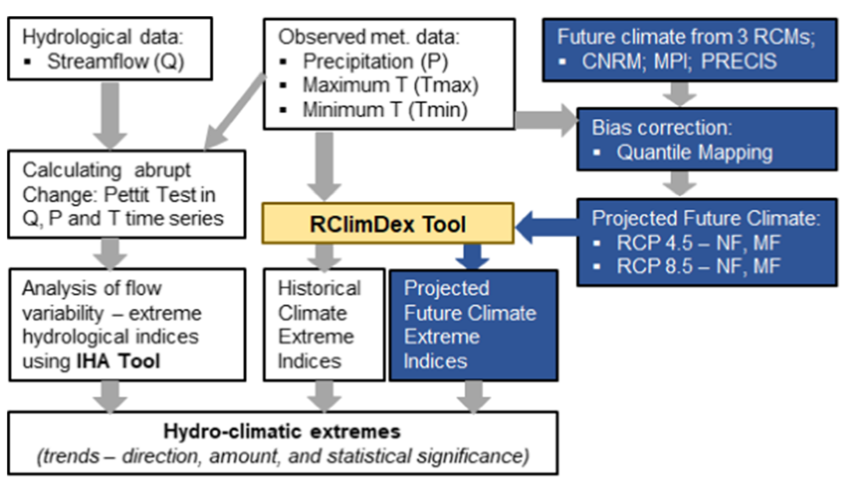

Fig. 2 Methodological framework. RCP, representative concentration pathways; RCMs, regional climate models; NF, near future; MF, mid-future; T, temperature; IHA, indicators of hydrological alteration; Met, meteorological

temperature and precipitation developed by an Expert Team on Climate Change Detection and Indices (ETCCDI) (WMO 2009). RClimDex (1.0) was used to calculate trends in the climatic indices on an annual basis at various stations using daily precipitation and temperature data of varying length, as presented in Appendix Table 7. Out of 27 extreme indices, 23 indices (13 related to temperature;10 related to precipitation) selected for analyzing climatic extremes in this study are presented in Table 1. The trends in terms of magnitude, direction, and statistical significance were estimated using the methods described by Zhang and Yang (2004).

2.3 Future climate extremes analysis

Future climate projection is based on outputs of the Coupled Model Inter-comparison Project-Phase 5 (CMIP5), a collaborative climate-modelling process coordinated by the World Climate Research Programme (WCRP) using different climate forcing's. Future climate projection was carried out at four meteorological stations, namely, *Thakmarpha (index:604)*, *Khudi Bazzar (index:802)*, *Gorkha (index:809)*, and *Chame (index:816)* as these stations have long-term time series of both temperature and precipitation data. Missing values in the daily time series were filled with long-term average daily values for all the variables. For example, value for day 1 (i.e., 1 January) was calculated as an average of 31 values of 1st January (i.e., from 1983 to 2013) and that for day 365 (i.e., 31 December) was calculated as an average of 31 values of 31st December (i.e., from 1983 to 2013). Then three different Regional Climate Models (RCMs), namely, ACCESS-1, CNRM-CM5, and MPI-ESM-LR of 0.5 × 0.5° horizontal resolution were downscaled from the South Asia CORDEX data portal (http://cccr.tropmet.res.in/home/index.jsp) and then divided into two periods namely, near-future (2014–2033) and mid-future (2034–2053) to project future scenarios. Considering the focus of this study on river health in connection to water infrastructure development, this study considered future period up to the mid-century only. These RCMs were selected based on literature review (Appendix Table 6). Generally, RCM outputs are only available for RCP4.5 and RCP8.5 and occasionally for RCP2.6. Hence, in this study, RCP4.5 is selected as a medium-stabilizing scenario, stabilization without overshoot pathway leading to 4.5 W/m^2 (~ 650 ppm CO_2) at stabilization after 2100 and RCP8.5 as a very high emission scenario, which refers to rising

Table 1 Definitions of extreme climatic indices used in this study (source: Zhang and Yang 2004)

S. No.	ID	Indicator name	Definitions	Unit
1	SU25	Summer days	Annual count when TX (daily maximum) > 25 °C	Days
2	TR20	Tropical nights	Annual count when TN (daily minimum) > 20 °C	Days
3	TXx	Max Tmax	Monthly maximum value of daily maximum temp	°C
4	TNx	Max Tmin	Monthly maximum value of daily minimum temp	°C
5	TXn	Min Tmax	Monthly minimum value of daily maximum temp	°C
6	TNn	Min Tmin	Monthly minimum value of daily minimum temp	°C
7	TN10p	Cool nights	Percentage of days when TN < 10th percentile days	Days
8	TX10p	Cool days	Percentage of days when TX < 10th percentile	Days
9	TN90p	Warm nights	Percentage of days when TN > 90th percentile	Days
10	TX90p	Warm days	Percentage of days when TX > 90th percentile	Days
11	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days
12	CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN > 90th percentile	Days
13	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
14	RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
15	RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
16	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days in the year	mm/day
17	R10	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm	Days
18	R20	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm	Days
19	CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
20	CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	Days
21	R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
22	R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
23	PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)	mm

radiative forcing pathways leading to 8.5 W/m^2 (~ 1370 ppm CO_2) by 2100. In order to remove the systematic bias in the downscaled data, quantile mapping bias correction technique was applied to all the raw daily temperature and precipitation time series prior to the calculation of the extreme climatic indices by using RClimDex as mentioned in Sect. 2.2. Future climatic extreme indices were analyzed based on ensemble time series data.

2.4 Hydrological extreme analysis

IHA as described in Mathews and Ritcher (2007) were used for evaluating hydrological extremes in the Marshyangdi watershed. IHA uses a nonparametric range of variability approach (RVA) (Richter et al. 1997) to characterize alterations in inter- and intra-annual variation in river flow. RVA is based upon comprehensive statistical characterization of the temporal variability in hydrologic regime quantifying the degree of alteration of 33 ecologically relevant hydrological parameters (Appendix Table 10) that describe crucial relationships between flow and ecological functions.

RVA analysis places the category boundaries of 17 percentiles from the median yielding an automatic delineation of three categories of equal size, as follows: the lowest category contains all values less than or equal to the 33rd percentile (low alteration); the middle category contains all values falling in the range of the 34th to 67th percentiles (moderate alteration); and the highest category contains all values greater than the 67th percentile (high alteration) (Richter et al. 1998). A positive hydrological alteration value means that the frequency of values in the category has increased from the pre- to the post-impact period (with a maximum value of infinity), while a negative value means that the frequency of values has decreased (with a minimum value of − 1). Each IHA is calculated in terms of median value, deviation degree, and degree of hydrological alteration (Appendix 1) between two periods to assess impacts of intervention on alterations. The pre- and post-impact periods were determined as per Pettitt's (1979) test on the annual average data to identify any abrupt change points in the streamflow time series in the Marshyangdi watershed.

2.5 Identification of change point

The approach after Pettitt 1979) was applied to detect a single abrupt change point in climatic as well as hydrological data (Pohlert 2018) to provide input in the IHA tool. The Pettit's test is a nonparametric test, which is useful for evaluating the occurrence of abrupt changes in climatic records (Sneyers 1990; Tarhule and Wool 1998; Smadi and Zghoul 2006; Gao et al. 2011). It tests the H0: The variables follow one or more distributions that have the same location parameter (no change), against the alternative: a change point exists. The Pettitt's test is one of the most commonly used tests for change point detection because of its sensitivity to breaks in the middle of any time series (Wijngarrd et al. 2003). This test is based on the Mann-Whitney two-sample test (rank-based test) and allows the detection of a single shift at an unknown point in time because of the lack of distributional assumptions (Javari 2016).

3 Results and discussion

3.1 Historical trends in climatic extremes

3.1.1 Temperature-based indices

Decadal trends of the 13 temperature-based extreme climatic indices at four meteorological stations are shown in Table 2. Statistically significant trend values at 5% ($p < 0.05$) level of significance are marked with an asterisk in Table 2. The results clearly indicate varying amount, direction, and significance (statistically) of the trends across the stations. Furthermore, such variations are clearly visible also among the indices under the same group (i.e., fixed-threshold index, absolute extreme index, percentile-based index, and duration-based index).

Among the threshold-based indices, "ice days (ID)" index does not have any trend (trend = 0) at three stations and insignificant negative trend at one station, i.e., at Chame (index:816); therefore, it was discarded for further analysis. However, "summer days (SU25)" index has shown significant positive trends at Khudi (index:802) and Gorkha (index:809) stations, insignificant positive trend at Thakmarpha (index:604), and insignificant negative trend at Chame (index:816) (Table 2). Among the absolute extreme indices, for example, "tropical nights (TR20)" index has significant positive trend at Gorkha (index:809) stations and insignificant positive trend at Khudi (index:802) whereas no trends were observed (trend = 0) at the other two stations. Similarly, index TXn has positive trends across all the stations with varying amount and level of significance and other three indices (TNx, TNn, TXx) have mixed trends in terms of magnitude, direction, and level of significance (Table 2). In case of three percentile-based indices, number of warm days (TX90p) has positive trends at all the stations, number of cool nights (TN10p) has positive trend only at two stations, while the number of warm nights (TN90p) has positive trend at only one station Khudi (index:802) and number of cool days (TX10p) has no positive trends (i.e., significant negative trends) at all the stations (Table 2). It again reflects heterogeneity in percentile-based climate extreme indices derived from temperature time series. Finally, among the duration-based indices, DTR has statistically significant positive trends at three stations, WSDI also has positive trends at those three stations but are statistically insignificant, and CSDI has

Table 2 Historical decadal trends in the climate extreme indices in the Marshyangdi watershed

Temperature-based extreme indices

Station Index	Station Name	Fixed Threshold Indices	Absolute Extreme Indices					Percentile based Indices				Duration-based Indices		
		SU 25	TR20	TXx	TNx	TXn	TNn	TN90p	TN10p	TX90p	TX10p	WSDI	CSDI	DTR
604	Thakmarpha	0.02	0.00	0.00	-0.01	***0.08***	-0.02	-0.14	0.20	***0.50***	***-0.38***	0.30	0.15	***0.09***
816	Chame	-0.03	0.00	-0.07	***-0.42***	***0.71***	***0.12***	***-0.48***	***0.57***	0.42	***-0.94***	0.75	***0.80***	***0.30***
802	Khudi	***0.24***	1.13	0.01	0.09	0.06	0.09	0.15	***-0.87***	***0.38***	***-0.26***	0.17	-2.40	-0.02
809	Gorkha	***1.81***	***1.33***	***0.10***	***0.04***	***0.09***	-0.01							***0.07***

Precipitation-based extreme indices

Station Index	Station Name	Fixed Threshold Indices		Absolute Extreme Indices			Percentile-based Indices		Duration-based Indices		
		R10	R20	RX1day	RX5day	PRCPTOT	R95p	R99p	CDD	CWD	SDII
604	Thakmarpha	-0.02	0.03	0.67	0.82	0.51	1.00	-0.07	1.14	-0.05	0.02
802	Khudi	-0.26	-0.11	***-2.47***	***-3.78***	-18.71	-15.55	-7.18	0.95	-0.32	-0.11
806	Larke Samdo	-1.32	-0.49	-0.04	-1.67	***-21.58***	***-8.06***	-3.32	-1.87	0.18	-0.17
807	Kunchha	0.04	0.06	0.32	1.44	1.42	3.35	-0.31	1.00	-0.04	0.17
808	Bandipur	-0.52	-0.33	-0.07	-0.46	***-15.83***	-1.25	-0.76	0.73	0.08	-0.09
809	Gorkha	-0.24	-0.14	-0.23	0.30	-5.36	2.65	0.01	0.40	-0.08	-0.01
816	Chame	0.76	-0.26	-0.72	0.80	-0.20	-9.33	-4.20	2.45	0.91	0.08
817	Damauli	0.04	0.00	-0.59	-0.08	-1.60	-2.73	-2.03	0.33	-0.10	0.07
820	Manang Bhot	-0.37	-0.11	-0.56	-1.67	***-8.38***	***-3.18***	-0.60	0.57	-0.04	-0.01
823	Gharedunga	0.31	0.28	0.73	0.7	10.07	10.13	2.76	0.59	-0.30	0.27

*Statistically significant indices

positive trends only at two stations (Table 2). Such rising trends in the warm temperature indices and decreasing trends in the cool temperature indices are reported in other recent studies as well (e.g., Karki et al. 2020; Poudel et al. 2020).

Though the temperature extreme indices have certain magnitude of trends over the years, the actual index value varies from year to year as indicated in Appendix Fig. 14 for TX90p as an example. For the period of 1984–2013, TX90p at Khudi Bazzar (index:802) station has an average value of 9.3 °C, trend of + 0.36°C/year, and the index value varies from 0.81 to 25.8 °C. This indicates the significance of understanding these variabilities in addition to average annual value and long-term trend while applying the results for informed decision-making.

3.1.2 Precipitation-based indices

Trends in 10 precipitation-based climate extreme indices are shown in Table 2. They are also grouped under the following four categories, namely, fixed threshold indies (2), absolute extreme indices (3), percentile-based indices (2), and duration-based indices (3). Trends in the indices are evaluated at 5% level of significance (i.e., $p < 0.05$) at 10 stations distributed across the Marshyangdi watershed. Precipitation-based indices also show variation in trend amounts, directions, and statistical significance across the 10 stations with no distinct spatial trends.

Both the indices under threshold-based category, namely, R10 (number of heavy precipitation days) and R20 (number of very heavy precipitation days), show insignificant decreasing trends at six out of 10 stations. Both indices, in most of the cases, show the same direction and significance in the trends, though the magnitude of trends are different (Table 2). Similar results are reported in other studies as well (e.g., Lamichhane et al. 2020). Among the duration-based indices, "consecutive dry days (CDD)" shows insignificant positive trends at seven out of 10 stations whereas at two stations *Kunchha (index: 807)* and Chame (index: 816), trends are significantly positive. "Simple daily intensity index (SDII)" show insignificant positive trends at five out of 10 stations, and "consecutive wet days (CWD)" show insignificant positive trends only at three out of 10 stations (Table 2). All the trends in remaining stations are negative but statistically insignificant. In case of three absolute extreme indices, RX1day and PRCPTOT have negative indices with varying magnitude at seven out of 10 stations. Some of those indices are also statistically significant, for example, PRCPTOT at three stations (i.e., *Larke Samdo*, *Bandipur*, and *Manang Bhot*) and RX1day at Khudi (Table 2). The RX5day index on the other hand has negative trends only at five out of 10 stations, with only one of them (i.e., Khudi) being statistically significant. There magnitude of indices varies widely across the stations for all three indices. Finally, for two percentile-based indices (i.e., R95p and R99p), R99p trends are negative (*insignificant*) at all eight stations and that of R95p are negative, two of them being statistically significant, at five out of 10 stations (Table 2).

The increasing trend of CDD index is also observed over the southern and northern slopes of Central Himalayas and across the Narayani river basin (Sigdel and Ma 2016; Lamichhane et al. 2020). Similarly, Karki et al. (2017) observed the similar trend of CDD across the country warning that such increase in the dry period can impact negatively in agricultural activities and hydropower generation, thus affecting economic aspects of the livelihood. Increasing trends in the climatic indices have also been reported at many stations of the Koshi basin of Nepal (Shrestha et al. 2017). Such climatic extremes may have implications in public health as well as it may cause respiratory-related health problems in Nepal (Karki et al.2017).

