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# Changing Urban Temperature and Rainfall Patterns in Jakarta: A Comprehensive Historical Analysis

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**Abstract:** The increasing global population and in-country migration have a significant impact on global land use land cover (LULC) change, which reduces green spaces and increases built-up areas altering the near-surface radiation and energy budgets, as well as the hydrological cycle over an urban area. The LULC change can lead to a combination of hazards such as increasing urban temperatures and intensified rainfall, ultimately resulting in increased flooding. This present study aims to discuss the changing pattern in urban temperature, daily rainfall, and flooding in Jakarta. The daily urban temperature and daily rainfall were based on a 30-year dataset from three meteorological stations of Jakarta in the period between 1987 and 2013. The changing trend was analyzed by using the Mann–Kendall and the Pettitt's tests. The relation between daily rainfall and flooding was analyzed using a 30-year flooding dataset collected from several sources including the international disaster database, research, and newspaper. The results show that there was an increasing trend in the daily temperature and the daily rainfall in Jakarta. The annual maximum daily temperature showed that an increasing trend started in 2001 at the KMY station, and in 1996 at the SHIA station. In general, the highest annual maximum daily temperature was about 37 °C, while the lowest was about 33 °C. Moreover, the maximum daily rainfall started increasing from 2001. An increase in the maximum daily rainfall was observed mainly in January and February, which coincided with the flood events recorded in these months in Jakarta. This indicates that Jakarta is not only vulnerable to high urban temperature but also to flooding. While these two hazards occur in distinct timeframes, there is potential for their convergence in the same geographical area. This study provides new and essential insights to enhance urban resilience and climate adaptation, advocating a holistic approach required to tackle these combined hazards.

**Keywords:** urbanization; land use land cover change; urban temperature; daily rainfall; flooding; Jakarta

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## 1. Introduction

The world has seen an increase in the global population in recent decades. In 2017, the world population reached 7.6 billion, which would increase to 8.5 billion by 2050, and 11.2 billion in 2100 [1]. Moreover, people living in urban areas was 54% higher than that in rural areas in 2014, and it is projected to be 66% in 2050 [2].

The increasing global population and in-country migration have a significant impact on global land use land cover (LULC) change [3–5]. According to Winkler et al. (2021) [4], approximately 32% of the Earth's surface experienced LULC changes between 1960 and 2019. Moreover, global LULC dynamics during the period from 1982 to 2016 led to a reduction in vegetation cover within various arid and semi-arid ecosystems, potentially linked to human activities [3]. The increase in built-up areas globally between 2000 and 2020 was about 50%, whereas in Asia, about 60% of the total built-up areas increased mainly due to urban expansion in China and India [6]. Anticipating the future, global projections indicate a growth in urban areas by a factor of 1.8 to 5.9, which would mainly occur in Africa and Asia by 2100 [7].

The land use transition of LULC change reduces green spaces and increases built-up areas, which changes the near-surface radiation and energy budgets over an urban area. As a consequence, there is a decrease in latent heat and an increase in sensible heat leading to an increase in urban temperature. Green spaces have an important role in controlling urban temperature through evapotranspiration, trees shading, or air movement modification [8]. Green spaces absorb solar radiation that is converted to latent heat which is used as the energy source to convert water from liquid form to gaseous form in the evapotranspiration process. Latent heat mainly ends up in water vapor, which does not raise the surrounding air temperature [9]. Moreover, urban materials mainly have a good thermal admittance capacity that allows solar radiation absorption and releases it as sensible heat, which causes increasing air temperatures [10]. An increase in urban temperature due to LULC change has been observed in many cities around the world, such as Atlanta [11], Dhaka [12], Ho Chi Minh City [13], Karachi [14], Jakarta [15], Colombo [16], and Tokyo [17]. During summertime, increasing urban temperatures are becoming more intensive which leads to health-related problems [14,18–21] and an increase in energy usage for cooling buildings [22].

Furthermore, increasing urban temperatures due to LULC change can influence urban rainfall. Urban-induced rainfall is a complex process, intricately influenced by the urban environment [23–26]. Temperature changes in urban areas are related to urbanization and global warming, which can affect local precipitation [27]. The impact of urbanization on urban rainfall has been studied by analyzing the land–atmosphere interactions in urban areas [28–32]. These interactions are mainly influenced by an increase in sensible heat fluxes and the surface roughness of an urban area [33–35]. Due to LULC change, natural surfaces and green spaces of urban areas are replaced by man-made artificial surfaces that absorb more solar energy. The latter is released as sensible heat. This process affects atmospheric circulations and the formation and distribution of extreme rainfall [36]. Many studies have been dedicated to investigate this interaction. Doan et al. (2021) [34] highlighted the strong urban effect on local rainfall in Singapore where urban areas contributed to about 20–30% of the total rainfall during late afternoons and evenings. Marelle et al. (2020) [35] showed that an increasing upward movement of warm air and moisture convergence to an increasing sensible heat could be an important driver of increasing rainfall due to urbanization. Umer et al. (2023) [25] showed that changes in an urban landscape dominated by urban and built-up areas increased extreme rainfall intensity resulting in flash floods in the city of Kampala, Uganda. Future urbanization and LULC changes are projected to sustain an increase in urban rainfall, as observed in Can Tho, Vietnam [37], as well as in cities like Paris and Shanghai [38], along with numerous other urban centers worldwide.

Moreover, decreasing green spaces and increasing built-up areas can make an urban area more susceptible to flooding. Loss of green spaces due to LULC change can alter the hydrological cycle of an urban area causing a decrease in infiltration, a decrease in flow resistance, or a reduction in rainfall interception leading to an increase in surface runoff [39–41]. Decreasing green spaces during urban development is associated with a loss of permeable surfaces of soils. Because of surface soil removal, soil tends to have a low infiltration capacity since it is compacted with decreased pore space [42,43]. The impact of increasing urban and built-up areas on infiltration and flooding has been discussed in a number of studies. In their study, Eshtawi et al. (2016) [44] found a linear relationship between the expansion of urban areas and the subsequent increase in surface runoff within the Gaza strip. Notably, a 50% increase in urban areas led to an increase in surface runoff of 13% to 27%. Skougaard Kaspersen et al. (2017) [45] demonstrated the significant impact of urban development on flooding in urban areas between 1984 and 2014. Their study revealed that a 1% increase in impervious surfaces could lead to a 10% increase in runoff volume in four European cities of Odense, Vienna, Strasbourg, and Nice.

A decrease in green spaces due to LULC change in Jakarta in the last decades has been observed in several studies [46–50]. Rustiadi et al. (2002) [47] studied the LULC change of Jakarta and its surrounding areas Bogor, Tangerang, and Bekasi between 1972 and 2001. They showed an increase in built-up areas by about 51% in Jakarta, which was higher than that in the surrounding areas. Carolita et al. (2002) [48] revealed that built-up areas in Jabotabek increased by about 12% between 1992 and 2001, while agricultural land decreased by about 6%. Ramdhoni and Rushayati (2016) [51] highlighted a decrease in green spaces in Jakarta by about 12% between 2001 and 2014. Maheng et al. (2021) [50] studied LULC change in Jakarta between 1995 and 2014. They revealed that the spatial-temporal distribution of land use and land cover (LULC) change in Jakarta was characterized by extensive urban development. The increase in built-up areas had a significant impact on the green spaces, which decreased by about 50%.

