Spatial and Temporal Variations of Surface Air Temperature (1962–2022) across Physiographic Regions in the Koshi Basin, Nepal

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(Received 01 January 2024; Accepted 05 September 2024)

ABSTRACT

This study analyzed the seasonal and annual trends of maximum temperature (Tmax), minimum temperature (Tmin), and mean temperature (Tavg) across the physiographic regions (Himalaya, High Mountain, Middle Mountain, Siwalik, and Terai) of the Koshi Basin using observed data from 23 stations between 1962 and 2022. Missing temperature data were filled using the lapse rate method. The Mann-Kendall (M-K) test was employed to assess the consistency of the temperature dataset. The analysis revealed distinct regional and seasonal temperature trends in the Koshi Basin. The seasonal variations were prominent, especially in the Monsoon and Winter. In the Middle Mountain and High Mountain regions, Tmax increased significantly during the Pre-monsoon season, while Tmin decreased substantially during the Monsoon and Winter. Conversely, the Siwalik and Terai regions experienced more pronounced cooling Himalayas, especially during the Monsoon and Winter. Overall, the Himalayas and High Mountain regions exhibited a cooling trend until the late 1990s, followed by a warming trend. The Middle Mountain region demonstrated similar patterns, with a significant temperature increase after the 1990s. The Siwalik and Terai regions experienced a general cooling trend, although the Siwalik region exhibited some fluctuations. The significant regional variations in temperature trends were the key findings. Similarly, the Himalayas and High Mountains showed a cooling-warming shift in the late 1990s. All these findings underscore the importance of considering both regional and seasonal factors when studying temperature trends in the Koshi Basin.

Keywords: Koshi Basin, Temperature trends, Spatial variation, Physiographic regions and Seasonal changes

1. Introduction

Climate change (CC) contributes to increased greenhouse gas emissions, which will cause a global temperature rise of 1.40 to 5.8 °C by the year 2100 compared to 1990 levels (McCarthy, 2001). The ongoing warming process is expected to significantly affect atmospheric and ecological processes, with wide-reaching consequences for ecosystems and human communities. The threat posed by climate change to mankind is growing, yet many of the most vulnerable individuals are still ignorant of the full effects of global warming (Maharjan et al., 2011). Globally, there has been an increase in the frequency and intensity of severe weather and climate events associated with human-induced climate change since the 1950s. These occurrences are predicted to get worse as long as global warming continues (Arias et al., 2021).

DOI: https://doi.org/10.3126/jhm.v12i1.72654

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The impacts of climate change pose significant threats to small, developing nations whose economies and livelihoods predominantly depend on natural resources. Nepal, as one such nation, is characterized by its landlocked geography, varied physiographic features within a limited area, and challenging hilly terrains (Shrestha and Aryal, 2011). Designated as the fourth most climate-vulnerable country, Nepal illustrates the difficulties presented by climate change (Manandhar et al., 2011; Reilly et al., 2001). Importantly, the rate of warming in Nepal's Himalayan regions is anticipated to surpass the global average, especially in high-altitude zones (Bhattarai and Leduc, 2008; Yao et al., 2019; Shrestha et al., 1999).

Seasonal shifts, such as heavy rainfall during the monsoon season and accelerated glacier melt, contribute to a range of climate-induced hazards, including landslides, floods, and droughts. The effects of these changes are becoming more apparent, and they present a significant challenge to the country's infrastructure and future development (Pokhrel and Pandey, 2011). Climate-related disasters are now the primary causes of natural disaster deaths in Nepal, with their frequency increasing in recent years. Because of its sensitivity and lack of preparation, Nepal is regarded as one of the countries most susceptible to catastrophic weather occurrences (Aksha et al., 2018; Eckstein et al., 2021). Environmental changes in the Koshi Basin, one of the significant subbasins of the Ganges River, have led to multiple challenges. Rising temperatures and changing precipitation patterns have increased the frequency and intensity of floods and droughts, leading to increased vulnerability in this region (Bastakoti et al., 2017). The Koshi Basin spans a wide geographical area, ranging from elevations nearly 100 meters to over 8,000 meters, including the highest point on Earth, Mount Everest. This varied topography results in significant temperature differences within the basin (Bhatt et al., 2014). Multiple studies have demonstrated that the Himalayan region is warming at a faster rate than the global average, with temperature trends showing significant variability across altitudes and seasons. While warming rates are generally consistent, they vary depending on altitude, commonly referred to as the elevation dependency of climate warming (Hingane et al., 1985; Shrestha et al., 2017; Sabin et al., 2020). Their studies revealed an increase in mean annual temperatures, with some areas experiencing a rise of 0.4 degrees Celsius over the past century. Stations in the hills and mountains exhibited significant warming, while in the plains, maximum temperatures showed a decreasing trend. In the Koshi Basin, the maximum temperature rose at a rate of 0.058 °C per year, while the minimum temperature increased by 0.014 °C per year over the 40 years from 1963 to 2009 (Nepal, 2016). A study conducted by (Nayava et al., 2017) on air temperature trends at different altitudinal zones of Nepal for 30 years (1981-2010) shows annual mean temperatures increase at varying rates, with the Terai warming by 0.024 °C/year, valley floors by 0.034 °C/year, hill valleys by 0.063°C/year, mountain valleys by 0.033 °C/year, hilltops by 0.072 °C/year, mountain tops by 0.038 °C/year, and the Trans-Himalaya by 0.029 °C/year.(Paudel et al., 2021) found that between 1980 and 2018, the mean annual temperature in the transboundary Koshi River Basin increased by 0.084 °C/year in the mountains, 0.097 5°C/year in the hills, and 0.0187 °C/year in the Terai. A study conducted by (Shrestha et al., 1999) for annual temperature trends from 1977 to 1994 revealed that the Trans-Himalaya experienced the most significant warming at 0.090 °C/year. The Himalayas and Middle Mountains also showed substantial warming, with trends of 0.057 °C/year and 0.075 °C/year, respectively. Siwalik and Terai regions had the lowest annual temperature trends, both at 0.041 °C/year. The all-Nepal average annual warming rate was 0.059°C/year, showing widespread temperature increases across the country.(Adhikari and Devkota, 2016) studied annual temperature trends in the Khumbu region from 1988 to 2010 and observed maximum temperature increasing by 0.0639 °C/year, while the minimum temperature showed a slight rise of 0.0036 °C/year. Overall, the mean annual temperature in Khumbu increased by 0.0639°C/year. This finding underscores the persistent warming trend in Nepal, particularly in higher-altitude regions. Recent studies further emphasized that the warming rates in the Himalayas are not uniform. Some regions, particularly in the western and central parts of Nepal, have experienced more rapid warming than others. The seasonal patterns also vary, with significant temperature increases noted during winter, followed by spring, autumn, and summer (Agarwal et al., 2016). In the Koshi Basin, (Shrestha et al., 2017) found that hill and mountain areas experienced warming between 1975 and 2010, while the plains showed minimal warming or even declines. (Bastakoti et al., 2017) observed an increasing variability in minimum temperatures and a narrowing of the range of maximum temperatures. A study conducted by (Bajracharya et al., 2023) indicates an increase in projected average temperature across Koshi basin, with higher rates in northern regions. These findings highlight the critical importance of understanding the specific temperature trends in regions like the Koshi Basin to assess their impact on ecosystems and communities. Additionally, studies such as those by Poudel et al. (2020) emphasize the growing complexity of climate impacts, particularly in regions with varying elevations and climatic conditions.