Like temperature-based extremes, precipitation-based extreme indices also have inter-annual variability as shown in Appendix Fig. 14 for Rx5day as an example. For the period of 1984–2013, Rx5day at Khudi Bazzar station (*index: 802*) has an average value of 299.6 mm, trend of − 3.78 mm/year, and the index value varies from 244 to 414 mm with a coefficient of variation of 43.6 mm. Understanding such variabilities are helpful to use the results cautiously.

3.2 Projected future trends in climatic extremes

Projected future trends in climatic extremes are based on an ensemble of three RCMs (CNRM, ACCESS, and MPI) under RCP4.5 and RCP8.5 scenarios for both NF and MF periods and presented in Table 3 (please refer to Appendix Table 6 for the detailed characteristics of the RCMs). The RCM outputs were bias corrected for the historical period (1983–2013) and projected for the future periods. The performance of the RCM outputs for the historical periods was of acceptable quality after bias corrections.

3.2.1 Projected climatic extreme trends in the Marshyangdi watershed

Temperature-based indices Across the stations, the trends in extreme climatic indices were evaluated for an ensemble time series generated based on the three RCMS (i.e., CNRM, ACCESS, and MPI). Result shows a gradual increase in the extreme temperature indices at some stations from baseline to MF, while some indices are observed to be decreasing gradually at all the stations and some indices shows mixed trends (Table 3). For example, summer days (SU25) index shows a gradual increase (*insignificant*) at the Chame (index: 816) station from baseline (− 0.03 days/year) to MF (0.11 days/year) under RCP4.5 and RCP8.5 scenarios, but it does not show any trend during NF under RCP8.5. Similarly, TXx at Chame shows increasing (*insignificant*) trend from baseline (− 0.07 °C/year) to NF and MF for both RCPs with a similar trend of 0.05 °C/year, but during MF under RCP4.5 shows a slight decreasing trend of 0.03 °C/year. TNx shows no change from baseline (− 0.01 °C/year) to NF under RCP4.5; however, it increases (*significant*) to NF and MF for both RCP4.5 and RCP8.5 with a trend amount of 0.07 °C/year at Thakmarpha (index:604). TNx at Chame (index:816) shows increasing (significant) trend from baseline (− 0.42 °C/year) to MF (0.09 °C/year) under RCP4.5 and RCP8.5; however, the trend was insignificant during NF under both RCPs.

At the Khudi Bazzar (index:802) station, TXn shows gradual increasing (*insignificant*) trend from baseline (0.06 °C/year) to increasing (significant) trend in MF under RCP4.5 and RCP8.5 (0.11 °C/year). However, some percentile-based extreme temperature indices show an increasing trend at more than one stations for the future scenarios. For example, TN90p increases from baseline at stations Thakmarpha (insignificant), Khudi (*insignificant*), as well as Chame (significant) (0.1 days/year, 0.15 days/year, − 0.48 days/year) to MF with significant trends at the three stations for both RCPs (0.56 days/year, 0.61 days/year, 0.62 days/year). At the Gorkha (index:809) station, though it does not show any change in trend in the baseline, it increases significantly from 0.2 days/year in NF4.5 to 0.5 days/year from NF to MF under both RCPs except during MF under RCP8.5 where it decreases slightly to 0.07 days/year. Other climatic extremes like "Warm Spell Duration Indicator (WSDI)"shows increasing (insignificant) trend from baseline (0.17 days/year) to MF under both RCP scenarios (0.52 days/year) at the Khudi bazzar station, but the trend is significant in NF for both RCPs (Table 3).

Precipitation-based indices Precipitation-based climate extreme indices do not show gradual increasing trend at any stations from baseline to future periods (NF and MF) under both RCP scenarios (4.5 and 8.5) (Table 3). For example, Rx1day at the Khudi Bazzar (index:802) is projected to increase (insignificant) from baseline (− 2.47 mm/year) to NF and MF (0.1 mm/days) under both RCPs, but the magnitude of trend value was less in comparison with NF for both RCPs. Index like "simple daily intensity index (SDII)" and number of very heavy precipitation days (R20) do not show any gradual increases from baseline to MF under both RCPs (mixed trend) at all the stations (Table 3). Similarly, annual total wet-day precipitation (PRCPTOT) at the Chame station shows increasing (insignificant) trend from baseline (− 0.20 mm/year) to MF (3.18 mm/year) under both RCPs whereas during NF under RCP8.5, it shows negative (insignificant) trend (− 1.81 mm/year).

Some extreme precipitation indices show increasing trend only from baseline to NF and then decreases during MF. For example, RX5day increases (insignificant) from baseline (0.82 mm/year) to NF (1.38 mm/year) and then decreases (insignificant) during MF under RCP4.5 (− 1.22 mm/year) and RCP8.5 (− 0.27 mm/year) at the Thakmarpha (index:604) station

Table 3 Projected trends in future climatic extreme indices based on an ensemble of three RCM outputs

S. No.	Baseline					Near future, RCP4.5				Mid-future, RCP4.5				Near future, RCP8.5				Mid-future, RCP8.5			
	Indices	604	816	802	809	604	816	802	809	604	816	802	809	604	816	802	809	604	816	802	809
1	SU25	0.02	− 0.03	1.09*	1.81*	0.00	0.01	0.85*	0.71*	− 0.03	0.06	0.39	0.17	0.00	0.00	0.51*	0.43	0.01	0.11	0.40	0.12*
2	Id0	0.00	− 0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	TR20	0.00	0.00	1.13*	1.33*	0.00	0.00	1.07*	0.66*	0.00	0.00	1.07*	1.84*	0.00	0.00	0.73	0.37	0.00	0.00	1.13*	0.00
4	Fd0	0.31	0.41	− 0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	GSL	1.36*	1.99	− 0.01	0.03	0.50	0.53	0.00	0.00	− 0.16	− 0.14	0.00	0.00	− 0.11	0.28	0.00	0.43	− 0.01	0.06	0.00	0.00
6	TXx	0.00	− 0.07	0.01	0.10*	0.02	0.05	0.06*	− 0.04	− 0.02	0.03	0.03	− 0.08*	0.04*	0.05	0.03	0.00	− 0.02	0.05	0.03	0.05
7	TXn	0.08	0.71*	0.06	0.09*	0.14*	0.07	0.11	0.08	0.05	− 0.02	0.11*	− 0.02	0.11	0.02	0.02	0.37	0.07	0.06	0.11*	− 0.02
8	TNx	− 0.01	− 0.42*	0.09	0.04*	− 0.01	0.02	0.00	0.01	0.06*	0.08*	0.08*	0.05*	0.04*	0.06	0.06*	0.00	0.07*	0.09*	0.08*	0.08*
9	TNn	− 0.02	0.12*	0.09	− 0.01	0.00	0.00	0.09*	0.07	0.00	0.00	0.02	0.08*	0.00	0.00	0.08	0.00	0.00	0.00	0.02	0.00
10	TX10p	− 0.38*	− 0.95*	− 0.26*		− 0.48*	− 0.23*	− 0.38*	− 0.36*	− 0.24	− 0.23*	− 0.45*	− 0.38*	− 0.63*	− 0.43*	− 0.46*	− 0.01*	− 0.41*	− 0.46*	− 0.44*	− 0.21*
11	TX90p	0.50	0.42	0.38*		0.44*	0.34*	0.34*	0.23*	0.16	0.13	0.47*	0.24	0.41*	0.26*	0.28*	0.04*	0.34*	0.45*	0.47*	0.25
12	TN10p	0.20	0.57*	− 0.87*		− 0.23*	− 0.26*	− 0.47*	− 0.32*	− 0.33*	− 0.33*	− 0.55	− 0.63*	− 0.43*	− 0.38*	− 0.45*	0.03*	− 0.51*	− 0.49*	− 0.54*	− 0.33*
13	TN90p	− 0.14	− 0.48*	0.15		0.28*	0.21*	0.27*	0.24*	0.49*	0.50*	0.62*	0.63*	0.31*	0.25*	0.30*	0.07*	0.56*	0.62*	0.61*	0.50*
14	WSDI	0.30	0.75	0.17		0.58	0.68	0.52*	− 0.01	0.39	0.11	0.52	0.13	0.57	0.37	0.44*	− 0.35	− 0.01	0.13	0.52	0.28
15	CSDI	0.15	0.80*	− 2.40		− 0.14	− 0.09*	− 0.74*	− 0.18*	− 0.17	− 0.25	− 0.85	− 0.13	− 0.22*	− 0.23*	− 0.19	0.30	− 0.49	− 0.26	− 0.69	− 0.25
16	DTR	0.09*	0.30*	− 0.02	0.07*	0.04*	0.01	0.00	0.01	− 0.01	− 0.03*	− 0.01	− 0.03*	0.03*	0.02	0.00	− 0.36	− 0.01	− 0.02	− 0.01	− 0.02
17	Rx1day	0.67	− 0.72	− 2.47*	− 0.23	0.87	0.88	0.54	− 0.23	− 1.12	− 0.17	0.10	− 0.99	− 0.58	− 0.14	0.31	0.25	− 0.14	− 0.46	0.10	− 0.17
18	Rx5day	0.82	0.80	− 3.78*	0.30	1.38	2.44*	− 0.58	− 1.60	− 1.12	− 0.14	− 0.13	− 0.20	− 0.80	0.18	0.24	0.43	− 0.27	− 0.13	− 0.13	− 0.14
19	SDII	0.02	0.08	− 0.11	− 0.01	0.04	0.01	− 0.04	− 0.05	− 0.03*	0.00	0.06	0.03	0.00	0.01	0.04	− 0.34	− 0.01	0.02	0.06	0.00
20	R10mm	− 0.02	0.76	− 0.26	− 0.24	0.29*	0.04	0.18	− 0.48*	− 0.20*	− 0.11	0.55	0.47	0.10	0.03	− 0.09	0.00*	− 0.15	0.31	0.56	− 0.11
21	R20mm	0.03	− 0.26	− 0.11	− 0.14	0.07	0.14	− 0.24	− 0.07	− 0.04	− 0.04	0.25	0.10	− 0.08	− 0.07	0.11	1.00	− 0.07	0.08	0.24	− 0.04
22	R25mm	0.03	− 0.18	− 0.07	− 0.12	0.09*	0.16	− 0.36	− 0.01	− 0.05	− 0.09	0.35	− 0.04	− 0.04	0.04	0.29	1.77	− 0.06	0.04	0.34	− 0.09
23	CDD	1.14*	2.45*	0.95	0.40	0.28	0.23	− 0.08	0.26	0.29	− 0.25	0.94*	0.66	0.94*	0.45	0.37	0.07	0.31	0.24	0.94*	− 0.25
24	CWD	− 0.05	0.91	− 0.32	− 0.08	− 0.09	0.29	− 0.03	0.23	0.07	− 0.22	− 0.32	0.03	0.10	− 0.27	− 1.35	0.57	− 0.02	− 0.30	− 0.32	− 0.22
25	R95p	1.00	− 9.33	− 15.55	2.65	5.83*	7.12	− 3.29	− 3.92	− 4.44*	− 0.43	7.22	0.54	0.16	− 1.65	9.53	0.00	− 3.45	1.99	7.64	− 0.43
26	R99p	− 0.07	− 4.20	− 7.18	0.01	3.01	5.48	5.48	− 4.02	− 2.47	− 0.88	3.59	− 0.99	− 1.50	− 1.52	− 3.81	0.09	− 1.90	− 0.55	3.59	− 0.88
27	PRCPTOT	0.51	− 0.20	− 18.71	− 5.36	5.42	3.54	− 6.46	− 9.57	− 2.34	0.89	14.67	7.17	− 0.99	− 1.81	3.30	0.48	− 1.71	3.18	14.77	0.89

*Significant at 95% confidence interval

Table 4 Projected changes in future climatic extreme indices (based on ensemble time series) for RCP8.5 scenarios across four stations in the Marshyangdi watershed

Indices	Thakmarpha (index:604)			Chame (index:816)			Khudi (index:802)			Gorkha (index:809)		
	Hist	Change (%)		Hist	Change (%)		Hist	Change (%)		Hist.	Change (%)	
		NF	MF		NF	MF		NF	MF		NF	MF
SU25	0.9	− 100.0	− 61.7	0.7	− 85.4	360.4	255.7	1.8	4.6	227.7	4.2	− 99.7
TX10p	9.8	− 29.9	− 30.7	7.7	− 9.6	− 12.7	10.4	− 34.5	− 35.0			
TXx	25.2	− 5.7	− 3.2	24.1	− 0.6	4.4	34.9	− 1.8	0.1	5.5	− 4.5	− 28.2
TNx	15.4	− 49.5	5.2	12.4	16.8	28.3	24.0	0.7	7.3	24.2	− 1.3	− 36.7
TXn	3.1	150.1	211.7	6.3	11.3	33.3	14.6	22.2	27.3	13.7	17.7	− 43.6
TN10p	8.9	− 39.7	− 35.9	7.3	− 29.1	− 22.7	10.7	− 36.9	− 35.9			
TX90p	9.2	− 25.5	− 25.4	7.3	− 8.2	− 5.7	9.7	− 30.8	− 29.1			
TN90p	9.6	− 29.4	− 30.6	7.3	− 9.5	− 7.6	9.7	− 30.5	− 30.9			
CSDI	3.2	− 70.2	9.6	6.7	− 84.3	− 66.3	15.2	− 88.5	− 72.3			
WSDI	70.5	50.6	52.0	8.2	− 51.6	− 52.2	4.7	− 19.9	− 23.1			
CDD	5.7	− 43.0	− 45.2	65.3	− 60.5	− 59.6	58.5	− 56.5	− 52.4	63.4	− 54.7	− 47.4
CWD	384.1	87.5	61.0	22.9	39.1	36.9	31.8	189.9	171.7	11.9	154.8	165.3
PRCPTOT	28.2	15.4	10.7	1101.4	5.7	4.4	3359.4	7.4	7.6	1735.1	2.7	− 30.8
R99p	35.7	58.6	33.6	93.2	− 2.1	4.1	155.1	18.6	20.0	129.4	− 17.4	− 25.1
RX1day	57.1	− 1.8	− 10.7	41.4	21.9	22.4	128.9	− 31.4	− 27.8	101.6	− 38.3	− 49.1
RX5day	2.6	− 38.5	− 16.3	105.1	− 13.1	− 10.6	294.1	− 16.8	− 14.0	195.6	− 27.3	− 52.2
R20	9.7	− 31.2	− 46.5	9.5	− 34.4	− 40.2	61.4	9.0	11.7	28.9	− 21.7	− 77.8
R10	9.7	− 37.3	− 32.7	42.0	− 39.3	− 39.6	90.8	30.1	27.7	53.3	22.4	− 49.3
SDII	3.7	− 30.5	− 31.7	9.9	− 38.7	− 38.6	22.6	− 25.5	− 25.7	16.2	− 38.0	− 61.9

Notes: Historical (Hist.) values are the actual values with units as indicated in Table 2; change (%) are the change in future w.r.t. baseline

NF, near future; *MF*, mid-future

(Table 3). Similarly, the number of heavy precipitation days (R10) at the same station shows an increasing (insignificant) trend from baseline (− 0.20 mm/year) to a significant increasing trend in NF (0.29 mm/year) for RCP4.5, but it decreases (insignificant) in MF (− 0.15 mm/year) under RCP8.5.

