

## Spatiotemporal variability of annual and seasonal rainfall time series in Ho Chi Minh city, Vietnam

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### ABSTRACT

This study analyzed spatial and temporal patterns of rainfall time series from 14 proportionally distributed stations in Ho Chi Minh City for the period 1980–2016. Both parametric and nonparametric approaches, specifically, linear regression, the Mann–Kendall test and Sen’s slope estimator, were applied to detect and estimate the annual and seasonal trends after using original and notched boxplots for the preliminary interpretation. The outcomes showed high domination of positive trends in the annual and seasonal rainfall time series over the 37-year period, but most statistically significant trends were observed in the dry season. The results of trend estimation also indicated higher increasing rates of rainfall in the dry season compared to the rainy season at most stations. Even though the total amount of annual rainfall is mainly contributed by rainfall during the rainy season, the pronounced increment in the dry season can be a determining factor of possible changes in annual rainfall. Additionally, the interpolated results revealed a consistently increasing trend in the southeastern parts of the study area (i.e., Can Gio district), where annual rainfall was by far the lowest intensity compared to other regions.

**Key words** | Ho Chi Minh city, linear regression, Mann–Kendall test, rainfall trend, trend detection

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### INTRODUCTION

Global climate change and variability cause various adverse effects on biophysical and human systems. At the regional and local scale, these impacts are more detrimental. Hence, climate change impact assessment studies have been emerging rapidly among diverse scientific communities in recent years. In particular, the field of hydro-meteorological trend analysis has attracted great attention from researchers across the globe. [Machiwal & Jha \(2006\)](#) conducted a comprehensive review of various time series analysis techniques for determining the essential characteristics of hydrologic and climatologic datasets, including homogeneity, stationarity, trend, periodicity, and persistence. [Sonali & Kumar \(2013\)](#) also presented a critical review of numerous statistical approaches for trend detection for multiple hydrologic and climatic parameters.

It is apparent that there have been various salient case studies for sites around the world. [Lamb \(1982\)](#) used rainfall variability index to demonstrate the persistent situation of sub-Saharan drought in the 20th century. Similarly, [L’hote et al. \(2002\)](#) applied this approach to confirm the prolonged existence of drought to the end of the year 2000 in the Sahel.

[Jaagus \(2006\)](#) found the significant warming tendencies in Estonia for the period 1951–2000 by using linear regression and the Mann–Kendall (MK) test. Additionally, the results of the conditional MK test indicated considerable influence of large-scale atmospheric circulation on temperature and precipitation trends. [Zhang et al. \(2009\)](#) also employed linear regression and the MK test to demonstrate a significant increase in both extreme temperatures over a 45-year period in western China, even though the minimum

temperature showed greater rates of increase. Therefore, they concluded that climate warming in western China was dominated by stronger increasing minimum temperature. Dash *et al.* (2009) used daily gridded rainfall data during 1951–2004 to evaluate possible changes in the characteristics of rain events in India in terms of duration and intensity. In general, their results showed significant declines in the number of low and moderate rain days, while heavy rain days increased insignificantly.

Tabari & Talaei (2011a) also found greater rates of increase in minimum temperature compared to maximum temperature in the western half of Iran by applying linear regression, the MK test, and Sen's slope estimator. In addition, Tabari & Talaei (2011b) showed that most stations over all of Iran experienced negative trends in annual precipitation for the period 1966–2005. According to Sonali & Kumar (2013), most regions in India have seen a consistently increasing trend in minimum temperature during the last three decades. Moreover, the magnitude of the positive trend in minimum temperature was more intense than maximum temperature. Additionally, application of the sequential MK test in this study indicated that most annual and seasonal trends in both extreme temperatures were likely to begin after 1970. Sonali & Kumar (2016) also examined the relationship between potential evapotranspiration and extreme temperatures over India for the period 1950–2005 by using Spearman rank correlation before trend detection step for these climatic parameters. Their investigation revealed high correlation between extreme temperatures and potential evapotranspiration, although maximum temperature showed better correlation.

Apart from these climatic variables, Punia *et al.* (2015) also indicated a significantly decreasing trend of  $-0.1$  to  $-0.7$  °C/decade in the diurnal temperature range over a 31-year period in the northwest region of India. Sayemuzzaman *et al.* (2015) also conducted an extensive investigation on spatial and temporal long-term extreme temperatures in North Carolina (USA) for the period 1950–2009 by applying the MK test, Theil–Sen, and sequential MK test to detect and estimate trend possibilities, including significance, magnitude, and changing point, respectively. Additionally, linkages between temperatures and atmospheric circulation were also found. Savić *et al.* (2015) presented a significant increase of  $0.9$  °C/60 years and  $1.1$  °C/60 years for maximum and minimum temperature

in Vojvodina (Serbia) from 1949 to 2008. These authors also contributed several linear and quadratic models that represented the relationship between extreme temperatures and large-scale atmospheric circulation.

On the river basin scale, Panthi *et al.* (2015) revealed a critical issue in Gandaki River Basin of Nepal Himalaya where the dry parts were likely to be dryer and the wet parts were likely to be wetter due to seasonal and regional rainfall changes for the period 1981–2012. Mir *et al.* (2015) also concluded that increasing trends in temperatures, particularly minimum temperature, were likely to affect trends in other climatic parameters in Satluj River Basin (western Himalaya). Their trend detection results inferred that precipitation in this river basin was likely to shift from solid (snowfall) to liquid (rainfall).

From historical literature reviews, most previous studies have focused on large-scale hydro-meteorological changes (country, county, or river basin). There have been few concerns at the local level, particularly for the cities in developing countries that are vulnerable to climate change. For Ho Chi Minh City (HCMC), which is ranked among the most vulnerable major coastal cities to climate extremes across the globe (Hanson *et al.* 2011; Hallegatte *et al.* 2013), it is imperative to carry out changes of climatic parameters that can provide fundamental, scientific insights for promoting more promising and reliable adaptation options in the context of climate change and variability. Khoi & Trang (2016) examined trends in precipitation and extremes events in HCMC by applying the MK test and five precipitation extremes indices. Nonetheless, these authors did not consider seasonal aspects and their spatial assessment was not explicit.