The impact of LULC change on increasing urban temperature in Jakarta has been studied by [15,51–54]. Tokairin et al. (2010) [15] revealed an increase in urban temperature in the old Jakarta area due to urban development. Sobri (2009) [54] highlighted that a decrease in urban green space in Jakarta and its metropolitan area could be associated with an increase in air temperature between 0.4 °C and 1.8 °C. Ramdhoni and Rushayati (2016) [51] revealed an increase in land surface temperature (LST) of about 30 °C between 2001 and 2014, and an average increase in air temperature from 24 °C to 30 °C in 2001 and 27 °C to 30 °C in 2014. Siswanto et al. (2016) [53] studied daily meteorological data for Jakarta for 134 years, which indicated that urbanization in the Jakarta area contributed to an increase in the daily mean temperature of almost 2 °C in the last 100 years. The maximum temperature increased sharply by almost 2.12 °C in 100 year, which is higher than the rise in global land surface temperature. A recent study by Maheng et al. (2023) [55] revealed that an increase in built-up areas resulting from urbanization between 1995 and 2014 had changed the spatial distribution of the urban temperature in Jakarta. The temperature increase was about 0.5 °C. They also highlighted that the temperature anomaly in the LULC change from green spaces to built-up areas was higher compared to that in changes in other LULC classes.

The increasing urban temperature in Jakarta is associated with extreme rainfall [56–58]. Tsiringakis et al. (2017) [56] studied urban flooding in Jakarta. They found that the flooding in February, 2015, could be associated with LULC change and an increasing urban temperature. The urban temperature and enhanced surface roughness contributed to an increase in precipitation of 12% and 4%, respectively. During the dry season, the rainfall intensity is influenced by surface temperature [53], which tends to increase due to increased urbanization [59]. Nuryanto et al. (2018) [58] have revealed that LULC change contributes to an increase of 0.2 °C in the urban temperature and 6% of the urban rainfall. Both changes were associated with the flood event in Jakarta on 17 January 2014.

The aforementioned studies indicate that as built-up areas increase and green spaces decrease, it can lead to a combination of hazards, including rising urban temperatures and intensified rainfall, ultimately resulting in flooding [34,37,53,56–58]. Some studies are devoted to discussing these relationships in Jakarta, with a predominant focus on flooding events post 2013. However, there was some flooding events in Jakarta before 2013, which were categorized as major floods, but insufficient information is available about urban temperature, extreme rainfall, and flooding. Hence, this present study aims to identify and discuss the changing pattern of urban temperature, daily rainfall, and flooding, as well as the potential combined hazards in Jakarta in the period between 1987 and 2013.

## 2. Study Area

This study is conducted in Jakarta, the capital of Indonesia, which has a strategic position in Indonesian political and economic activities. Jakarta consists of five municipalities (Figure 1) and one regency, which are Central Jakarta (CJ), West Jakarta (WJ), North Jakarta (NJ), South Jakarta (SJ), East Jakarta (EJ), and Kepulauan Seribu regency (not seen in the figure). In 2018, Jakarta's population increased from about 7 million in 1987 to about 10 million in 2017 (as shown in Figure 2), with a population growth rate of 1.57% per year [60]. Among the municipalities, East Jakarta is the most populated area, whereas West Jakarta is the most densely populated area.

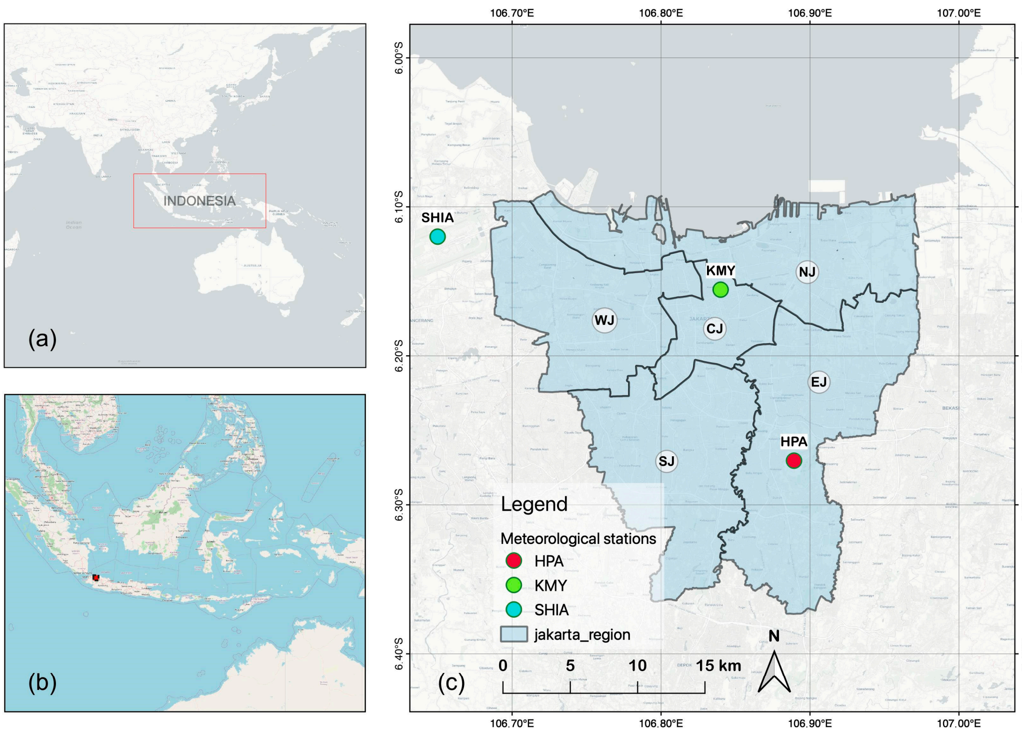


**Figure 1.** Study area (**a**) map of Asia; (**b**) map of Indonesia; (**c**) map of Jakarta and meteorological stations location.

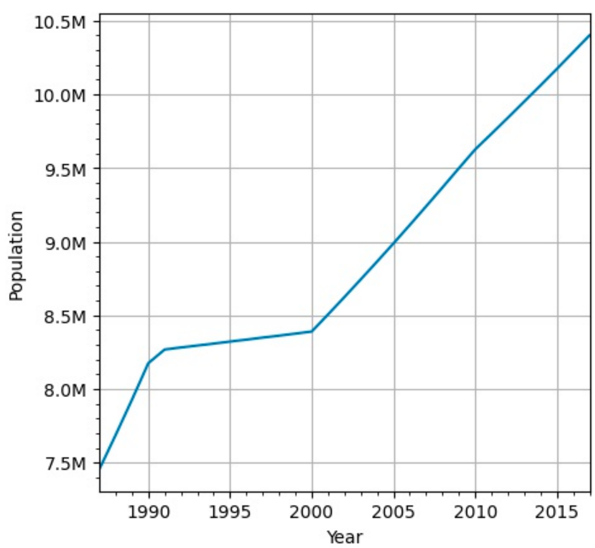


**Figure 2.** The population of Jakarta between 1987 and 2017.

Jakarta's climate is influenced by its location in the tropical monsoon climate zone, which is close to the equator [61]. Jakarta has wet and dry seasons. During the wet season, particularly from December to March, the monthly average rainfall values in Jakarta are higher than 150 mm. During the dry season (from June to September) the monthly average rainfall values are lower than 100 mm [62].

*Data Source*

This study is based on 30-year dataset of air temperature, daily rainfall, and flooding in Jakarta. The meteorological data for rainfall and temperature were made available on a daily basis from https://dataonline.bmkg.go.id accessed on 17 July 2022, as given in Table 1 [63]. The rainfall and temperature data were provided by the meteorological stations and comprised collected data for the period between 1987 and 2017. The historical flooding data were collected from various sources, including newspapers, research papers, reports, and the international disaster database [64].

**Table 1.** Temperature and rainfall data source.

| Meteorological Stations | Data | Time Period | Source |
|---|---|---|---|
| KMY | daily temperature, daily rainfall | 1987 to 2017 | https://dataonline.bmkg.go.id, accessed on 17 July 2022 |
| SHIA | daily temperature, daily rainfall | 1987 to 2017 | https://dataonline.bmkg.go.id, accessed on 17 July 2022 |
| HPA | daily temperature, daily rainfall | 1987 to 2017 | https://dataonline.bmkg.go.id, accessed on 17 July 2022 |

The daily rainfall and the daily air temperature data are from three meteorological stations of the Meteorological, Climatological, and Geophysical Agency (BMKG) of Indonesia. The meteorological stations are located in Jakarta (HPA and KMY) and at the Soekarno–Hatta international airport (SHIA) on the outskirts of Jakarta, as depicted in Figure 1.