Furthermore, some stations show decreasing trends in extreme precipitation indices from baseline to NF and then to MF under both RCP scenarios. For example, consecutive dry days (CDD) as well as CWD decrease (insignificant) at the Chame station from baseline (2.45 days/year, 0.91 days/year) to NF and MF (0.24 days/year, − 0.30 days/year) under RCP4.5 and RCP8.5. Simple daily intensity index (SDII) also shows decreasing trend from the baseline (0.08 days/year) to MF (0.02 days/year), but it does not show any trend during MF under RCP4.5.

3.2.2 Projected changes in future climatic extreme indices w.r.t. baseline

Projected changes in temperature-based extremes Changes in the model-based extreme climatic indices at the four meteorological stations Thakmarpha (index:604), Khudi (index:802), Gorkha (index:809), and Chame (index:816) of the Marshyangdi basin for NF (2014–2033) and MF (2034–2053) against the historical period (1983–2013) for RCP4.5 and RCP8.5 scenarios are shown in Appendix Table 8 and Table 4, respectively. Temperature-based extreme indices for both scenarios are projected to increase more in MF compared with NF, with higher magnitude of changes being projected in RCP8.5 than in RCP4.5. For example, TNx increases at all the stations gradually from NF to MF but at the Chame station, its magnitude was the highest at NF (15.9%) as well as at MF (23.6%) for RCP4.5. In contrast, TXx decreases at all the stations except during MF at the Chame and Khudi, respectively.

Likewise, for RCP4.5 (Appendix Table 8), summer days (SU25) gradually increases at two stations only, Khudi and Gorkha. In case of RCP8.5 (Table 4), it increases for both NF and MF at Khudi, only during NF at Gorkha and only during MF at Chame, with the highest average values (360.4%). Furthermore, index TXx at Chame is the highest for RCP4.5 (1.9%) and RCP8.5 (4.4%) in MF but decreases at the rest of the three stations for both RCPs except at Khudi.

In overall, trends in hot nights (TN90p, *significant*), warm days (TX90p; *insignificant at 1 station*), Max Tmin (TNx, *significant*), hot days (TXx; *insignificant*), and WSDI are projected to increase from baseline to future under both RCP scenarios at all the stations. On the contrary, cool nights

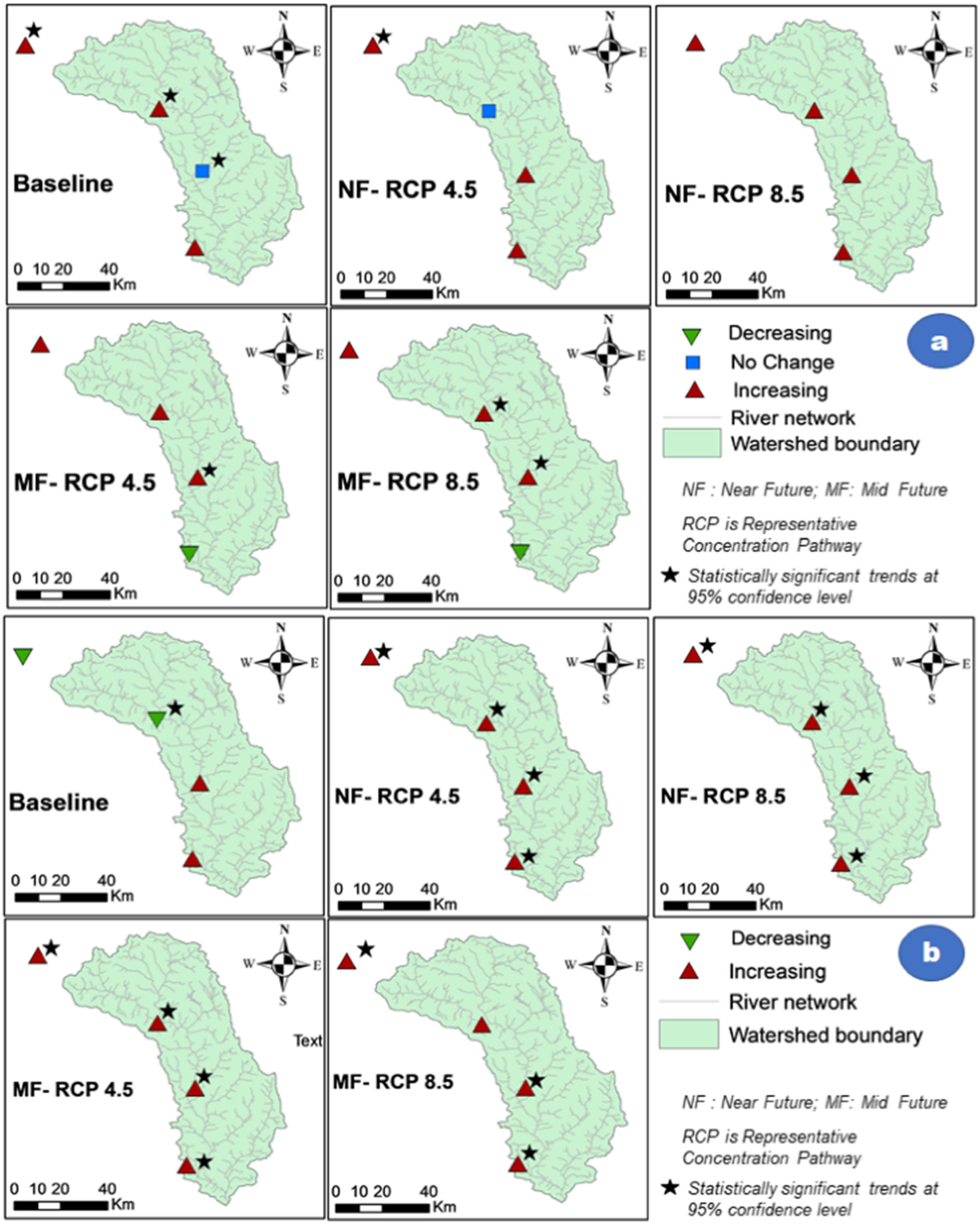

Fig. 3 Spatial distribution in trends across the stations **a** TXn and **b** TN90p

(TN10p; *significant*), cool days (TX10p; *significant*), and CSDI (*insignificant*) are projected to decrease from baseline to future under both RCP scenarios. The diurnal temperature range (DTR) is also projected to decrease (*insignificant*) in future periods for both RCP scenarios.

Projected changes in precipitation-based extremes Precipitation-based extreme indices are projected to decrease in the future at most of the stations for both RCPs, but with varying magnitudes (Appendix Table 8; Table 4). For example, SDII is projected to decrease at all the stations for both the RCPs. Also, CDD are projected to decrease at all the stations for future scenarios for both RCPs and CWD is projected to increase. PRCPTOT is projected to increase gradually at most of the stations from NF to MF for RCP4.5 with the highest percentage increase during MF (16%) at Thakmarpha. However, for RCP8.5, PRCPTOT increases only during NF at the three stations (except *Gorkha during MF*) with the highest percentage increase during NF at Thakmarpha (15.4%). Importantly, R99p at two stations Thakmarpha and Khudi is projected to increase from NF to MF for both the RCP scenarios whereas at Chame only for MF. Likewise, RX1day is projected to increase widely (from − 1.8 to 8.4%) at Thakmarpha but decrease from 27.4% in NF to 24.8% in MF at Chame. Other intense precipitation indices like RX5day are projected to decrease at all the stations (except in NF at Thakmarpha) for both the RCP scenarios. The R10, on the other hand, is projected to increase with higher percentages in NF in comparison with MF at Khudi and Gorkha stations and decrease at other two stations with varying percentages. Furthermore, R20 for RCP4.5and RCP8.5 is projected to increase only at the Khudi station albeit with different magnitudes.

The changes in the annual occurrence of summer days (SU), annual occurrence of tropical nights (TR), number of heavy precipitation days (R10), and number of very heavy precipitation days (R20) can have profound impacts on various sectors including ecosystems, as elaborated in literatures such as Alexander et al. (2006). And increase in projected warm temperature indices (warm days and nights (WSDI)) and the corresponding decreases in cool temperature indices (cool days, cool nights (CSDI)) have been observed all over Nepal under both RCP scenarios (4.5, 8.5) for the future (MoFE 2019).

3.2.3 Spatial distribution of climatic extremes

The spatial distribution in projected changes of the extreme climatic indices for RCP4.5 and RCP8.5 from the baseline and future periods (i.e., NF and MF) at four meteorological stations are discussed hereunder. As expected, different indices show varying degree of variation across the stations in terms of magnitude and direction of trends. Some indices may have some distinct trends from upstream to downstream while some may not. This section discusses spatial variation in selected set of indices.

Trends in monthly minimum of daily maximum temperature (TXn) are increasing significantly at all the stations in baseline (expect no significant trend at a station located in the middle of the watershed) and MF (both the scenarios), increasing insignificant trends in MF under both RCP scenarios (significant at middle of the watershed), and decreasing trends when towards north under both RCPs and scenarios (Fig. 3a). The rate of increase is higher from south towards north in the watershed.

Consecutive dry days (CDD) show distinct increasing trends from baseline to near and mid-future (significant trends towards north for baseline and NF4.5). However, the Gorkha station does not show any trends during baseline and NF8.5 while at some stations, insignificant decreasing trends are depicted (Appendix Fig. 6). In case of CWD, the trends for baseline as well as all future periods and scenarios are also increasing insignificantly at all the stations, except the case for MF under RCP4.5 (mixed trends) and insignificantly decreasing trends at all the stations in MF8.5 scenarios as well as at Thakmarpha and Khudi for NF both scenarios (Appendix Fig. 7).

Trends in warm days (TX90p) are increasing insignificantly at three stations (except Khudi located in the southern part of the watershed) during the baseline. However, it shows significant increasing trends at all the stations in NF for both RCPs except at Khudi where the trend was significantly decreasing and at Gorkha showing no distinct trend. Similar increasing trends were also observed across all the stations for mid-future for both RCP scenarios (significant at MF8.5; Appendix Fig. 8). Similar historical (or baseline) trends were also observed by other studies in different parts of Nepal (e.g., Baidya et al. 2008; Shrestha et al. 2016a; Rajbhandari et al. 2017).

Trends in warm nights (TN90p) are significantly increasing in northern mountainous part of the watershed from the baseline to NF and MF under both scenarios. However, it shows significant decreasing trends in baseline at the Chame station while insignificant decreasing trend at Thakmarpha (Fig. 3b). Trends in cold nights (TN10p) are decreasing at all the stations for all future periods and scenarios; however, mixed for baseline, with increasing trends at the stations located in the northern mountainous part of the watershed (Appendix Fig. 9). These results are consistent with the result of Panday et al. (2015) and Rajbhandari et al. (2017) for the Eastern Himalaya.

Trends in extreme wet days (R99p) show insignificant mixed trends for baseline and NF under RCP4.5 scenarios while it shows insignificant decreasing trends at most of the stations for NF8.5 (except Gorkha) and MF in both scenarios (expect at Khudi) (Appendix Fig. 10). In case of very wet days (R95p), the trends are also increasing insignificantly at all the stations for future except at that at baseline, it shows mixed trends (Appendix Fig. 11).

3.3 Trends in hydrological extremes

3.3.1 Change point analysis

Change point analysis (CPA), a powerful statistical technique to determine abrupt changes in a time series (Chang and Byun 2012), was used to identify pre- and post-impact periods for assessing hydrological extremes. In this study, the change points were identified for annual maximum (Tmax), minimum (Tmin), and average (Tav) temperatures at four stations;

Table 5 Degree of hydrological alterations of IHA parameters at *Bimalnagar* hydrological station in *Marshyangdi* watershed

Parameters	Pre-impact	CD	Post-impact	CD	P (%)	HA (%)
Group 1 (Magnitude of monthly water conditions (m^3/s)) parameters						24.4.0 (L)
January	50.2	0.09	50.02	0.10	− 0.4	59.4 (M)
February	43.3	0.16	44.10	0.14	1.8	28.9 (L)
March	43.3	0.20	42.90	0.16	− 0.9	28.9 (L)
April	50.15	0.26	54.53	0.30	8.7	21.9 (L)
May	71.4	0.58	82.95	0.42	16.2	28.9 (L)
June	197.5	0.38	210.00	0.75	6.3	21.9 (L)
July	414	0.70	573.00	0.15	38.4	7.1 (L)
August	648	0.25	659.50	0.18	1.8	21.9 (L)
September	390	0.24	444.80	0.43	14.1	7.1 (L)
October	167	0.26	195.40	0.28	17.0	28.9 (L)
November	93.7	0.21	95.60	0.25	2.0	28.9 (L)
December	63	0.08	65.45	0.12	3.9	8.6 (L)
Group 2 (Magnitude and duration of annual water extreme conditions (m^3/s)) parameters						16.8 (L)
1-day minimum	39	0.17	37.25	0.12	− 4.5	7.1 (L)
3-day minimum	39.97	0.17	38.50	0.14	− 3.7	7.1 (L)
7-day minimum	40.57	0.17	40.70	0.21	0.3	28.9 (L)
30-day minimum	42.57	0.17	42.63	0.16	0.1	7.1 (L)
90-day minimum	45.7	0.15	45.23	0.14	− 1.0	7.1 (L)
1-day maximum	1090	0.26	1219.00	0.31	11.8	21.9 (L)
3-day maximum	966.3	0.21	1086.00	0.19	12.4	62.5 (H)
7-day maximum	836.9	0.31	930.90	0.24	11.2	7.1 (L)
30-day maximum	674.4	0.28	761.40	0.21	12.9	21.9 (L)
90-day maximum	525	0.27	609.30	0.19	16.1	7.1 (L)
Baseflow index	0.20	0.18	0.17	0.26		7.1 (L)
Group 3 (Timing of annual extreme (days)) parameters						29.3 (L)
Date of minimum (*J*min)	73	0.09	69	0.14	− 5.5	36.8 (M)
Date of maximum (*J*max)	207	0.13	208	0.09	0.5	21.9 (L)
Group 4 (Frequency and duration of high and low pulses (numbers)) parameters						16.0 (L)
Low pulse count	4	1.13	5	2.0	25.0	36.8 (M)
Low pulse duration	5.5	2.64	5	3.2	− 9.1	21.9 (L)
High pulse count	3	1.50	3	0.3	0.0	0.7 (L)
High pulse duration	5	9.25	3.5	10.3	− 30.0	4.5 (L)
Group 5 (frequency and rate of change of water (m^3/s)) parameters						54.4 (M)
Rise rate	8.3	0.56	9.5	0.51	14.5	27.8 (L)
Fall rate	− 3.1	− 0.32	− 4.75	− 1.20	53.2	55.7 (M)
Number of reversals (number)	137	0.22	132.5	0.79	− 3.3	79.7 (H)
Overall degree (OD)						27.9 (L)

CD, coefficient of dispersion; *H*, high; *HA*, hydrological alteration; *L*, low; *M*, moderate; *P*, percentage of deviation

annual precipitation at nine stations; and annual flow time series at one hydrological station in the Marshyangdi watershed. Results are tabulated in Appendix Table 9. The change points for various variables occurred at different years, some with statistical significance and some without. For example, change point for Tmax and Tmin at the Thakmarpha station is identified in 2002 (significant) and 2000 (insignificant). Similarly, at the Khudi station, change points for Tmax, Tmin, and precipitation are detected in 1992 (insignificant), 1986 (significant), and 1990/2004 (insignificant), respectively. In case of river discharge, CP in time series is detected in 1999 (insignificant). The CP at other stations are reported in Appendix Table 9. Following the CP detected in discharge time series as 1999, as well as significant CP for the