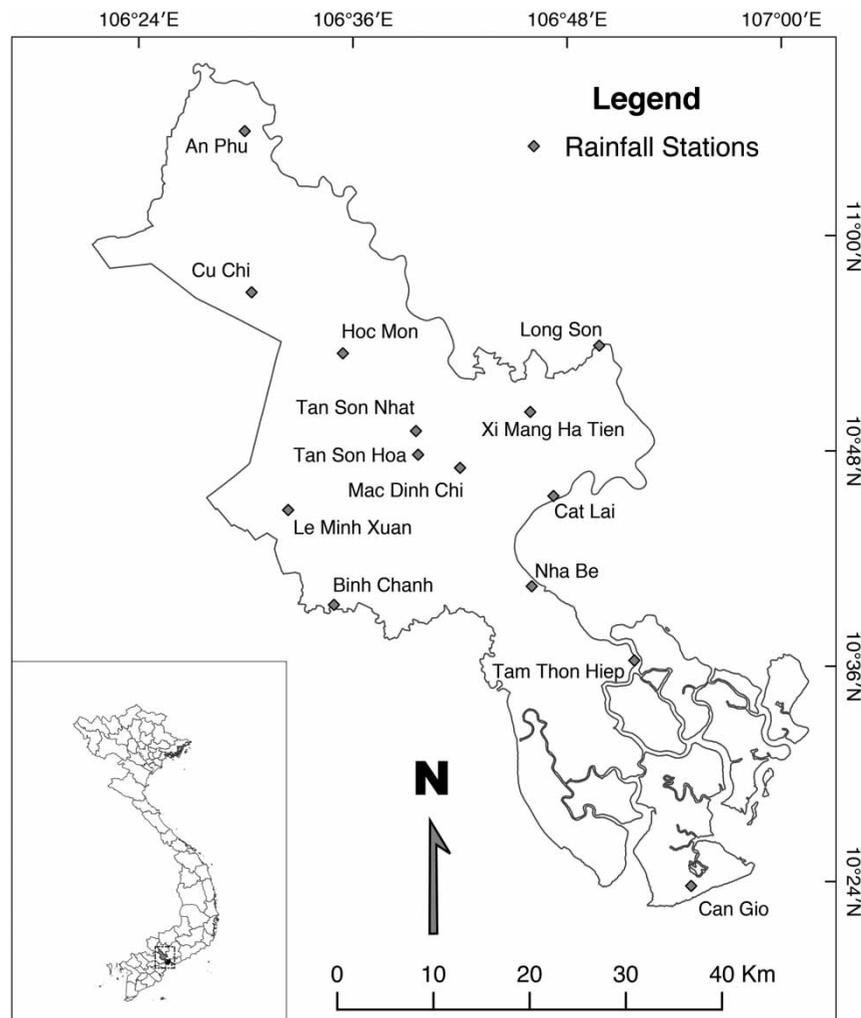
Hence, the present study was conducted to explore and understand rainfall patterns in terms of space and time in HCMC for the period 1980–2016. The main objectives were drawn out as follows: (i) to examine annual and seasonal rainfall distribution by using original and notched boxplot; (ii) to detect and estimate the significance and magnitude of rainfall trends by applying both parametric and nonparametric approaches such as linear regression, the MK test, and Sen's slope estimator; and (iii) to interpolate temporal outcomes for spatial assessment by employing the inverse distance weighting algorithm in GIS. In general, it is expected that these findings will yield a number of

physical basis of long-term rainfall changes in HCMC, which are conducive to further investigations with regard to vulnerability assessment to climate change and variability.

## STUDY AREA AND DATA

The selected study area is Ho Chi Minh City, which is located in the southeast region of Vietnam (Figure 1). This city lies approximately  $10^{\circ}20'–11^{\circ}10'N$  in latitude and  $106^{\circ}20'–107^{\circ}05'E$  in longitude, and has an area of around 2,095 km<sup>2</sup>. There are a total of 24 urban and rural districts and the number of inhabitants was about 8.2 million in 2015, which

was predicted to rise to nearly 9.5 million by 2035 (General Statistics Office of Viet Nam 2016). According to Asean Development Bank (2010), the majority of regions in HCMC are low-lying areas; indeed, elevations of 0–1 and 1–2 meters are responsible for approximately 40–45% and 15–20% of the total metropolitan area, respectively. Additionally, the current issue of population growth is overwhelming and local development patterns are inadequate to accommodate projected growth. As a consequence, the combination of these problems with climate extremes can cause HCMC to become increasingly vulnerable to climate change and variability. According to Hanson *et al.* (2011), the currently exposed population and assets to coastal flooding in HCMC are about 1.9 million and 26.86 billion dollars, respectively. These figures were also



**Figure 1** | Geographical location and spatial distribution of 14 rainfall stations in HCMC.

projected to rise to 9.2 million and 652.82 billion by 2070 (Hanson *et al.* 2011). Furthermore, the economic average annual flood losses were estimated to reach 0.74% of local GDP (Hallegatte *et al.* 2013). Therefore, it is evident that the study area is extremely vulnerable to climate change.

There are 14 rainfall stations in the study area (Figure 1). It is discernible that their spatial distribution is quite proportional to the whole extent of HCMC. In this study, daily rainfall time series were collected from the Southern Regional Hydro-meteorological Center. These datasets were then processed to obtain the monthly and annual values for further computation. All of these time series cover the 37-year period (1980–2016), except An Phu station (1990–2014). Missing values are found in the time series of Tan Son Nhat, Binh Chanh, Nha Be, and Tam Thon Hiep stations; however, the number of data gaps is less than four years. These missing values were filled in by the interpolated values from neighboring stations. In general, it is worth noting that these time series are adequate and reliable for the purpose of rainfall trend analysis in HCMC.

## METHODOLOGY

Figure 2 shows a brief description of the statistical approach. First, total monthly and annual rainfall data were calculated. Then, original and notched boxplots were employed to portray rainfall distribution for the period 1980–2016 prior to applying linear regression, the MK test, and Sen's slope estimator to examine temporal rainfall trends. Afterwards, annual and seasonal rainfall values were further used for the interpolating procedure for comparative spatial assessment. Inverse distance weighting algorithm was employed from the common spatial interpolation techniques because it is easy to use and readily available (Mitas & Mitasova 1999).

### Boxplot

The original boxplot was introduced by Tukey (1977) and has been widely used to visualize time series data in various scientific as well as unscientific applications. This graphical tool is more informative than classical plots and tabular forms. To be more specific, boxplot provides five robust measures of data: median, first/third quartiles, upper/lower whiskers, and

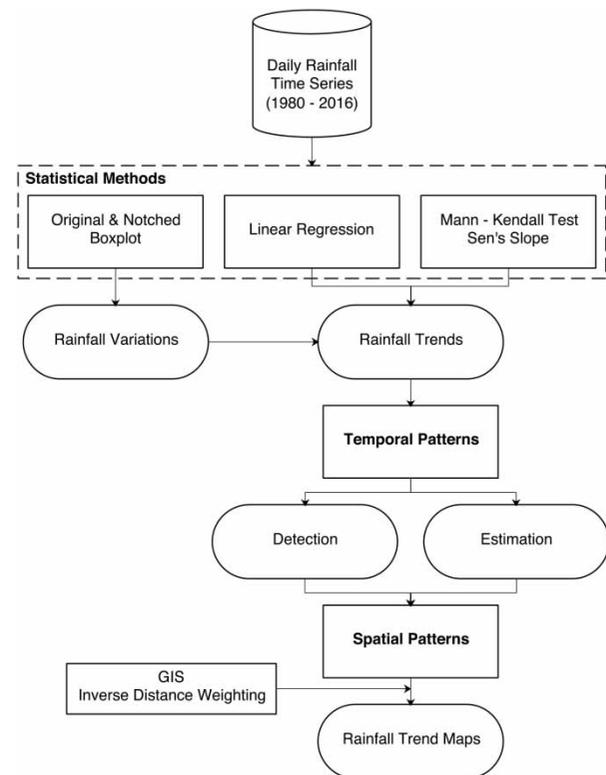


Figure 2 | Schematic framework of research methodology.

