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Contemporary Temperature Fluctuation in Urban Areas of Pakistan

Raheel Anjum [1,2,3], Xiubin He [1,*], Javed Iqbal Tanoli [1,2,4] and Syed Turab Raza [1,2]

1 Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, No. 9, Block 4, South Renmin Road, Chengdu 610041, China; rhyousafzai@gmail.com (R.A.); javedtanoli@gmail.com (J.I.T.); s.turabkazmi@imde.ac.cn (S.T.R.)
2 Institute of Mountain Hazards and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
3 Department of Economics, Abdul Wali Khan University, Khyber Pakhtunkhwa, Mardan 23200, Pakistan
4 Department of Earth Sciences, COMSATS Institute of Information Technology, Abbottabad 22060, Pakistan
* Correspondence: xiubinh@imde.ac.cn; Tel.: +86-28-8543-7396

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Abstract: Annual temperature data from thirty meteorological stations in Pakistan's major urban areas were selected to investigate trends in annual average and maximum temperature during 1970–2009. A combination of parametric and non-parametric tests including linear regression, the Mann-Kendall trend test and Sen's slope estimator was used for the analysis. Annual average and maximum temperature series showed an overall increasing trend for 90% of the stations and a decreasing trend for 10% of the stations in the study area. The highest significant increment of annual average temperature was observed at Gilgit, Hyderabad, Quetta and Lasbela stations at the rate of 0.49 °C per decade. The highest increment of annual maximum temperature was obtained at Chitral, Gilgit, Nawabshah and Quetta at the rate of 0.31 °C per decade. According to simple linear regression and the Mann-Kendall test, the annual average temperature showed a significant increasing trend for 43% of the stations (at a 0.001 level of significance) and 23% of the stations (at the 0.05 level). Annual maximum temperature showed a significant increasing trend for 26% of the stations (at the 0.001 level of significance) and 23% of the stations (at the 0.05 level). In general, the results showed increasing trends for the considered parameters, although annual average temperature showed a higher increasing rate than annual maximum temperature during the study period.

Keywords: urban areas; temperature trends; parametric and non-parametric tests; Pakistan

1. Introduction

Since the 1950's, a continuous increase in carbon dioxide, associated radioactive gases and related anthropogenic activities has been documented, and future changes in climate are anticipated [1,2]. Climate change is the detection of persistent or extended variability of mean properties caused by natural variability or human activities [3]. The global meteorological data show overall warming trends with different spatial and temporal variations depending on local climatic regimes [1,4]. According to the Fourth Assessment Report of the International Panel on Climate Change [5], the global average surface temperature rose by 0.74 °C during the twentieth century. The recent five decade warming rate of 0.13 ± 0.03 °C/decade is almost twice that of last ten decades (0.07 ± 0.02 °C/decade). The global average surface temperature is predicted to rise by 1.8–4.0 °C and expected to reach 6.4 °C in a worst-case scenario by the end of the twenty-first century [6]. The issue of climate change and temperature variability because of urbanization, industrialization and greenhouse gases has been investigated extensively throughout the world. Most of the studies focused on climatic changes in metropolitans and economic hubs, e.g., seasonal temperature trends [4,6–8], urbanization affects, reduced rainfall and potential evapotranspiration, effect of cloud cover and suspended particulate matter [9,10], trends in minimum or maximum temperature [1,2,7] and diurnal temperature range [11,12].

Annual and seasonal significant increasing trends of maximum and minimum temperature were detected in the Western half of Iran due to urbanization and greenhouse gas emissions from human activities [1]. The Maharlo watershed, South-western, arid and semi-arid regions of Iran showed definite signs of climate change and global warming with significantly increasing annual air temperature and a decreasing trend in precipitation. The increasing trends in minimum temperature were stronger than those of maximum temperature in the Maharlo watershed which experienced a step change in 1977 [3]. Rising annual mean air temperature and warming trends were concentrated in northern Shanxi with an abrupt increasing trend in the late 1980's and 1990's associated with enhanced CO_2 emissions over the last fifty years in China, according to Fan and Wang [13]. Climatic sensitivity of Bangladesh assessed by Siddik and Rahman [14] revealed a highly significant positive trend for annual mean and mean maximum temperature and significant positive trends were found for mean maximum and mean minimum temperature from June–November and November–February, respectively. Urban areas are affected globally by climate change; the temperature in Sao Paolo, Brazil, rose by 2 °C since 1993, and increasing temperature trends were found in Beijing, China, and the annual mean temperature in Seoul, Korea, increased by 1.5 °C during the last 29 years as mentioned by Sajjad et al. [15].

The annual temperature variation in urban areas is higher than in rural areas; urbanization and land use change initially influence the microclimate and minimum temperature of cities [4,9,10,15]. Therefore, analysis of local temperature is an important climatic factor to assess the climatic changes in the growing urban areas because of urbanization and industrialization. Due to the importance of temperature being the major factor for climatic changes, regional temperature trends in growing urban areas of Pakistan are of major interest.

These cities are becoming urban clusters in the regions due to population and urban pressure. The openness of the economy, land reforms and establishment of different industries in the 1960's–1990's around the urban areas played a vital role in rural–urban migration. Environmental degradation was neglected and resources were over exploited, and the Pakistan Environmental Protection Agency (PAK-EPA) started operation in 1997. The urban areas of Pakistan are highly vulnerable to global warming and climate change [16]. The cities have grown irregularly and dense buildings enhanced the urban heat island effect. Industrial zones developed in these areas affected the microclimate due to low quality fuel combustion and massive greenhouse gas emissions. The additional fleet of vehicles and fuel combustible electricity generators in urban areas consume almost half of the country's fuel consumption which adds to the environmental pollution and stress of the existing infrastructure. Massive deforestation throughout the country, especially in the northern part, further exasperates climatic trends. Severe heat wave incidents were repeatedly reported throughout the country, especially in Sindh and Balochistan provinces during the past few decades, claiming lives. Daily sulphur dioxide and nitrogen dioxide levels and limited studies on ozone in the 1990's showed higher values than the World Health Organization (WHO) standards at several sites. Pakistan is located in a subtropical zone with unique geography that exhibits spatial and temporal variability of temperature, and stations are scattered across the country with different elevations.