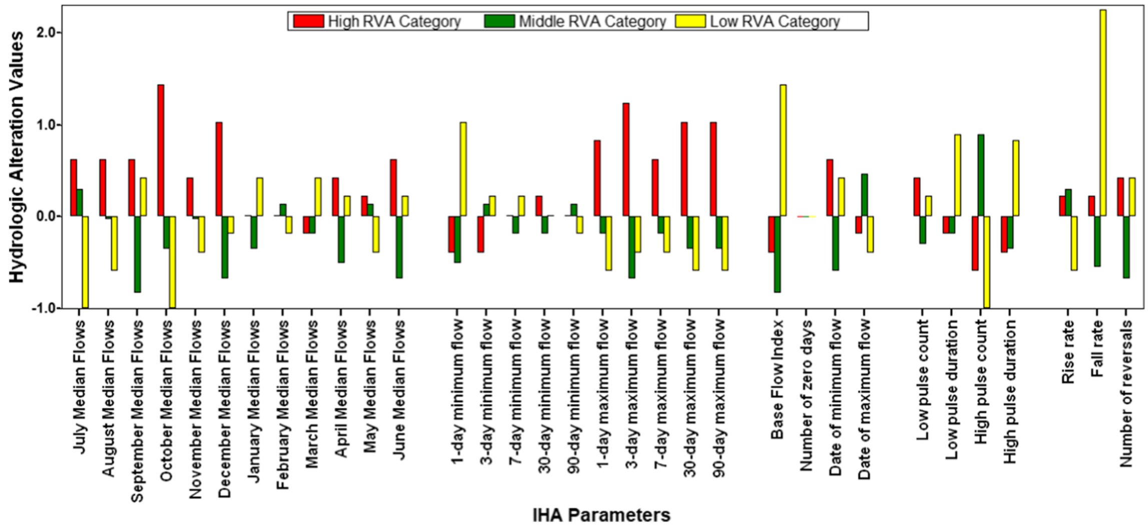

Fig. 4 Hydrological alterations (values shown in bars) for all 33 IHAs

precipitation at Manang Bhot, we have taken this year to separate pre- and post-impact periods in the IHA tool. Literatures (e.g., Khadka and Pathak 2016) also report flood causalities in the Barpak village of Gorkha district, located within the watershed, during the same year the CP was detected. However, no specific mechanism for the CP could be identified.

3.3.2 Changes in flow characteristics after change point

The median value, degree of deviation, and degree of alteration for the IHA parameters characterizing five groups of extreme flow regimes at Bimalnagar hydrological station in the Marshyangdi watershed are listed in Table 5 and elaborated hereunder. Percentage of deviation (P), degree of hydrological alteration (HA), and overall hydrological alteration were calculated using Eqs. (1), (2), and (3) detailed in Appendix 1. Values of hydrological alterations for each indicator are shown in Fig. 4. An overall mean hydrological alteration of all the 32 parameters is estimated as low, with a value of 27.9%, whereas alterations of 32 parameters within five groups vary widely as elaborated in following sub-sections.

Alterations in magnitude of monthly streamflow As depicted from Table 5 and plotted in Appendix Fig. 12, the monthly median parameters increased from pre- to post-impact period, and the increases in monthly median values under high RVA category, except in January and March, have been observed indicating an insignificant increase of the frequency of observed values than the upper RVA limit. The degree of deviation (P) is negative only for the January and March out of 12 months (Table 5), suggesting that streamflow has been increased from pre- to post-impacted period. Calculation of degree of HA for monthly stream flow shows that monthly stream flows fall within the category of low alteration (D < 33%), except in the month of January where the alteration is moderate (33% < D < 67%). In a nutshell, median values among the Group-1 IHAs show low hydrological alteration (24.4%).

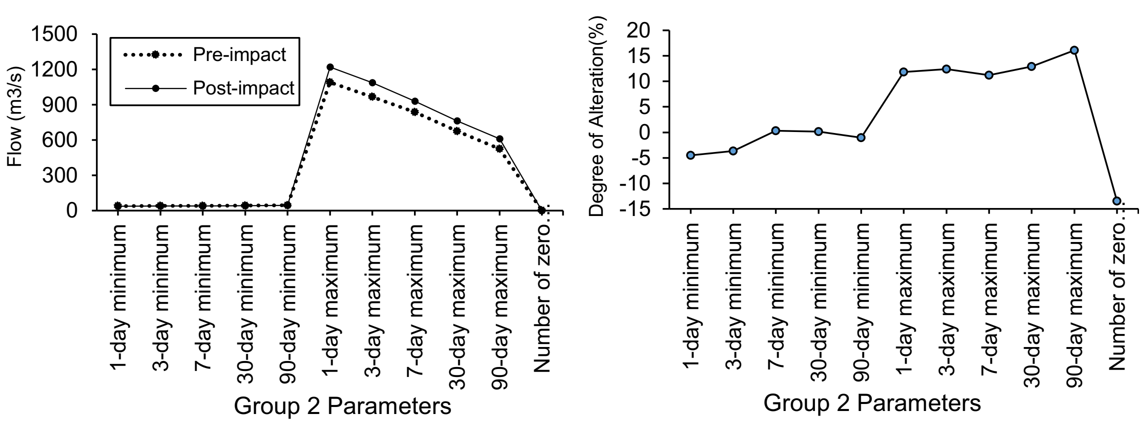

Fig. 5 Annual extreme flows—flow value (left) and degree of deviation (right)

Alterations in annual extreme flow conditions Analysis of median values of degree of deviation and degree of hydrological alteration for the annual extreme flow conditions (11 IHAs under Group-2 and 2 IHAs under Group-3) reveal that degree of deviation is highest (16.1%) for a 90-day maximum, followed by 30-day maximum (12.9%) (Fig. 5) whereas it decreases in 1-day, 3-day, and 90-day minimum extreme flow parameter from pre- to post-impact period. This suggests a possible increase in flood magnitude, which may have been both beneficial as well as harmful effects depending on channel morphology, types of substrate, depth, and other geomorphological characteristics (Stefanidis et al. 2016). Furthermore, increase in 1-day, 3-day, and 7-day maximum flow causes change in the floodplains due to dominant particle size of bed materials inducing ecological implications like low oxygen and prolongation of duration of stressful high temperatures (Graf 2006). HA indicates low degree of alteration (< 33%) among the indices; however, for the 3-day maximum, it shows moderate alteration (Table 5). Overall, the degree of hydrological alteration for Group-2 is 16.8%, indicating the low hydrological alteration (D < 33%).

In case of timing of annual minimum extremes (i.e., indicators under Group-3), the degree of deviations (%) is negative, i.e., timing of 1-day minimum is moving backward from the 69th day to 73rd (delayed by 5 days); however, 1-day maximum is also moving forward from the 207th day to 208th day from pre- to post-impact period. Thus, lagging of Julian date of minimum streamflow indicates that annual minimum values will appear early in the year threating the riverine environment (Xue et al. 2017). The hydrological alterations for timing of 1-day minimum (Jmax) and 1-day maximum (Jul-min) are identified as moderate and low category, respectively (Table 5). The overall degree of hydrological alteration of IHAs under Group-3 is low with a value of 29.3% (33% < D < 67%). Thus, observed shift in occurrence of low flows implies earlier drying up of the downstream channel, which may have adverse consequences on the flood plain habitats, ecology, and navigability of a river (Sharma et al. 2019).

Alterations in frequency and duration of high and low flow pulses Among the Group-4 parameters, the frequency of low (25th percentile) pulse count increases from the pre- to post-impact period; however, the and high (75th percentile) pulse counts does not show any change, while the duration of high and low pulse counts decreases from the pre- to post-impact period (Table 5). The degree of deviation (5, Appendix Fig. 13) for the low pulse counts is 25% which falls under high RVA category (Fig. 4). Degree of hydrological alteration for low pulse count is characterized as "moderate (M)" but for other three parameters under Group-4 are characterized as "low (L)." Thus, four parameters under Group-4, altogether, show low degree of hydrological alteration (16%). The increase in the low pulse counts may cause frequent dry and wet situations, thus, potentially worsening the ecological development of the Marshyangdi river floodplain. However, the low alteration in the high pulse count as well as duration may not favor the riverine ecosystem due to the limited nutrients availability for plants along the riverbank affecting the promotion of river biodiversity (Xue et al. 2017). Thus, low pulse count may induce geomorphic implications like the prolongation of a channel and bank stability, which increased frequency of depositional regimes in the channels. Concomitantly associated ecological implications include stress for plants due to the changes in frequency and magnitude of soil moisture, which causes anaerobic condition and may lack availability of floodplain for aquatic organisms (Graf 2006).

Alterations in rate and frequency of flow conditions The Group-5 parameters, altogether, exhibit moderate hydrological alteration of 54.4%. However, the hydrological alteration varies across the parameters; showing highest alteration in reversals (79.9%) followed by fall rate (55.7%) (Table 5). The increase in rise rate and fall rate in the post-impact period, suggests that the rate of change from high flow to low flow conditions and vice versa would be accelerated. It implies early arrival of peak streamflow in the downstream channel (Sharma et al. 2019), which corresponds well to the results of backward shifting of timing of 1-day maximum as discussed earlier. Number of reversals (number of times that flow switches from one type of period to another) of streamflow conditions which indicate change from rising water condition to falling water condition and vice versa decreases from pre- to post-impact period (Table 5), indicating low intra-annual fluctuations in water conditions of the downstream channel. Higher degree of deviation (53.2%) for the fall rate compared with deviations in number of reversals (−3.3%) indicates high hydrological alteration for the number of reversals and moderate alteration for fall rate, respectively. This increase in rise and fall rate indicates the rise in abruptness in streamflow. The accelerated rise and fall rate, which indicates the rise in abruptness of streamflow, could trap aquatic organisms in floodplains and strand terrestrial organisms on floodplain island The Nature Conservancy (2009). This may affect the stability of plant and animal habitat (Xue et al. 2017). Based on RVA results, most of the parameters in groups 1 and 2 as well as indicators related to low pulse count (group 4) and group 5 parameters increased under high RVA category, which reflects increase in frequency of observed values than the upper RVA limit (Fig. 4).

3.3.3 Trends in extreme hydrological indices

We analyzed trends in 15 hydrological extreme indices and tabulated results (i.e., trends, average value of indices, and inter-annual variability) in Appendix Table 11. Fifteen selected hydrological extreme indices having varying direction and magnitude of trends. Some indices such as 3-, 7-, and 30-day maximum flows show increasing (statistically insignificant) annual trends of + 7.5 m^3/s/year, 4.4 m^3/s/year, and 5.5 m^3/s/year, respectively; whereas 1-day and 90-day maximum flows have increasing (statistically significant) trends of 0.4 m^3/s/year and 4.8 m^3/s/year, respectively. However, 3-, 7-, 30- and 90-day minimum flows have insignificantly decreasing trend (Appendix Table 11).

Like climate extreme indices, hydrological extremes also have inter-annual variability in the index value, as shown in Appendix 2, Table 11 for 1-day maximum flow as an example. The index has an average value of 1287.21 m^3/s with a trend (statistically significant) of + 0.36 m^3/s/year during1987–2015; however, the index value varies from 679 to 2270 m^3/s for the aforementioned period, with a coefficient of variation of 0.30. It is therefore important to note those variabilities too while using the results for informed decision-making on managing hydrological extremes.

4 Conclusions

This study assessed hydro-climatic extremes in the Marshyangdi watershed for historical as well as future periods at four climatic stations and one hydrological station. An ensemble of three regional climate models (RCMs) were used to project future climate and assess projected trends in the climatic extremes under RCP4.5 and RCP8.5 scenarios for two future periods, namely, near future and mid-future. Key conclusions specific to the study of watershed, based on analysis of the results, are listed hereunder. Though it reflects some aspects of the Himalayan watersheds, we need to study more on watersheds to generalize the conclusions for the entire Himalayan region.

- Climatic extremes over the historical period (1983–2013) indicate hotter and drier conditions in the watershed, albeit with varying amount and significance (statistical) across the stations. Temperature-related indices such as WSDI and TX90p have increasing trends whereas TN90p and TX10p have decreasing trends. Heavy precipitation indices such as R10, R20, RX1day, and R99p show increasing trends for almost half of the 10 stations where CDD are increasing at most of the stations.
- Future is projected to be wetter and warmer in the Marshyangdi watershed. Significant increase in trends for maximum temperature-related extremes (e.g., TN90p, TX90p, and TNx) and significant decrease for minimum-temperature-related extremes (e.g., TN10p, TX10p) from baseline to future periods under both the scenarios and future periods are considered. However, precipitation extremes such as R99, RX5day, CWD, and CDD are projected to decrease, with potential implications on water availability and its distribution across seasons.
- Overall hydrological alterations as an indication of hydrological extremes is estimated as low (HA = 27.9%) in the Marshyangdi watershed. Increase in the median flow values especially during the period of March–August and consequent increase in the 30- and 90-day maximum values indicates the possibility of flood in the basin. On the other hand, increase in rise rate and decreases in the fall rate represent abruptness in the streamflow and inter-annual variability. Further, projected increase in climate change along with anthropogenic influences may affect the natural flow regime of the Marshyangdi watershed which may exacerbate in the future and the implications pointed out could have severe ecological consequences with the high degree of hydrological alteration

The watershed spans from the mountains in the north to the plains in the south, and the climatic extremes are analyzed at multiple stations spanning from north to south. The results therefore could be indicative of extremes at particular physiographic regions at other basins in Nepal as well. Like other snow-fed and glacierized catchments, which are highly influenced by climate change and associated melting of snow/glacier (Mingjie et al. 2013), projected increase in average annual precipitation at all the stations and higher increase in temperature in the Marshyangdi watershed and associated melting of snow/glacier may lead to an increase in water availability. As there are many hydropower projects as well as agricultural areas in the watershed, increase in water availability can lead to positive implications, if that could be harnessed properly. However, increase in average annual rainfall is associated with increase in number of heavy and very heavy precipitation days too, which means, available rainfall will be highly skewed over certain periods in a year. If excess precipitations are not stored in watersheds, hydrological extremes may increase in magnitude as well as frequency, which is clearly evident in the analysis of hydrological alteration indicators in this study. The increase in hydrological extremes means potential increase in loss and damage in the watershed. These results imply that investment in various water storage mechanisms, such as soil water storage in watershed, rainwater harvesting at household and community levels, storage in aquifers, and storage in river corridor itself is required to make productive use of excess rainfall and runoff and at the same time reduce potential losses and damages associated with hydrological extremes. Therefore, analyzing historical as well as future climatic extremes together with hydrological extremes are valuable to get a bigger picture for designing interventions for water resources development and management in a holistic way.

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Appendix 1. Formula for calculating hydrological alteration

The percentage of deviation degree of each hydrological alteration of streamflow regime is calculated as (Timpe and Kaplan 2017; Xue et al.2017):

$$P_i\ (\%)\frac{(M\text{post}-M\text{pre})}{M\text{pre}}*100 \quad (1)$$

where M_{post} is the median for the post-impact period and M_{pre} is the median for the pre-impact period. After calculation of percentage of deviation degree, these values were then averaged by parameter groups and across all parameters. A positive P_i value indicates an increased median value in the post-impacted period compared with the pre-impacted period while a negative P_i suggests a decreased median value in the post-impacted period compared with the pre-impacted period.