possible outliers. So far, there has been a variety of modified versions. McGill *et al.* (1978) proposed the variable-width notched boxplot in order to show a comparative measure of group size and confidence intervals around the medians. Benjamini (1988) suggested opening the box of a boxplot and formed two variants: histplot and vaseplot. Carr (1994) made use of color availability in basic boxplot to enhance visual display. Other alternatives, namely, violin plot and box-percentile plot, were introduced by Hintze & Nelson (1998) and Esty & Banfield (2003), respectively, which take the density distribution of data into consideration. Recently, Kampstra (2008) proposed another version, called beanplot, that can minimize the disadvantages of previous variants.

It is worth noting that most modified versions of the original boxplot focus on displaying the properties of the probability density. However, this study primarily addresses annual and monthly variations in rainfall time series over the 37-year period, so only the basic and notched boxplot are employed for this purpose.

For seasonal analysis, it is important to determine the duration of each season. As a rule-of-thumb, local

meteorologists have stated that there are two distinct seasons in the study area: the dry and rainy seasons. Herein, seasonal division was based on the application of notched boxplot and previous studies on the onset dates of the summer monsoon and rainy season. According to Pham *et al.* (2010), the summer monsoon onset mean date in the southern region of Vietnam is on 12 May (with a standard deviation of 11.6 days) over the period 1979–2004. In addition, Huong *et al.* (2013) indicated that rainy season onset dates have usually lasted from early to mid May for the period 1961–2000 over the southern region of Vietnam. Therefore, this study also determined that the rainy season begins in May and its duration lasts until the month that the total amount of rainfall is lower than rainfall in May. The notched boxplot can be used to compare the total amount of monthly rainfall. There is a statistically evident indication of difference between two medians in case the notches of two boxes do not overlap (McGill *et al.* 1978).

### Linear regression

Linear regression is a parametric approach, which requires a normal distribution of data. According to Machiwal & Jha (2012), this test has been widely used to characterize linear trends in hydro-meteorological time series. Theoretically, linear trends can be detected based on the estimated slopes. Positive values indicate increasing trends, while negative values show decreasing tendencies. To check the statistical significance of detected trends, the  $t_{test}$  is used (Machiwal & Jha 2012; Sonali & Kumar 2013; Punia *et al.* 2015) and its formulation can be expressed as follows:

$$t_{test} = \frac{\hat{\beta}}{se(\hat{\beta})}$$

where  $\hat{\beta}$  is the estimated slope of the regression line between time and an observed variable (i.e., rainfall) and the standard error of estimated slope is denoted by  $se(\hat{\beta})$ . In case the computed value of  $t_{test}$  is greater than its critical value  $t_{\alpha/2}$ , the null hypothesis of trend-free series can be rejected and it is strongly evident that there is a linear trend in the time series at  $\alpha$  significance level with  $n-2$

degrees of freedom. In this research,  $\alpha = 0.05$  and  $0.01$  were used.

### Mann-Kendall test

The rank-based MK test is a nonparametric approach that is commonly used to explore monotonic trends (linear/non-linear) in hydro-meteorological time series. This test was originally used by Mann (1945) and Kendall (1975) derived the test statistic distribution. Machiwal & Jha (2012) ascertained that the MK test is the most reliable and powerful tool for the purpose of trend detection. The MK test has the advantage of not assuming normal distribution of time series data (Zhang *et al.* 2009). Additionally, this test has low sensitivity to abrupt breaks due to inhomogeneous time series (Jaagus 2006).

According to Jaagus (2006) and Machiwal & Jha (2012), each value of the series is compared with all subsequent values and the test statistic  $S_{MK}$  is defined as follows:

$$S_{MK} = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sign}(x_j - x_k)$$

$$\text{sign}(x_j - x_k) = \begin{cases} +1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases}$$

where  $x_j, x_k$  are the sequential data in the series and  $n$  is the length of the data series.

In cases where sample size  $\geq 10$ , the standardized test statistic  $Z_{MK}$  is calculated as follows:

$$Z_{MK} \begin{cases} \frac{S_{MK} - 1}{\sqrt{\text{Var}(S)}} & \text{if } S_{MK} > 0 \\ 0 & \text{if } S_{MK} = 0 \\ \frac{S_{MK} + 1}{\sqrt{\text{Var}(S)}} & \text{if } S_{MK} < 0 \end{cases}$$

$$\text{Var}(S_{MK}) = \frac{[n(n-1)(2n+5) - \sum_{t=1}^m t(t-1)(2t+5)]}{18}$$

where  $t$  stands for the extent of any given tie and  $m$  denotes the number of tied groups.

To examine trends in a given time series, positive and negative values of  $Z_{MK}$  show upward and downward trends, respectively. Then, the null hypothesis of no trend

can be rejected at the specific  $\alpha$  significance level when  $|Z_{MK}|$  is greater than  $Z_{1-\alpha/2}$  obtained from the standard normal cumulative distribution table. In the present work, the significance levels of  $\alpha = 0.05$  and  $0.01$  were adopted so  $Z_{1-\alpha/2} = 1.96$  and  $2.576$ , respectively.