Until now, climatic changes and their potential variability with respect to meteorological aspects have not yet been vigorously investigated in urban areas of Pakistan. [17,18] observed obvious climatic changes and global warming with increasing trends in maximum and minimum temperature with no obvious precipitation trends in the upper middle and lower Indus River basin. Hussain et al. [19] indicated an increasing trend in winter temperature for high and sub-mountains with warmer days and cooler nights in high mountains. Both regions showed rising trends for maximum temperature during the monsoon season. Particularly high mountainous areas showed a rising maximum temperature trend in October–November and April–May. These seasonal variations have implications for water resources and food security for the country, as Sultana et al. [20] found drastically declined yields due to increasing temperature and CO_2 emissions in arid, semi-arid and sub-humid climatic zones. Concerning global warming and climate change, Zahid and Rasul [21] found a nationwide positive trend for a heat wave of magnitude ≥40 °C and ≥45 °C for 5 and 7 consecutive days, respectively; a heat wave frequency ≥40 °C and ≥45 °C for 10 consecutive days occurred in Punjab, Sindh, and an increasing trend throughout the period was observed in Balochistan. Heat waves prevailing for several days with 5 °C higher temperature than normal were also evident in the Eastern Mediterranean climate according to Kostopoulou and Jones [22]. However, Sadiq and Qureshi [16] found a maximum increment for annual mean temperature at Quetta (0.057 °C) and the lowest increment at Peshawar (0.019 °C), both greater than the global mean increment. Prolonged monsoon rains and especially rainfall during the 1990's caused a strange negative trend in maximum temperature at Lahore Ahmad, Fatima, Awan and Anwar [18]. Karachi is an urbanized and industrialized economic hub, and Sajjad, Hussain, Ahmed Khan, Raza, Zaman and Ahmed [15] found increasing mean maximum and mean annual temperature with extreme variability during 1976–2005 and no change in mean minimum temperature. Ambreen et al. [23] found a slightly rising, spatially severe varying temperature trend in December for the mountainous areas compared with the plain areas of Pakistan.

Better knowledge of the temperature variability of the selected 30 meteorological stations located in urban areas with a dense and relatively complete data set, rather than global networks, would enable us to understand the regional temperature dynamics, water management and effects of climatic shocks in the near future. The urban areas of Pakistan are under severe stress caused by population growth, unplanned urbanization and industrialization, fuel consumption and rising levels of air pollution, directly affecting the microclimate. The climatic changes in the region are visible as recent heat waves, droughts and flood events, but no systematic studies have been reported to evaluate the climatic trends over these urban areas. The trend analysis of temperature in urban areas will provide an understanding of widespread climatic trends over the region.

The purpose of the present study is to investigate the local trends in annual average and annual maximum temperature over major urban areas of Pakistan during 1970–2009. The objectives of this study are (1) to analyze and discuss the temperature trends in the urban areas for a possible linkage to global warming/climate change and (2) to understand the regional and micro climatic trends using linear regression and the Mann-Kendall test.

2. Profile of the Study Area

Geographically, Pakistan lies between (24°–37°) North latitudes and (62°–75°) East longitudes (Figure 1). The climatic conditions in Pakistan have a wide range of regional variability. The north of the country, including regions of Skardu, Chitral, Gilgit, Drosh, Dir, Astor, Peshawar, Kakul, Kotli and Murree, is dominated by mountains where climate ranges from humid to arid, and higher altitudes receive winter precipitation in the form of snow. The climate in the middle Indus River basin that mostly lies in Punjab province, including regions of Sialkot, Multan, Faisalabad, Lahore, Bahawalpur, Bahawalnagar, Mianwali and the capital city of Islamabad, is of a tropical and continental nature. The middle basin receives mean annual rainfall ranging from 300 to 800 mm, and annual mean air temperature ranges between 23 and 33 °C. The lower Indus River basin in Sindh province, including regions of Badin, Hyderabad, Nawabshah, Jacobabad, Khanpur and Karachi, is characterised by arid climate. The lower basin receives mean annual rainfall less than 200 mm, and annual mean temperature ranges between 17 and 28 °C [18]. The province of Balochistan, including regions of Sibi, Panjgur, Lasbela, Pasni, Quetta and Kalat, is characterised by an arid climate that receives the lowest rainfall and is prone to desertification [21].

Since the industrial boom in Pakistan, the selected urban areas became home to industrial agglomeration and sources of total nitrogen oxide (NO_x), sulphur dioxide (SO_2), and particulate matter (PM_{10}) emissions to the environment [24]. The concentrations of the toxic materials Pb, Zn, Cd and PM_{10} are 4.4 μg·m^{-3}, 12 μg·m^{-3}, 0.077 μg·m^{-3} and 340 μg·m^{-3}, respectively, i.e., well above the World Health Organization guidelines due to industrial coal and biomass burning in the urban areas of Pakistan [25]. Unplanned increases in automobiles and industries deteriorated the environment as average values of suspended particulate matter (160.28 μg·m^{-3}), SO_2 (15–50 μg·m^{-3}), NO_x (97 μg·m^{-3}), lead and carbon mono-oxide (3800.6 μg·m^{-3}) were above acceptable levels [26,27]. Mega cities are responsible for higher carbon dioxide (CO_2) emissions and contribution to the global gross domestic product. In addition, with an annual growth rate of 6.5% in the industrial zones and a rise in the number of vehicles from 0.8 million to 4.0 million, almost a 400% increase in the last few decades, Karachi consumes considerable energy and contributes CO_2 and other emissions to the environment [15]. These cities have high urban population density and CO_2 emissions according to GoP [28], as during the study period, the average population density rose from 80 to 220 people per square kilometre, and the CO_2 emissions rose from 4 to 32 million metric tons (Figure 2).