Degree of hydrological alteration of a flow regime can be further calculated for each indicator according to the following equation (Ritcher et al.1998)

$$D_i = \left|\frac{\text{OF}-\text{EF}}{\text{EF}}\right| \times 100 \quad (2)$$

where OF is the observed number of post-impacted years for which the value of the indicator falls within the RVA target range, from 25th percentile to 75th percentile, as suggested by Richter et al. (1998); EF is the expected number of post-impacted years for which the value of indicator falls within the targeted range and can be estimated by $r \times$ NT (r is percentage of pre-impacted years for which the value of an indicator falls within the RVA target range and NT is total number of post-impacted years). As different hydrological indices may show different variabilities in flow regime, hence, an overall degree (OD) of hydrological alteration of all indices may be computed as:

$$D_i = \sqrt{\frac{\sum_{i=1}^{32} D_i^2}{32}} \quad (3)$$

Appendix 2. Relevant tables referred in the manuscript

Table 6 Climatic models and scenarios used in climate change-related studies in Nepal

S. No.	River basin/ watershed	Climate model(s)	Scenarios	Time period	Focus	References
1	•Bagmati	•HadCM3	•SRES: A2; B2	B: 1970–1999 NF: 2010–2039 MF: 2040–2069 FF: 2070–2099	•Hydrological impact of future climate	Babel et al. (2013)
2	•Bagmati	•HadCM3	•SRES: A2; B2	Future decades: 2020; 2050;2080	•Climate change impact on irrigation water requirement	Shrestha et al. (2013)
3	•Chamelia	•ACCESS_CCAM •CNRM_CCAM •MPI.ESM_CCAM •MPI.E.MPI_REMO •ICHEC_RCA4	•RCP: 4.5; 8.5	B: 1980–2005 NF: 2021–2045 MF: 2046–2070 FF: 2071–2095	•Climate change impact on hydrology	Pandey et al. (2019)
4	•Dudhkoshi	•PRECIS	•SRES: A1B	B: 2000–2010 NF:2040–2050 FF:2086–2096	•Climate change impact on hydrological regime	Nepal (2016)
5	•Hindukush Himalaya	•PRECIS	•SRES: A1B	NF: 2011–2040 MF: 2041–2070 FF: 2071–2098	•Climate change	Kulkarni et al. (2013)
6	•Hindukush Himalaya	•CMIP3 •CMIP5	•SRES: B1, A1B, and A2 for CMIP3 •RCP8.5 for CMIP5	B: 1970-1999 MF: 2020–2049 FF: 2070–2099	•Change and trends of temperature and precipitation indices	Panday et al. (2015)
7	•Indrawati	•ECHAM4/OPYC3 •HadCM3 model	•SRES: A2; B2	B: 1961–1999 Future decades: 2020; 2050; 2080	•Climate change impact on flow regime	Bhatta (2016)
8	•Indrawati	•HadGEM3-RA •MIROC-ESM	•RCP: 4.5; 8.5	B: 1995–2004		Shrestha et al. (2016d)

Table 6 (continued)

S. No.	River basin/ watershed	Climate model(s)	Scenarios	Time period	Focus	References
		•MRI-CGCM3		Future decades: 2020; 2030; 2040; 2050; 2060; 2070; 2080; 2090	•Climate change impact on hydrology and water availability	
9	•Kaligandaki	•GCM •CMCC-CMS	•RCP: 4.5; 8.5	B:1981–2010 F: 2041–2070 FF: 2071–2100	•Climate change impact on hydrological regime and water balance	Bajracharya et al. (2018)
10	•Karnali	•GCM from CanESM2	•RCP: 2.6; 4.5; 8.5	NF: 2011–2040 MF: 2041–2070 FF: 2071–2100	•Climate change	Shrestha et al. (2016b)
11	•Koshi	•CNRM-CM3 •CSIRO-Mk3.0 •ECHam5 MIROC 3.2	•SRES: A2; B1	B: 1971–2000 F: 2016–2045	•Climate change imp act on hydrological regime	Bharati et al. (2012)
12	•Koshi	•GCMs (10)	•SRES: B1; A1B; A2	3 future periods: 2020s; 2055s; 2090s	•Precipitation projection	Agarwal et al. (2014)
13	•Koshi	•CSIRO-Mk3.5 •ECHam5 •MIROC3 •CNRM-CM3	•SRES: A2; B1	B: 971–2000 NF: 2016–2045 FF: 2036–2065	•Climate change impact on water availability	Bharati et al. (2014)
14	•Koshi	•PRECIS-HADCM3Q •PRECIS-ECHAM05	•SRES: A1B	B: 1976–2000 F: 2040–2060	•Climate change •Hydrological regime	Devkota and Gyawali (2015)
15	•Koshi	•CNRM-CM3 •CSIRO-Mk3.5 •ECHam5 MIROC3.2	•SRES: A2; B1	B: 1971–2000 NF: 2030 FF: 2050	•Climate change impact on hydrological regime	Bharati et al. (2016)
16	•Koshi	•GCMS (10)	•SRES: B1; A1B; A2	NF: 2011–2030 MF: 2046–2065 FF: 2080–2099	•Climate projection	Agarwal et al. (2016)
17	•Koshi: Tamor, Arun, Dudhkoshi, Tamakoshi, Sunkoshi	•PRECIS-ECHAM05 •PRECIS-HadCM3	•SRES: A1B	B: 2000–2008 F: 2041–2060	•Climate change •Snowmelt hydrology	Khadka et al. (2016)
18	•Koshi	•CMIP5 GCMs (8)	•RCP: 4.5; 8.5	B: 1961–1990 F: 2021–2050	•Projection of future climate	Rajbhandari et al. (2016)
19	•Koshi	•PRECIS	•SRES: A1B	NF: 2011–2040 MF: 2041–2070 FF: 2071–2098	•Project future extreme climate	Rajbhandari et al. (2017)
20	•Kulekhani	•CCSR/NIE •CGCM3 •CSIROECHM4 •HadCM3	•SRES: A2; B2	B: 2010–2039 NF: 2040–2069 FF: 2070–2099	•Climate change impact on future river discharge	Shrestha et al. (2014)
21	•Marshyangdi	•GCM SDSM (4.2)	•SRES: A1B	Future decades: 2030–2050, 2080	•Future water availability •Change in rainfall pattern	Parajuli et al. (2015)
22	•Marshyangdi	•CanESM2	•RCP: 2.6; 4.5; 8.5	NF: 2011–2040 MF: 2041–2070 FF: 2071–2100	•Climate change projection	Khadka and Pathak (2016)
23	•Narayani	•HadCM3 •PRECIS RCM	•SRES: AIB	B: 1970–2000 F: 2030–2060	•Climate change impact on hydrology •Future flood magnitude	Bhattarai et al. (2018)
24	•Sunkoshi	•PRECIS •ECHAM5 •RegCM4 •ECHAM4	•SRES: A1B; A2	NF: 2041–2050 FF: 2051–2060	•Climate change impact on hydrology	Magar et al. (2016)
25	•Tamakoshi	•HADCM3 •CGCM3	•SRES: A2 and B2; A2 and A1B	B: 2000–2009 F: 2000–2059	•Future change in climate	Khadka et al. (2014)
26	•Tamakoshi	•MIROC-ESM, MRI •CGCM3 •MPI-ESM M	•RCP: 4.5; 8.5	NF: 2015–2039 MF: 2040–2069 FF: 2070–2099	•Climate change impact in hydropower	Shrestha et al. (2016c)
27	•West Seti	•ECHAM5 •HadCM3 in PRECIS •Era40, CCSM •ECHAM5 GFDL •HadCM3 in WRF	•SRES: A1B	B: 1971–2000 F: 2031–2060	•Climate change impact on water balance and crop yields	Gurung et al. (2013)
28	•West Seti	•WRF/GRADS	•RCP: 4.5	B: 1996–2013 F: 2050	•Impact of climate change on water availability and future flow	Maharjan et al. 2016
29	•West Seti	• •MPI-ESM-LR	•RCP: 4.5; 8.5	B: 1976–2005	•Streamflow projection	

Table 6 (continued)

S. No.	River basin/ watershed	Climate model(s)	Scenarios	Time period	Focus	References
		• •PRECIS-1 • •NorESMI1-M • •ICHEC-EC-EAR-TH •CCM4 •CNRM-CM5 •MPI-M-MPI •ESM-LR		F: 2071–2100		Shrestha et al. (2017)

B, baseline; *F*, future; *FF*, far future; *MF*, mid-future; *NF*, near future; *RCP*, representative concentration pathway; *SRES*, special report on emission scenarios

Table 7 Details of the hydro-meteorological stations used in this study

Index	Station	Data	Data length	Latitude (°N)	Longitude (°E)	Altitude (m)	District
604	Thakmarpha	P, T	1983–2013	28.8	83.7	2566	Mustang
802	Khudi Bazar	P, T	1983–2013	28.3	84.4	823	Lamjung
806	Larke Samdo	P	1979–2017	28.7	84.6	3650	Gorkha
807	Kunchha	P	1977–2017	28.1	84.4	855	Lamjung
808	Bandipur	P	1977–2017	27.9	84.4	965	Tanahu
809	Gorkha	P, T	1977–2017	28.0	84.2	1097	Gorkha
816	Chame	P, T	1990–2011	28.6	84.2	2680	Manang
817	Damauli	P	1977–2014	28.0	84.3	334	Tanahu
820	Manang Bhot	P	1981–2012	28.7	84.0	3420	Manang
823	Gharedunga	P	1977–2013	28.2	84.6	1120	Lamjung
439.3	Bimalnagar	Q	1987–2015	27.57	84.25	354	Tanahu

Source: DHM, Nepal

P, precipitation; *T*, temperature; *Q*, discharge

Table 8 Projected changes in future climatic extreme indices (based on ensemble time series) for RCP4.5 scenarios across four stations in the Marshyangdi watershed

Indices	Thakmarpha (index:604)			Chame (index:816)			Khudi (index:802)			Gorkha (index:809)		
	Hist.	Change (%)		Hist.	Change (%)		Hist	Change (%)		Hist	Change (%)	
		NF	MF		NF	MF		NF	MF		NF	MF
SU25	0.9	− 100.0	− 61.7	0.7	− 78.1	− 41.5	255.7	1.6	5.0	227.7	3.5	8.8
TX10p	9.8	− 30.3	− 31.4	7.7	− 11.1	− 11.2	10.4	− 34.2	− 32.8			
TXx	25.2	− 5.5	− 3.4	24.1	− 1.2	1.9	34.9	− 1.3	0.1	34.4	− 4.1	− 3.4
TNx	15.4	− 0.8	2.8	12.4	15.9	23.6	24.0	2.1	7.3	24.2	− 0.9	2.5
TXn	3.1	146.7	178.7	6.3	12.9	21.9	14.6	23.4	27.4	13.7	16.9	25.2
TN10p	8.9	− 42.3	− 38.8	7.3	− 29.4	− 26.4	10.7	− 35.4	− 34.0			
TX90p	9.2	− 26.2	− 24.5	7.3	− 6.7	− 7.0	9.7	− 28.9	− 26.5			
TN90p	9.6	− 30.7	− 30.0	7.3	− 8.8	− 8.0	9.7	− 31.0	− 28.4			
CSDI	3.2	− 29.5	− 49.9	6.7	− 78.3	− 70.1	15.2	− 75.9	− 68.0			
WSDI	3.7	39.6	78.0	8.2	− 41.8	− 59.5	4.7	− 18.8	− 22.0			
CDD	70.5	− 40.4	− 36.6	65.3	− 61.9	− 48.9	58.5	− 56.8	− 52.4	63.4	− 57.8	− 44.5
CWD	5.7	66.3	71.6	22.9	43.2	38.0	31.8	226.0	171.7	11.9	164.0	117.9
PRCPTOT	384.1	8.1	16.0	1101.4	6.6	9.1	3359.4	7.3	7.6	1735.1	− 0.3	2.1
R99p	28.2	50.0	64.8	93.2	4.7	4.0	155.1	16.0	20.0	129.4	− 28.0	− 20.6
RX1day	35.7	− 1.8	8.4	41.4	27.4	24.8	128.9	− 33.5	− 27.8	101.6	− 47.5	− 40.5
RX5day	57.1	2.5	− 2.1	105.1	− 4.6	− 11.1	294.1	− 18.2	− 14.0	195.6	− 34.9	− 26.7
R20	2.6	− 36.9	− 19.7	9.5	− 38.6	− 32.8	61.4	10.7	11.3	28.9	− 25.9	− 17.9
R10	9.7	− 39.9	− 30.1	42.0	− 42.1	− 35.6	90.8	32.4	27.4	53.3	19.5	17.3
SDII	9.7	− 32.5	− 30.0	9.9	− 38.1	− 37.6	22.6	− 26.5	− 25.3	16.2	− 40.5	− 38.4

Notes: Historical (Hist.) values are the actual values with units as indicated in Table 2; change (%) are the change in future w.r.t. baseline

NF, near future; *MF*, mid-future

Table 9 Change-point analysis for hydro-meteorological variables in the Marshyangdi watershed

S. No.	Station name (index)	Variable	Change point (year)	*p* value
1	Thakmarpha (604)	Minimum temperature (Tmin)	2000	0.26
		Maximum temperature (Tmax)	2002	0.01*
		Average temperature (Tav)	2000	0.01
		Precipitation (PPT)	NA	
2	Khudi (802)	Tmin	1986	0.001*
		Tmax	1992	0.01
		Tav	2000	0.01*
		PPT	1990/2004	0.38
3	Gorkha (809)	Tmin	2002	0.03*
		Tmax	1991	1E−04
		Tav	2000	0.01*
		PPT	1986/1996	0.41
4	Chame (816)	Tmin	2002	0.002*
		Tmax	2000	0.001*
		Tav	1997	0.840
		PPT	1998	1.100
5	Larke Samdo (806)	PPT	1998	0.002*
6	Kunchha (807)	PPT	1997	0.910
7	Damauli (817)	PPT	1990	0.120
8	Gharedunga (823)	PPT	1985	0.690
9	Manang Bhot (820)	PPT	1999	0.010*
10	Bimalnagar (439.3)	Q	1999	0.37

*Significant at 95% confidence interval

Table 10 Summary of hydrologic parameters used in the indicators of hydrologic alteration

IHA statistics group (number of parameters)	Regime characteristics	Hydrological characteristics
Group 1: Magnitude of monthly water conditions (12 parameters)	•Magnitude •timing	•Mean or median value for each calendar month
Group 2: Magnitude and duration of annual water extreme conditions (12 parameters)	•Magnitude •Duration	•Annual maxima and minima, 1-day mean •Annual maxima and minima of 3-day mean •Annual maxima and minima of 7-day mean (weekly) •Annual Maxima and minima of 30-day mean(monthly) •Annual maxima and minima of 90-day mean •Number of zero-flow days •Base flow index
Group 3: Timing of annual extreme (2 parameters)	•Timing	•Julian date of each annual 1-day maxima •Julian date of each annual 1-day maxima
Group 4: Frequency and duration of high and low pulses (4 parameters)	•Magnitude •Frequency •Duration	•No of high pulses in each year •No of low pulses in each year •Mean or median duration of high pulses within each year •Mean or median duration of low pulses within each year
Group 5: Rate and frequency of water (3 parameters)	•Frequency •Rate of change	•Rise rates: mean or median of all positive differences between consecutive daily means •Fall rates: mean or median of all negative differences between consecutive daily means •Number of hydrologic reversals

