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Characterizing The Trends of Hydroclimatic Extremes In Manohara Watershed

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Abstract
Assessing the changing patterns of extreme climate events is crucial to mitigate potential risks associated with future climate conditions. This study focuses on the Manohara Watershed, where an analysis of hydroclimatic extremes was conducted. The ClimPACT2 tool was applied to assess climatic extremes related to precipitation and temperature. Results revealed rising warm extremes and declining cold extremes. Meanwhile, trends in rainfall exhibited variations across different stations. In terms of hydrological extremes, both minimum and maximum extremes increased, with minimum extremes displaying higher statistical significance compared to maximum extremes. These findings emphasize the importance of monitoring and adapting to shifting hydro-climatic patterns in the Manohara Watershed to enhance resilience in the face of climate change.

Keywords
Climate change, climatic extremes, hydrological extremes, Nepal

1. Introduction

The adverse effects of climate variability and change, along with associated hazards, are becoming more pronounced on a global scale [1]. Physical exposure and vulnerability make these effects worse, especially when there is not enough adaptive capacity to cope with the changing climate[2]. The hydro-climatic extremes, encompassing floods and droughts, are dynamic phenomena greatly influenced by climate variability and anthropogenic activities[1]. Nepal, a geographically diverse nation, exemplifies the confluence of these factors, rendering it vulnerable to the adverse impacts of hydro-climatic extremes[3]. The frequency and intensity of hydro-climatic extremes events leading to floods, such as heavy rainfall, have intensified in Nepal over the yearsas observed by [3, 4, 5]. In a warming global context, the occurrence and severity of hydro-climatic extremes have been on the rise, presenting an escalating challenge to the environment, human well-being, and socioeconomic progress[6].

The Manohara River, is a perennial river that traverses the Kathmandu Valley, has historically shaped the lives of the people living along its banks. However, the mounting pressures of population growth and unplanned urbanization, have introduced unprecedented complexities and risks [7]. When coupled with alterations in hydro-climatic extremes, the potential consequences for the growing urban region become notably significant[8]. The IHA (Indicators of Hydrologic Alteration) and ETCCDI (Expert Team on Climate Change Detection and Indices) indices are crucial in the Manohara Basin for understanding and quantifying hydroclimatic extremes. The IHA indices help in identifying and quantifying hydrologic extremes, such as changes in river discharge, which is essential for assessing the potential risk of flash floods in the region. On the other hand, the ETCCDI indices provide insights into extreme climate events, including precipitation and temperature extremes, which are vital for understanding the changing weather conditions in the basin.

The escalating impacts of hydro-climatic extremes highlight the urgency for robust adaptation strategies that enhance the resilience of communities[9, 10]. Recognizing the complex interplay between climate change, hydrology, and societal vulnerabilities, there is a growing imperative to explore and implement context-specific adaptation measures[11, 12]. Integrating local knowledge, scientific insights, and policy interventions is crucial to foster adaptive capacities that can effectively mitigate the impacts of hydro-climatic extremes [13]. In response to aforementioned challenges, this study delves into the complex interactions of hydro-climatic extremes in the Manohara Watershed, Nepal employing a comprehensive approach that involves hydrology and meteorology. By analyzing and integrating these factors, the study seeks to gain insights into the growing challenges posed by a changing climate and increasingly severe hydro-climatic events.

2. Description of the study area

Manohara River is one of the major tributaries of the Bagmati river. The study area lies between latitude 27° 38’ 00” N to 27° 45’ 00” N and longitudes 85° 25’ 00” E to 85° 30’ 00” N. It runs through Lapsifedi, Sankhu, Mulpani, Gothataar, Pepsicola, Jadibuti, Balkumari and mixes into the Bagmati River near Sankhamul. The Manohara Watershed incorporates parts of Kathmandu Metropolitan City, Kageshwari Manohara Municipality, Madhyapur Thimi Municipality and Lalitpur Metropolitan City among others as shown in Figure 1. The study area spans over an elevation range from 1270 meters to 2670 meters above sea level , showcasing the diverse topography of this region. Encompassing three districts,