## 3. Methodology

Climate change impacts such as high urban temperature, urban rainfall, and urban flooding have a relationship with urban form (described by urban density, LULC, and materials) [8]. Urban density is related to several issues from the population density to the number of buildings in an urban area. Furthermore, materials in an urban area include asphalt, concrete, or metal. The relationship between climate change impacts and urban form indicates that urban forms can have direct impacts at urban scale, resulting in high urban temperature/urban heat island, and urban flooding [8]. The impacts may be further exacerbated by urban, regional, and global climate change.

This study is conducted in four steps, as shown in Figure 3. Firstly, air temperature data for Jakarta were collected from three meteorological stations of BMKG for the period between 1987 and 2017. The maximum daily temperature was used for air temperature analysis since the data available for the minimum and the average daily temperature were incomplete. The air temperature dataset was used to extract the annual maximum daily temperature to see the general trend of maximum daily temperature over a 30-year period. The temperature trend was analyzed using the statistical analysis of Mann–Kendall and the Pettitt's test to identify the change point. Those two statistical tests are non-parametric tests that have been widely used to identify the trend and change points of historical climate and hydrological data [65–67]. Furthermore, the monthly maximum daily temperature was prepared to understand the maximum daily temperature trend over a year. Monthly analysis divided the temperature dataset into three periods, namely the 1st period (1987 and 1996), the 2nd period (1997 and 2006), and the 3rd period (2007 and 2017).

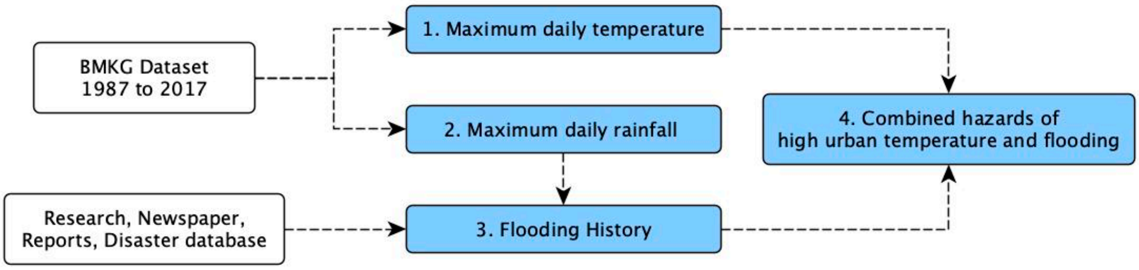


**Figure 3.** Research framework.

Secondly, daily rainfall analysis was based on the annual maximum daily rainfall in Jakarta between 1987 and 2017. The annual maximum daily rainfall was used to calculate the rainfall amount from one-day to three-day rainfall. The maximum daily rainfall was the average values of maximum daily rainfall from three stations, which was calculated using the Thiessen polygon method [68]. The statistical test was also conducted to analyze the trend and changing point of the maximum daily rainfall in Jakarta. Furthermore, the rainfall amount was classified into four classes, namely low, medium, high, and very high. Classification was based on a statistical approach to identify rainfall extremes following some previous studies on rainfall analysis [69–72]. The statistical approach was used to calculate the mean values and the standard deviation of the rainfall dataset. The first class is the low class in which the rainfall amount is between its mean value and mean plus one standard deviation. The second class is the medium class where the rainfall amount is between its mean plus one standard deviation and mean plus two standard deviation. The third class is the high class where the rainfall amount is between its mean plus two standard deviation and mean plus three standard deviation. The fourth class is the very high class where the rainfall amount is higher than its mean plus three standard deviation. Furthermore, extreme rainfall is defined as the rainfall amount associated with major flooding or severe flooding in Jakarta. The rainfall classification used in this study is given in Table 2.

**Table 2.** Rainfall classification used in this study; μ and σ denote mean and standard deviation of the daily rainfall amount, respectively, whereas *p* denotes the daily rainfall amount.

| Proposed Rainfall Classification in Jakarta | Daily Rainfall Amount (*p*) |
|---|---|
| Low | $p < (\mu + \sigma)$ |
| Medium | $(\mu + \sigma) < p < (\mu + 2\sigma)$ |
| High | $(\mu + 2\sigma) < p < (\mu + 3\sigma)$ |
| Very high | $p > (\mu + 3\ \sigma)$ |

Thirdly, flooding history in Jakarta from 1987 to 2017 was documented from various sources, such as newspaper, reports, websites, and scientific research. Historical flooding was used to identify flooding between 1987 and 2013, which helped to indicate the rainfall threshold of flooding in Jakarta.

Fourthly, the combined hazards of high urban temperature and flooding were analyzed. This section looks into the results of urban temperature analysis and flooding history documentation. By looking at the two outputs, it is possible to identify the combined hazards in Jakarta.

## 4. Results

### *4.1. Maximum Daily Temperature*

Between 1987 and 2017, the air temperature in Jakarta exhibited an increasing trend, as depicted in Figure 4. Figure 4 shows that three meteorological stations recorded an increasing trend for annual maximum daily temperature. The highest annual maximum daily temperature was about 37 °C, recorded at all stations, while the SHIA station recorded the lowest annual maximum daily temperature to be about 33 °C. Figure 4a shows the changing temperature trend line at the HPA station with a significant $p$-value of < 0.05. At the HPA station, the lowest annual maximum daily temperature recorded was close to 34 °C in 1992, while the highest annual maximum daily temperature was about 37 °C, observed in 2009, as depicted. The Pettitt's test results showed that the significant value for the HPA station was $p$-value > 0.05, indicating the homogeneity of the temperature data. As a result, the HPA station probably did not have a changing point. The temperature change trend line of the KMY station is shown in Figure 4b. Figure 4b shows that the lowest annual maximum daily temperature at the KMY station was almost similar to that at the HPA station, but it was observed in 2001 for the KMY station. The highest annual maximum daily temperature at the KMY station was about 37 °C, observed in 2014. The temperature trend line of the KMY station had a significant $p$-value of <0.05. The annual maximum daily temperature started increasing at the KMY station in 2001, as indicated by the changing point as a result of the Pettitt's test with a significant $p$-value of <0.05. Figure 4c shows the temperature change trend line of the SHIA station. It is shown that the annual maximum daily temperature of the SHIA station started increasing in 1996, as indicated by the changing point of the Pettitt's test with a significant $p$-value < 0.05. Furthermore, the lowest annual maximum daily temperature at the SHIA station was about 33 °C, observed in 1995, while the highest temperature was a bit higher than 37 °C, observed in 1999.