Nepal's climate ranges from subtropical in the Terai to arctic in the high Himalayas due to its unique physiographic and topographic diversity within a narrow north-south span. The mean maximum temperature in the Terai exceeds 30 °C, gradually decreasing with altitude to below 22 °C in the high mountains. Similarly, the mean minimum temperature ranges from above 18 °C in the Terai to below 6 °C in the northwest, reflecting a distinct temperature gradient across the country's varied altitudes (Marahatta et al., 2009). The study of temperature is an integral part of climate change studies; those changes can vary based on space and time (Bajracharya et al., 2023), and temperature, which varies largely with altitude (Chand et al., 2021). Research in Nepal demonstrates the urgency of addressing climate change, as the country faces heightened vulnerability to extreme weather events and significant challenges in preparedness (Chapagain et al., 2021). This research aims to contribute to the growing body of knowledge on climate trends in the Himalayas and their implications for environmental and social resilience in vulnerable regions like the Koshi Basin.

2. Study area, Data and Methods

2.1. Study Area

Koshi Basin is situated in the eastern part of Nepal and constitutes one of the five major river basins in the country, recognized as the largest. This transboundary river, known as the Koshi River, meanders through China, Nepal, and

India, with its origin in China before flowing southward into Nepal and onward into India. Koshi Basin encompasses diverse geographical regions, with 32% in China, 45% in Nepal, and 23% in India (Bastakoti et al., 2017). The study area was delineated by creating a basin map, with Chatara assumed as the river's outlet point. The elevation ranges from 65 m asl in the Terai to over 8848 m asl in the High Himalayas.

2.2. Data and Methods

Daily maximum and minimum temperature measurements from synoptic, aero-synoptic, and agrometeorological stations throughout the Koshi basin for a 30-year period (1962–2022) were provided for this research by the Department of Hydrology and Meteorology (DHM) in Nepal. Twenty-three temperature stations from 101 m asl to 5200 m asl (Table 1) were selected for this study. Python version 3.12 is used for the data analysis. Pandas, Numpy, sklearn, pymannkendall, scipy, and pykrig are used for data analysis; geopandas, matplotlib, and shapely are used for graphical representation. The study data exhibited no significant inhomogeneity, although some data points were missing. Missing data were calculated and filled in by the lapse rate formula:

$$T_{cal} = T_{obs} + H_{Elevation} – L_{Elevation} * (-0.0065) \quad (1)$$

where,
T_{cal} = High elevation calculating temperature
T_{obs} =Low elevation observed temperature
$H_{Elevation}$ = High elevation (calculating temperature station's elevation)
$L_{Elevation}$= Low elevation (Observed temperature station's elevation)
Annual and seasonal averages were computed for each year across all stations, with the seasonal categorization defined as winter (including December of the previous year, January, and February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October and November). Physiographically, Nepal is divided into five regions: Terai, Siwalik, Middle Mountains, High Mountains, and Himalayas (Nayava et al., 2017), and in line with this classification, this study also considers five physiographic regions to analyze the spatial variations of temperatures in the Koshi Basin. Seasonal and annual temperature trends for all stations were analyzed using linear regression, and the spatial distribution of these trends was mapped through interpolation utilizing Kriging based on the station trends.Chand et al. (2021) calculated a lapse rate of $0.006\,°\mathrm{C\,m^{-1}}$ in the Narayani River Basin, while Nayava et al. (2017) found lapse rates of $0.0058\,°\mathrm{C\,m^{-1}}$ for eastern Nepal and $0.0057\,°\mathrm{C\,m^{-1}}$ for the entire country. This research utilized a theoretical lapse rate value of $0.0065\,°\mathrm{C\,m^{-1}}$.

Spatial and temporal variations in air temperature are influenced by factors such as physiography (e.g., slope, aspect, hilltops, and valleys), land cover characteristics, and incoming solar radiation; therefore, Quantification of the contribution of each factor is complicated. This study has focused solely on temperature variations based on altitude, specifically within five physiographic regions. Three types of temperature data were analyzed: Tmax, the mean of daily maximum temperature; Tmin, the mean of daily minimum temperature; and Tavg, the daily average temperature. To compare the relative magnitudes of the temperature data, the Mann-Kendall (MK) Mann and against Trend (1945) and Kendall (1949) test was employed to estimate monotonic trends—whether positive or negative—and their statistical significance. This analysis was conducted using Equations (1) and (2), with the variance determined through Equation (3):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{Sgn}(x_j - x_i) \quad (2)$$

$$\mathrm{Sgn}(x_j - x_i) = \begin{cases} 1, & \text{if } x_j - x_i > 1, \\ 0, & \text{if } x_j - x_i = 0, \\ -1, & \text{if } x_j - x_i < 0. \end{cases} \quad (3)$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \quad (4)$$

where n is the number of data points, m is the number of tied groups, and t_i is the number of observations in the i^{th} tied group.