### Sen's slope estimator

In order to quantify the magnitude of trend, the nonparametric Sen's slope approach, which was initially introduced by Sen (1968), was applied here. This slope estimator is calculated as follows:

$$\beta_{SS} = \text{median} \left( \frac{x_j - x_k}{j - k} \right) \text{ for all } j < k$$

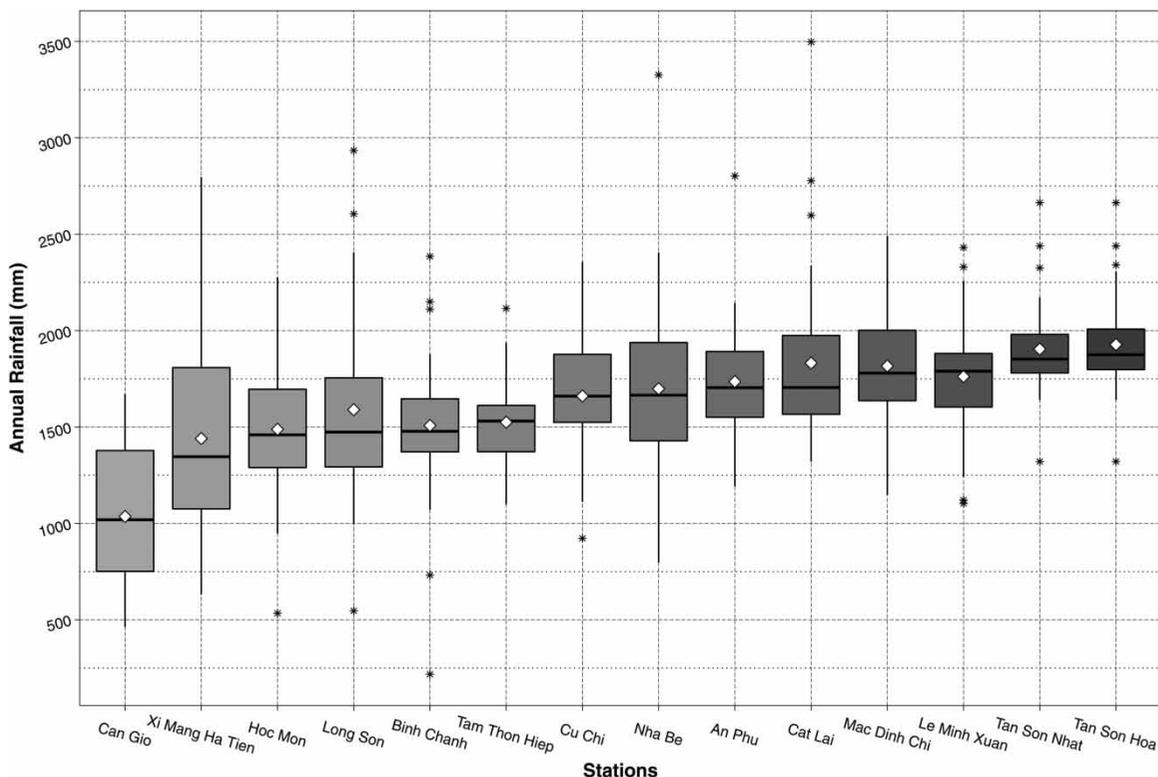
where  $\beta_{SS}$  is Sen's slope estimator and  $x_j, x_k$  are the data values at times  $j$  and  $k$ , respectively. The positive and negative signs of the estimated slopes show increasing and decreasing trends, respectively. According to Machiwal &

Jha (2012), this nonparametric method is resistant and robust in the presence of extreme observations and outliers.

## RESULTS AND DISCUSSION

### Preliminary interpretation

It is absolutely necessary to perform an initial assessment of data prior to analyzing trends in terms of space and time. The original and notched boxplots were applied to draw out an overall picture of the annual and seasonal rainfall variations. Figure 3 reveals a considerable difference in annual rainfall at 14 stations for the entire study period. In detail, the highest temporal variation was found in Xi Mang Ha Tien station, with an interquartile range (IQR) value around 732.5 mm/year. The annual rainfall at Can Gio station also varied notably, with 37-year IQR reaching approximately 626.6 mm/year. Conversely, the variations in time were lowest for Tan Son Nhat and Tan Son Hoa



**Figure 3** | Temporal variations of annual rainfall at 14 stations. The inside diamond symbols stand for arithmetic means.

stations. The *IQR* values of these stations were 199.9 and 209.9 mm/year, respectively. The other stations were comparatively similar in the temporal variations of annual rainfall, with *IQR* values around 250–500 mm/year.

In addition, Figure 3 shows a relative comparison of annual rainfall intensity. It is evident that Tan Son Hoa and Tan Son Nhat stations were responsible for the highest rainfall intensity, with long-term median values reaching 1,875.2 and 1,852.0 mm/year, respectively. By contrast, annual rainfall at Can Gio and Xi Mang Ha Tien stations were by far the lowest intensity. The medians of these stations were 1,018.9 and 1,346.0 mm/year, respectively. In comparison, the annual rainfall intensity of the other stations ranged approximately from 1,400 to 1,700 mm/year.

Another remarkable finding from Figure 3 is the presence of several mild outliers in the annual rainfall time series at 11 stations. It can be inferred that extreme rainfall events have occurred during the period 1980–2016. Moreover, the

robust medians of several stations (i.e., Xi Mang Ha Tien, Long Son, and Cat Lai) are completely different from their arithmetic means. It is also noticeable that a few median lines are adjacent to the top or bottom horizontal lines in the boxes and the length of upper fences is unequal with the length of lower ones as well. This implies that rainfall time series at several stations do not meet the fundamental assumption of normal distribution. Therefore, it is necessary to apply a nonparametric approach along with the parametric method to analyze rainfall trends.

For the seasonal analysis, the notched boxplots were applied to the monthly time series at 14 stations for seasonal division, as mentioned in the Methodology section. Figure 4 depicts monthly distribution of rainfall time series for the considered period (1980–2016). It is apparent that the total amount of rainfall in November at most stations (10 out of 14) was significantly lower than that in May. Similarly, total rainfall in November at Hoc Mon, An Phu, Cu