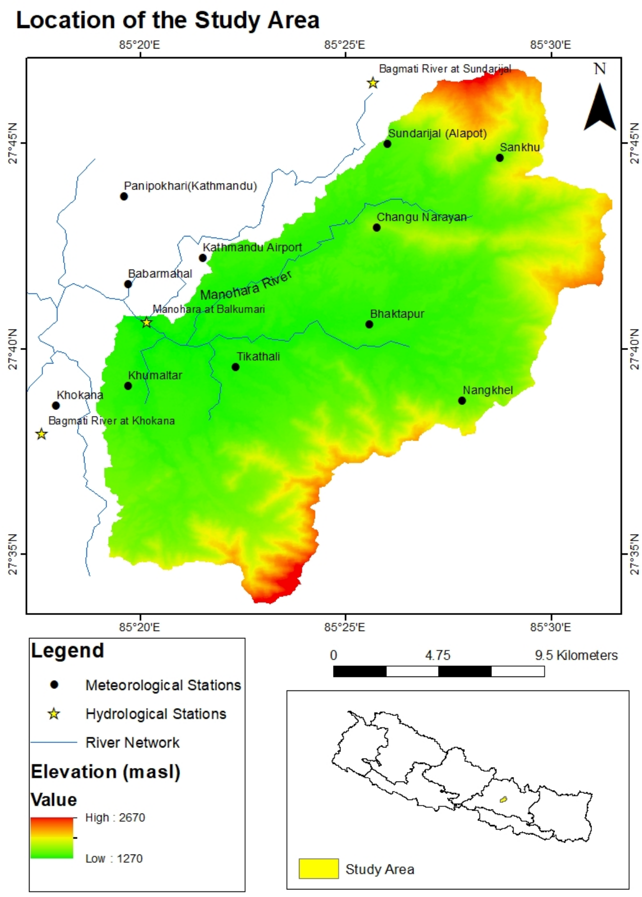

Figure 1: Study area

namely Lalitpur, Bhaktapur, and Kathmandu, the study area showcases the rich cultural and geographical diversity of the Kathmandu Valley. There are many meteorological stations in and around the watershed as listed in 1 According to the 2019 land cover/use data provided by ICIMOD [14] , this area boasts a mosaic of land covers, with 3 percent of the landscape designated as lush forest, 46 percent devoted to vital cropland, and 18.75 percent allocated for essential built-up areas. This complex mixture of natural and human-modified environments highlights the complex interactions between society and the environment in this region. The settlement within this catchment is undergoing rapid expansion due to the overpopulation of the nearby Kathmandu city [7]. The area faces a potential risk of flash floods, particularly during the monsoon season when heavy rainfall is a frequent occurrence [15]. Thus, the analysis of hydro-climatic extremes in this region is necessary to understand how there have been alterations in the climatic and hydrological extremes in this region.

3. Data and Methods

3.1 Data collection

Data was collected from six stations near the Manohara River, including meteorological data like rainfall and temperature from stations set by the Department of Hydrology and Meteorology (DHM) as shown in Table 1.

Table 1: Stations considered for the study of the hydro climatic extremes

Index	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Data Length
1029	Khumaltar	27.65	85.32	1334	1967-2022
1039	Panipokhari	27.72	85.32	1463	1971-2022
1052	Bhaktapur	27.67	85.42	1329	1971-2022
1059	Changunarayan	27.71	85.42	1502	1974-2022
1073	Khokana	27.64	85.29	1309	1991-2022
1030	Airport	27.70	85.35	1337	1968-2022

Among the stations shown above, almost all the stations had data for oth the precipitation and temperatue for the listed data length except Bhaktapur (Station ID: 1052) with data spanning from 1971 to 2022 for precipitation records and from 2013 to 2022 for temperature records, Changunarayan (Station ID: 1059) with data from 1974 to 2022 for precipitation and from 2011 to 2022 for temperature, and Khokana (Station ID: 1073) covering the period from 1991 to 2022 for precipitation and from 1999 to 2022 for temperature.

Although there's only one station on the Manohara Watershed that records water levels, this data is not yet available to the public. Therefore, for this study, data generated by an earlier study for the entire Bagmati Basin was utilized, specifically data at the Manohara River's inlet. The study had previously calibrated and validated the model using the measured discharge data from the hydrological station at Khokana (st. no 550.05).

3.2 Data pre-processing

The dataset acquired from DHM for the different stations contained various instances of missing data, presenting a challenge in the analysis. To address this issue, the following strategies were employed to effectively manage and fill the gaps in the dataset. For rainfall data, the normal-ratio method was utilized, considering the elevation variation with a maximum difference of 400 meters and an annual rainfall variation capped at 300 mm. Temperature data gaps were addressed through the long-term average daily method. In the case of hydrological data, which originated from a simulated model, it was considered complete without missing entries. However, stations with a high frequency of missing data and limited measured data across time were excluded from the analysis. These strategies collectively helped address the missing data challenge and ensured the dataset's reliability for subsequent analyses.