The collected data were thoroughly examined and evaluated to ensure quality and consistency. Linear regression was employed to analyze the temporal and spatial variations of temperature. Subsequently, a time series analysis was performed, facilitating the fitting of a linear trend between the time series data (represented as y) and time (denoted as t), as articulated by the equation:

$$y = a + bt \quad (5)$$

Where: y represents the temperature or rainfall, t represents time (in years), a and b are constants estimated using the least squares method, which minimizes the sum of the squared differences between the observed and predicted values.
This method provides an accurate and reliable estimation of the overall trend in rainfall and temperature data across the study period.

3. Results

3.1. Seasonal Temperature Trends

Figs. 2, 3, 4, and 5 display temperature trend analyses based on three primary factors: temperature categories

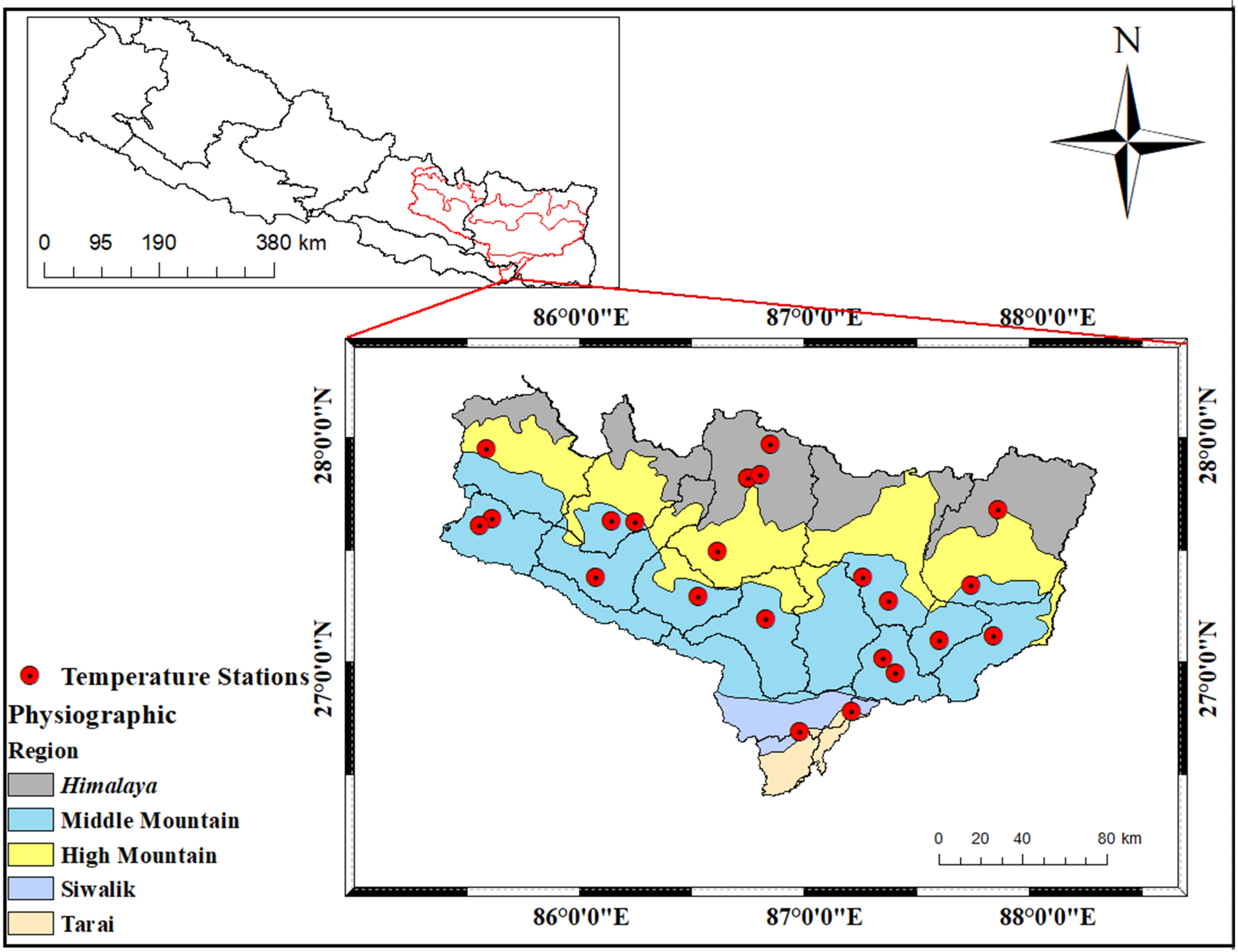


Figure 1: Selected stations for the study in the Koshi basin of Nepal inset map.

(Tavg, Tmax, Tmin), geographic regions (Himalayas, High Mountain, Middle Mountain, Siwalik, Terai, and the entire Koshi Basin), and seasonal classifications (Monsoon, Post-monsoon, Pre-monsoon, Winter, and annual trends) across various decades. The trends reveal substantial variability influenced by decade, temperature type, physiographic region, and seasonal attributes.

3.2. Pre-monsoon

Pre-monsoon season reveals overall cooling trends in the 1962-1971 decade except in the Himalayas regions, with a similar cooling trend from 1972 to 1981, and the later decade experienced a warming trend except for maximum and average temperatures showing the cooling trend in 2012-2021 (Fig. 2). For the overall period from 1962 to 2022, only the Siwalik region demonstrates a cooling trend; all other regions
display warming trends, particularly the Himalayan region, which shows a higher rate of warming at 0.02 °C/year.

3.3. Monsoon

During the Monsoon season (Fig. 3), temperature fluctuations have accelerated in recent decades, particularly from 2012 to 2021, with significant warming observed in average and minimum temperatures, while maximum temperatures predominantly show a cooling trend. Overall, from 1962 to 2022, the Monsoon season reflects a cooling trend across the various regions.

3.4. Post-monsoon

A cooling trend is evident in the post-monsoon period from 1962 to 1981 (Fig. 4), followed by a notable warming trend that has intensified in recent decades.