Table 11 Trends in selected hydrologic extreme indices

S. No.	Index name	Index value (mean)	Index value range	CV	Amount of trend
1	1-day min	39.3	30.4–51.7	0.14	− 0.35
2	3-day min	40.1	30.6–51.7	0.13	− 0.21
3	7-day min	41.1	31.2–52.3	0.13	− 0.19
4	30-day min	43.3	34.8–54.6	0.12	− 0.11
5	90-day min	46.7	37.6–60.8	0.12	− 0.09
6	1-day max	1287.2	679–2270	0.30*	+ 0.36*
7	3-day max	1049.3	450–1773	0.25	7.51
8	7-day max	881.1	324.4–1140	0.20	4.43
9	30-day max	701.2	210.9–909.3	0.21	5.51
10	90-day max	558.6	117.1–729.8	0.22	4.77*
11	Low pulse count	6.6	0–19	0.81	0.23*
12	High pulse count	3.6	1–8	0.54	0.00*
13	Rise rate	8.8	0.8–23	0.49	0.01
14	Fall rate	− 4.7	− 10.8 to (− 1.6)	0.57	− 0.12
15	Reversals	139.9	44–224	0.33	2.80*

*Statistically significant trends at 95% confidence level

Appendix 3. Relevant figures referred in the manuscript

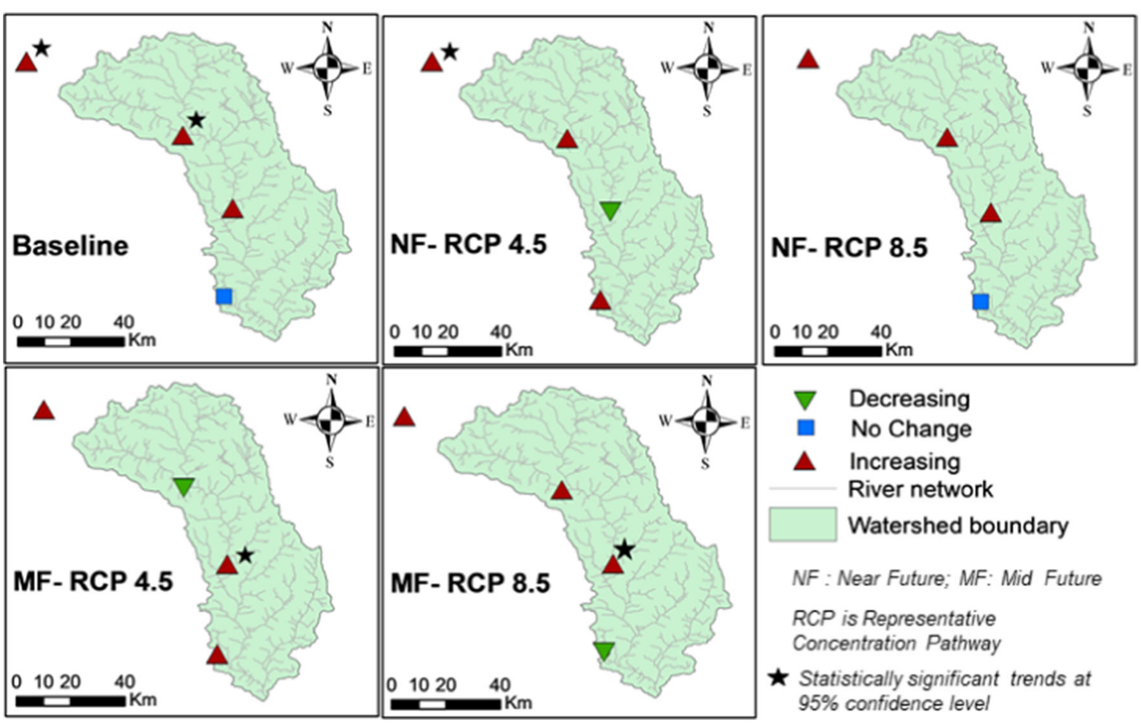

Fig. 6 Trends in consecutive dry days (CDD) across the stations

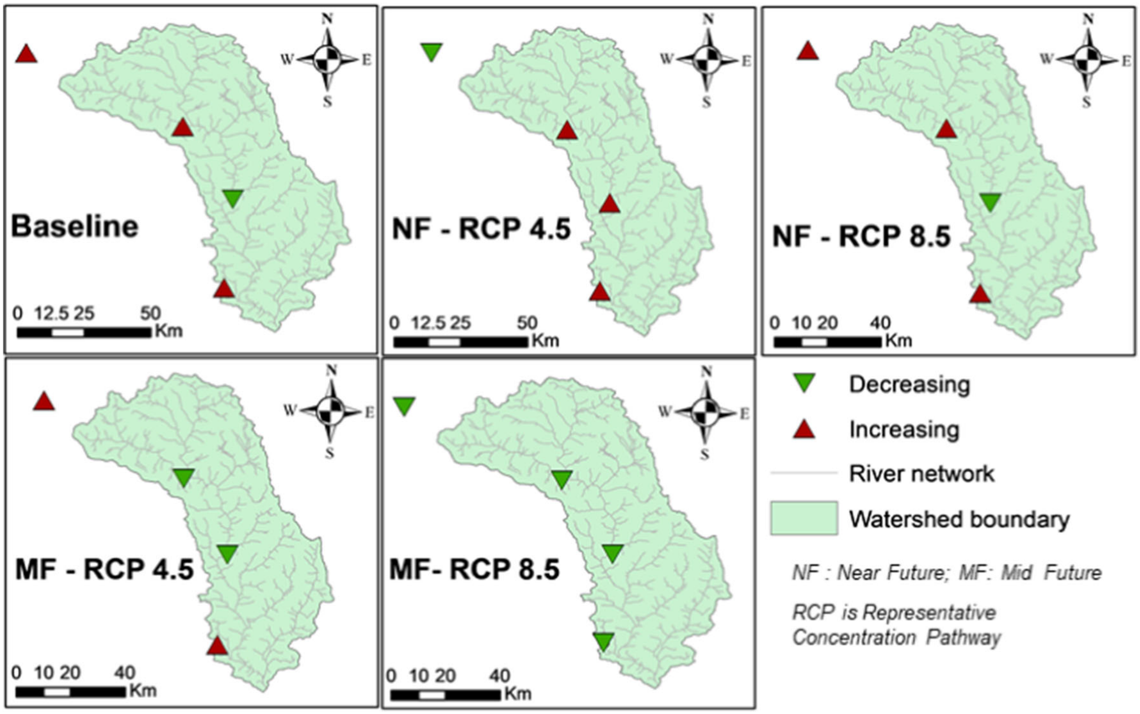

Fig. 7 Trends in consecutive wet days (CWD) across the stations

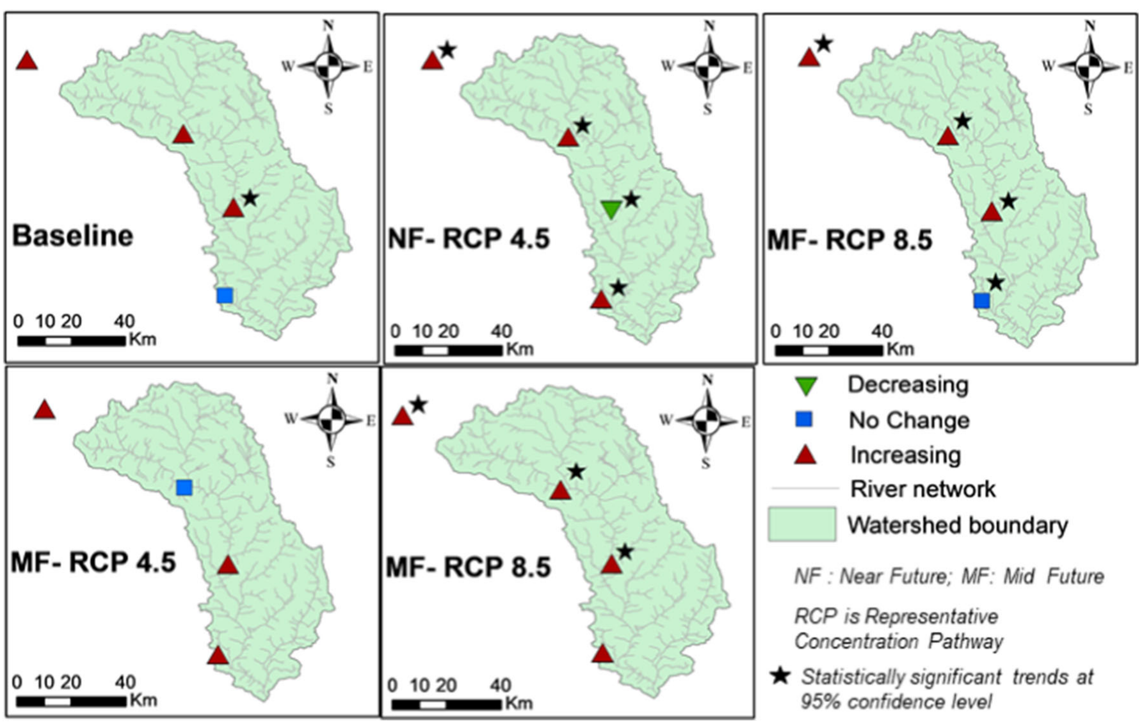

Fig. 8 Spatial distribution in warm days (TX90p) trends

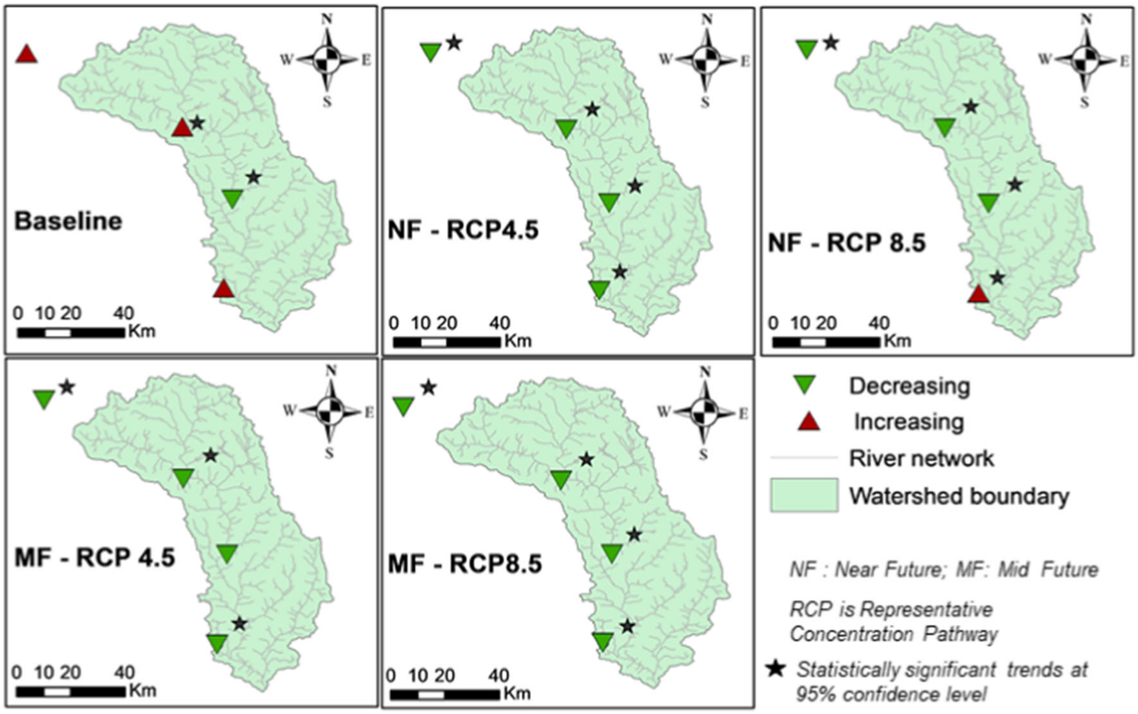

Fig. 9 Spatial distribution in cold nights (TN10p) trends

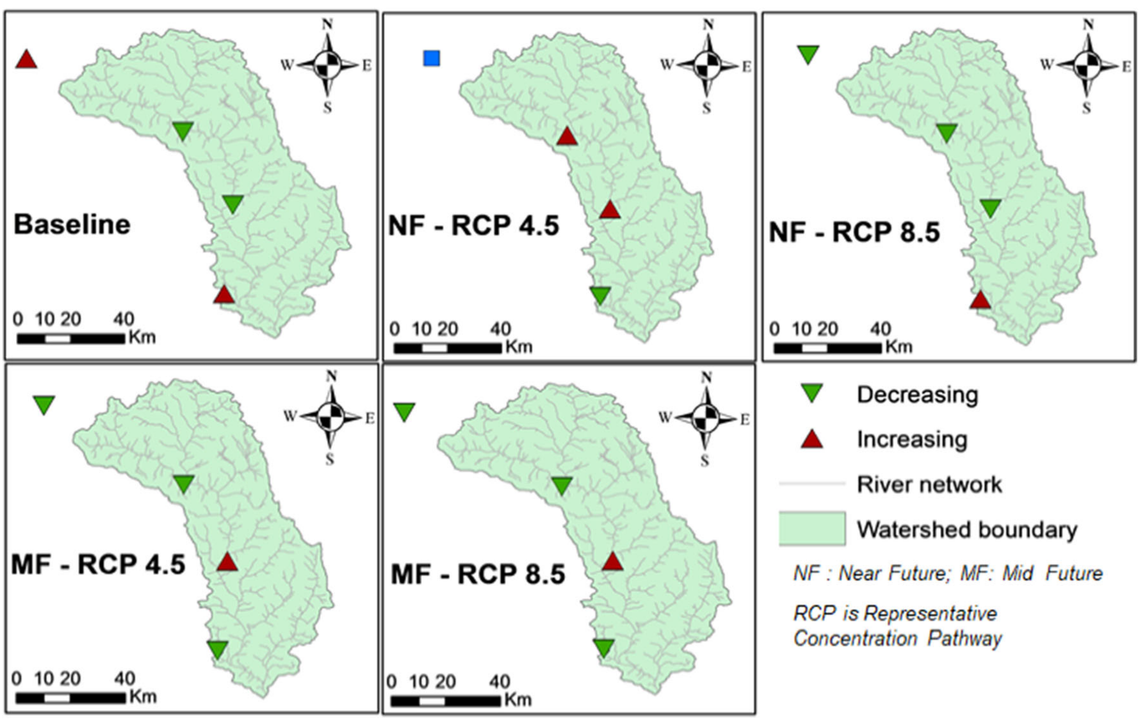

Fig. 10 Extremely wet days (R99p) for different future scenarios

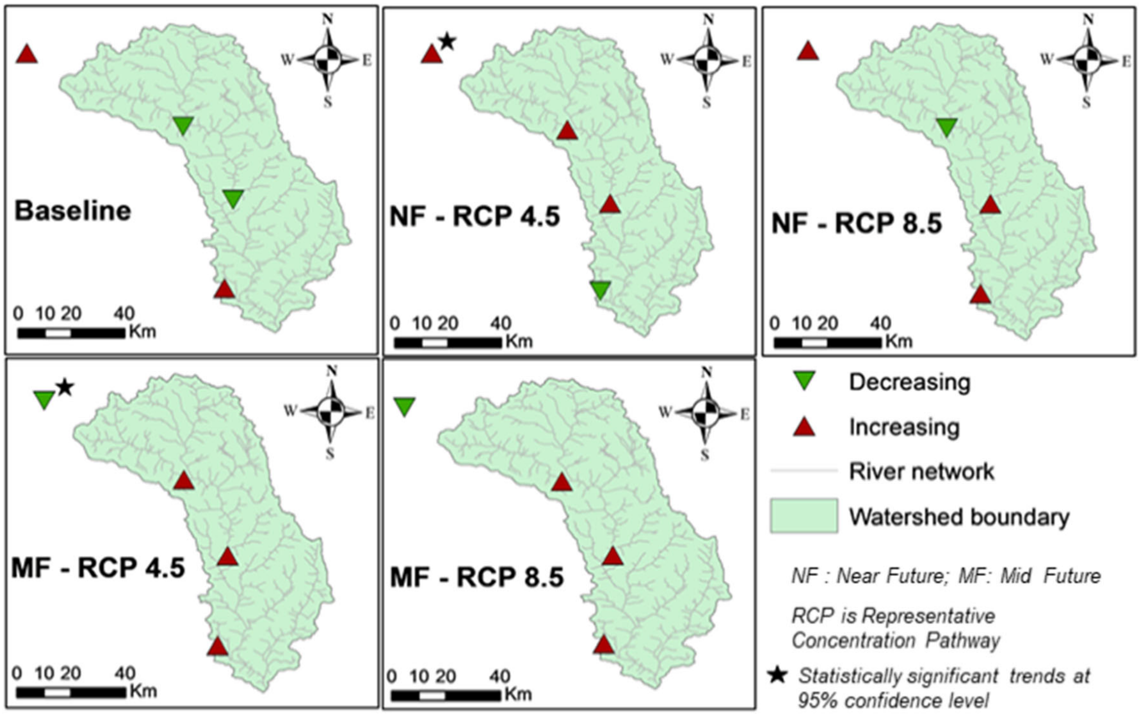

Fig. 11 Very wet days (R95p) for different future scenarios

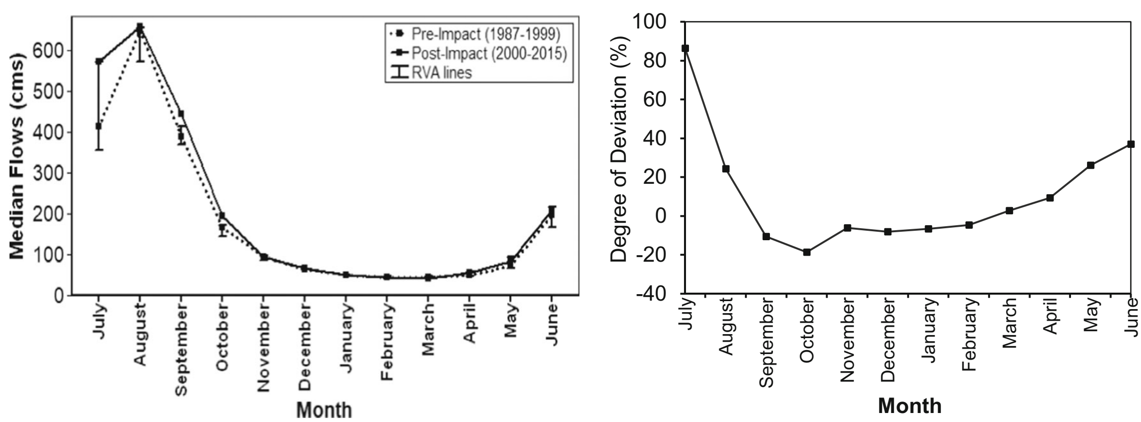

Fig. 12 Monthly median flows (group 1 parameters)—flow value (left) and degree of deviation (right)

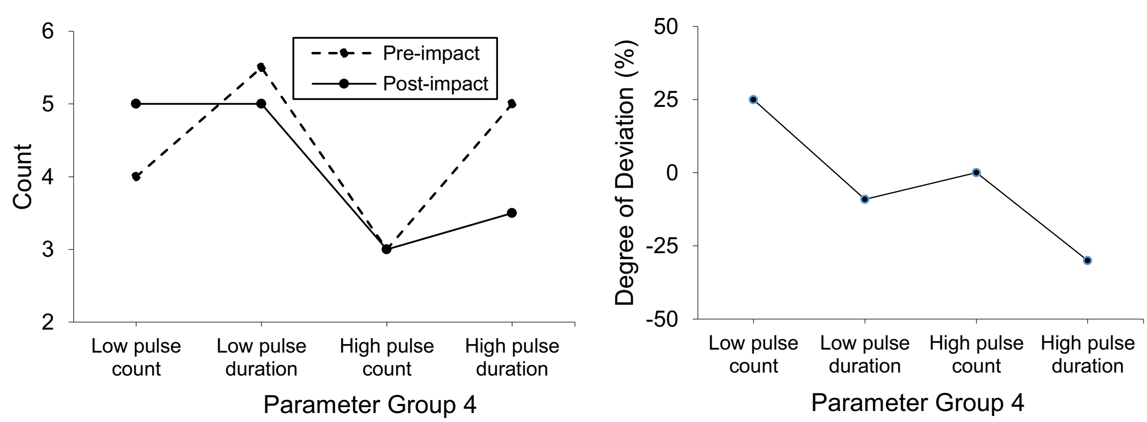

Fig. 13 Pulse count and duration (left and degree of deviation on those values (right))

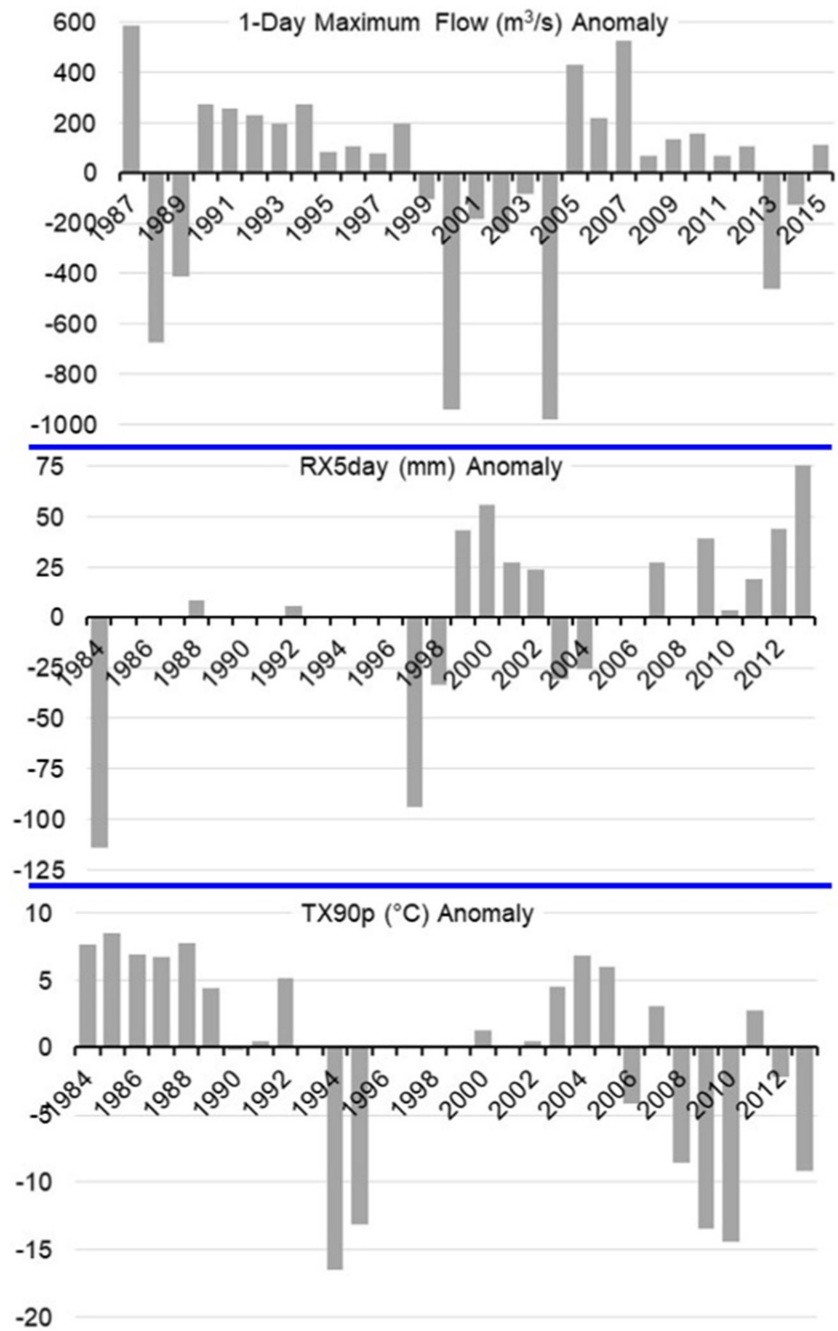

Fig. 14 Anomaly of selected hydro-climatic extreme indices

References

Agarwal A, Babel MS, Maskey S (2014) Analysis of future precipitation in the Koshi River Basin, Nepal. J Hydrol 513:422–434. https://doi.org/10.1016/j.jhydrol.2014.03.04

Agarwal, Babel MS, Maskey S, Shrestha S, Kawasaki A, Tripathi NK (2016) Analysis of temperature projections in the Koshi River Basin, Nepal. Int J Climatol 36L:266–279. https://doi.org/10.1002/joc.4342

Agrawala S, Raksakulthai V, Aalst MV, Larsen P, Smith J, Reynolds J (2003) Environment Directorate, Development Co-operation Directorate, Working Party on Global and Structural Policies, Working Party on Development Co-operation and Environment Development and climate change in Nepal: Focus on water resources and Hydropower,1–64

Alexander V, Zhang X, Peterson TC, Caesar J, Gleason B, Tank AMGK, Vincent L (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:1–22. D05109. https://doi.org/10.1029/2005JD006290

Asadieh, Krakauer NY, Fekete, Balázs M (2016) Historical Trends in Mean and Extreme Runoff and Streamflow Based on Observations and Climate Model. Water 8(5):1–18. https://doi.org/10.3390/w8050189 www.mdpi.com/journal/water

Babel MS, Bhusal SP, Wahid SM, Agarwal A (2013) Climate Change and Water Resources in the Bagmati River Basin, Nepal. Theory Appl Climatol 115:639–654. https://doi.org/10.1007/s00704-013-0910-4

Baidya SK, Shrestha ML, Sheikh MM (2008) Trends in daily climatic extremes of temperature and precipitation in Nepal. J Hydrol Meteorol 5(1):38–51

Bajracharya AR, Bajracharya SR, Shrestha AB, Maharjan B (2018) Climate change impact assessment on the hydrological regime. Sci Total Environ 625:837–848. https://doi.org/10.1016/j.scitotenv.2017.12.332

Bastakoti RC, Bharati L, Bhattarai U, Wahid SM (2016) Agriculture under changing climate conditions and adaptation options in the Koshi Basin. Clim Dev 9(7):634–648. https://doi.org/10.1080/17565529.2016.1223594