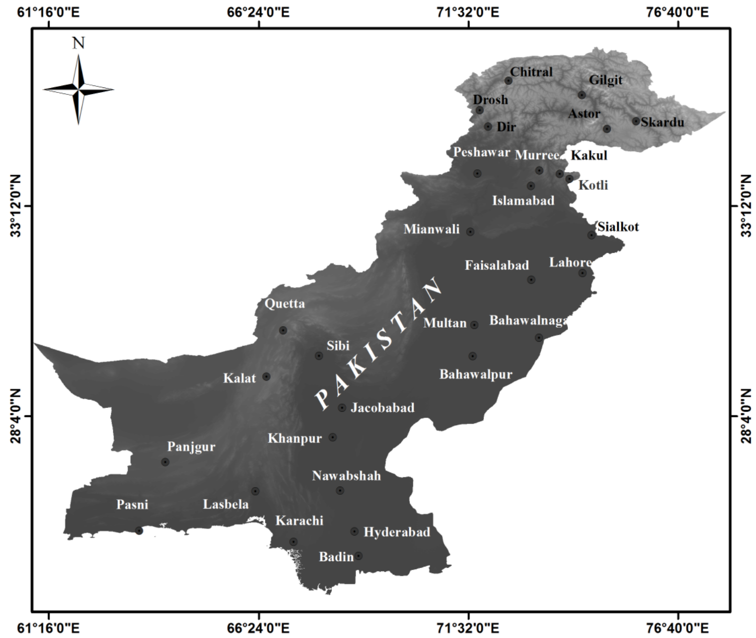

Figure 1. Spatial distribution of stations in Pakistan.

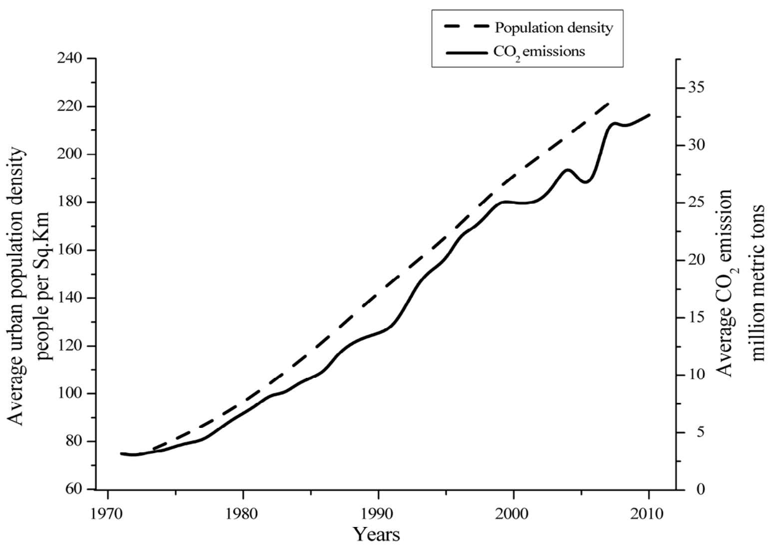

Figure 2. Commutative average urban population density and carbon dioxide emissions for urban areas.

3. Materials and Methods

3.1. Data

Annual average and maximum temperature data for 40 years (1970–2009) were used to assess possible temperature trends at 30 selected meteorological stations located in urban areas of Pakistan. The data were collected from the Pakistan Meteorological Department, Islamabad, for all the available stations in the national database. The information about the stations, geographical location, elevation in meters above sea level and climatic zones is presented in Table 1 and Figure 1. Data quality was considered as non-parametric tests are robust to outliers, while the magnitude of the possible trend based on parametric tests is greatly affected by outliers [7]. The collected data set was plotted and visually inspected for outliers and missing values. The normal ratio method was used for suspicious values by following [7,29], but there were no missing values found in the data set, and the data set was used without any treatment.

Table 1. Location and description of the weather stations.

Station No	Station	Latitude (E)	Longitude (N)	Elevation (m a.s.l *)	Climatic Zone
1	Skardu	35°30′	75°68′	2317	Humid to arid
2	Chitral	35°85′	71°83′	1498	Humid to arid
3	Gilgit	35°55′	74°20′	1460	Humid to arid
4	Drosh	35°56′	71°85′	1464	Humid to arid
5	Dir	35°20′	71°85′	1375	Humid to arid
6	Astor	35°33′	74°90′	2168	Humid to arid
7	Peshawar	34°02′	71°56′	327	Humid to arid
8	Kakul	34°18′	73°25′	1308	Humid to arid
9	Kotli	33°51′	73°90′	614	Humid to arid
10	Murree	33°91′	73°38′	2167	Humid to arid
11	Sialkot	32°51′	74°53′	255	Tropical to continental
12	Multan	30°20′	71°43′	122	Tropical to continental
13	Faisalabad	31°43′	73°13′	186	Tropical to continental
14	Lahore	31°33′	74°20′	214	Tropical to continental
15	Bahawalpur	29°20′	71°47′	110	Tropical to continental
16	Bahawalnagar	29°20′	73°51′	161	Tropical to continental
17	Mianwali	32°91′	71°85′	212	Tropical to continental
18	Islamabad	33°72′	73°04′	579	Tropical to continental
19	Badin	24°38′	68°54′	9	Arid
20	Hyderabad	25°23′	68°25′	28	Arid
21	Nawabshah	26°15′	68°22′	37	Arid
22	Jacobabad	28°18′	68°28′	55	Arid
23	Khanpur	27°53′	68°23′	53	Arid
24	Karachi	24°54′	66°56′	22	Coastal
25	Sibi	28°95′	66°91′	133	Hyper arid
26	Panjgur	26°96′	64°10′	968	Hyper arid
27	Lasbela	26°23′	66°16′	87	Hyper arid
28	Pasni	25°26′	63°48′	9	Hyper arid
29	Quetta	30°11′	66°57′	1626	Dry
30	Kalat	29°02′	66°35′	2015	Hyper arid

Notes: * m a.s.l refers to meters above sea level.

3.2. Statistical Tests for Trend Detection

There are a variety of trend detection tests which can be used for meteorological trends [2,30]. In the present study, a combination of parametric and non-parametric methods was applied. The parametric methods are known for their simplicity and strict assumptions, while their counterparts have similar power with no strict assumptions [31,32]. The methods used in this study are as follows.