3.3 Identifying climatic extremes

In this paper, several key climatic indices to assess extreme climate events were examined. A set of 29 ETCCDI climate indices, derived from daily time series of precipitation and temperature, was computed utilizing the R-based ClimPACT2 tool . These indices have gained widespread recognition for their utility in examining global trends in extreme climate events. Out of the 29 indices, 14 climate extreme indices—comprising seven related to precipitation and seven related to temperature— were selected as outlined in Table 2 and Table 3.

The selected set of indices was chosen for their ability to comprehensively capture extreme climate conditions, effectively representing both precipitation and temperature extremes. These indices provide a holistic view of climatic variations, ensuring that the analysis accounts for the full spectrum of extreme weather events.

Table 2: Precipitation extremes considered in this study

Index	Notation [Units]	Description
Max 1-day PR	Rx1 Day [mm]	Maximum 1-day PR total i.e., Maximum amount of rain that falls in one day
Max 5-day PR	Rx 5 Day [mm]	Maximum 5-day PR total i.e.Maximum amount of rain that falls in five consecutive days
Total annual PR from heavy rain days	R95p [mm]	Amount of rainfall from very wet days, Annual sum of daily PR greater than 95th percentile
Annual total wet-day PR	PRCPTOT [mm]	Total wet-day rainfall where sum of daily PR greater than or rqual to 1.0 mm
Consecutive Wet Days	CWD [days]	Maximum annual number of consecutive wet days (when PR greater than or equal to 1.0 mm)
Consecutive Dry Days	CDD [days]	Maximum number of consecutive dry days (when PR less than 1.0 mm)
Number of very heavy rain days	R20mm[days]	Number of days when PR greater or equal to 20 mm

Table 3: Temperature extremes considered in this study

Index	Notation [Units]	Description
Max TX	TXx [°C]	Warmest daily TX
Min TN	TNn [°C]	Coldest daily TN
Min TX	TXn [°C]	Coldest daily TX
Max TN	TNx [°C]	Warmest daily TN
Amount of hot days	Tx90p [percent]	Percentage of days when TX greater than 90th percentile
Amount of warm nights	Tn90p [percent]	Percentage of days when TN greater than 90th percentile
Warm spell duration indicator	WSDI [days]	Annual number of days contributing to events where 6 or more consecutive days experience TX greater than 90th percentile

3.4 Identifying hydrologic extremes

There are no historical discharge measurements in Manohara River as the river was ungauged until the 26th of June 2023, so the discharge data for this study was taken from an analysis made on the broader Bagmati catchment which gave the inflow of Manohara. This data was analyzed using the Indicators of Hydrologic Alteration (IHA) tool [16]. There are 33 IHA parameters that are divided in 5 parametrical groups as shown in the Table 4

Table 4: IHA indicators for hydrological extremes

Group	Name	Parameters
Group 1	Magnitude of monthly water conditions	Mean or median value for each calendar month
		Subtotal 12 parameters
Group 2	Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year
		Subtotal 12 parameters
Group 3	Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum
		Subtotal 2 parameters
Group 4	Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days)
		Subtotal 4 parameters
Group 5	Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values
		Fall rates: Mean or median of all negative differences between consecutive daily values
		Number of hydrologic reversals
		Subtotal 3 parameters
		A total of 33 parameters

3.5 Statistical Trend Analysis

The Mann-Kendall test, a popular non-parametric statistical method, is commonly employed for identifying trends in hydro-climatic time series data[17] . In this study trends in the climate extreme indices were analyzed using the non-parametric modified Mann-Kendall test (M-MKT)[18] , and the Sen's slope [19] was calculated. Hydrologic extreme indices were also subjected to trend analysis using the non-parametric M-MKT, a statistical method that evaluates the presence of trends without relying on specific distribution assumptions. Simultaneously, Sen's slope was calculated.

Kendall Tau, also known as Kendall's rank correlation coefficient, it gauges the monotonic nature of the slope. Its range lies between -1 and 1; positive values signify an increasing trend, while negative values indicate a decreasing trend. Significance or simply P-value,signifies the threshold at which the hypothesis of no trend is accepted. The trend becomes statistically significant when the p-value is less than 0.05. Sen's slope provides a quantifiable measure of the trend's magnitude, capturing the rate of change in hydrologic extremes over time. It corresponds to the median of all slopes computed between each pair of data points in the series. This combination of MKT and Sen's slope assessment allows for a comprehensive evaluation of the temporal evolution of hydrologic extreme events, offering valuable insights into the direction and intensity of changes in these critical water-related parameters.