3.5. Winter

Distinct temperature trends are observed during the Winter season (Fig. 5) across different regions and time periods.

Table 1: Descriptions of the selected stations included in this study

Station No.[a]	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Physiographic Regions [b]
1316	Chatara	26.82	87.16	105	TAR
1201	Namche Bazar	27.82	86.72	3450	H
1401	Olangchuhg G	27.68	87.78	3119	H
1225	Syangboche	27.82	86.72	3700	H
1218	Tengboche	27.83	86.77	3857	H
1206	Okhaldhunga	27.31	86.50	1731	MM
1405	Taplejung	27.36	87.67	1744	MM
1103	Jiri	27.63	86.23	1877	MM
1036	Panchkhal	27.65	85.62	857	MM
1016	Sarmathang	27.94	85.59	2574	HM
1123	Manthali	27.39	86.06	497	MM
1124	Kabre	27.63	86.13	1755	MM
1212	Phatepur	26.73	86.93	101	TAR
1219	Salleri	27.51	86.59	2383	HM
1222	Diktel	27.21	86.79	1612	MM
1304	Pakhribas	27.05	87.29	1720	MM
1327	Khadbari	27.39	87.20	1064	MM
1303	Chainpur (East)	27.29	87.32	1277	MM
1307	Dhankuta	26.98	87.35	1192	MM
1024	Dhulikhel	27.62	85.57	1543	MM
1419	Phidim (Panchther)	27.14	87.77	1157	MM
1314	Terhathum	27.12	87.54	1525	MM
XXXX	Lubuche	27.96	86.81	5200	H

[a] Station numbers correspond to Department of Hydrology and Meteorology station index numbers. Numbers increase from west to east, and north to south.
[b] TAR stands for Terai, SW stands for Siwalik, MM represents Middle Mountain, HM stands for High Mountains, and H stands for Himalaya regions.

Minimum and average temperatures showed warming between 1982–1991 and 2012–2021, while a cooling trend occurred from 1962–1971. Maximum temperatures increased during the 1992–2001 and 2002–2011 decades, with a notable cooling of 0.52 °C in the High Mountain region from 2012 to 2021. Overall, from 1962 to 2022, the Siwalik region experienced a general cooling trend, while only the High Mountain region exhibited a warming trend.

3.6. Annual

Fig. 6 illustrates the annual temperature trends across different regions of the Koshi Basin revealing significant
* Indicates $p \leq 0.05$, which denotes significant changes.
variations over the decades. The first two decades (1962-1981) exhibit an overall cooling trend, with the exception of warming observed in the Himalayan regions, where maximum temperatures increased by 0.02 °C and minimum temperatures rose by 0.04 °C in later decades. The period from 1982 to 2021 predominantly shows a warming trend; however, from 2002 to 2011, the Siwalik region experienced a cooling trend, and from 2012 to 2021, maximum temperatures again exhibited a cooling trend. Overall annual temperature trends in Koshi Basin showed a decreasing trend followed by an increasing trend similar to the study conducted by Chand et al. (2021) at Narayani Basin Nepal. Shrestha et al. (1999) investigated maximum temperature trends in Nepal from 1971 to 1994, reporting an average annual temperature increase of 0.06 °C/year. Shrestha et al. (2017) observed a clear warming trend in maximum and minimum temperatures over the Transboundary Koshi basin from 1975 to 2010, with notable spatial variations. The past study of temporal and spatial analysis of five physiographic regions- Terai, Siwalik, Middle-mountain, and High-mountain and Himalayas of Koshi Basin presented via Table 2.