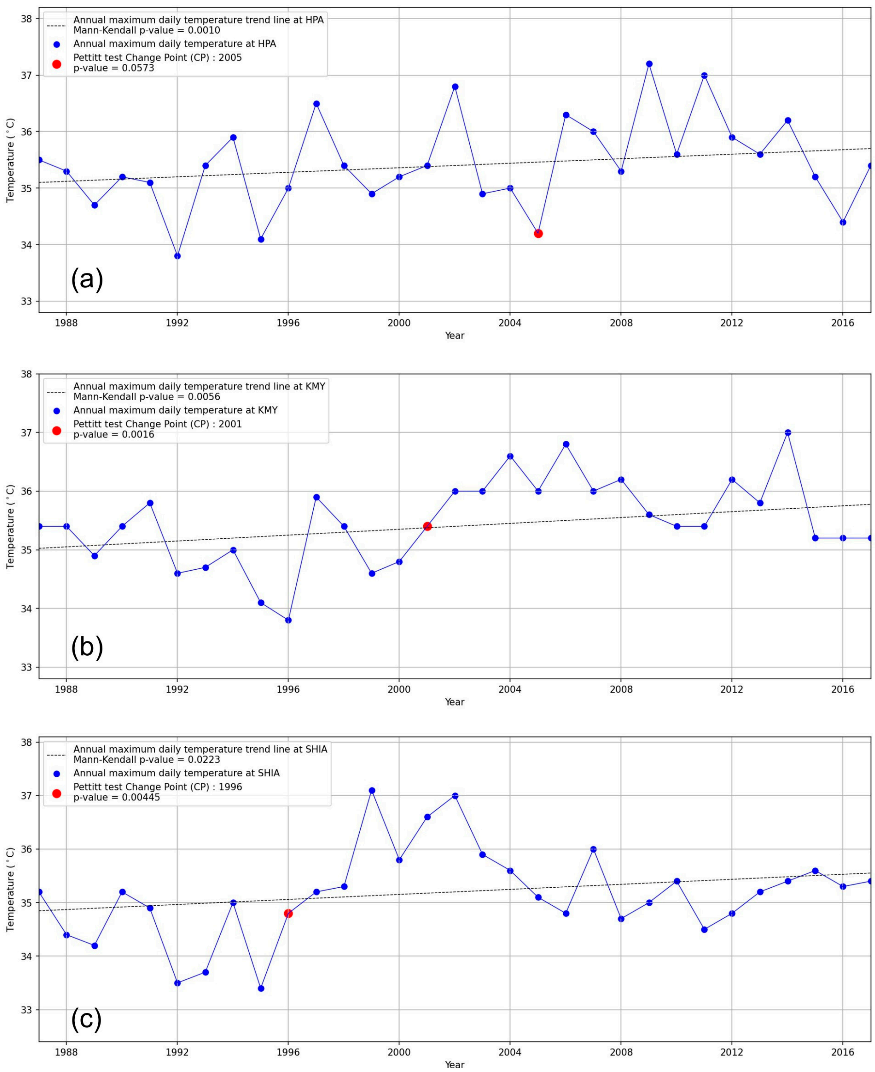


**Figure 4.** The annual maximum daily temperature change trend and the changing point at the meteorological stations. (**a**) The HPA station; (**b**) the KMY station; (**c**) the SHIA station.

The increasing trend of maximum daily temperature was also observed in the monthly maximum daily temperature, as given in Figure 5a–c. The monthly maximum daily temperature observations were divided into three periods: from 1987 to 1996 (first period), from 1997 to 2006 (second period), and from 2007 to 2017 (third period).

Figure 5a shows a consistent increase in the monthly maximum daily temperature at the HPA station over the 30 years spanning the three periods. At the HPA station, the lowest maximum daily temperature increased from about 33 °C in the second period to about 35 °C in the third period. The highest maximum daily temperature increased from about 35 °C in the first period to about 37 °C in the third period. The maximum daily temperature at the HPA station had an increasing trend starting from February to October in the first period and the second period, while the highest maximum daily temperature of the third period was observed in July. The maximum daily temperature in the first period increased from about 33 °C in February to about 35 °C in October. In the second period, the maximum daily temperature increased from 33 °C in February to about 36 °C in October. The third period showed a significant increase in maximum daily temperature. The maximum daily temperature increased from about 35 °C to about 37 °C in July.

The increasing trend of maximum daily temperature at the KMY station is given in Figure 5b. The lowest maximum daily temperature increased from about 33 °C in the first period to about 34 °C in the third period. Moreover, the highest maximum daily temperature also increased from about 35 °C in the first period to about 37 °C in the third period. Furthermore, it was observed that the maximum daily temperature increased gradually from February to October in the first period and the second period, while it increased from February to September in the third period. In the first period, the maximum daily temperature increased from 33 °C in February to almost 36 °C in October when the rainy season normally begins. In the second period, the maximum daily temperature increased from about 34 °C in February to almost 37 °C in October. In the third period, the maximum daily temperature had a similar pattern as two other periods, but the highest maximum daily temperature was observed to be 37 °C in September.

The maximum daily temperature pattern at the SHIA station is given in Figure 5c. Compared to the other two stations, the SHIA station showed an increase in the maximum daily temperature from the first period to the second period. At the SHIA station, the lowest maximum daily temperature increased from about 33 °C in the first period to about 35 °C in the second period. The highest maximum daily temperature increased from about 35 °C in the first period to about 37 °C in the second period. Furthermore, the maximum daily temperature in the first period showed an increasing trend, from about 33 °C in February to about 35 °C in October. In the second period, the maximum daily temperature had a high variation. The maximum daily temperature started increasing from about 35 °C in February to the highest value of about 37 °C in March. Afterwards, the trend decreased gradually to reach the lowest maximum daily temperature of about 34 °C in August. The third period shows a lower maximum daily temperature compared to that in the second period. The lowest maximum daily temperature in the third period was about 34 °C in February, while the highest temperature was about 36 °C, observed in November.

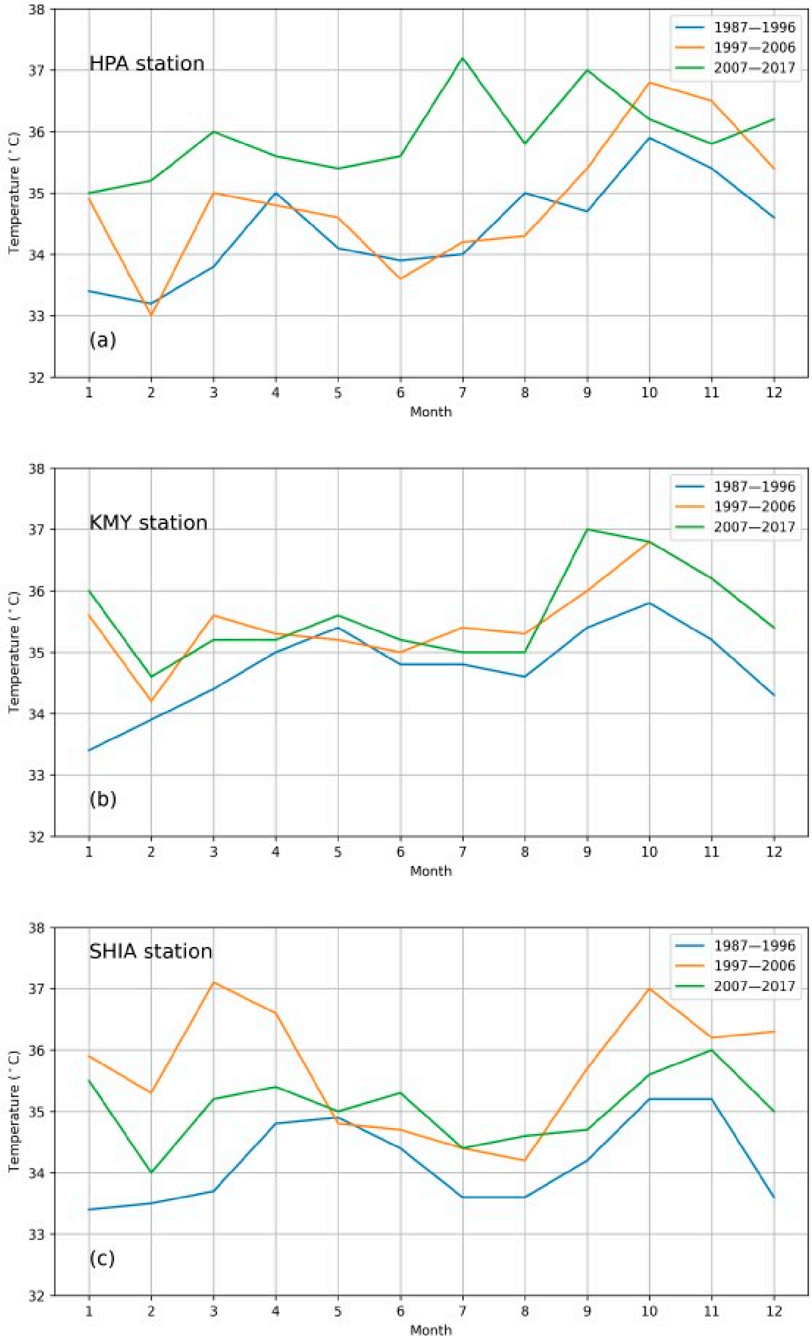


**Figure 5.** Maximum daily temperature between 1987 and 2017 in Jakarta. (**a**) Monthly maximum daily temperature at the KMY station; (**b**) monthly maximum daily temperature at the HPA station; (**c**) monthly maximum daily temperature at the SHIA station.