4. Results

4.1 Precipitation extremes

The analysis of various precipitation indices is crucial in understanding the complex patterns of rainfall and dryness across different meteorological stations. In this study, we focused on seven key precipitation indices, namely Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), annual total wet days (PRCPTOT), maximum 1-day precipitation (Rx1day), maximum 5-day precipitation (Rx5day), and the number of heavy precipitation days (R20mm), along with total annual precipitation from heavy precipitation days (R95p). These indices have been examined at six distinct meteorological stations, namely, Khumaltar, Panipokhari, Bhaktapur, Changunarayan, the Airport station, and Khokana. The analysis provides valuable insights into the trends and variations in precipitation patterns at these locations, shedding light on the potential implications of changing weather conditions. The Mann-Kendall's Tau, p-values, Sen's Slope, and significance levels have been used to assess the statistical significance and magnitude of these trends Table 5. This comprehensive examination of precipitation indices contributes to our understanding of local climate dynamics and their broader implications.

The analysis of meteorological data at various stations reveals diverse trends in precipitation patterns. In terms of CDD, Khumaltar shows a non-significant positive trend, suggesting an increase in dry periods (Mann-Kendall's Tau: 0.13, P-value: 0.202). Conversely, Panipokhari exhibits a significant upward trend in CDD, indicating a substantial increase in dry conditions (Mann-Kendall's Tau: 0.260, P-value: 0.002). Bhaktapur displays a non-significant negative trend, implying a decrease in dry spells. Both Changunarayan and the Airport station show non-significant trends, suggesting stability in dryness conditions.Regarding CWD, Khumaltar and Panipokhari display non-significant downward trends (Khumaltar: Mann-Kendall's Tau: -0.006, P-value: 0.955; Panipokhari: Mann-Kendall's Tau: -0.160, P-value: 0.097), indicating slight decreases in wetness. The Airport station and Khokana also show non-significant trends, with minor declines in wetness. Bhaktapur and Changunarayan exhibit non-significant trends, suggesting wetness stability.

When analyzing annual total wet days (PRCPTOT), most stations show non-significant patterns. Khumaltar reflects precipitation stability with a non-significant negative trend (Mann-Kendall's Tau: -0.002, P-value: 0.441). Panipokhari indicates slight, non-significant increases in precipitation (Mann-Kendall's Tau: 0.010, P-value: 0.910). Bhaktapur and Changunarayan both exhibit precipitation stability with non-significant trends (Bhaktapur: Mann-Kendall's Tau: -0.001, P-value: 0.990; Changunarayan: Mann-Kendall's Tau: 0.003, P-value: >0.95). The Airport station suggests a minor rise in precipitation, but this trend is not statistically significant (Mann-Kendall's Tau: 0.157, P-value: 0.094). Khokana also shows precipitation stability with a non-significant negative trend (Mann-Kendall's Tau: -0.0021, P-value: 0.603).

In terms of Rx1day, Panipokhari and Bhaktapur exhibit non-significant decreasing trends (Panipokhari: Mann-Kendall's Tau: -0.034, P-value: 0.695; Bhaktapur: Mann-Kendall's Tau: -0.026, P-value: 0.290). Changunarayan and the Airport station display significant positive trends, indicating notable increases in maximum 1-day precipitation (Changunarayan: Mann-Kendall's Tau: 0.059, P-value: 0.113; Airport: Mann-Kendall's Tau: 0.082, P-value: 0.382). Khokana shows precipitation stability with a non-significant negative trend (Mann-Kendall's Tau: -0.002, P-value: 0.530). Analyzing Rx5day, Khumaltar reflects precipitation stability with a non-significant negative trend (Mann-Kendall's Tau: -0.001, P-value: 0.483). Panipokhari suggests minor increases, albeit non-significant (Mann-Kendall's Tau: 0.003, P-value: 0.980), while Bhaktapur exhibits slight variations (Mann-Kendall's Tau: 0.001, P-value: 0.990). Changunarayan indicates notable increases (Mann-Kendall's Tau: 0.002, P-value: 0.950), and the Airport station shows significant rises (Mann-Kendall's Tau: 0.070, P-value: 0.455). Khokana reflects precipitation stability (Mann-Kendall's Tau: -0.004, P-value: 0.310).