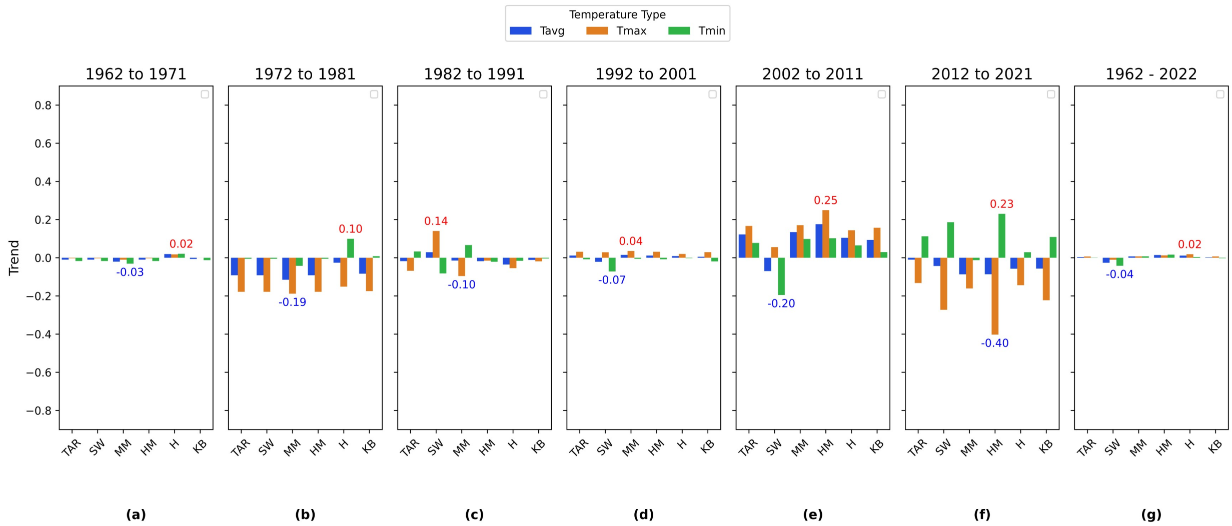


Figure 2: Pre-monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

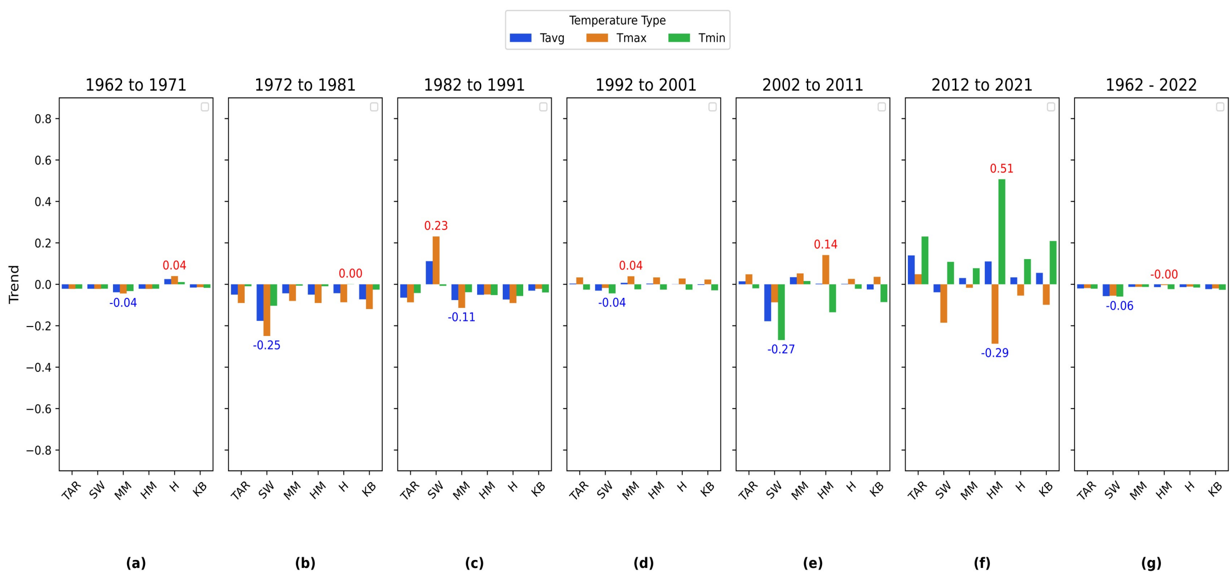


Figure 3: Monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

In the five physiographic regions of the Koshi Basin, temperature trends display distinct seasonal variations across physiographic regions (Table 2). In the Himalaya region, a significant warming trend is observed during the pre-monsoon season in $T_{\max}$ (0.0186, $p = 0.0115$), while other trends remain largely non-significant, including slight cooling in the monsoon ($T_{\max} : -0.0111, p = 0.1672$; $T_{\min} : -0.0160, p = 0.2340$) and winter seasons ($T_{\min} : -0.0177, p = 0.0972$).

The High Mountain region exhibits significant temperature changes across multiple seasons. In the post-monsoon, $T_{\max}$ and T_{avg} show strong warming trends ($T_{\max} : 0.0233, p = 0.0035$; $T_{\text{avg}} : 0.0200, p = 0.0035$), while the monsoon season shows a significant cooling trend in $T_{\min}$ ($-0.0230, p = 0.0019$). The pre-monsoon season also re-

