



A novel evaluation method-based effect analysis of urbanization on extreme precipitation in Guangxi, South China

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Abstract

Intense rainfall occurrences are increasing globally due to rapid urbanization, necessitating effective flood management and disaster reduction in urban areas. This study examines the spatiotemporal patterns of extreme precipitation (EP) in Guangxi Zhuang Autonomous Region, China, from 1985 to 2014 using the Mann–Kendall test. By categorizing 88 meteorological stations as urban or rural based on impervious area percentages in their buffer zones, a correlation is established between EP and urban impervious area. The study proposes an improved normalization method for urbanization effect on extreme precipitation (INM-UEEP). Key findings include: (i) Ten EP indices displayed increasing trends in Guangxi from 1985 to 2014, predominantly in central and northeastern areas with higher urbanization levels; (ii) Urbanization accelerated after 2000, resulting in the number of urban meteorological stations in Guangxi rising from two to twelve. Urban areas experienced more frequent extreme precipitation events compared to rural areas, with significant influence from short-term heavy precipitation indices such as R50, R95p, R99p, and RX1day; and (iii) Liuzhou and Nanning exhibited notable urbanization effects on extreme precipitation among urban stations, while Laibin and Qinzhou had minimal impact. The INM-UEEP overcomes limitations of traditional approaches in assessing urban–rural disparities by providing a standardized evaluation criteria.

1 Introduction

Extreme precipitation events have become more frequent as a consequence of the combined impacts of global climate change and human activities. These events are characterized by their suddenness and unpredictability, and have the

potential to cause significant damage to ecosystems and human societies. Since the late 1970s, China has undergone unprecedented urbanization following the implementation of its reform and opening-up policy, leading to a remarkable increase in the urbanization rate from 17.9% in 1978 to 57.4% in 2016 (Yang et al. 2017b; Zhao et al. 2019; Yao et al. 2022). Urbanization has significantly modified the surface and atmospheric boundary layer, altering the water and energy balance, and exerting a substantial impact on the regional climate (Masson 2006; Lamptey 2010; Ren 2015; Fu et al. 2024). As a result of rapid urbanization, the frequency of extreme precipitation events has witnessed a substantial rise, resulting in urban waterlogging, severe economic losses, and loss of life (Huang et al. 2018; Paprotny et al. 2018; Zhang et al. 2019, 2022; Tang et al. 2024). Consequently, it is of immense significance to explore the impacts of urbanization on extreme precipitation, as it can provide valuable insights for urban planning and disaster prevention.

Numerous scholars have conducted research on the effects of extreme precipitation induced by urbanization. In 1968, Changnon (1968) analyzed the increase in summer precipitation attributable to urbanization. There exists a correlation between the rapid progress of urbanization and variations in

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the intensity and frequency of extreme precipitation (Zhang et al. 2018; Yang et al. 2019; Jiang et al. 2020; Lei et al. 2023). Some scholars have discovered that urban areas often experience larger amounts of precipitation and more frequent heavy precipitation compared to rural areas, resulting in heightened intensity of extreme precipitation in cities (Yan et al. 2020; Yao et al. 2022), which displays significant local and abrupt characteristics (Yu et al. 2007; Yang et al. 2013; Liang and Ding 2017). Urbanization has contributed to a notable increase in short-term precipitation intensity, leading to intensified extreme precipitation events (Liang and Ding 2017; Yan et al. 2023). Furthermore, certain studies have indicated that urbanization can lead to an increase in precipitation in the central urban area and downwind areas of large cities compared to upwind areas (Burian and Shepherd 2005; Kishtawal et al. 2010; Zhong et al. 2015; Liu and Niyogi 2019).