### *4.2. Maximum Daily Rainfall*

The statistical test results from the Mann–Kendall test showed that there was an increase in daily rainfall and daily accumulated rainfall in Jakarta between 1987 and 2017, as depicted in Figure 6, with a significant *p*-value of <0.05. The increasing trend of accumulated daily rainfall was observed for daily rainfall (Figure 6a), two-day rainfall (Figure 6b), and three-day rainfall (Figure 6c). Furthermore, the accumulated daily rainfall started increasing in 2001, as indicated by the changing point of the Pettitt's test with a significant *p*-value of <0.05.

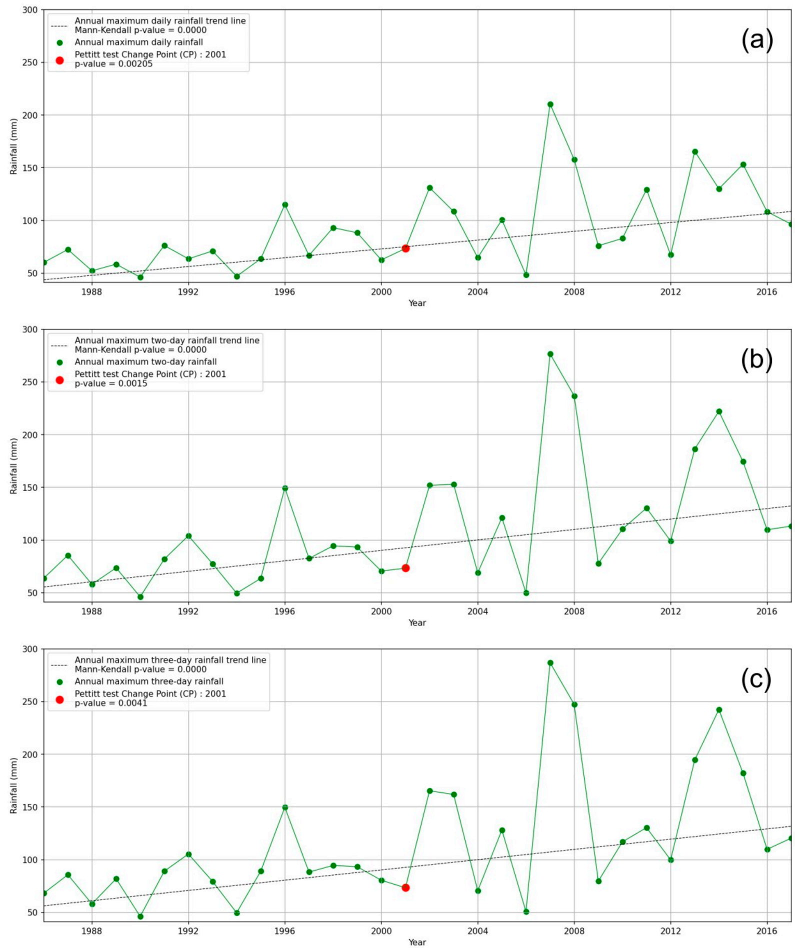


**Figure 6.** The daily accumulated rainfall and the changing point in Jakarta. (**a**) daily rainfall; (**b**) two-day rainfall; (**c**) three-day rainfall.

The increase in the maximum daily rainfall is observed mainly in January and February, which coincides with the flood events recorded in these months in Jakarta, as given in Table 3.

**Table 3.** The daily accumulated rainfall of flood events based on BMKG data in Table 1.

| Dates | Daily Accumulated Rainfall (mm) | | |
|---|---|---|---|
| | One-Day | Two-Day | Three-Day |
| 9 February 1996 | 114.96 | 149.45 | 149.65 |
| 25 February 1998 | 93.16 | 94.54 | 94.54 |
| 1 February 2002 | 131.11 | 151.88 | 165.41 |
| 29 December 2003 | 108.50 | 152.88 | 161.82 |
| 18 January 2005 | 100.62 | 121.26 | 128.16 |
| 1 February 2007 | 210.49 | 276.56 | 286.86 |
| 1 February 2008 | 157.70 | 236.80 | 247.33 |
| 28 February 2011 | 129.34 | 130.37 | 130.42 |
| 17 January 2013 | 165.57 | 186.50 | 194.67 |
| 17 January 2014 | 130.02 | 222.09 | 242.39 |
| 10 February 2015 | 153.34 | 174.50 | 182.16 |
| 21 April 2016 | 108.36 | 109.79 | 109.79 |

Figure 7 shows the annual maximum daily rainfall in Jakarta. It shows that for one-day rainfall, flooding could be associated with maximum daily rainfall above a mean value of about 92 mm. Figure 7 indicates that the flooding identified in 1996, 1998, 2002, 2003, 2005, 2011, 2014, and 2016 could be associated with the low class of rainfall. Furthermore, the medium class of rainfall was identified in 2008, 2013, and 2015. The maximum daily rainfall in 2007 was classified into the very high class since it was above 200 mm.

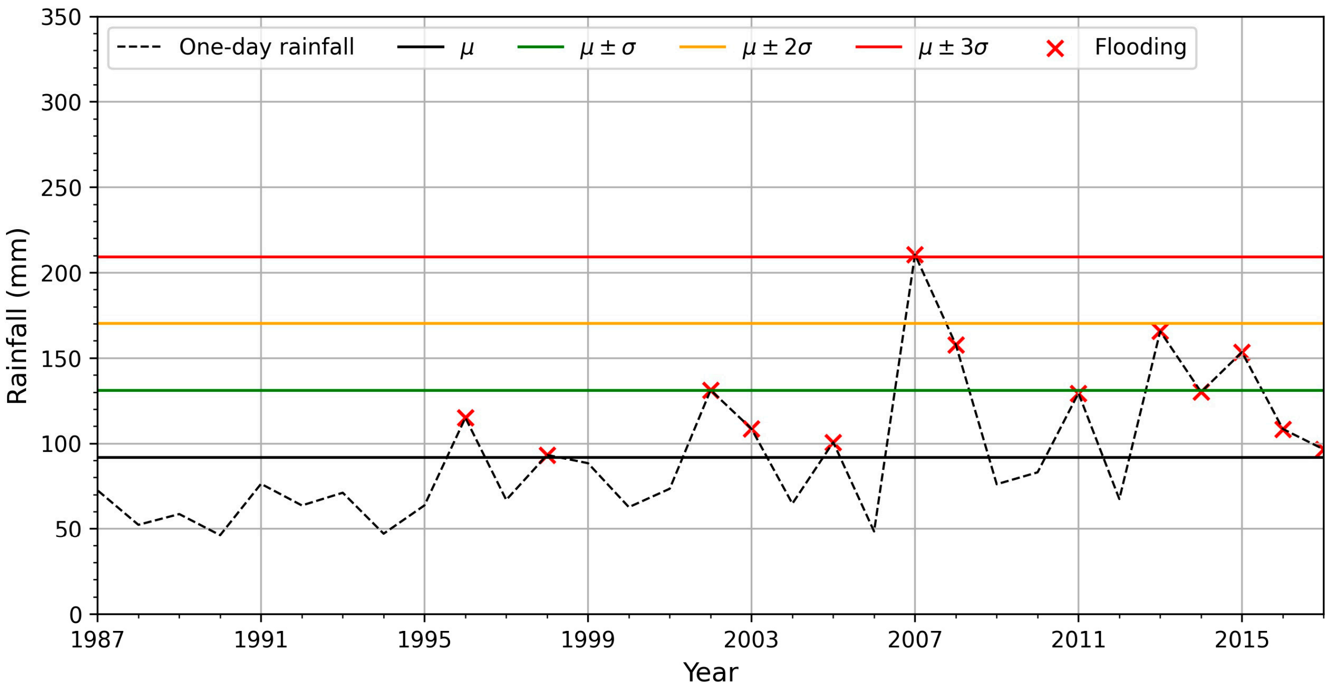


**Figure 7.** Annual maximum daily rainfall in Jakarta between 1987 and 2017. The maximum daily rainfall values that resulted in flooding are presented with a red cross. Here, μ and σ denote the standard deviation and the mean value of the annual maximum daily rainfall (Pm) time series during 1987–2017 for Jakarta, respectively.