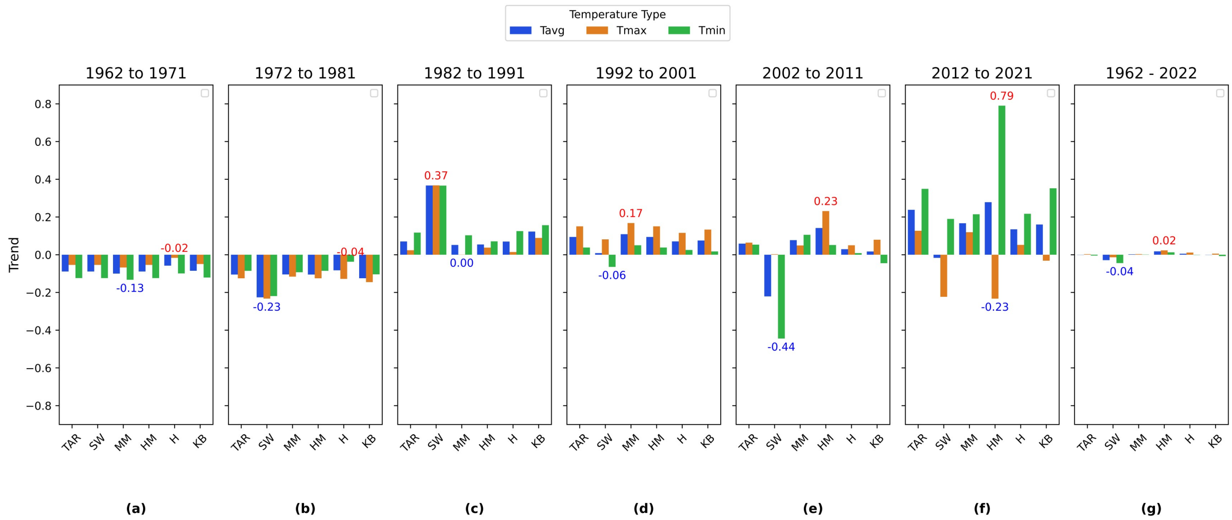


Figure 4: Post-monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

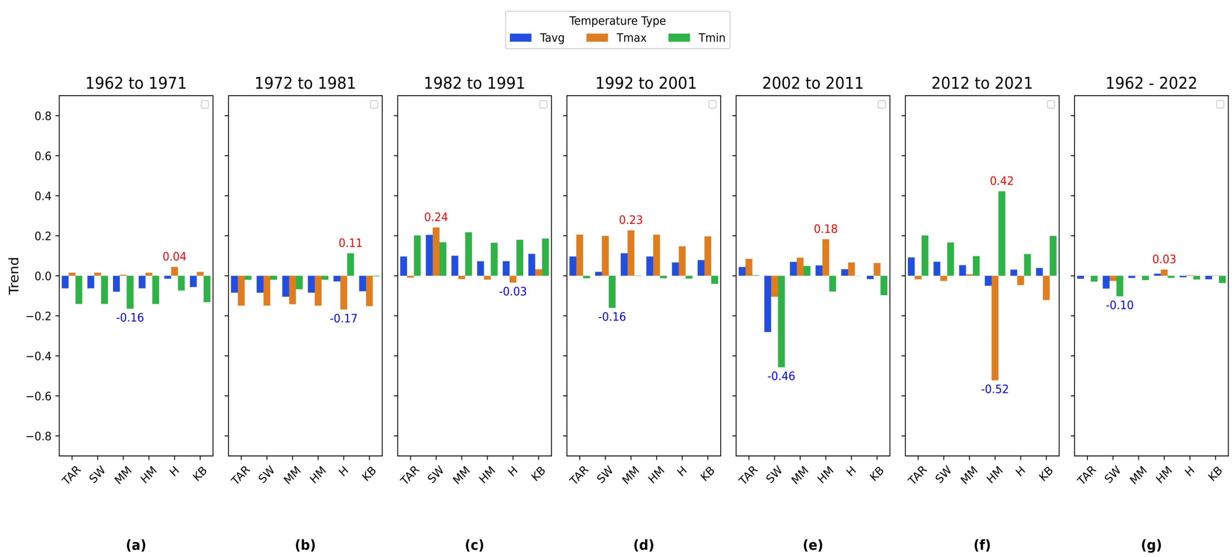


Figure 5: Winter temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

flects a notable warming in $T_{\min}$ $(0.0164, p = 0.0103)$ and T_{avg} $(0.0100, p = 0.0084)$, with additional warming in $T_{\max}$ during winter $(0.0317, p = 0.0058)$.

In the Middle Mountain region, a significant cooling trend is observed in the monsoon for both $T_{\max}$ $(-0.0122, p = 0.0338)$ and $T_{\min}$ $(-0.0130, p = 0.0076)$. The winter season also displays significant cooling in $T_{\min}$ $(-0.0210, p = 0.0002)$ and T_{avg} $(-0.0100, p = 0.0466)$, while other seasons show minimal changes.

The Siwalik region experiences substantial cooling across all seasons, particularly in the monsoon, where strong cooling trends are present in $T_{\max}$ $(-0.0552, p = 0.0000)$, $T_{\min}$ $(-0.0600, p = 0.0000)$, and T_{avg} $(-0.0600, p = 0.0000)$. Similarly, significant cooling trends persist in the winter

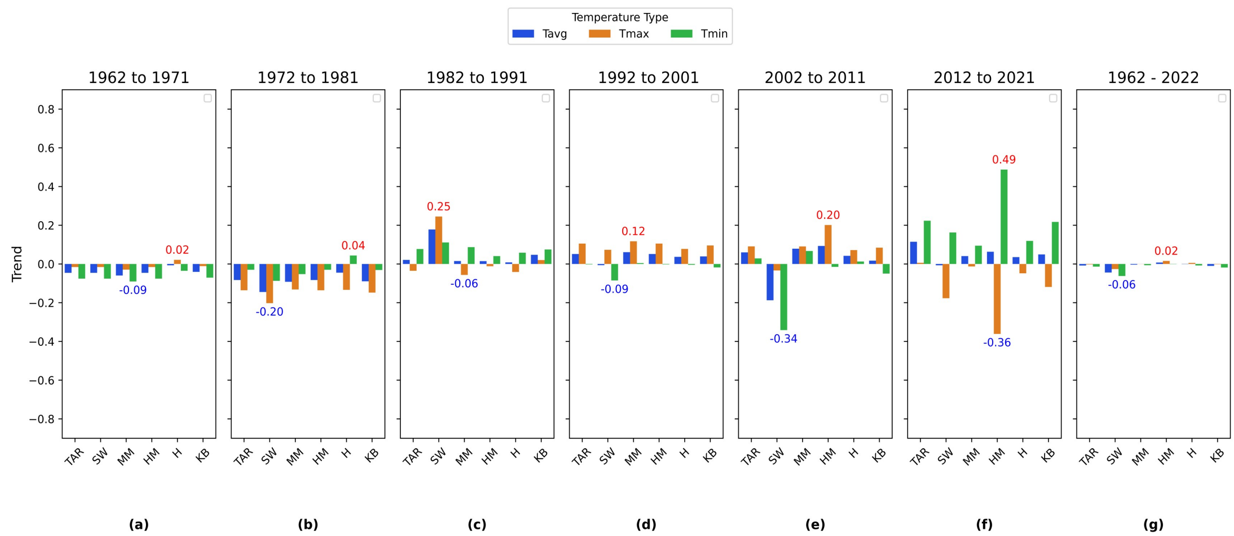


Figure 6: Annual temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

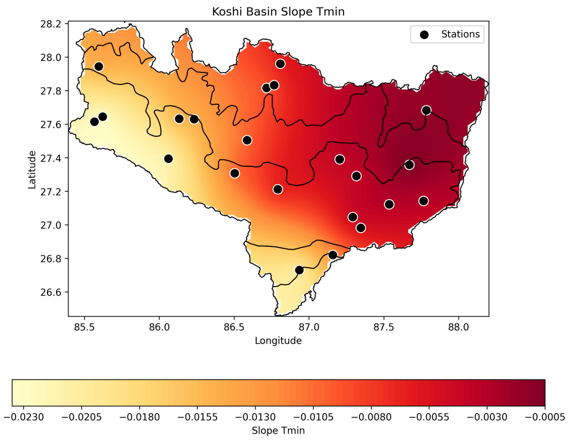
Table 2: **Spatial distribution of temporal trends of temperature for 1962-2022**