In the case of R20mm index, Panipokhari and the Airport station display significant positive trends, suggesting more days with heavy precipitation (Panipokhari: Mann-Kendall's Tau: 0.210, P-value: 0.013; Airport: Mann-Kendall's Tau: 0.157, P-value: 0.101). Khumaltar and Changunarayan exhibit stability in the occurrence of heavy precipitation days, with non-significant trends (Khumaltar: Mann-Kendall's Tau: -0.001, P-value: 0.980; Changunarayan: Mann-Kendall's Tau: 0.002, P-value: 0.891). Bhaktapur indicates minor variations but with a non-significant positive trend (Mann-Kendall's Tau: 0.003, P-value: 0.960). Khokana reflects stability, although with a non-significant negative trend (Mann-Kendall's Tau: -0.004, P-value: 0.338).

Analyzing R95p, Khumaltar shows a non-significant decrease (Mann-Kendall's Tau: -0.007, P-value: 0.107). Panipokhari exhibits fluctuations but with a non-significant downward

Table 5: Results of trend analysis of precipitation indices

Index	Stations	St. Name	Mann-Kendall's Tau	P-value	Sen's Slope		Significance
CDD	1029	Khumaltar	0.13	0.202	0.612	↑	NS
	1039	Panipokhari	0.260	0.002	1.000	↑	S
	1052	Bhaktapur	-0.031	0.413	0	-	NS
	1059	Changunarayan	0.009	0.866	0	-	NS
	1030	Airport	0.061	0.521	0.214	↑	NS
	1073	Khokana	0.001	0.726	0	-	NS
CWD	1029	Khumaltar	-0.006	0.955	0	-	NS
	1039	Panipokhari	-0.160	0.097	-0.625	↓	NS
	1052	Bhaktapur	-0.027	0.156	0	-	NS
	1059	Changunarayan	-0.044	0.369	0	-	NS
	1030	Airport	-0.155	0.111	-0.051	↓	NS
	1073	Khokana	0.001	0.803	0	-	NS
PRCPTOT	1029	Khumaltar	-0.002	0.441	0	-	NS
	1039	Panipokhari	0.010	0.910	0.320	↑	NS
	1052	Bhaktapur	-0.001	0.99	0.002	↑	NS
	1059	Changunarayan	0.003	0.94	0.003	↑	NS
	1030	Airport	0.157	0.094	3.66	↑	NS
	1073	Khokana	-0.0021	0.603	0	-	NS
Rx1day	1029	Khumaltar	-0.002	0.668	0	-	NS
	1039	Panipokhari	-0.034	0.695	-0.081	↓	NS
	1052	Bhaktapur	-0.026	0.29	-0.03	↓	NS
	1059	Changunarayan	0.059	0.113	0.07	↑	NS
	1030	Airport	0.082	0.382	0.129	↑	NS
	1073	Khokana	-0.002	0.530	0	-	NS
Rx5day	1029	Khumaltar	-0.001	0.483	-0.001	↓	NS
	1039	Panipokhari	0.003	0.980	0.010	↑	NS
	1052	Bhaktapur	0.001	0.990	0	-	NS
	1059	Changunarayan	0.002	0.950	0.003	↑	NS
	1030	Airport	0.070	0.455	0.229	↑	NS
	1073	Khokana	-0.004	0.310	-0.010	↓	NS
R20mm	1029	Khumaltar	-0.001	0.980	0	-	NS
	1039	Panipokhari	0.210	0.013	0.140	↑	S
	1052	Bhaktapur	0.003	0.960	0	-	NS
	1059	Changunarayan	0.002	0.891	0	-	NS
	1030	Airport	0.157	0.101	0.0816	↑	NS
	1073	Khokana	-0.004	0.338	0	-	NS
R95p	1029	Khumaltar	-0.007	0.107	-0.09	↓	NS
	1039	Panipokhari	-0.617	0.420	-0.870	↓	NS
	1052	Bhaktapur	0.285	0.133	0.5	↑	NS
	1059	Changunarayan	-0.030	1.944	0	-	NS
	1030	Airport	0.129	0.169	2.11	↑	NS
	1073	Khokana	-0.177	0.245	-0.99	↓	NS

trend (Mann-Kendall's Tau: -0.617, P-value: 0.420). Bhaktapur displays stability with a non-significant positive trend (Mann-Kendall's Tau: 0.285, P-value: 0.133). Changunarayan indicates stability (Mann-Kendall's Tau: -0.030, P-value: 1.944), while the Airport station suggests minor variations with a non-significant positive trend (Mann-Kendall's Tau: 0.129, P-value: 0.169). Khokana reflects stability with a non-significant negative trend (Mann-Kendall's Tau: -0.177, P-value: 0.245).