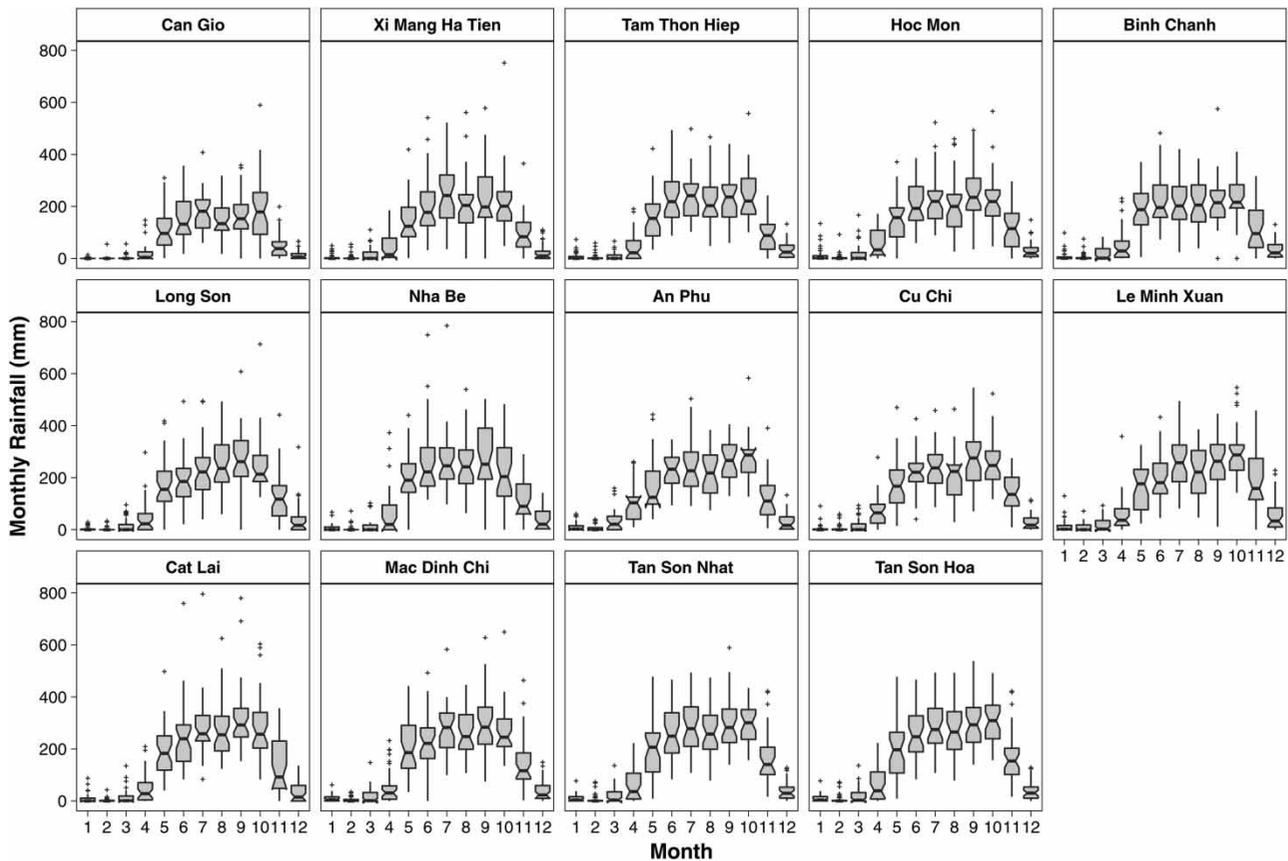


Figure 4 | Temporal variations of monthly rainfall at 14 stations.

Chi, and Le Minh Xuan stations was also lower than total rainfall in May, but the difference was not statistically significant. Generally, it was shown that the rainy season in the study area lasts six months from May to October. This seasonal division is used for further trend analysis.

Figure 4 also represents temporal variations of monthly rainfall time series. The temporal variation in monthly rainfall was the highest for Nha Be station, with *IQR* in September and October reaching nearly 196.5 and 186.4 mm/year, respectively. Similar to the annual variability, the highest rainfall intensity on a monthly basis was observed at Tan Son Nhat and Tan Son Hoa stations. The highest monthly median values of these stations were 300.6 and 309.0 mm/year, respectively. The total amount of monthly rainfall at Can Gio station was also lower than the figures for other stations. In general, it is inferred that the annual rainfall variations at all stations are dominated by rainfall in the rainy season. Additionally, it is worth mentioning that the total amount of annual rainfall for the entire study area is mainly contributed by rainfall in the rainy season, accounting for approximately 80–90%.

### Temporal trend assessment

In this study, the annual and seasonal rainfall time series at 14 stations in HCMC were taken as the subjects for trend

analysis. The results obtained by linear regression, the MK test, and Sen's slope estimator are represented in Figures 5–7, respectively. It is apparent that the temporal trends found by the parametric method (i.e., linear regression) were mostly similar to those obtained by non-parametric methods (i.e., the MK test and Sen's slope estimator). These findings are in accordance with the results of the extreme temperature and precipitation trend analysis conducted by Tabari & Talaei (2011a, 2011b), respectively.

It is noticeable from Figures 5 and 6 that the annual and seasonal rainfall time series in HCMC were characterized by increasing trends over the 37-year period (1980–2016). Annually, the majority of stations exhibited upward trends, accounting for approximately 85.7% and 64.3% of the stations as for linear regression and the MK test. However, most of the detected trends were insignificant at the 95% and 99% confidence levels. In particular, statistically significant positive trends were only obtained in Can Gio and Hoc Mon stations. The computed  $t_{test}$  and  $Z_{MK}$  values of these stations were 3.377/2.408 and 2.786/2.027, respectively. In addition, there was no statistically significant decreasing trend as for the annual basis.

On the seasonal scale, it is worth noting that all rainfall trend detection results using linear regression as well as the MK test showed increasing trends in the dry season, while 9/14 stations experienced declining trends in the rainy