Region	Season	T_{max} Trend	T_{max} p-value	T_{min} Trend	T_{min} p-value	T_{avg} Trend	T_{avg} p-value
Himalaya	Monsoon	-0.01	0.17	-0.02	0.23	-0.01	0.20
	Postmonsoon	0.01	0.14	0.00	0.94	0.01	0.65
	Premonsoon	0.02*	0.01	0.00	0.80	0.01	0.31
	Winter	0.00	0.71	-0.02	0.10	-0.01	0.43
High Mountain	Monsoon	0.00	0.58	-0.02*	0.00	-0.01*	0.01
	Postmonsoon	0.02*	0.00	0.01	0.10	0.02*	0.00
	Premonsoon	0.01	0.08	0.02*	0.01	0.01*	0.01
	Winter	0.03*	0.01	-0.01	0.26	0.01	0.14
Middle Mountain	Monsoon	-0.01*	0.03	-0.01*	0.01	-0.01*	0.02
	Postmonsoon	0.00	0.59	0.00	0.83	0.00	0.68
	Premonsoon	0.01	0.23	0.01	0.16	0.01	0.17
	Winter	0.00	0.94	-0.02*	0.00	-0.01*	0.05
Siwalik	Monsoon	-0.06*	0.00	-0.06*	0.00	-0.06*	0.00
	Postmonsoon	-0.01	0.09	-0.04*	0.00	-0.03*	0.00
	Premonsoon	-0.01	0.19	-0.04*	0.00	-0.03*	0.00
	Winter	-0.03*	0.00	-0.10*	0.00	-0.06*	0.00
Terai	Monsoon	-0.02*	0.00	-0.02	0.00	-0.02	0.00
	Postmonsoon	0.00	0.58	0.00	0.46	0.00	0.86
	Premonsoon	0.01	0.26	0.00	0.83	0.00	0.43
	Winter	0.00	0.91	-0.03	0.00	-0.01	0.01

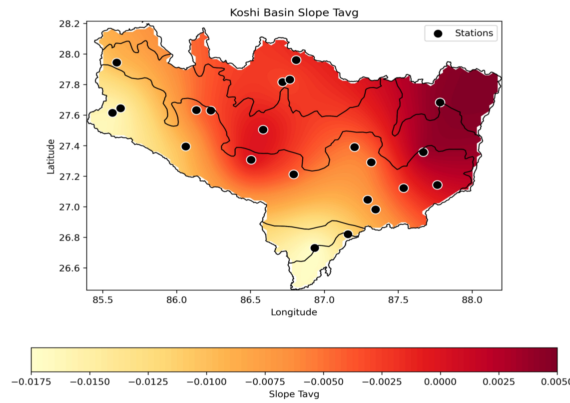
* Indicates $p \leq 0.05$ which denotes significant changes.

season (T_{max} : $-0.0260, p = 0.0030$; T_{min} : $-0.1000, p = 0.0000$; T_{avg} : $-0.0600, p = 0.0000$).

In the Terai region, notable cooling is observed during the monsoon in T_{max} ($-0.0183, p = 0.0005$), T_{min}



(a)



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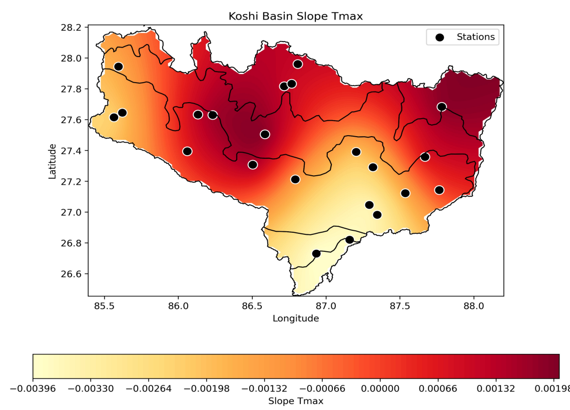

(c)

Figure 7: Spatial distributions of annual temperature trends for the period 1962–2022 for (a) Tmin, (b) Tavg, (c) Tmax

Table 3: **Regional temperature regression equations.**

Region	T_{min} **Equation**	T_{max} **Equation**	T_{avg} **Equation**
Himalaya	y = -0.01x + 15.46	y = 0.00x + 2.58	y = -0.00x + 9.02
High Mountain	y = -0.00x + 13.97	y = 0.01x + -9.35	y = 0.00x + 2.31
Middle Mountain	y = -0.01x + 27.88	y = -0.00x + 27.81	y = -0.00x + 27.85
Siwalik	y = -0.06x + 145.24	y = -0.03x + 91.55	y = -0.05x + 118.40
Terai	y = -0.01x + 50.79	y = -0.00x + 41.15	y = -0.01x + 45.97

$(-0.0215, p = 0.0000)$, and T_{avg} $(-0.0199, p = 0.0000)$. Additionally, the winter season shows a marked cooling trend in T_{min} $(-0.0280, p = 0.0000)$ and T_{avg} $(-0.0143, p = 0.0104)$, while other seasons display minimal trends.

3.7. Regional Temperature Trends

The Annual Regional Mann-Kendall test findings are shown in Table 4. This test evaluates trends in minimum (T_{min}), maximum (T_{max}), and average (T_{avg}) temperatures in five regions: Terai, Siwalik, Middle Mountains, High Mountains, and Himalaya. While T_{max} and T_{avg} show rising tendencies (0.005** and -0.000**, respectively) in the Himalaya, the T_{min} shows a decreasing trend (-0.009), and the latter two are not statistically significant ($p \geq 0.05$). T_{min} and T_{avg} (-0.008 and -0.003**) also exhibit declining patterns in the Middle Mountains, although T_{max} (-0.001**) shows a rather constant trend. The High Mountains, on the other hand, show an increasing trend in T_{min} (-0.016) and a more marked reduction in T_{max} and T_{avg} (0.008**

Table 4: Spatial distribution of temporal trends of temperature for 1962-2022

Regions	T_{min} Slope	T_{max} Slope	T_{avg} Slope
Himalaya	-0.009	0.005**	-0.000**
High Mountains	-0.016	0.008**	0.002**
Middle Mountains	-0.008	-0.001**	-0.003**
Siwalik	-0.063	-0.033	-0.05
Terai	-0.015	-0.003**	-0.006**

** indicates p ≥ 0.05 which denotes no significant changes.

and 0.002**). All temperature measurements exhibit similar declines in the Siwalik region: T_{min} (-0.063), T_{max} (-0.033), and T_{avg} (-0.05). Lastly, with T_{min} (-0.015), T_{max} (-0.003**), and T_{avg} (-0.006**) showing diminishing trends across all temperature parameters, the Terai likewise shows declining trends, but T_{max} and T_{avg} is not statistically significant. In a similar vein, the Koshi region's maximum temperature grew at a rate of 0.058 °C/year and its lowest temperature increased at a rate of 0.014 °C/year during the forty years leading up to 1963–2009 (Nepal, 2016). The Annual Regional Mann-Kendall test (Table 4) showed that higher elevation Himalaya and High Mountains temperatures appear to be increasing, while lower elevation temperatures did not display significant change. Similarly, Shrestha and Aryal (2011) found pronounced warming in higher elevations and lower or even lacking temperature trends in lower elevations (Terai, Siwalik).