Bates B, Kundzewicz Z, Wu S, Palutikof J (2008) Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva 210 pp

Bharati L, Gurung P, Jayakody P (2012) Hydrologic characterization of the Koshi Basin and the impact of climate change. Hydro Nepal J Water Energy Environ 11(1):18–22. https://doi.org/10.3126/hn.v11i1.7198

Bharati L, Gurung P, Jayakody P, Smakhtin V, Bhattarai U (2014) The projected impact of climate change on water availability and development in the Koshi Basin, Nepal. Mt Res Dev 34(2):118–130 https://bioone.org/journals/Mountain-Research-and-Development

Bharati L, Gurung P, Maharjan L, Bhattarai U (2016) Past and future variability in the hydrological regime of the Koshi Basin, Nepal. Hydrol Sci J 61(1):79–93. https://doi.org/10.1080/02626667.2014.95263

Bhatta RP (2016) Climate change impacts and flow regime alternation in Indrawati River affecting the fish diversity. J Environ Sci Comput Sci Eng Technol (Sec A) 5(3):612–639

Bhattarai SN, Zhou Y, Shakya NM, Zhao C (2018) Hydrological modelling and climate change impact assessment using HBV light model: a case study of Narayani River Basin. Nat Environ Pollut Technol Int Q Sci J 17(3):691–702

Bhutiyani MR, Kale VS, Pawar NJ (2007) Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. Clim Chang 85:159–177. https://doi.org/10.1007/s10584-006-9196-1

CBS (2019) Environmental Statistics of Nepal. National Planning Commission, Central Bureau of Statistics (CBS), Government of Nepal. Kathmandu: Nepal

Chang S-W, Byun Y-I (2012) Variability detection by change-point analysis. In: Feigelson E, Babu G (eds) Statistical challenges in modern astronomy V. Lecture notes in statistics, vol 902. Springer, New York

Chaulagain NP (2006) Impacts of climate change on water resources of Nepal. The Physical and Socioeconomic Dimensions. Unpublished M.Sc Thesis

Chen HA, Guo SA, Xu C-Y, Singh VP (2007) Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. J Hydrol 344:171–184. https://doi.org/10.1016/j.jhydrol.06.034

Dery SJ, Stadnyk TA, Macdonald MK, Gauli-sharma B (2016) Recent trends and variability in river discharge across northern Canada. Hydrol Earth Syst Sci 20:4801–4818. https://doi.org/10.5194/hess-20-4801-2016

Devkota RP, Bhattarai U (2015) Assessment of climate change impact on floods from a techno-social perspective. J Flood Risk Manag 8(4):300–307

Devkota LP, Gyawali DR (2015) Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin. J Hydrol Reg Stud 4:502–515

Devkota RP, Maraseni TN (2018) Flood risk management under climate change: a hydro-economic perspective. 18:1832–1840. https://doi.org/10.2166/ws.2018.003

Donat M, Alexander L, Yang H, Durre I, Vose R, Dunn R, Willett K, Aguilar E, Brunet M, Caesar J (2013) Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: the HadEX2 dataset. J Geophys Res Atmos 118:2098–2118. https://doi.org/10.1002/jgrd.50150

Duhan D, Pandey A (2013) Statistical analysis of long term spatial and temporal trends of precipitation during 1901-2002 at Madhya Pradesh, India. Atmos Res 122:136–149. https://doi.org/10.1016/j.atmosres.2012.10.010

Fang GH, Yang J, Chen YN, Zammit C (2015) Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. Hydrol Earth Syst Sci 19:2547–2559

Gao P, Mu XM, Wang F, Li R (2011) Changes in streamflow and sediment discharge in response to human activities in the middle reaches of the Yellow River. Hydrol Earth Syst Sci 15:1–10

Graf WL (2006) Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79:336–360

Gudmundsson L, Bremnes JB, Haugen JE, Engen-Skaugen T (2012) Technical note: downscaling RCM precipitation to the station scale using statistical transformations − a comparison of methods. Hydrol Earth Syst Sci 16(9):3383–3390