These analyses provide insights into the varied precipitation trends across these stations, encompassing stability, minor changes, and occasional significant shifts in different aspects of precipitation.

4.2 Temperature extremes

The analysis of various temperature indices provides valuable insights into climatic trends across multiple meteorological stations in the region. Specifically, we examined six key temperature-related indices, including TXx, TNx, TXn, TNn, Tx90p, and Tn90p, along with the Warm Spell Duration Index (WSDI). These indices were assessed across six strategically located stations: Khumaltar, Panipokhari, Bhaktapur, Changunarayan, the Airport station, and Khokana. The results of this comprehensive analysis are presented in Table 6, which highlights key statistical parameters such as Mann-Kendall's Tau, P-values, Sen's Slope, and Significance, offering a detailed perspective on temperature trends and their significance across these stations.

Temperature trends at various meteorological stations in the region display diverse patterns. Notably, Panipokhari station (1039) reveals a significant upward trend in the TXx, with a Mann-Kendall's Tau of 0.246 and a low P-value of 0.03, indicating a substantial rise in extreme high temperatures.

In terms TNx, meteorological stations like Panipokhari and Bhaktapur exhibit significant upward trends, with Mann-Kendall's Tau values of 0.090 and 0.076, along with low P-values of 0.01 and 0.001, respectively, suggesting notable annual increases in minimum maximum temperatures. The Airport station also demonstrates a highly significant upward trend in TNx, with Mann-Kendall's Tau of 0.346 and a low P-value of 0.001, reflecting substantial annual increases in minimum maximum temperatures. The index TXn reveals varying trends across meteorological stations. Panipokhari and Bhaktapur show statistically significant upward trends, indicating annual increases in minimum minimum temperatures. Furthermore, while the Airport station displays a statistically significant trend in TXn (Mann-Kendall's Tau: 0.133, P-value: 0.158), the Sen's Slope of 0.031 suggests a gradual annual increase.

TNn index exhibit diverse trends across meteorological stations. Khumaltar displays a highly significant upward trend, while Panipokhari and Bhaktapur also show statistically significant upward trends, signifying notable annual temperature increases.

Khumaltar demonstrates a highly significant upward trend in TX90p, with a Mann-Kendall's Tau of 0.5 and a very low P-value of 0.328, indicating a substantial increase in the occurrence of days with high maximum temperatures. Bhaktapur also displays a statistically significant upward trend in TX90p, with a Mann-Kendall's Tau of 0.344 and a low P-value of 0.013, implying increased occurrences of days with high maximum temperatures.

The analysis of Tn90p at meteorological stations reveals diverse trends. Bhaktapur exhibits a statistically significant upward trend, signifying notable rises in the percentage of such days, while Panipokhari also shows a significant increase in Tn90p, indicating increased occurrences of days with high minimum temperatures.

The analysis of the WSDI across meteorological stations reveals varying trends. The Airport station demonstrates a highly significant upward trend in WSDI, implying an extended duration of warm spells. Khumaltar shows a significant increase in the duration of warm spells, while Bhaktapur and Changunarayan exhibit stability. Panipokhari exhibits a non-significant trend, while Khokana shows temperature stability

These findings underscore the complexity of temperature trends across the region, with significant variations in different temperature parameters and locations.

4.3 Hydrological extremes

Hydrological indices play a pivotal role in assessing the characteristics of water-related phenomena, offering valuable insights into the variability of extreme conditions in our environment. In this analysis, we delve into a set of ten key extreme hydrological indices, each calculated to assess various aspects of minimum and maximum water flow conditions. These indices encompass 1-day, 3-day, 7-day, 30-day, and 90-day periods, capturing both short-term and long-term hydrological patterns. The results of these calculations are presented in the accompanying table, featuring essential statistical parameters such as Mann-Kendall's Tau, P-values, Sen's Slope, and significance levels. This comprehensive examination of hydrological indices provides crucial information for understanding and managing water resources, particularly in the context of changing climate and environmental conditions.

Table 7 presents a detailed analysis of hydrological parameters over varying time scales, focusing on both minimum and maximum values. The key parameters include 1-day, 3-day, 7-day, 30-day, and 90-day extremes. The Mann-Kendall's Tau values in the table are indicative of the trend direction, with positive values suggesting increasing trends. These trends are further substantiated by low P-values, indicating statistical significance. Specifically, the minimum values across all time scales exhibit clear and significant increasing trends, with Mann-Kendall's Tau values ranging from 0.39 to 0.466 and corresponding P-values below 0.05. Sen's Slope values, which quantify the magnitude of these trends, vary from 0.029 to 0.038, affirming the rate of change over time.