Fig. 7 illustrates a heterogeneous temperature trend across the Koshi Basin region. An annual average of daily minimum temperatures shows an overall cooling trend, as shown in Fig. 7a, ranging from -0.0005 °C to -0.023 °C, with higher elevations experiencing less cooling. As shown in Fig. 7b, the annual average temperatures reveal both warming and cooling trends, ranging from -0.0175 °C to 0.005 °C, where higher elevations tend to warm or cool less when compared to the Terai and Siwalik regions. Similarly, the annual average of daily maximum temperatures shows trends from cooling to slight warming (Fig. 7c), ranging from -0.00396°C to 0.00198 °C, with T_{max} exhibiting a warming trend in higher elevation areas. A study conducted by Paudel et al. (2021) in the transboundary Koshi Basin for the years between 1980 and 2018 revealed an increase in the mean annual temperature by 0.084 °C/year in the mountain region ($p = 0.0005$), by 0.0975 °C/year in the hill region ($p = 0.0002$), and by 0.0187 °C/year in the Terai region ($p = 0.0206$), with significant correlations throughout.

4. Discussion

The temperature distribution of spatial and temporal trends across Koshi regions in Nepal, with detailed information from a previous study presented in Table 5 from 1962 to 2022. In the Hills and Middle Mountains, mixed patterns are evident, with significant declines in Tmin during the monsoon and winter seasons. In contrast, the High Mountains display minimal seasonal variation, aside from a notable increase in Tmax primarily during the pre-monsoon season. Significant seasonal cooling tendencies are visible in the Siwalik and Terai areas, especially during the Monsoon and Winter, indicating different regional temperature behaviors.

Shrestha et al. (2017) analyzed long-term trends in seasonal maximum and minimum temperatures from 1975 to 2010, finding widespread significant warming, particularly in minimum temperature indices, with stronger warming trends in recent decades; however, some stations showed declines in winter and pre-monsoon temperatures, and seasonal minimum temperatures generally increased more than maximum temperatures. The study conducted by Shrestha and Aryal (2011) identified consistent warming trends in seasonal mean maximum temperatures across all regions of Nepal from 1977 to 1994. Their study observed warming during the winter, post-monsoon, pre-monsoon, and monsoon seasons. A study by Nayava et al. (2017) for 1981–2010 showed varying seasonal temperature trends across Nepal. There is warming in the Terai, Valley, Hill and Mountain regions across all seasons from 0.01-0.13 °C/year, with the Trans-Himalaya showing 0.03 °C in pre-monsoon, -0.02 °C in post-monsoon, 0.01 °C in monsoon, and 0.08°C in winter. Similarly, Shrestha et al. (1999) showed significant regional and seasonal variations for 1977 to 1994 in temperature trends across Nepal, with the Trans-Himalaya experiencing the highest winter warming at 0.124 °C/year, the Middle Mountains seeing the largest monsoon increase at 0.094 °C/year, and the post-monsoon season showing an overall national average warming rate of 0.059 °C/year, while the Terai region exhibited a much lower warming rate of 0.006 °C/year in winter and -0.004 °C/year in pre-monsoon.

Adhikari and Devkota (2016) studied temperature trends from 1988 to 2010 in the Annapurna, Langtang, and Khumbu regions of Nepal. In the Khumbu region, moderate warming was observed across all seasons, with maximum temperatures rising by 0.0857 °C/year in winter and 0.0628 °C/year in pre-monsoon. The trend in the change of minimum temperatures was slightly different with a small increase of 0.0101 °C/year in spring and a decrease of -0.0024 °C/year during monsoon. Overall, mean temperatures increased by 0.0857 °C/year in winter, with Khumbu showing lower trends compared to Langtang and Annapurna, particularly in minimum temperatures. Similarly, Marahatta et al. (2009) report consistent warming trends across Nepal, with mean increasing annually by temperatures 0.025 °C, maximum temperatures by 0.043 °C and minimum temperatures by 0.007 °C. Nayava et al. (2017) emphasizes that warming is altitude-dependent, with higher elevations, such as hilltops and mountain tops, experiencing greater temperature increases. Shrestha et al. (1999) and Shrestha and Aryal (2011) also found significant warming in higher altitudes, while Paudel et al. (2021) identified annual higher temperature trends in the Hill regions closely followed by Mountain's regions than Tarai regions of Koshi Basin.

5. Conclusion

Temperature trends across the Koshi Basin show regional variations. The Himalaya region shows warming in the premonsoon, while the High Mountain region exhibits significant seasonal temperature changes. The Middle Mountain region shows cooling in the monsoon and winter. The Siwalik and Tarai regions experience consistent cooling across seasons, particularly in T_{min} and T_{avg}.

Seasonal temperatures show heterogeneous trends across decades, temperature categories, and physiographic regions. Overall, observed seasonal and annual temperature trends decreased in the initial decades and increased in later decades.

The Mann-Kendall Test for annual regional trends from 1962 to 2022 revealed varied temperature patterns across the Koshi Basin. In the Himalaya region, T_{max} and T_{avg} slightly increased, while T_{min} decreased, though the changes in T_{max} and T_{avg} were not statistically significant. The Middle Mountains exhibited a cooling trend in T_{min} and T_{avg}, with T_{max} remaining constant. In the High Mountains, T_{min} increased significantly, while T_{max} and T_{avg} experienced a notable decrease. The Siwalik region showed consistent declines in all temperature parameters, and the Tarai region also displayed decreasing trends in T_{min}, T_{max}, and T_{avg}, though T_{max} and T_{avg} were not statistically significant.

Acknowledgments

We thank the Department of Hydrology and Meteorology, Government of Nepal for kindly providing us with meteorological data. We are also grateful to the Department of Environmental Science and Engineering, Kathmandu University for providing the necessary resources and conducive environment for conducting this study and Dr. Janak Lal Nayava for valuable suggestions along with reviewing our work.

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