Gurung P, Bharati L, Karki S (2013) Application of SWAT model to assess climate change on water balances and crop yields in West Seti River Basin. In: Proceedings of 2013 International SWAT Conference, Toulouse, France

Helsel DR, Hirsch RM (2002) Statistical methods in water resources. Techniques of Water Resources Investigations. Book 4, chapter A3. U.S. Geological Survey, pp 552

IPCC (2013) The physical science basis. In: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Islam Md N (2009) Understanding the rainfall climatology and detection of extreme weather events in the SAARC region: Part II-Utilization of RCM data, SMRC – No. 29. SAARC Meteorological Research Centre (SMRC) E-4/C, Agargaon, Dhaka-1207, Bangladesh

Javari M (2016) Trend and homogeneity analysis of precipitation in Iran. Climate 4(44):1–23. https://doi.org/10.3390/cli4030044

Jha R (2010) Total Run-of-River type Hydropower Potential of Nepal. J Water Energy Environ 7:8–13. https://doi.org/10.3126/hn.v7i0.4226

Karki R, Talchabhadel R, Alto J, Baidya SK (2016) New climatic classification of Nepal. Theory Appl Climatol 125:799–808. https://doi.org/10.1007/s00704-015-1549-0

Karki R, Hasson SU, Schickhoff U, Scholten T, Bohner J (2017) Rising Precipitation Extremes across Nepal. Climate *5*(1):1–25. https://doi.org/10.3390/cli5010004

Karki R, ul Hasson S, Gerlitz L, Talchabhadel R, Schickhoff U, Scholten T, Böhner J (2020) Rising mean and extreme near-surface air temperature across Nepal. Int J Climatol 40(4):2445–2463. https://doi.org/10.1002/joc.6344

Kendall MG (1975) Rank Correlation Methods, 4th edn. Charles Griffin, London

Khadka D, Pathak D (2016) Climate change projection for the Marshyangdi river basin, Nepal using statistical downscaling of GCM and its implications in Geodisasters. GeoenvironDisasters 3:15. https://doi.org/10.1186/s40677-016-0050-0

Khadka D, Babel MS, Shrestha S, Tripathi NK (2014) Climate change impact on glacier and snow melt and runoff in Tamakoshi basin in the Hindu Kush Himalayan (HKH) region. J Hydrol 511:49–60. https://doi.org/10.1016/j.jhydrol.2014.01.005

Khadka A, Devkota L, Kayastha R (2016) Impact of climate change on the snow hydrology of Koshi River Basin. J Hydrol Meteorol 9(1): 28–44. https://doi.org/10.3126/jhm.v9i1.15580

Khatiwada KR, Panthi J, Shrestha ML (2016) Hydro-climatic variability in the Karnali River Basin of Nepal Himalaya. Climate 4(17):1–15. https://doi.org/10.3390/cli4020017

Khon VC, Mokhov II, Roeckner E, Semenov VA (2007) Regional changes of precipitation characteristics in Northern Eurasia from simulations with global climate model. Glob Planet Chang 57:118–123. https://doi.org/10.1016/j.gloplacha

Kiesling R L (2003) Applying indicators of hydrologic alteration to Texas Streams-overview of methods with examples from the Trinity River Basin. Us Geological Survey Fact Sheet

Kiktev D, Sexton DMH, Alexander L, Folland CK (2003) Comparison of modeled and observed trends in indices of daily climate extremes. J Clim 16:3560–3571

Kulkarni A, Patwardhan S, Kumar KK, Ashok K, Krishnan R (2013) Projected climate change in the Hindu Kush Himalayan Region by using the high-resolution regional climate model PRECIS. Mt Res Dev 33(2):142–151. https://doi.org/10.1659/MRD-JOURNAL-D-11-00131.1

Kundzewicz ZW, Merz B, Vorogushyn S, Hartmann H, Duethmann D, Wortmann M, Krysanova V (2015) Analysis of changes in climate and river discharge with focus on seasonal runoff predictability in the Aksu River Basin. Environ Earth Sci 73:501–516. https://doi.org/10.1007/s12665-014-3137-5

Lal PN, Mitchell T, Aldunce P, Auld H, Mechler R, Miyan A, Romano LE, Zakaria S (2012) National systems for managing the risks from climate extremes and disasters. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, pp 339–392

Lamichhane D, Dawadi B, Acharya RH (2020) Observed trends and spatial distribution in daily precipitation indices of extremes over the Narayani River Basin, Central Nepal. 8(April):106–118. https://doi.org/10.12691/aees-8-3-6

Liu L, Xu Z-X, Huang JX (2012) Spatio-temporal variation and abrupt changes for major climate variables in the Taihu Basin, China. Stoch Env Res Risk A 26:777–791. https://doi.org/10.1007/s00477-011-0547

Magar MR, Adhikari TR, Gyawali D (2016) Modeling the impacts of climate change on hydrology of Sunkoshi river basin, Nepal. J Hydrol Meteorol 10(1):80–100

Maharjan B, Adhikari TR, Maharjan LD (2016) Climate change impact on water availability: a case study of West Seti, Gopaghat of Karnali Basin Using SWAT Model. J Hydrol Meteorol 10(1):57–69

Mallakpour I, Villarini G (2016) A simulation study to examine the sensitivity of the Pettitt test to detect abrupt changes in mean. Hydrol Sci J 61(2):245–254. https://doi.org/10.1080/02626667.2015.1008482

Manandhar S, Pandey VP, Kazama F (2012) Hydro-climatic trends and people' s perceptions: case of Kali Gandaki River Basin, Nepal. Clim Res 54(2):167–179. https://doi.org/10.3354/cr01108

Mann HB (1945) Non-parametric tests against trend. Econometrica 13: 245–249

Manton MJ, Della-Marta PM, Haylock MR, Hennessy KJ, Nicholls N, Chambers LE (2001) Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1916– 1998. Int J Climatol 21:269–284. https://doi.org/10.1002/joc.610

Mathews R, Ritcher BD (2007) Application of the indicators of hydrologic alteration software in environmental flow setting. Journal of American Water Resources. Association 43(6):1400–1413. https://doi.org/10.1111/j.1752-1688.2007.00099.x

Mingjie G, Tianding H, Baisheng Y, Keqin J (2013) Characteristics of melt water discharge in the Glacier No. 1 basin, headwater of Urumqi River. J Hydrol 489:180–188

MOFE (2019) Climate change scenarios for Nepal for National Adaptation Plan (NAP). Ministry of Forests and Environment (MOFE). Kathmandu: Nepal

Moraes JM, Pellegrino GQ, Maria V (1998) Trends in hydrological parameters of a Southern Brazilian watershed and its relation to human induced changes. Water Resour Manag 12:295–311

The Nature Conservancy (2009) Indicators of hydrologic alteration version 7.1: user's manual. The Nature Conservancy, Charlottesville, Virginia

Nepal S (2016) Impacts of climate change on the hydrological regime of the Koshi River Basin in the Himalayan Region. J Hydro Environ Research 10:76–89. https://doi.org/10.1016/j.jher.2015.12.001

Panda DK, Kumar A, Ghosh A, Mohanty RK (2013) Streamflow trends in the Mahanadi River basin (India): linkages to tropical climate variability. J Hydrol 495:135–149

Panday PK, Thibeault J, Frey KE (2015) Changing temperature and precipitation extremes in the Hindu Kush-Himalayan region: an analysis of CMIP3 and CMIP5 simulations and projections. Int J Climatol 35:3058–3077. https://doi.org/10.1002/joc.4192

Pandey VP, Dhaubanjar S, Bharati L, Thapa BR (2019) Hydrological response of Chamelia watershed in Mahakali Basin to climate change. Sci Total Environ 650:365–383. https://doi.org/10.1016/j.scitotenv.2018.09.053

Pandey VP, Dhaubanjar S, Bharati L, Thapa BR (2020) Spatio-temporal distribution of water availability in Karnali-Mohana basin, Western Nepal: Climate change impact assessment (Part-B). J Hydrol Reg Stud 29:100690

Parajuli A, Devkota LP, Adhikari TR, Dhakal S (2015) Impact of climate change on River discharge and rainfall pattern: a case study from Marshyangdi River basin, Nepal. J Hydrol Meteorol 9(1):60–73

Pettitt AN (1979) A non-parametric approach to the change-point problem. Appl Stat 28(2):126–135

Pohlert T (2018) Non-Parametric Trend Tests and Change-Point Detection: pp 18

Poudel A, Cuo L, Ding G, Gyawalia AR (2020) Spatio-temporal variability of the annual and monthly extreme temperature indices in Nepal. Int J Climatol, joc.6499. https://doi.org/10.1002/joc.6499

Rajbhandari R, Shrestha AB, Nepal S, Wahid S (2016) Projection of future climate over the Koshi River Basin based on CMIP5 GCMs. Atmos Clim Sci 6:190–204

Rajbhandari R, Shrestha AB, Wahid S, Guo-Yu R (2017) Extreme climate projections over the transboundary Koshi River Basin using a high-resolution regional climate model. Adv Clim Chang Res 8(3): 199–211. https://doi.org/10.1016/j.accre.2017.08.00

Richter BD, Baumgartner JV, Braun DP, Powell J (1996) A method for Assessing Hydrologic Alteration within ecosystem. Conserv Biol 10(4):163–1174

Richter B, Baumgartne J, Wigington R, Braun D (1997) How much water does a river need? Freshwat Biol 37:231–249. https://doi.org/10.1046/j.1365-2427.1997.00153

Richter BD, Baumgartner JV, Braun P, Powell J (1998) A spatial assessment of hydrologic alteration within a river network. Regul Rivers Res Manag 14:329–340

Ruiter A (2012) Delta-change approach for CMIP5 GCMs. Royal Netherlands Meteorological Institute, Internship Report

Sharma S (2017) Climate change impacts on water resources of Marshyangdi river. Unpublished M.Sc Thesis, Central Department of Environmental Science, Tribhuvan University, Nepal

Sharma P, Patel P, Jothiprakash V (2019) Impact assessment of Hathnur reservoir on hydrological regimes of Tapi River, India. ISH J Hydraul Eng:1–14. https://doi.org/10.1080/09715010.2019.1574616

Shrestha N (2017) Projection of future streamflow and their uncertainty over West Rapti Basin, Nepal. Unpublished M.Sc Thesis, Geo-information Science and Earth. https://doi.org/10.13140/RG.2.2.30312.67842

Shrestha RP, Nepal N (2016) An assessment by subsistence farmers of the risks to food security attributable to climate change in Makwanpur, Nepal. Food Security 8(2):415–425. https://doi.org/10.1007/s12571-016-0554-1

Shrestha AB, Wake CP, Mayewski PA, Dibb JE (1999) Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971–94. J Clim 12(9):2775–2786

Shrestha S, Gyawali B, Bhattarai U (2013) Impacts of climate change on irrigation water requirements for rice-wheat cultivation in Bagmati River Basin, Nepal. J Water Clim Chang 8(2):320–335. https://doi.org/10.2166/wcc.2013.050

Shrestha S, Khatiwada M, Babel MS, Parajuli K (2014) Impact of climate change on river flow and hydropower production in Kulekhani hydropower project of Nepal. Environ Process 1:231–250. https://doi.org/10.1007/s40710-014-0020-z

Shrestha AB, Bajracharya SR, Sharma AR (2016a) Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin. Int J Climatol 37(2):1066–1083. https://doi.org/10.1002/joc.4761

Shrestha H, Bhattarai U, Dulal KN, Adhikari S, Marahatta S, Devkota LP (2016b) Impact of Climate Change in the Karnali Basin, Nepal. J Hydrol Meteorol 10(1):1–19

Shrestha S, Bajracharya AR, Babel MS (2016c) Assessment of risks due to climate change for the Upper Tamakoshi Hydropower Project in Nepal. Clim Risk Manag 14(C):27–41. https://doi.org/10.1016/j.crm.2016.08.002

Shrestha S, Shrestha M, Babel MS (2016d) Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. Environ Earth Sci 75(4):280. https://doi.org/10.1007/s12665-015-5150-8

Shrestha M, Acharya SC, Shrestha PK (2017) Bias correction of climate models for hydrological modelling – are simple methods still useful? Meteorol Appl 24(3):531–539. https://doi.org/10.1002/met.1655

Sigdel M, Ma Y (2016) Variability and trends in daily precipitation extremes on the northern and southern slopes of the central Himalaya. Theor Appl Climatol 130:571–581. https://doi.org/10.1007/s00704-016-1916-5

Smadi MM, Zghoul A (2006) A sudden change in rainfall characteristics in Amman, Jordan during the Mid 1950's. Am J Environ Sci 2(3):84–91

Sneyers S (1990) On the statistical analysis of series of observations. Technical note No. 143, WMO No 415. World Meteorological Organization, Geneva, p 192

Society of Hydrologists and Meteorologist (2012) Integration of climate change considerations in hydropower developments - adaptations and policy recommendation final report

Some'e BS, Ezani A, Tabari H (2012) Spatiotemporal trends and change point of precipitation in Iran. Atmos Res 113:1–12. https://doi.org/10.1016/j.atmosres.2012.04.016

Stefanidis K, Panagopoulos Y, Psomas A, Mimikou M (2016) Assessment of the natural flow regime in a Mediterranean river impacted from irrigated agriculture. Sci Total Environ 57:1492–1502. https://doi.org/10.1016/j.scitotenv.2016.08.046

Tank AMGK, Peterson TC, Quadir D, Dorji S, Zou X, Tang H, Deshpande NR (2006) Changes in daily temperature and precipitation extremes in central and south Asia. J Geophys Res 111: D16105. https://doi.org/10.1029/2005jd006316

Tarhule A, Wool M (1998) Changes in rainfall characteristics in northern Nigeria. Int J Climatol 18:1261–1271

Teutschbein C, Seibert J (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. J Hydrol 56(457):12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052

Timpe K, Kaplan D (2017) The changing hydrology of a dammed Amazon. Sci Adv 3(1-14):e1700611

Vincent LA, Peterson TC, Barros V, Marino MB (2005) Observed trends in indices of daily temperature extremes in South America 1960–2000. J Clim 18(23):5011–5023. https://doi.org/10.1175/JCLI3589.1

Wang GQ, Zhang JY, Jin JL, Pagano TC, Calow R, Bao ZX, Liu CS, Liu YL, Yan XL (2012) Assessing water resources in China using PRECIS projections and a VIC model. Hydrol Earth Syst Sci 16: 231–240. https://doi.org/10.5194/hess-16-231

Wijngarrd JB, Klein Tank AMG, Konnen GP (2003) Homogeneity of 20th Century European Daily Temperature and Precipitation Series. Int J Climatol 23:679–692. https://doi.org/10.1002/joc.906

WMO (2009) Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. WCDMP 72, World Meteorological Organization, Geneva

Xia J, Zeng S, Du H, Zhan C, Xia J, Zeng S, Zhan C (2014) Quantifying the effects of climate change and human activities on runoff in the water source area of Beijing, China. Hydrological Sciences 59(10): 1794–1807. https://doi.org/10.1080/02626667.2014.952237

Xue L, Zhang H, Yang C, Zhang L, Sun C (2017) Quantitative assessment of hydrological alteration caused by irrigation projects in the Tarim River basin, China. Sci Rep 7(4291):1–13. https://doi.org/10.1038/s41598-017-04583-y

Zhang X, Yang F (2004) RClimDex (1.0) User guide. Climate Research Branch Environment Canada: Downsview, Ontario, Canada