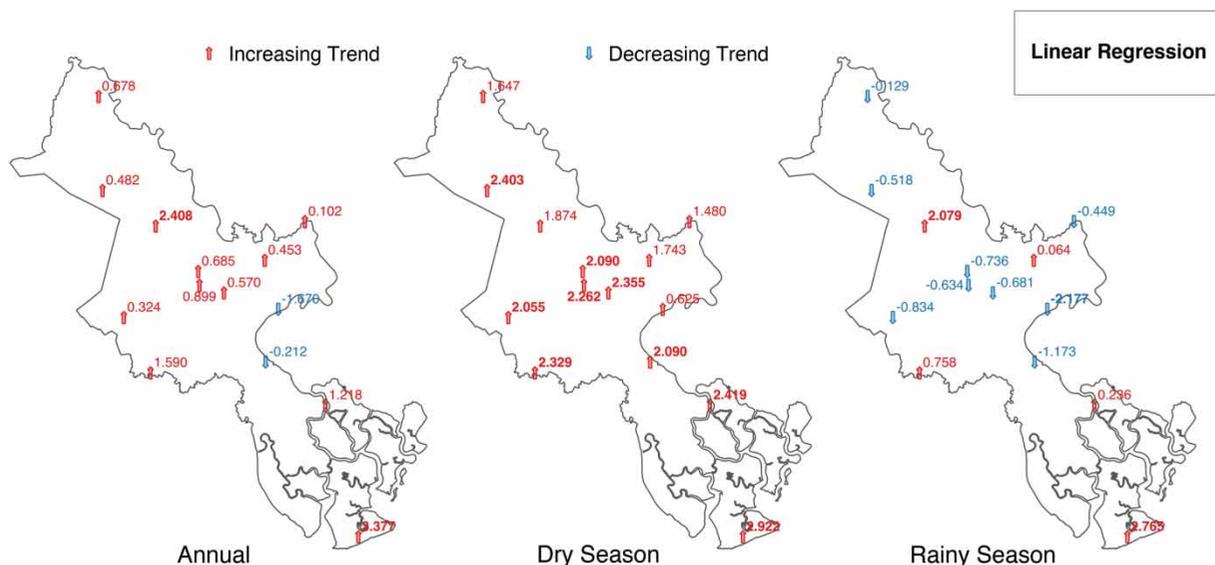
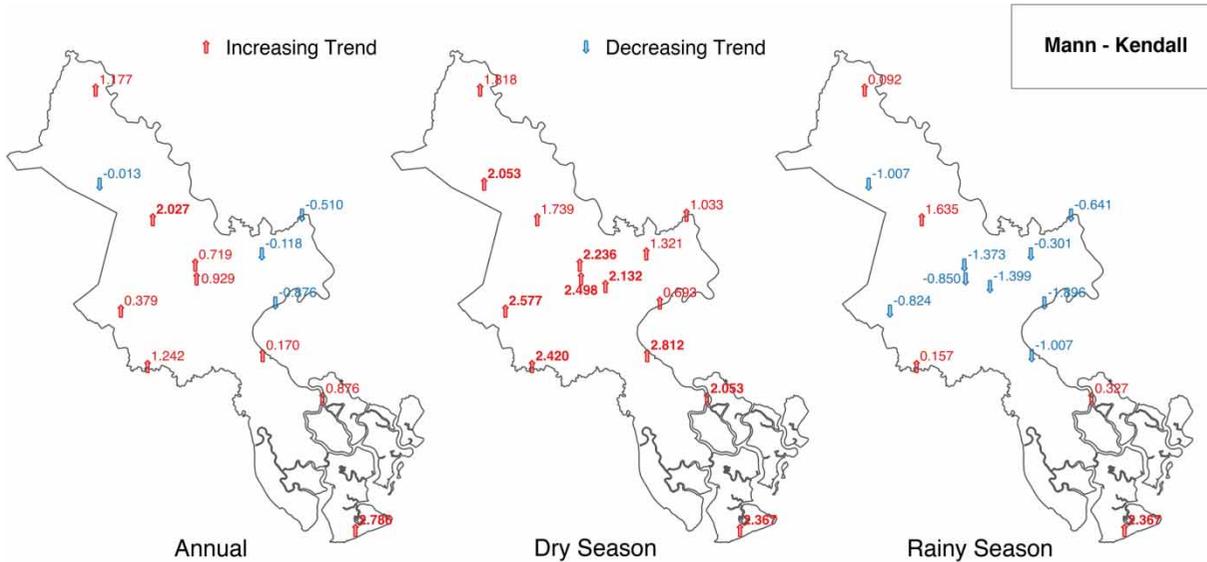
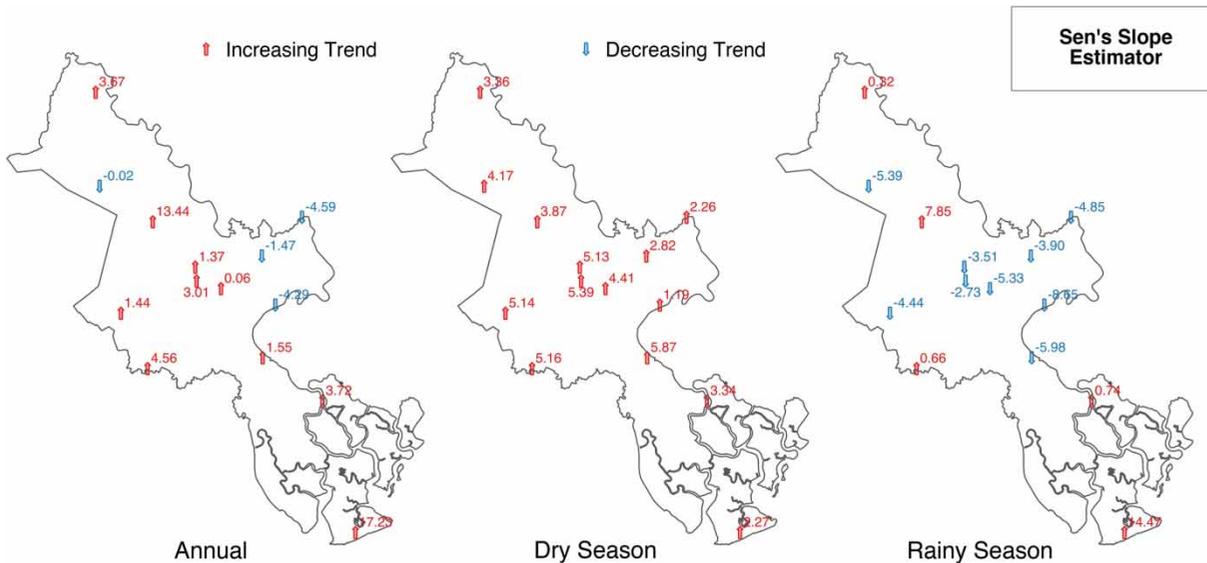


Figure 5 | Results of annual and seasonal rainfall trend detection using linear regression. Figures in bold indicate statistically significant trends.



**Figure 6** | Results of annual and seasonal rainfall trend detection using the Mann-Kendall test. Figures in bold indicate statistically significant trends.



**Figure 7** | Results of annual and seasonal rainfall trend estimation using Sen's slope estimator (unit: mm/year).

season. Additionally, the number of statistically significant trends in the dry season is more than those in the rainy season and the annual basis. Another point to note is that only Cat Lai station exhibited statistically significant decreasing trend in the rainy season by linear regression, with  $t_{test} = -2.177$ .

To estimate the magnitude of these detected trends, Sen's slope estimator was applied to the annual and seasonal rainfall time series. The results of the trend estimation

are illustrated in Figure 7. It is discernible that Can Gio station was responsible for the highest increment of annual rainfall at the rate of 17.23 mm/year. Likewise, the second highest increase was found in Hoc Mon station, with  $\beta_{SS} = 13.44$  mm/year. The other increments varied slightly from 1.37 mm/year at Tan Son Nhat station to 4.56 mm/year at Binh Chanh station, while negative trends ranged between  $-1.47$  mm/year at Xi Mang Ha Tien station and  $-4.59$  mm/year at Long Son station.

In the dry season, the magnitude of rainfall trends varied slightly from approximately 3 to 5 mm/year. Nha Be station was responsible for the highest increase at the rate of 5.87 mm/year. In addition, it is worth mentioning that the magnitude of rainfall trend in Can Gio station ( $\beta_{SS} = 2.27$  mm/year) was lowest compared to the remaining stations that were characterized by statistically significant increasing trends, even though this station held the first position for the annual basis and in the rainy season. Likewise, the highest increase was found in Can Gio station at the rate of 14.47 mm/year in the rainy season. Similarly, Hoc Mon station was responsible for the second position, at 7.85 mm/year. Conversely, the highest decline was obtained in Cat Lai station at the rate of  $-8.65$  mm/year. The other decrements varied slightly from  $-2.73$  mm/year at Tan Son Hoa station to  $-5.98$  mm/year at Nha Be station.