3.2.1. Mann-Kendall Trend Test

Mann-Kendall (Z) is a ranked based non-parametric trend detection test. Its application does not require the data to be normally distributed, as non-parametric trend detection techniques are not sensitive to the assumption of normal distribution and can tolerate outliers [1,8,17,33]. According to this technique, the null hypothesis H_0 states that the sample data have no significant trend, if $-Z_{\alpha/2} < Z < Z_{\alpha/2}$, where $Z_{\alpha/2}$ is the standard normal deviation. This technique has been commonly used for identification of significant trends in hydro meteorological time series because these time series often depart from normality so the non-parametric techniques are considered most appropriate [6,17,33]. The test statistic S of Mann-Kendall can be given as:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \mathrm{Sign}(X_i - X_j) \tag{1}$$

$$\mathrm{Sign}(X_i - X_j) = \left\{ \begin{array}{c} \text{if } (X_i - X_j) < 0 \text{ then } -1 \\ \text{if } (X_i - X_j) = 0 \text{ then } 0 \\ \text{if } (X_i - X_j) > 0 \text{ then } 1 \end{array} \right\} \tag{2}$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{n} t_k(t_k-1)(2t_k+5)}{18} \tag{3}$$

where n is the number of data points and X_i and X_j are the sequential data in the time series, $\sum t_k$ is the number of ties for the k-th value. The second term in Equation (3) is given for tied censored data. The Mann-Kendall Z standard test statistic can be computed as:

$$Z = \left\{ \begin{array}{c} \text{if } S < 0 \text{ then } \frac{s+1}{\sqrt{\mathrm{var}\ (S)}} \\ \text{if } (X_i - X_j) = 0 \text{ then } 0 \\ \text{if } (X_i - X_j) > \text{ then } \frac{s-1}{\sqrt{\mathrm{var}\ (S)}} \end{array} \right\} \tag{4}$$

The value of the Mann-Kendall Z statistic follows a standard normal distribution with mean 0 and variance 1 [17]. Positive Z values indicate upward (increasing) trends while negative Z values reveal downward (decreasing) trends. When testing for both increasing and decreasing trends at a significance level α that shows the strength of the trend, the null hypothesis is rejected for the absolute value of Z greater than $Z_{1\text{-}\alpha/2}$, obtained from the standard normal cumulative distribution tables [1,17,34]. The strength of trend for the present study was assessed at different significance levels as; (p = 0.000) "Very strong"; ($p \leq 0.05$) "Strong"; (p = 0.10) "Low".

The Mann-Kendall test requires the data series to be serially independent, the trends may be over estimated or under estimated in the presence of positive or negative serial correlation in the time series that threatens the significance level of the trend [8,17,34–36]. We applied the Breusch-Godfrey serial correlation LM test to all the stations at significance level α = 0.05. The test statistic for all the stations was insignificant and original series were used for analysis.

3.2.2. Sen's Slope Estimator

Using the slope estimator method (Q_{sen}) proposed by Sen [37] assumes the series trend to be linear [1,6,17,31,34], the magnitude of the trend in hydro meteorological parameters can be obtained as follows,

$$Q_{sen} = \mathrm{Median}\left[(Y_i - Y_j)/(i-j)\right] \forall j < i \tag{5}$$

Y_i and Y_j are the data points for time period i and j, respectively. The estimate provides the rate of change in any variable for the period under consideration, enabling determination of the total change. If there are n numbers of observations, then the Sen's estimator is computed by following [1,38,39],

$$f = \begin{cases} Q_{\left[\frac{n+1}{2}\right]} \text{ if } n \text{ is odd} \\ \frac{1}{2}\left(Q_{\left[\frac{n}{2}\right]} + Q_{\left[\frac{n+2}{2}\right]}\right) \text{ if } n \text{ is even} \end{cases} \tag{6}$$

The test statistics Q_{sen} is the median of all slope estimates. Positive and negative signs of the test statistics indicate increasing and decreasing trends, respectively.

3.2.3. Linear Regression Method

A linear regression method was applied to analyze the trends in annual average and maximum temperature. A wide range of statistical methods have been commonly used in trend detection at global and local scales [4]. The trend significance is assessed through Student's *t*-test following [4,6,15,40]. The relationship between temperature and time is specified as

$$\begin{gathered} \text{Temperature} = f\ (\text{time}) \\ Y = \alpha + \beta X + \varepsilon_{\text{i}} \end{gathered} \tag{7}$$

where Y shows annual average and maximum temperature, X shows the time period under consideration, and ε_i shows the error term. Student's *t*-value is calculated to check the statistical significance of null hypothesis H_0: $\beta = 0$ for each parameter as

$$t_{\text{cal}} = \frac{\hat{\beta}}{SE(\hat{\beta})} \tag{8}$$

where β shows the slope coefficient of the regression and SE is the standard error of the slope showing the change rate in a parameter per unit time.

The slope of the regression, indicating mean temporal change, was calculated for the considered temperature parameters. The positive and negative values for the slope showed increasing and decreasing trends, respectively. The slope was multiplied by the number of years to calculate the total change during the period under consideration [1]. Different significance levels, i.e., (p = 0.000) "Very strong"; ($p \leq$ 0. 05) "Strong"; (p = 0.10) "Low" were used to assess the estimated results.

4. Results and Discussion

Trends in annual average and maximum temperature series were assessed through simple linear regression (r), the Mann-Kendall trend test (Z) and Sen's slope estimator (Q). The trend statistics from the analysis were very similar for all methods. The results for annual average temperature (Annual T_{avg}) and annual maximum temperature (Annual T_{max}) are shown in Table 2. Mann-Kendall statistic (Z) values for annual average and maximum temperature were plotted for observational analysis as shown in Figures 3 and 4; the significance of the temperature trend is represented by values with asterisks.

The results from Table 2 and Figures 3 and 4 are further explained as increasing trends in annual average and maximum temperature series were detected at all stations except Kakul, Faisalabad and Lahore. Based on the Mann-Kendall trend test and Sen's slope estimator method, annual average temperature showed significant increasing trends at 7 meteorological stations at the 95% and 13 meteorological stations at the 99% significance levels. According to Sen's slope estimator, the significant increasing trend for annual average temperature ranged from 0.26 °C per decade at Nawabshah to 0.49 °C per decade at the Gilgit, Hyderabad, Quetta and Lasbela stations. On the contrary, the decreasing trend for annual average temperature at Lahore, Kakul and Faisalabad was statistically insignificant. In the northern part of the country, a decadal significant increasing trend in annual average temperature was found at a rate of 0.1 °C at Murree, 0.2 °C at Dir and Drosh, 0.3 °C at Chitral and Astor and 0.4 °C at the Gilgit station. In the middle and lower Indus basin valley, a significant increasing trend at Bahawalnagar, Badin, Jacobabad, Khanpur and Karachi was found at a rate of 0.3 °C per decade, whereas, the annual average temperature trend in Hyderabad was