Conversely, the maximum values generally show no statistically significant trends, as evidenced by higher P-values exceeding the 0.05 threshold. The positive Mann-Kendall's Tau values for maximum values suggest potential increases in extremes, but the lack of statistical significance implies a higher degree of variability or limited directional changes.

Table 6: Results of trend analysis of temperature indices

Index	Stations	St. Name	M-K Tau	P-value	Sen's Slope		Significance
TXx	1029	Khumaltar	0.021	0.037	0.024	↑	S
	1039	Panipokhari	0.246	0.03	0.007	↑	S
	1052	Bhaktapur	0.186	0.001	0.005	↑	S
	1059	Changunarayan	0.061	0.202	0.007	↑	NS
	1030	Airport	0.378	0.006	0.042	↑	S
	1073	Khokana	0	1	0	-	NS
TNx	1029	Khumaltar	0.005	0.585	0	-	NS
	1039	Panipokhari	0.090	0.01	0.003	↑	S
	1052	Bhaktapur	0.076	0.001	0.002	↑	S
	1059	Changunarayan	0.011	0.755	0	-	NS
	1030	Airport	0.346	0.001	0.015	↑	S
	1073	Khokana	0.054	0.748	0	-	NS
TXn	1029	Khumaltar	0.182	0.075	0.065	↑	NS
	1039	Panipokhari	0.157	0.010	0.006	↑	S
	1052	Bhaktapur	0.086	0.005	0.003	↑	S
	1059	Changunarayan	0.004	0.919	0	-	NS
	1030	Airport	0.133	0.158	0.031	↑	NS
	1073	Khokana	-0.015	0.936	-0.016	↓	NS
TNn	1029	Khumaltar	0.505	0	0.078	↑	S
	1039	Panipokhari	0.064	0.013	0.003	↑	S
	1052	Bhaktapur	0.075	0.001	0.003	↑	S
	1059	Changunarayan	-0.009	0.814	0	-	NS
	1030	Airport	0.513	0.035	0.054	↑	S
	1073	Khokana	-0.272	0.079	-0.063	↓	NS
Tx90p	1029	Khumaltar	0.5	0	0.328	↑	S
	1039	Panipokhari	0.331	0.058	0.000	-	NS
	1052	Bhaktapur	0.344	0	0.013	↑	S
	1059	Changunarayan	0.192	0.006	0.039	↑	S
	1030	Airport	0.595	0.016	0.345	↑	S
	1073	Khokana	0.225	0.139	0.327	↑	NS
Tn90p	1029	Khumaltar	0.470	0	0.274	↑	S
	1039	Panipokhari	0.240	0.027	0.001	↑	S
	1052	Bhaktapur	0.294	0	0.017	↑	S
	1059	Changunarayan	0.169	0.006	0.054	↑	S
	1030	Airport	0.557	0.02	0.289	↑	S
	1073	Khokana	0.146	0.341	0.11	↑	NS
WSDI	1029	Khumaltar	0.242	0.025	0.095	↑	S
	1039	Panipokhari	0.371	0.051	0.000	-	NS
	1052	Bhaktapur	0.178	0.382	0	-	NS
	1059	Changunarayan	0.090	0.708	0	-	NS
	1030	Airport	0.431	0.002	0.174	↑	S
	1073	Khokana	0.001	1	0	-	NS

Table 7: Result of trend analysis of hydrological extreme parameters

Parameters	Mann-Kendall's Tau	P-value	Sen's Slope		Significance
1-day minimum	0.39	0.047	0.03	↑	S
3-day minimum	0.409	0.003	0.038	↑	S
7-day minimum	0.447	0.022	0.031	↑	S
30-day minimum	0.428	0.029	0.029	↑	S
90-day minimum	0.466	0.017	0.036	↑	S
1-day maximum	0.104	0.621	0.726	↑	NS
3-day maximum	0.143	0.488	0.361	↑	NS
7-day maximum	0.104	0.621	0.136	↑	NS
30-day maximum	0.2	0.322	0.136	↑	NS
90-day maximum	0.162	0.428	0.152	↑	NS