The annual maximum two-day rainfall is depicted in Figure 8. It can be seen that there was a slight change in the rainfall classification compared to that of the daily maximum rainfall, particularly in 1998 and 2016. The maximum two-day rainfall in 1998 and 2016 was below its mean value of 110 mm. The maximum two-day rainfall that could be associated with flooding was observed in 1996, 2002, 2003, 2005, 2007, 2008, 2011, 2013, 2014, and 2015. Low-class rainfall was identified in 1996, 2002, 2003, 2005, and 2011. The medium class was observed in 2013, 2014, and 2015, while the high class was identified in 2007 and 2008. For two-day rainfall, there was no rainfall classified into the very high class.

The annual maximum three-day rainfall is depicted in Figure 9. The figure indicates that the maximum three-day rainfall associated with flooding appeared in 1996, 2002, 2003, 2005, 2007, 2008, 2010, 2011, 2013, 2014, and 2015. Low-class rainfall was identified in 1996, 2002, 2003, 2005, 2010, and 2011. Moreover, the maximum three-day rainfall in 2011 at 72 h was higher than that at 24 h. The medium class was observed in 2013, and 2015. Furthermore, the maximum three-day rainfall in 2007, 2008, and 2014 were classified into the high class.

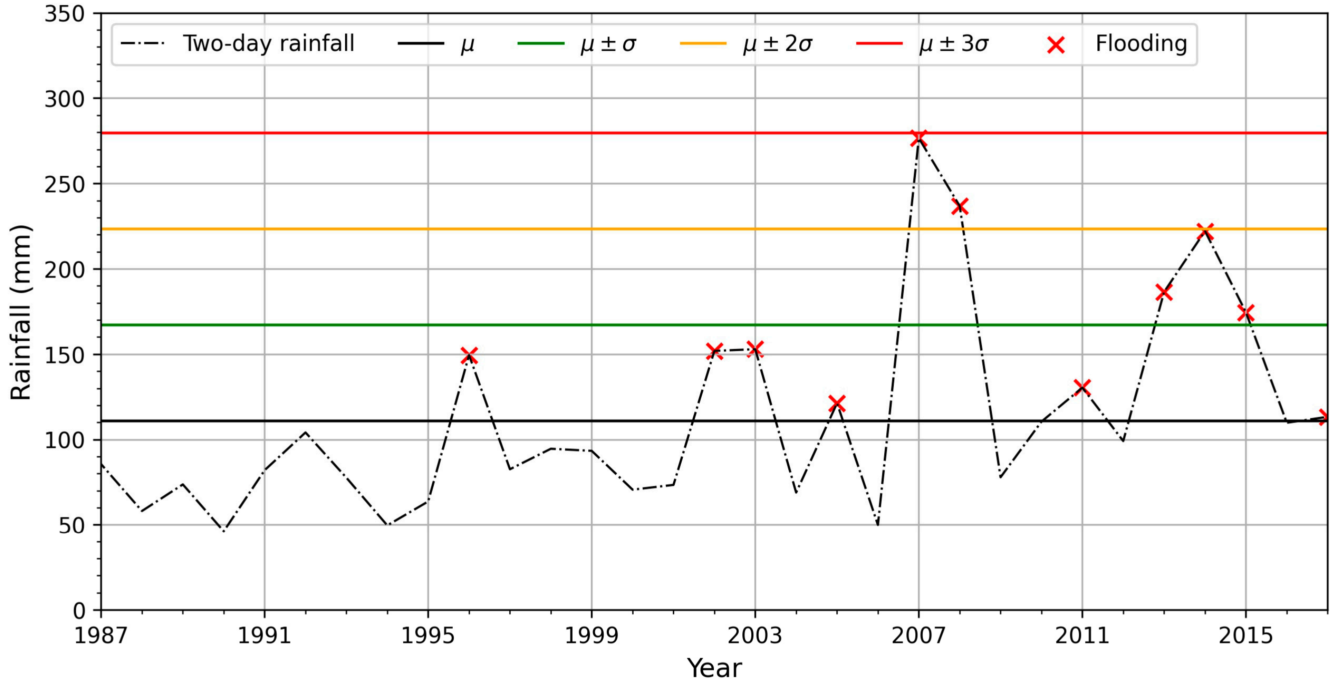


**Figure 8.** Annual maximum two-day rainfall in Jakarta between 1987 and 2017. Here, μ and σ denote the standard deviation and the mean value of the annual maximum two-day rainfall (Pm) time series during 1987–2017 for Jakarta, respectively.

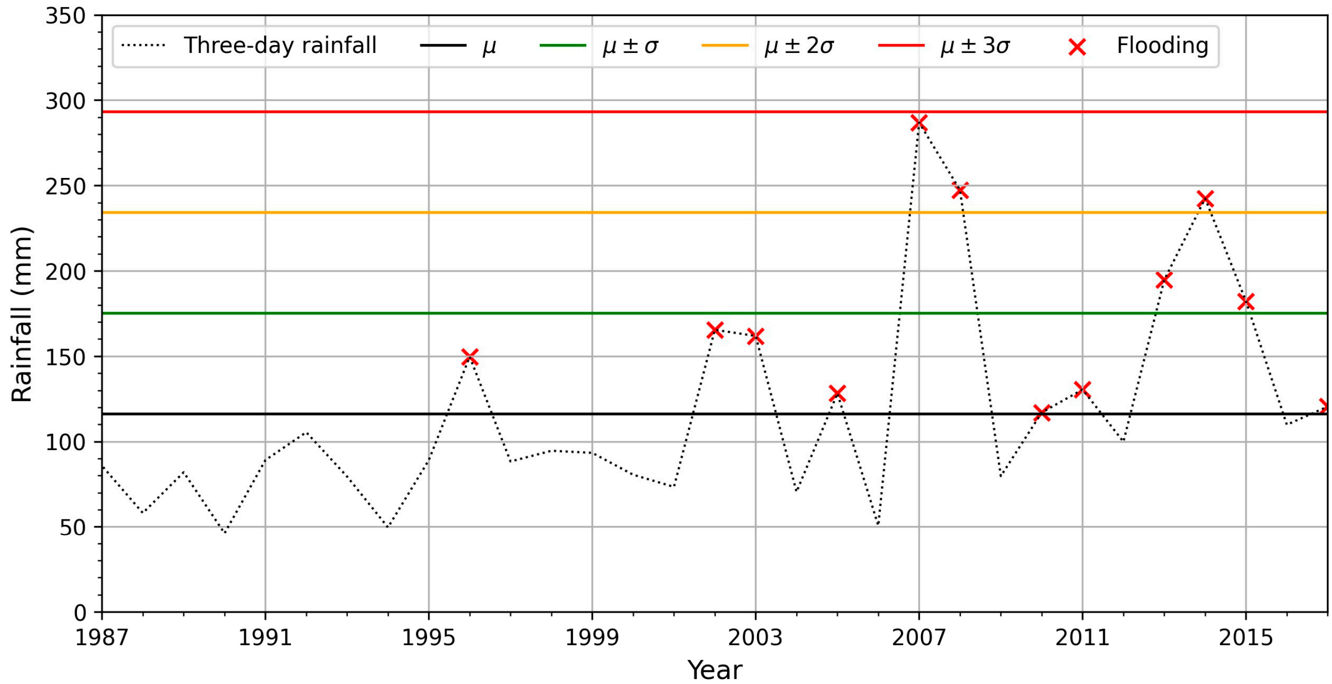


**Figure 9.** Annual maximum three-day rainfall in Jakarta between 1987 and 2017. μ and σ denote the standard deviation and the mean value of the annual maximum three-day rainfall (Pm) time series during 1987–2017 for Jakarta, respectively.