0.49 °C per decade. In Balochistan province, Sibi, Panjgur and Pasni showed a significant increasing trend for annual average temperature at 0.3 °C per decade, and the trend in Lasbela and Quetta remained at 0.49 °C per decade. The derived results in the present study are in accordance with Ambreen, Ahmad, Sultan, Sun and Nawaz [23], who specified an isothermal shift and temperature variability in mountainous areas compared with plain areas of Pakistan, as the stations in northern regions and Balochistan province showed a significant increasing temperature trend that depicted the regional warming trend in the northern areas and some hilly areas of Balochistan. Heat wave historical records for Pakistan presented by Zahid and Rasul [21] reported previous events and expected higher intensity heat waves for Sindh and Balochistan. Heat waves have been reported for being responsible for alteration in temperature trends in the Mediterranean region, according to Galdies [41]. Another logical reason for increasing temperature was highlighted by Ambreen et al. [42] as annual Extraterrestrial Solar Radiation (ESR) reduced from south to north in Pakistan; the coastal areas received the maximum amount of ESR that ranged from 11,865–12,326 Mega joule (MJ/m^2) while Balochistan Plateau and northern parts of the lower Indus plain received the second highest ERS that ranged from 11,505 to 11,864 (MJ/m^2). The results derived in the present study verified the rising trends in respective meteorological stations in the urban areas of Sindh and Balochistan. Karachi is a highly urbanized and industrialized city and Sajjad, Hussain, Ahmed Khan, Raza, Zaman and Ahmed [15] also found an overall increasing trend in annual mean temperature. In addition, an insignificant increasing trend was found for Peshawar and Islamabad.

Table 2. Statistical test results for annual average and maximum temperature over the period 1970–2009.

Station No	Station	Annual Tavg			Annual Tmax		
		Mann-Kendall (Z)	**Sen's Slope (Q)**	**Regression Slopes (r)**	**Mann-Kendall (Z)**	**Sen's Slope (Q)**	**Regression Slopes (r)**
1	Skardu	3.02	0.02	0.015	1.01	0.02	0.027
2	Chitral	2.21 ***	0.03	0.04 ***	1.02 ***	0.031	0.048 ***
3	Gilgit	3.06 ***	0.049	0.035 ***	0.69 ***	0.031	0.013
4	Drosh	2.50 **	0.02	0.04 **	1.20 **	0.01	0.014 **
5	Dir	3.10 **	0.02	0.01 **	2.00	0.03	0.051
6	Astor	2.83 **	0.03	1.92 **	1.40	0.02	0.034
7	Peshawar	0.29	0.02	0.003	0.46	0.01	0.008
8	Kakul	−1.30	−0.01	−0.002	−0.23	−0.01	−0.030
9	Kotli	2.41	0.03	0.24	1.00	0.01	0.024
10	Murree	1.60 ***	0.01	0.2 ***	0.90 **	0.03	0.045 **
11	Sialkot	3.30	0.03	0.043	1.23	0.03	0.043
12	Multan	2.02 ***	0.02	0.14 ***	1.11 **	0.02	0.031 **
13	Faisalabad	−1.21	−0.02	−0.019	−1.65	−0.03	−0.025
14	Lahore	−1.11	−0.01	−0.009	−1.43	−0.02	−0.023
15	Bahawalpur	2.07	0.03	0.06	1.26	0.03	0.0281
16	Bahawalnagar	4.82 ***	0.03	0.054 ***	2.89 ***	0.02	0.034 ***
17	Mianwali	3.41	0.02	0.031	1.90	0.03	0.041
18	Islamabad	1.48	0.01	0.014	0.06	0.01	0.002
19	Badin	4.69 **	0.03	0.043 **	1.19	0.01	0.02
20	Hyderabad	3.16 ***	0.049	0.054 ***	2.17 ***	0.02	0.025 **
21	Nawabshah	2.05 ***	0.026	0.035 ***	2.00 ***	0.031	0.036 ***
22	Jacobabad	3.62 ***	0.03	0.041***	2.01 **	0.01	0.02 **
23	Khanpur	4.64 ***	0.03	0.039 ***	0.14	0.01	0.023
24	Karachi	4.23 ***	0.03	0.029 ***	0.74 ***	0.017	0.025
25	Sibi	2.80 **	0.03	0.05 ***	1.62 **	0.02	0.03
26	Panjgur	3.01 **	0.03	0.029 **	1.34	0.03	0.029
27	Lasbela	2.62 ***	0.049	0.042 ***	2.56 **	0.03	0.034 **
28	Pasni	1.99 ***	0.03	0.041 ***	2.00 ***	0.02	0.013 ***
29	Quetta	3.30 ***	0.049	0.0405 **	2.86 ***	0.031	0.041 **
30	Kalat	2.00 **	0.02	0.3 **	1.96 **	0.01	0.03 **

Notes: ** Statistically significant trend at 0.05 level; *** Statistically significant trend at 0.001 level.

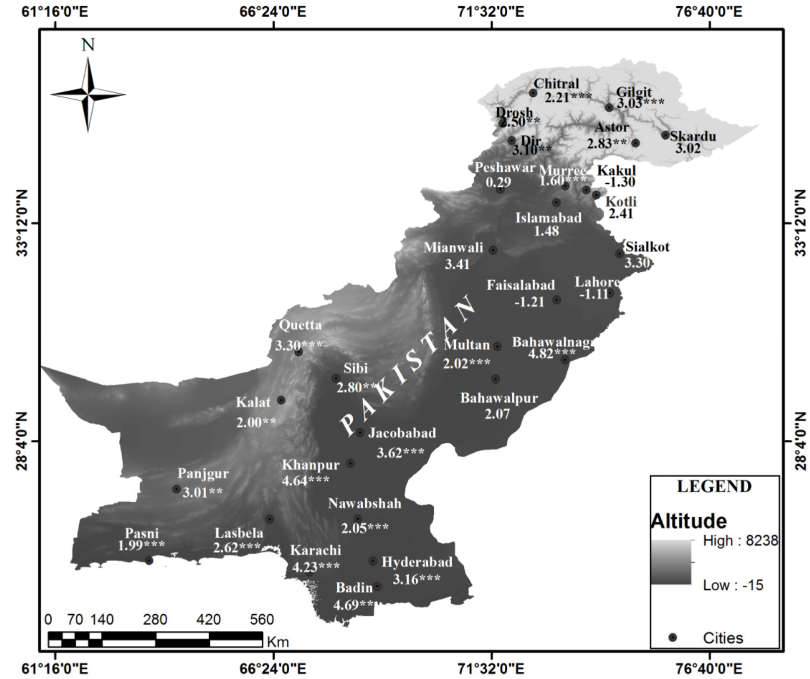

Figure 3. Values of the Mann-Kendall statistic for annual average temperature during 1970–2009 (Values with asterisks indicate significant trends).