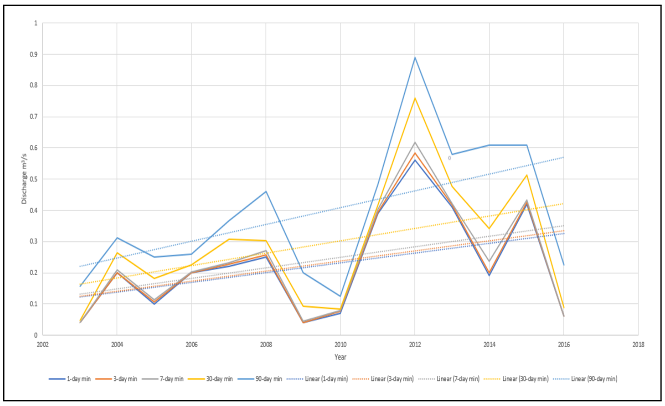

Figure 2: Trends of minimum extreme parameters

Sen's Slope values for maximum parameters, range from 0.136 to 0.726, implying positive trends in the extreme values.

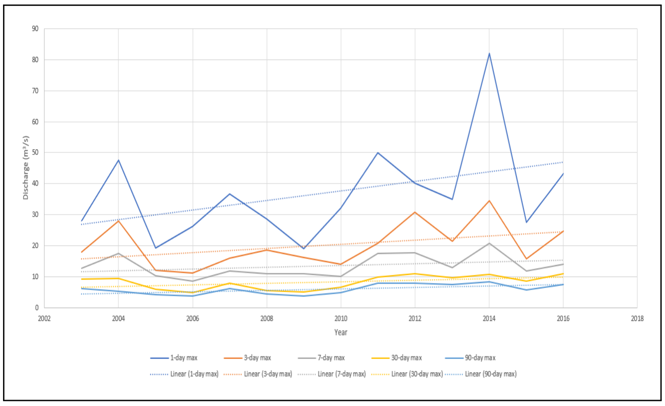

Figure 3: Trends of maximum extreme parameters

In summary, this comprehensive analysis underscores the substantial and significant increasing trends in minimum hydrological parameters across different time scales, while maximum values exhibit a more stable or less pronounced trend pattern, highlighting the complexity of hydrological variations over time. The trends of the hydrological extremes have been shown in the Figure 2 and Figure 3.

5. Discussion

The analysis of meteorological data across these stations highlights the diverse and nuanced precipitation trends in the region. While some stations show stability or minor fluctuations in various precipitation indices, others exhibit significant increases or decreases, underlining the complex nature of regional precipitation patterns. It's noteworthy that despite some small and insignificant precipitation extremes, there are stations where temperature extremes are increasing, indicating a warming climate. Notably, Panipokhari and Bhaktapur have experienced significant increases in both maximum and minimum temperatures, reflecting the warming trend, while other stations demonstrate varying degrees of temperature stability or gradual changes.

Furthermore, the hydrological analysis reveals a significant upward trend in minimum flow conditions across multiple time scales, indicating potential shifts in water availability and hydrological dynamics. Conversely, maximum flow conditions show no significant changes, suggesting relative stability in extreme flow events. It's important to mention that while both hydrological extremes are increasing, the significance of this increase is higher in minimum flow conditions, emphasizing potential challenges in managing water resources under changing climatic conditions.

6. Conclusions

The observed trends in hydro-climatic extremes in the Manohara Watershed carry significant implications for water resource management and ecosystem dynamics. The varying trends in precipitation extremes across meteorological stations suggest localized changes in rainfall patterns. Such disparities could pose challenges for water availability and agricultural practices in specific areas, necessitating region-specific adaptation strategies.

The consistent warming trend in maximum and minimum temperatures underscores the broader impact of climate change on the region. Elevated temperatures can influence evaporation rates, soil moisture content, and overall hydrological processes. This warming trend may lead to shifts in ecosystems, affecting vegetation, wildlife, and water balance.

The upward trend in minimum flow conditions implies alterations in base flow, which is crucial for maintaining stream health and supporting aquatic ecosystems. This shift may influence both human water consumption and ecological integrity.

Similarly, the increasing trends in maximum flow conditions suggest a heightened risk of extreme flooding events. These events can result in adverse impacts on infrastructure, agriculture, and communities located in flood-prone areas.

In conclusion, the observed hydro-climatic trends in the Manohara Watershed signal the need for proactive and adaptive water management strategies. Understanding these trends allows for the development of resilient policies and practices that can mitigate the potential impacts of climate change on water resources and associated ecosystems in the region.

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