According to the daily rainfall analyses above, it can be seen that Jakarta could be inundated once the daily rainfall amount is about 92 mm. Figure 7 shows that a maximum daily rainfall above the mean value was observed in 1996, 1998, 2002, 2003, 2005, 2007, 2008, 2011, 2013, 2014, 2015, and 2016. Furthermore, severe flooding was observed when there was extreme rainfall higher than 150 mm.

An increase in the number of flooding events between 1987 and 2017 in Jakarta has a relationship with an increase in daily rainfall, as depicted in Figure 10. The number of flooding events between 1987 and 1996 was one, which occurred when the maximum daily rainfall was about 114 mm. The number increased to four events between 1997 and 2006 when the maximum daily rainfall was about 131 mm. Afterwards, the number of flooding events between 2007 and 2017 also increased to eight when the maximum daily rainfall was about 210 mm, observed in 2007.

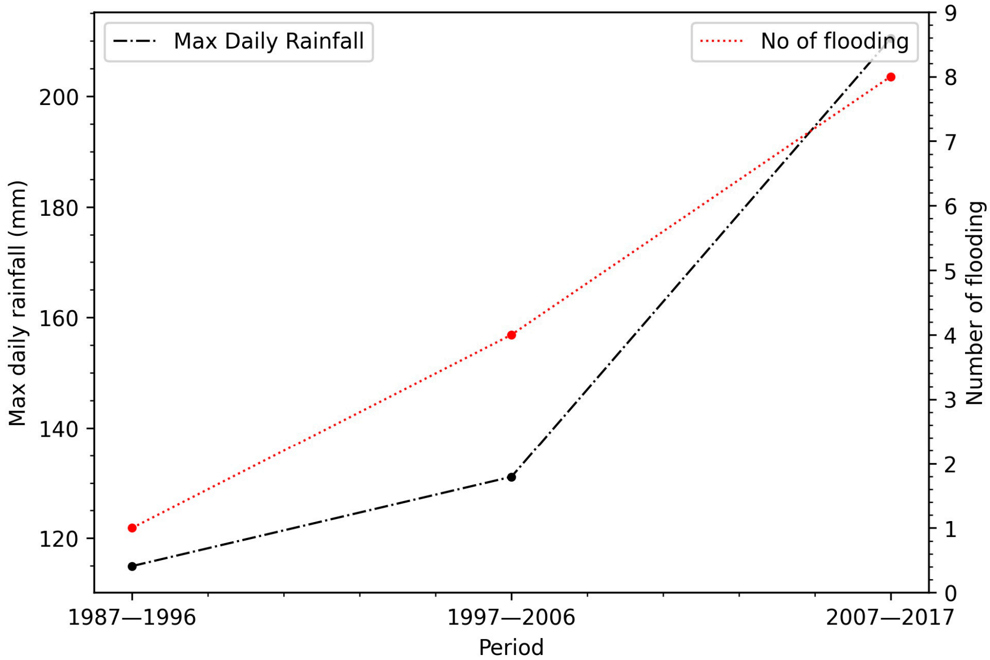


**Figure 10.** Maximum daily rainfall and number of flooding events in several observation periods.

### 4.3. Flooding History in Jakarta

Jakarta has a long history of flooding. It goes back to the kingdom and colonization era when the city's name was Batavia. Noorduyn and Verstappen (1972) [73] revealed that the first flood in Jakarta was documented in the Prasasti Tugu in the 5th century.

Over the last three decades, spanning from 1987 to 2017, Jakarta has experienced numerous floods, which have been documented in research papers, working papers, and newspapers, as shown in Table 4. Among them, major floods were observed in 1996, 2002, 2007, 2008, 2013, and 2014. This study did not have access to direct damage data for the floods that occurred between 1987 and 2017. Hence, the severity of the floods was based on the affected people and the number of deaths. In the decade between 1990 and 2000, Jakarta experienced a significant flood in 1996, resulting in the loss of 20 lives and affecting 30,000 people [64,74]. From 2001 to 2010, at least three major floods were recorded. One of them was in 2002 when the number of affected people reached more than 400,000 and 22 people died [64,74,75]. Diposaptono et al. (2004) [76] highlighted that the 2002 flood was one of the most severe floods in Jakarta. However, the flood in 2007 had a more significant impact as the number of casualties was high [74,77,78]. The areas inundated with flooding in 2007 are provided in [79]. Flooding in 2008 did not cause a significant impact since the number of affected people was less than that of other flooding events. Between 2011 and 2017, two major floods were recorded. In 2013, flooding affected 25,000 people [78,80]. Moreover, flooding in 2014 had a relatively small impact compared to that of previous flooding as the number of affected people decreased. However, the 2014 flooding still caused damages to the city, though the flood was not comparable to those in 2007 and 2013 [78].

**Table 4.** Years of flooding, the impacts, and information sources.

| Dates | Number of Affected People | Number of Deaths | Remarks | Information Sources |
|---|---|---|---|---|
| 9 February 1996 | ~30,000 | ~20 | Major flooding | [64,74] |
| 1998 | NA | NA | | NA |
| 1 February 2002 | ~400,000 | ~33 | Major flooding | [64,74,75] |
| 29 December 2003 | NA | NA | | [64] |
| 2005 | NA | NA | | [81] |
| 1 February 2007 | ~400,000 | ~ 57 | Major flooding | [74,77,78,82] |
| 1 February 2008 | ~80,000 | NA | Major flooding | [83,84] |
| 2011 | NA | NA | | NA |
| 17 January 2013 | ~250,000 | ~ 20 | Major flooding | [78,80,85] |
| 17 January 2014 | ~130,000 | ~ 20 | Major Flooding | [58,62,64,78] |
| 10 February 2015 | NA | NA | | [64,86,87] |

## 5. Discussion

### *5.1. Increasing Maximum Daily Temperature and Maximum Daily Rainfall*

From 1987 to 2013, Jakarta experienced an upward trend in both maximum daily temperature and maximum daily rainfall, which has been linked to the rising frequency of flooding events in recent years. In general, an increasing maximum daily temperature was observed in the three stations of BMKG. The monthly maximum daily temperature showed an increase in February to September, October, or November, when the maximum daily temperature reached the highest temperature. Daily rainfall is associated with flooding, observed mainly during the rainy season, particularly in January and February.

An increase in the maximum daily temperature was observed in Jakarta. At the HPA station, an increasing maximum daily temperature was observed, but there was no clear evidence when the temperature started increasing at the station. On the other hand, two other stations, the KMY and the SHIA stations, showed that the maximum daily temperature started increasing in 2001 and 1996, respectively. In general, the maximum daily temperature in Jakarta started to increase at the end of the rainy season in February and March, and reached the highest temperature in September and October at the KMY and the HPA station, respectively. After this period, the maximum daily temperature decreased gradually until February of the coming year at all the stations. The highest maximum daily temperature was about 37 °C, while the lowest one was about 33 °C. At the KMY and the HPA stations, the first and the second period showed that the maximum daily temperature started to increase from February to reach the highest temperature in October. In the third period, the maximum daily temperature shifted from October to September. However, the SHIA station showed a different maximum daily temperature pattern compared to those of the other stations. The increasing urban temperature in Jakarta can be related to the observed LULC change, which shows an increase in the proportion of built-up areas and a decrease in the green spaces in Jakarta. In the last few decades, the increase in built-up areas in Jakarta is associated with an increasing urban temperature. The increasing urban temperature in this study is consistent with earlier findings on the impact of LULC change on the urban temperature in Jakarta [15,51,52,55].