Research on the impact of urbanization on precipitation has primarily focused on qualitative analysis, lacking quantitative evaluations and limited research methods. Currently, physical modeling and statistical analysis are the most widely used methods (Zhao et al. 2019; Kang et al. 2021; Luo et al. 2023). However, physical modeling has drawbacks such as uncertain model parameters, high-resolution data requirements, and computational costs (Yang et al. 2019; Kim et al. 2021; Yuan et al. 2022; Hu et al. 2023). On the other hand, statistical analysis is simpler and more suitable for small-scale studies (Kang et al. 2021). The urban minus rural (UMR) method is commonly employed in statistical analyses (Yang et al. 2011; Park et al. 2017; Pimonsree et al. 2022). This method quantifies the effects and contributions of urbanization by comparing trends in the sequence of extreme precipitation index between urban and rural areas (Liao et al. 2017; Zhao et al. 2019; Lin et al. 2020; Yang et al. 2024). In recent years, researchers have attempted to incorporate non-stationary models into the evaluation of urbanization effects on extreme precipitation (Yan et al. 2023). They have also introduced new methods and indicators for quantitative analysis. For instance, Liu et al. (2022) integrated atmospheric characteristics and urbanization processes into nonstationary generalized additive models to quantify the relative contribution rate index. Their findings reveal that urbanization has a greater impact on the non-stationarity of extreme precipitation compared to climate change. Similarly, Yao et al. (2022) utilized a nonstationary generalized extreme value model to assess the urbanization effect on extreme precipitation indices during the urbanization process, calculating the magnitude of change in recurrence levels.

Some researchers have conducted studies on the relationship between climate change and land-use dynamics in cities to investigate the effects of urbanization (Hu et al. 2021,

2024; Luo et al. 2023). To explore this further, Luo and Lau (2019) analyzed the impact of urban expansion on urban atmospheric humidity. They found a significant correlation between the rate of urban expansion and atmospheric humidity indicators using the Spearman correlation coefficient, suggesting that urban expansion contributes to changes in atmospheric humidity and exacerbates the urban dry island effect. Sun et al. (2021) argued that the urbanization effect cannot be solely explained by precipitation attributes and emphasized the importance of changes in land cover within the city in influencing land–atmosphere interactions. They proposed an improved indicator for urbanization effects, using the correlation coefficient between urban precipitation and built-up area data as weights.

However, few studies have examined the correlation between underlying urban surface changes and extreme precipitation. Moreover, existing research on urbanization effects on extreme precipitation has mainly focused on economically developed areas, such as the Yangtze River Delta urban agglomerations (Liu et al. 2022), Beijing-Tianjin-Hebei (Zhao et al. 2019), the Pearl River Delta (Hu et al. 2021, 2024), Tokyo in Japan, Seoul in South Korea (Oh et al. 2021), and New York in the United States (Marelle et al. 2020). There is limited research on economically underdeveloped regions currently experiencing rapid urbanization, such as Guangxi.

Located in southern China, Guangxi has a complex terrain and a well-developed karst landscape (Tian et al. 2024). The region experiences abundant annual precipitation with uneven spatial distribution, resulting in frequent extreme rainfall events and floods. While previous studies have investigated the frequency, cycle, and spatial distribution of extreme rainfall in Guangxi (Nie et al. 2012), there is a dearth of research on the urbanization effects on extreme precipitation. In recent years, urbanization in Guangxi has accelerated (Qiu et al. 2021; Lan et al. 2022), leading to a significant increase in the proportion of impermeable surfaces and exacerbating the urban heat island effect. The rise of extreme precipitation and urban flooding disasters have become increasingly pronounced (Liu et al. 2022; Pimonsree et al. 2022; Tang et al. 2024). Consequently, it is crucial to analyze the effects of urbanization on extreme precipitation in Guangxi.