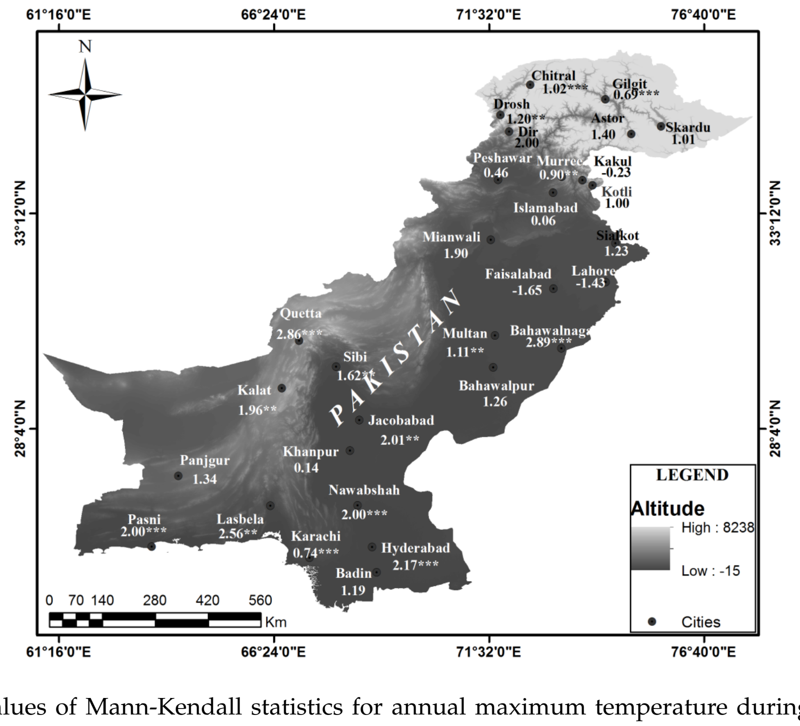

Figure 4. Values of Mann-Kendall statistics for annual maximum temperature during 1970–2009 (Values with asterisks indicate significant trends).

On the other hand, annual maximum temperature showed a significant increasing trend for 7 meteorological stations at the 95% and for 8 meteorological stations at the 99% levels of significance. According to the Sen's slope estimator, the significant increasing trend for annual maximum temperature varied from 0.17 °C per decade at Karachi to 0.31 °C per decade at Chitral, Gilgit, Nawabshah and Quetta stations. The negative trend for annual maximum temperature found at Kakul, Faisalabad and Lahore was statistically insignificant. In the northern mountains, the annual maximum temperature showed a significant increasing trend at a rate of 0.3 °C per decade at Chitral, Gilgit and Murree stations. In the middle and lower Indus valley, annual maximum temperature at Bahawalnagar and Hyderabad showed a significant increasing trend at 0.2 °C per decade and 0.3 °C per decade at Nawabshah. In the Balochistan province, annual maximum temperature showed a significant increasing trend at Sibi and Pasni at 0.2 °C per decade and it remained 0.3 °C per decade at Lasbela and 0.4 °C per decade at Quetta. This increase in maximum temperature may be due to higher ESR, frequent heat waves, unplanned dense building of the city and pollution from vehicles and industry in the previous years. Sami et al. and Ilyas et al. [26,27] found increased concentration of lead and suspended particulate matter in the urban areas. In the adjacent arid and semi arid region of Iran, Tabari and Hosseinzadeh Talaee [2] also found an increasing trend in annual mean maximum temperature. Furthermore, an insignificant increasing trend for annual maximum temperature was found at other stations. An unexpected insignificant negative trend for annual average and maximum temperature was detected at Kakul, Lahore and Faisalabad; such an unexpected negative trend was explained by the massive rainfall from monsoons, specifically in the 1990's for Lahore and the nearby city of Faisalabad [16,18,43]. The results are verified by the region adjacent to Lahore in the Indian part of the Sutlej River basin, Himachal Pradesh, where Singh et al. [44] found an insignificant negative trend for annual maximum temperature at Kasol and Sunni stations that explaineds the regional trend variation along the Pakistan–India boundary line. Considering the significant decreasing trend in the industrialized and urbanized city of Pune, India, [9] held anthropogenic aerosols and cloud cover responsible for such a decreasing trend in annual maximum temperature.

According to the simple linear regression analysis, stations with the most significant trend for annual average and maximum temperature are provided in Figure 5 with time series plots and their linear trends. Significant increasing trend magnitudes for annual average temperature varied from 0.29 °C at Karachi, 0.34 °C at Gilgit and 0.4 °C per decade at Quetta station. In addition, a significant trend for annual maximum temperature was found at Gilgit and Chitral at 0.34, Bahawalnagar, Hyderabad and Pasni at 0.28 and Quetta at rate of 0.4 °C per decade (Figure 5). On the other hand, a statistically insignificant decreasing trend at Kakul, Lahore and Faisalabad stations was found for annual average and maximum temperature.