An increase in the maximum daily rainfall observed during the rainy season can be associated with the occurrence of major floods in Jakarta. The maximum daily rainfall started increasing in 2001, after which Jakarta experienced major flooding in 2002. In general, the daily rainfall analysis results reveal that inundations in Jakarta occur when the daily rainfall amount is about 92 mm. In addition, flooding is more severe when the daily rainfall or the accumulated daily rainfall amount is above 150 mm. These results are consistent with previous studies which suggest that major flood events have been recorded in 1996, 2002, 2007, 2008, 2013, 2014, and 2015 as a result of accumulated rainfall over two to three days [62,78,83,88]. In this study, it was observed that the rainfall amount in those years (1996, 2002, 2007, 2008, 2013, 2014, and 2015) was about 150 mm. For instance, the two-day rainfall in 1996, which caused flooding, was about 150 mm. In 2002, the two-day and three-day rainfall were about 152 mm and 165 mm, respectively. The major flood in 2003 can be related to two-day and three-day rainfall of about 153 mm and 162 mm, respectively. The major flood in 2007 was the worst flood event in Jakarta and occurred when the rainfall amount was about 211 mm. Furthermore, the two-day and the three-day rainfall in 2007 were about 277 mm and 287 mm, respectively. In 2008, the one-day, the two-day, and the three-day rainfall were about 158 mm, 237 mm, and 247 mm, respectively. The one-day rainfall in 2013 could be related to the flooding in Jakarta since the rainfall amount was about 165 mm over 24 h.

The present study shows that an increase in maximum daily rainfall can be associated with increased flooding. From 1987 to 2013, it was observed that an increase in flooding in Jakarta began after the year 2001, and the maximum daily rainfall increased gradually from 2001. Furthermore, increased flooding in Jakarta from 1987 to 2013 could also have been influenced by several other factors, such as land subsidence, particularly in the Northern part of Jakarta [89,90], and an inadequate drainage system in Jakarta [91]. These are typical problems in many cities in the Global South where flooding is likely to increase due to an increase in hazard frequency and intensity and vulnerability [92].

In this study, the results indicate that there was an implicit relationship between the increasing urban temperature during the rainy season and the rising maximum daily rainfall amounts. An increase in urban temperature can affect rainfall intensity through the complex process of land–atmosphere interaction influenced by LULC change and urbanization. The results show consistency with previous research on the relationship between an increasing urban temperature and extreme rainfall intensity in Jakarta [57]. Siswanto et al. (2022) [57] observed an increase in urban temperature with an increase in the atmospheric moisture content with an increase in extreme rainfall intensity in Jakarta between 1900 and 2010. It is noted here that extreme rainfall intensity in Jakarta is also influenced by several other factors, such as the Asian monsoon system, The Madden Julian Oscillation (MJO), and El Niño–Southern Oscillation (ENSO) [57,62,83,93], which are not taken into account in this study.

### *5.2. Combined Hazards of High Urban Temperature and Flooding*

The analysis of urban temperature and daily rainfall in this study shows that both hazards, high urban temperature and flooding, are implicitly interrelated. The daily air temperature time series indicate that the air temperature in Jakarta has increased in the 30-year study period. The highest maximum daily temperature has increased from about 33 °C to 37 °C. These high temperatures can have an impact on human health, particularly when the air temperature is higher than 35 °C, which is the temperature threshold for human health [94]. Therefore, maintaining an air temperature below 35 °C is vital to prevent hyperthermia [95].

People in some areas of Jakarta are already impacted by high urban temperatures and flooding. For an area affected by both hazards, people would experience a high urban temperature during the dry season, particularly those who are living in a built-up environment. On the other hand, they can be exposed to flooding during the rainy season. The combined hazards of high urban temperature and flooding are also observed in some other cities, such as Bangkok [96].

### *5.3. Limitations of This Study and Future Perspectives*

This study used a methodology that considered recorded data from meteorological stations along with historical flooding data from various sources. The meteorological data are publicly available on a daily resolution. The non-availability of meteo data on a sub-daily scale is seen as a limitation; the availability of such data may provide further insight into connecting increased rainfall to increased flooding [97]. Moreover, flood maps before 2013, except for 2007, were not available.

In future studies, the use of hourly temperature and rainfall data, if available, is recommended. This will allow for a more detailed analysis of the relationship between local warming and changing rainfall intensity. Furthermore, maps of flooding before 2013 could be produced with the help of flood modeling. However, flood modeling requires thorough data preparation, including the provision of an appropriate layout of drainage systems. To address health-related risks, acquiring patient data in Jakarta becomes crucial. This information will reveal the number of people affected by high urban temperatures and their respective residential areas. With these data, it becomes feasible to identify areas impacted by the combined hazards of high urban temperatures and flooding.

## 6. Conclusions

The present study discusses the changing pattern of daily temperature, daily rainfall, and flooding in Jakarta from 1987 to 2013. This study shows that there was a changing pattern indicated by an increase in maximum daily temperature, which coincides with an increase in daily rainfall and flooding. The daily temperature increased at all stations, but these increases did not start at the same time. Furthermore, the increase in daily rainfall started in 2001. Afterward, the number of flooding events increased in Jakarta. This study reveals Jakarta's vulnerability not only to rising urban temperatures but also to the consequent heightened risk of increased flooding.

The increase in urban temperature in Jakarta can be attributed to the reduction in green spaces. Over the past few decades, the city has experienced significant losses in its green areas due to urbanization, urban development, and industrialization. These changes have led to a decrease in the latent heat provided by green spaces and an increase in sensible heat. Consequently, Jakarta experienced elevated maximum daily temperatures, posing potential impacts on human health. Furthermore, an increase in urban temperature is associated with an increase in rainfall intensity, particularly in the rainy season. The increased urban temperature along with the specific regional atmospheric conditions of Jakarta could be related to an increase in rainfall intensity.

In this study, an increase in flooding is associated with an increase in daily rainfall in Jakarta. Some of these floods are categorized as major floods. Since 2001, an increase in daily rainfall along with an increase in flooding has been observed in Jakarta. These hazards became more frequent from 2002. Flooding in Jakarta is primarily caused by extreme rainfall accumulated over one day, two days, and three days crossing rainfall thresholds. The rainfall thresholds highlighted in this study indicate that Jakarta faces flooding when the maximum daily rainfall surpasses the mean value of the annual maximum daily rainfall. In addition, the increased occurrence of flooding in Jakarta is also influenced by other factors, such as land subsidence and inadequate drainage systems, which are not covered in this study.

This study indicates that Jakarta is vulnerable to the combined hazards of high urban temperature and flooding. Elevated urban temperatures, revealing an increasing trend since 1987, are observed during the dry season. At the same time, the flooding history shows an increase in flooding in Jakarta. The two hazards occur in two different time periods, but they could occur in the same area. This observation stresses the importance of integrated urban water management solutions such as water-sensitive urban design, climate-sensitive urban design, and nature-based solutions to be considered in sustainable urban development and planning for enhancing flood resilience, while providing ecosystem services and other benefits. Hence, these approaches aim to minimize water-related risks and maximize the benefits of interventions. They foster the preservation and/or the introduction of green spaces in cities to simultaneously address flooding and high temperatures.

For Jakarta, this study is one of the first studies to analyze the relationship between the combined hazards of high urban temperature and flooding. While previous studies in Jakarta have predominantly concentrated on flooding and rainfall intensity, this study offers novel insights by examining the simultaneous occurrence of these hazards. The results of this study provide new and essential insights to enhance flood resilience and climate adaptation, advocating that a holistic approach is required to tackle these combined hazards.

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