In general, the temporal patterns of annual and seasonal rainfall in HCMC were dominated by increasing trends over the 37-year period. It is also evident that most of pronounced tendencies were observed in the dry season. In addition, the results of trend estimation using Sen's slope estimator revealed that the magnitude of increasing trends in the dry season was more intense than those in the rainy season at most stations (12 out of 14). Therefore, it is inferred that

even though the total amount of annual rainfall is contributed by rainfall in the rainy season, the increasing trends in the dry season could be a determining factor of possible changes in annual rainfall patterns. Station-wise, the upward trends at Can Gio, Hoc Mon, Binh Chanh, and Tam Thon Hiep stations were more consistent than those at the remaining rainfall stations, although the significant trends were only observed at Can Gio station for all statistical trend tests.

### Spatial trend assessment

In this final step, the spatial patterns of annual and season rainfall were examined by interpolation technique. Figure 8 illustrates the spatial distribution of annual and seasonal rainfall in HCMC for the considered period. The interpolated results of  $Z_{MK}$  values and Sen's slope values are also depicted in Figures 9 and 10, respectively. In the present work, the yearly values of annual and seasonal rainfall at each station were adopted as data input in the interpolating procedure.

It can be seen from Figure 8 that the annual rainfall in HCMC varied substantially from around 1,100 to nearly 2,000 mm/year. The highest rainfall intensity of values greater than 1,700 mm/year was found in the city center

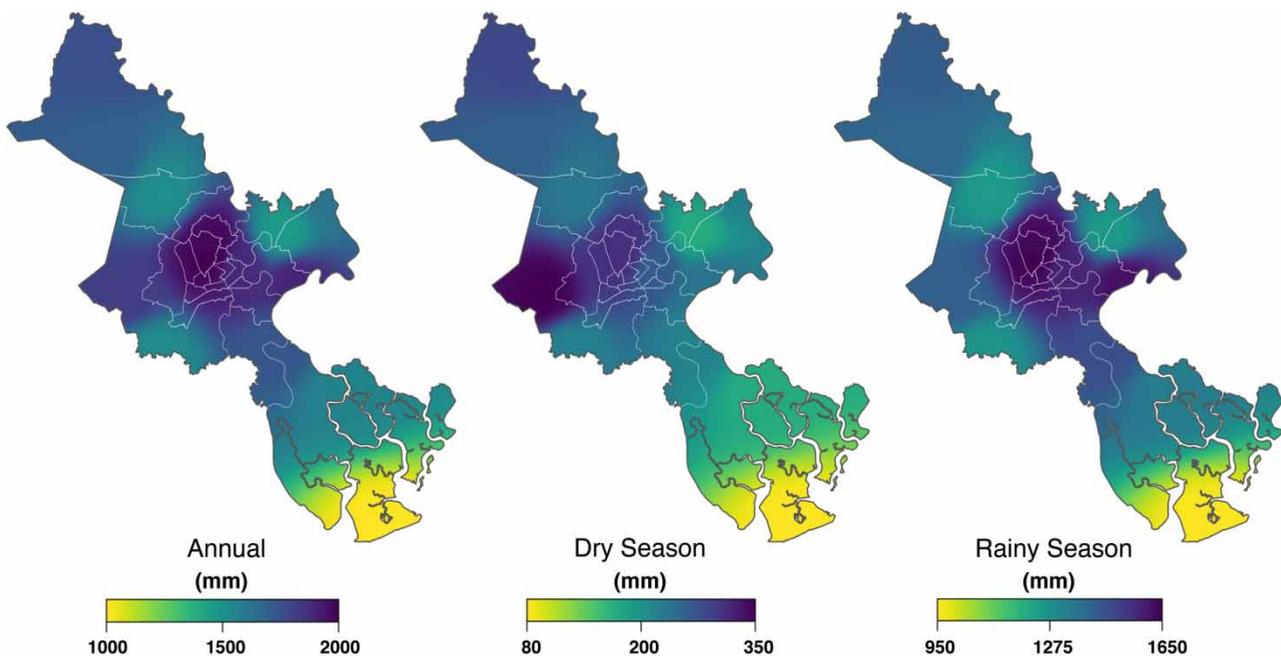
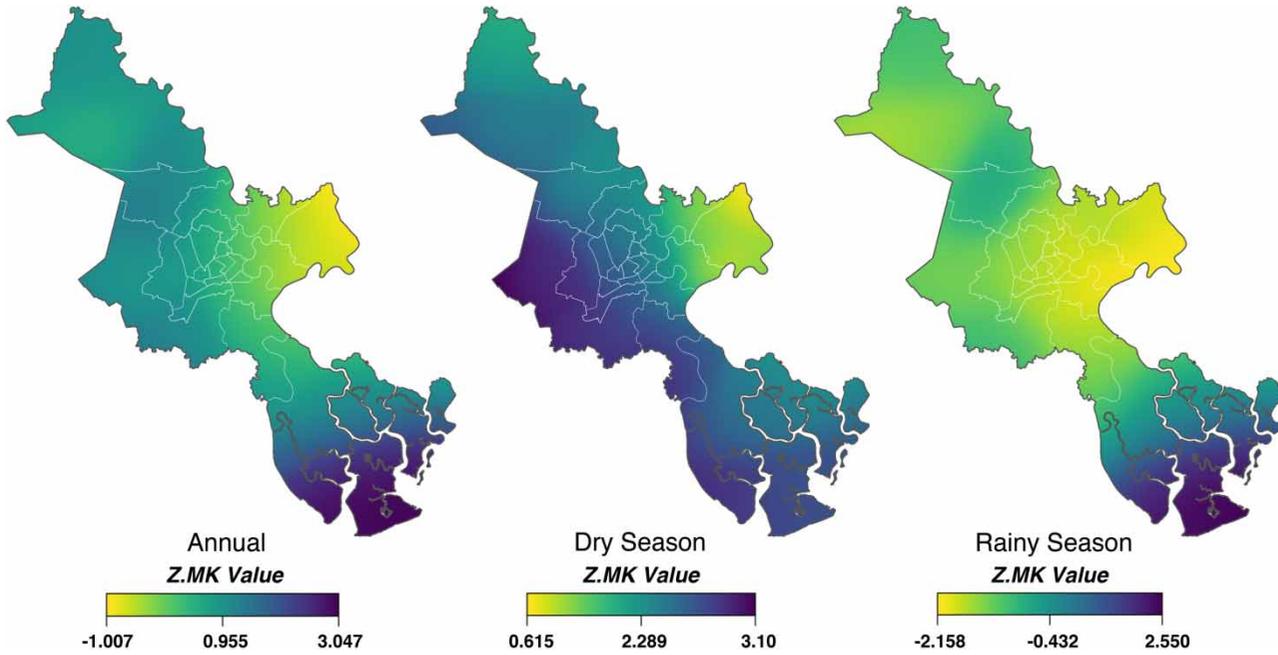
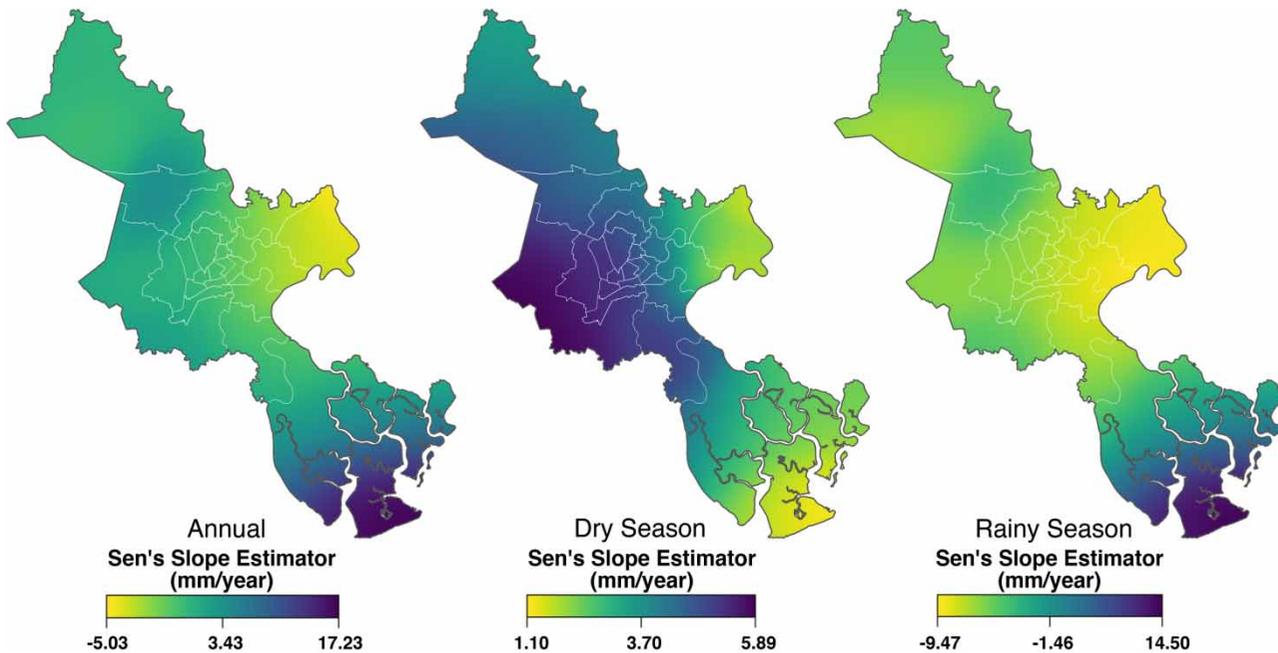