Existing studies on the impact of urbanization on extreme precipitation in Guangxi have primarily focused on the issue of urban waterlogging in specific cities (Li et al. 2023), with limited comparative research on the overall and regional effects of urbanization on extreme precipitation in Guangxi. Furthermore, current evaluation methods for urbanization effects inadequately consider the influence of changes in impermeable surfaces in urban areas on extreme rainfall. To address these gaps, this study utilizes land use/land cover

and economic data to determine the urban and rural attributes of all regional meteorological stations. It compares the differences in extreme precipitation indices (EPIs) between urban and rural areas in Guangxi and various cities at different time periods. Additionally, it quantifies the urbanization effect on extreme precipitation based on the correlation coefficient between urban extreme precipitation and impermeable surfaces in urban areas. The theoretical contribution of this study lies in the proposal of a highly applicable standard evaluation method for assessing the urbanization effect on extreme precipitation, which can serve as a scientific reference for urban flooding prevention and planning.

2 Material and methods

2.1 Study area

Guangxi, situated in southern China, exhibits diverse topography and a well-established water system. The region's northwestern area is predominantly mountainous, while the central and southern regions comprise hills and plains that resemble a basin. These landscapes are characterized by karst formations, including hills, sinkholes, and depressions, which present challenges in terms of sediment transport and flow dynamics due to shallow soil layers and limited water-retention capacities. Furthermore, Guangxi experiences a subtropical climate with unevenly distributed annual precipitation. On average, the region sees temperatures ranging between 17°C and 23°C and receives rainfall ranging from 1250 to 1750 mm annually (Nie et al. 2012). During the flood season, warm and moist air currents from the ocean interact with cold fronts from the north, resulting in frequent instances of heavy and extreme rainfall. Consequently, floods occur frequently in Guangxi's small- and medium-sized watersheds, causing severe economic losses (Mo et al. 2018).

Guangxi holds the distinction of being the sole minority autonomous region in China situated along the coast. The region's urbanization has gained momentum due to the implementation of national strategies such as the New Land-Sea Corridor in Western China, the Beibu Gulf urban agglomeration, and the Pearl River-Xijiang River Economic Belt. Consequently, the expansion of urban land has been observed. In 2019, Guangxi had a permanent population of 49.6 million, of which 25.34 million resided in urban areas, resulting in an urbanization rate of 51.09% (Qiu et al. 2021).

2.2 Data

In this study, we utilized a dataset spanning the 1985–2014 period, which consisted of daily precipitation measurements,

land use/land cover information, and urban GDP data. The daily precipitation data, obtained from the China Meteorological Science Data Sharing Service Network (<http://cdc.cma.gov.cn/>), covered a total of 88 meteorological stations, as depicted in Fig. 1. The land use/land cover data, with a spatial resolution of 30 m, was acquired from the China Land Cover Dataset (CLCD). The CLCD, developed by Yang and Huang (2021) using 335,709 Landsat images available on the Google Earth Engine (<https://zenodo.org/record/5210928#collapseCitations>), categorized land-cover types into nine classes, including impervious surfaces that served as indicators of urbanization. This dataset provided continuous information spanning 30 years. To analyze the different stages of urban development during the study period, we employed urban GDP data (Fig. 2), which were extracted from the Guangxi Statistical Yearbook.

2.3 Methods

2.3.1 Extreme precipitation indices (EPIs)

In this study, we applied the recommendations provided by the Commission for Climatology of the World Meteorological Organization (WMOCCI), the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), and the Climate Variability and Predictability (CLIVAR) to identify indicators for detecting climate change. These indicators, referred to as EPIs (Table 1), encompass various aspects such as magnitude, duration, and intensity. By incorporating these indicators, we can comprehensively capture the characteristics of extreme regional precipitation. These EPIs are widely employed in global studies on extreme precipitation (Kim et al. 2020; Pimonsree et al. 2022; Lei et al. 2023).

To calculate the EPIs for the daily precipitation series obtained from the 88 stations in Guangxi spanning the 1985–2014 period, we utilized the RCLimDex software. Developed by the Climate Research Branch of the Meteorological Service of Canada (CMC). This software enables accurate computation of the EPIs.