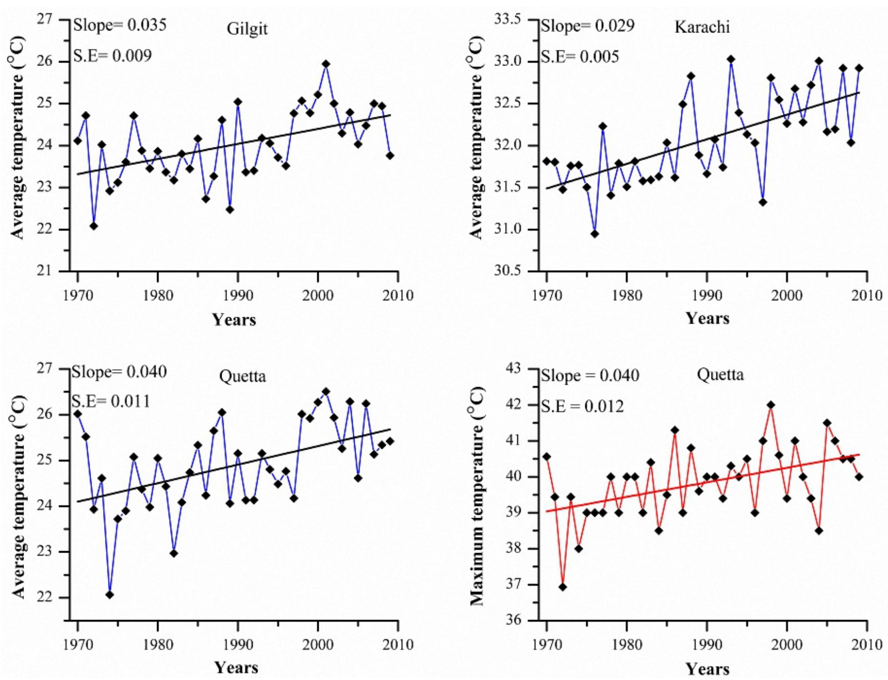

Figure 5. Time series and linear trends for annual average and maximum temperature at stations with significant trends.

The analysis for the study period also revealed that annual average temperature showed a slightly higher rate of change than annual maximum temperature. Such results were in accordance with Gadgil and Dhorde [9], Sajjad et al. [15], Sadiq and Qureshi [16]. However, Oguntunde et al. [45] found variation in minimum temperature highly responsive to temporal trends in temperature in harsh climatic settings. The derived results of the present study indicated that warming in the urban areas was caused by increasing annual average temperature rather than annual maximum temperature. Different factors may be involved in increasing annual average temperature in these urban areas, such as increased concentrations of CO_2 and GHG_s, urbanization, land use change and global warming. Such activities enhanced after the land reforms and industrialization campaigns and establishment of industrial zones around the urban areas which were engulfed by their massive expansion.

Overall, increasing temperature trends were detected in the study area during the last few decades. According to Tabari and Hosseinzadeh Talaee [1], the increasing temperature trends in the urban areas might have numerous reasons such as the greenhouse effect, anthropogenic activities, natural cloud formation, haze from cities, industries, burning forests and fields and the urban heat island affect [46]. Highly significant and increasing trends for annual average and maximum temperature in the northern areas are worrisome for retreating glaciers that feed the Indus River. In the Balochistan province and extreme South, the coastal areas where droughts and severe heat waves are reported frequently, are threatened by further environmental degradation and desertification [21] and such climatic conditions require a great deal of attention [47].

The Fourth Assessment Report of the Inter Governmental Panel on Climate Change (IPCC), observed that the natural systems have been affected by the regional climate changes [48]. The change in temperature is not uniform over the entire region; spatial and temporal variations are expected between climatically different regions depending on the local geophysical conditions [1]. The regional variation in Annual T_{avg} and Annual T_{max} was analyzed using a kriging interpolation technique with the help of ArcGIS software.

Figure 6 shows the spatial distribution of Annual T_{avg} in Pakistan during 1970–2009. The spatial trend analysis for Annual T_{avg} showed most significant trends for the regions in the southern part of the country including Balochistan and Sindh provinces and a moderate to increasing trend remained in the Multan and Bahawalpur regions [42]. The Annual T_{avg} showed lower trends for the central part of the country including the upper part of Punjab and plain areas of Khyber Pakhtoonkhwa province (Bahawalpur, Lahore, Faisalabad, Mianwali, Peshawar, Islamabad and Kotli) because of frequent rainfall during the last few decades [49,50]. Similar temperature trends were also found in the adjacent regions in India by Singh et al. [44]. However, Annual $T_{\mathbf{avg}}$ showed a slightly increasing trend for stations in the northern mountainous part of the country which are supposed to be the water reserves in form of ice and glaciers (Murree, Kakul, Astore, Dir, Drosh, Chitral, Gilgit and Skardu) [44].

The spatial distribution of regional Annual T_{max} is presented in Figure 7. Annual T_{max} also showed a maximum significant trend for the southern part of the country including Balochistan province (Quetta and the surrounding regions such as Sibi and Kalat) Sindh province (Karachi, Badin, Hyderabad, Nawabshah, Khanpur and some regions of Jackobabad) as repeated severe heat wave events [21], desertification and productivity loss [20] have been reported in this part of the country. The Annual T_{max} showed a moderate to increasing trend at Bahawalpur, Multan and Bahawalnagar; whereas other regions including the central part of the country (Lahore, Sialkot, Islamabad, Kotli, Skardu and Peshawar) showed minimum trends. The Annual T_{max} trend also remained moderate to high in the hilly region [51].

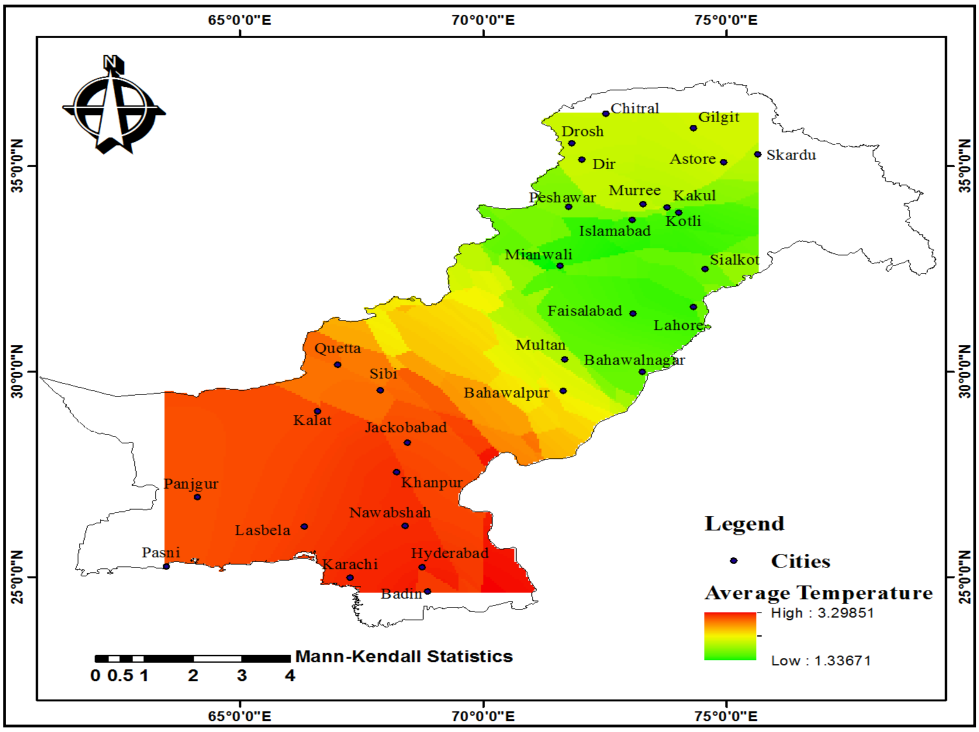

Figure 6. Regional trend in annual average temperature based on Mann-Kendall statistics for the selected stations in Pakistan during 1970–2009.