Figure 8 | Spatial distribution of annual and seasonal rainfall in HCMC.



**Figure 9** | Spatial distribution of interpolated  $Z_{MK}$  values.



**Figure 10** | Spatial distribution of estimated Sen's slope estimator values.

towards both east and west directions of HCMC and a part of Cu Chi district located in the northwest of the city, accounting for around 31.8% of the total area of HCMC. Conversely, annual rainfall was lowest over the southeast

of HCMC (i.e., Can Gio district), accounting for approximately 13.9% of the total area of HCMC. Likewise, spatial distribution of seasonal rainfall is mostly similar to the annual patterns. In particular, the total amount of rainfall

in the dry season varied from around 100 to 300 mm/year, while the figure for the rainy season mainly ranged between 1,000 mm/year and 1,600 mm/year.

On the annual basis, the interpolated results indicated that most of the area of HCMC was characterized by increasing trends, accounting for around 86.1% of the total area of HCMC. However, very few significant trend scores ( $Z_{MK} > 1.96$ ) were obtained. In addition, the southeastern parts of HCMC (i.e., Can Gio district), where experienced statistically significant increase, were also responsible for the highest increasing levels, ranging from approximately 5 to 17 mm/year. In the dry season, the whole extent of HCMC experienced upward trends and around 76.3% of the total area of HCMC was characterized by statistically significant trends ( $Z_{MK} > 1.96$ ), with interpolated Sen's slope values varying from 2 to nearly 6 mm/year. On the contrary, more than half of the total area of HCMC exhibited declining trends in the rainy season, but very few significant trend scores ( $Z_{MK} < -1.96$ ) were obtained. It is worth noting that statistically significant increasing trends were also found in several parts of Can Gio district, with the interpolated Sen's slope values ranging between 5 and 14 mm/year.

In general, most of the area of HCMC was dominated by increasing trends on the annual and seasonal scales, except during the rainy season. It is also evident that the positive trends in the southeastern parts of HCMC (i.e., Can Gio district) were by far the most pronounced increment with higher increasing levels compared to other regions, even though the total amount of annual rainfall in such district was lower than that in other areas.

## CONCLUSIONS

In the present study, the spatial and temporal patterns of rainfall time series at 14 stations in Ho Chi Minh City were examined by using both parametric and nonparametric approaches, including linear regression, the Mann–Kendall test and Sen's slope estimator. The outcomes from these statistical trend tests were almost the same. As for seasonal trend analysis, it is definitely necessary to determine the duration of each season. An interesting contribution of this study is the application of the notched boxplot to monthly time series for the purpose of seasonal division. It is

apparent that there are two distinct seasons: the dry and rainy seasons. Over the considered period (1980–2016), the rainy season lasts from May to October and rainfall in the rainy season contributes mainly to the total amount of annual rainfall, accounting for approximately 80–90%.

The results of trend detection showed high domination of increasing trends in the annual and seasonal rainfall time series, but most statistically significant trends were observed in the dry season. Additionally, the results of trend estimation indicated that the magnitude of increasing trends in the dry season was more intense than that in the rainy season at the majority of stations (12 out of 14). Therefore, a key finding can be inferred that even though the total amount of annual rainfall is contributed by rainfall in the rainy season, the pronounced increment in the dry season can be a determining factor of possible changes in annual rainfall. Another remarkable finding is that even though the annual rainfall intensity in the southeastern parts of HCMC (i.e., Can Gio district) was by far the lowest when compared with other regions, the consistent upward tendencies in such district were more pronounced with higher increasing levels.

In general, this study paints an overall picture of long-term rainfall variability in terms of space and time, which yields a great deal of the physical basis of rainfall patterns over the 37-year period. It is expected that these detailed results are helpful to address climate-induced risks in Ho Chi Minh City. In particular, it is anticipated that the annual and seasonal rainfall zonation and the rainfall trend maps will serve as an exposure indicator and data input for urban inundation modeling for forthcoming investigations on vulnerability assessment to climate change.

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