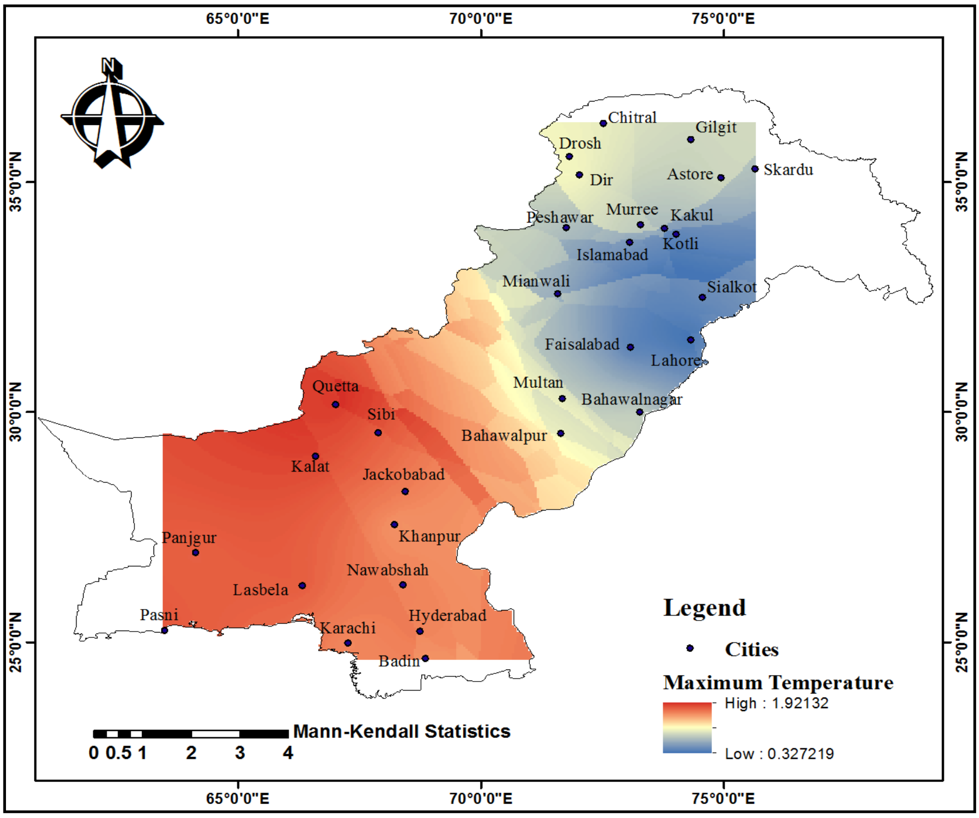

Figure 7. Regional trend in annual maximum temperature based on Mann-Kendall statistics for the selected stations in Pakistan during 1970–2009.

5. Conclusions

Climatic assessment demands understanding of temperature and related trends. The urban areas of Pakistan are growing with respect to urban population, economic and trade activities and city area amongst South Asian urban areas. The present study analysed annual average and annual maximum temperature trends at 30 selected meteorological stations located in urban areas of Pakistan from 1970 to 2009 as important indicators of changes in microclimate and regional warming. The results of parametric and non-parametric tests were almost similar. Linear regression, Sen's slope and the Mann-Kendall trend test showed similar results for the considered parameters; the annual average temperature had a higher increasing rate than annual maximum temperature. The important aspects of the present study were that annual average and maximum temperature showed overall increasing trends for all the stations except Kakul, Lahore and Faisalabad. Annual average and maximum temperature series showed a positive trend for 90% of the stations and a negative trend for 10% of the stations. The decadal annual average temperature ranged from 0.26 °C at Nawabshah to 0.49 °C per decade at Gilgit, Hyderabad, Quetta and Lasbela stations. In addition, the decadal annual maximum temperature varied from 0.17 °C at Karachi to 0.31 °C per decade at Chitral, Gilgit, Nawabshah and Quetta stations.

In the northern part of the country, the annual average temperature had a significant increasing trend from 1970–2009 at Gilgit and Chitral at a rate of 1.4 °C and 1.2 °C, respectively. In the middle and lower Indus River valley Bahawalpur, Jacobabad and Khanpur had a significant trend of 1.2 °C, whereas Hyderabad had a slightly higher rate of 1.4 °C over the study period. In Balochistan province, the trend in annual average temperature at Lasbela and Quetta was 1.6 °C and 1.2 °C at Pasni. On the other hand, an increasing trend in annual maximum temperature for the entire study period was significant for Gilgit and Chitral, at a rate of 1.24 °C in the northern region. In the middle and lower Indus Valley, Bahawalnagar and Hyderabad had a trend of 0.8 °C and 1.24 °C at Nawabshah. In Balochistan province, the rate of the increasing trend was recorded at Pasni at 0.8 °C and Quetta at 1.24 °C over the study period. Climate evolutions occur in urban areas; regional variation in Annual T_{avg} and T_{max} has multiple factors such as unplanned population and urban growth, industrialization and emissions, deforestation and negligence of the environmental protection by masses that bear harsh consequences for the next generations. The regional temperature changes in the northern part of the country have implications for water supply from the mountains, agricultural productivity and loss of biodiversity throughout the country [52]. Population pressure, massive construction activities and elevated particulate matter and greenhouse gases emission since 1960–1970 in these urban areas have deteriorated the environment and elevated the local temperature. Repeated heat waves in the southern and south-western part of the country signals an alarming situation of climatic changes that needs to be addressed. Urbanization, growing population and climatic changes in these urban areas require infrastructure modification and adoption of environmentally friendly practices to ensure quality life and development.

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