2.3.2 Mann–Kendall trend test

The Mann–Kendall (M–K) test is known for its computational simplicity and lack of specific requirements pertaining to sample distributions (Mann 1945). It finds wide application in the fields of meteorology and hydrology (Zhao et al. 2019; Espinosa and Portela 2020; Liu et al. 2022). In this study, we utilize the M–K test to examine trends within the sequence. The formula employed for testing is as follows:

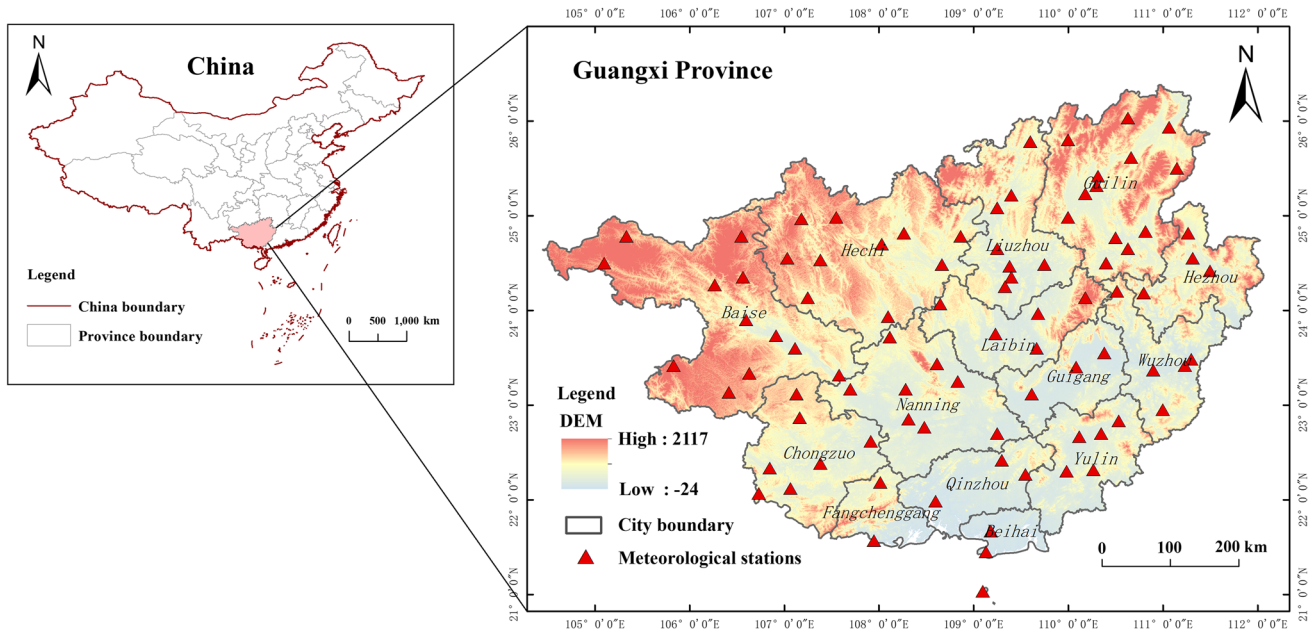


Fig. 1 Geographic location and distribution of meteorological stations in Guangxi

$$\begin{cases} S = \sum_{i=1}^{n-1} \sum_{j=i+1}^N \text{sgn}(X_j - X_i) \\ \text{sgn}(X_j - X_i) = \begin{cases} 1 & X_j - X_i > 0 \\ 0 & X_j - X_i = 0 \\ -1 & X_j - X_i < 0 \end{cases} \end{cases} \quad (1)$$

where S represents a non-parametric statistical quantity for a sample that adheres to a normal distribution; X_i and X_j denote the i -th and j -th values of the time sequence, respectively; N denotes the length of said sequence.

To determine the M–K detection statistic Z , the following formula is employed:

$$Z = \begin{cases} (S - 1)\sqrt{n(n-1)(2n+5)/18} & S > 0 \\ 0 & S = 0 \\ (S + 1)\sqrt{n(n-1)(2n+5)/18} & S < 0 \end{cases} \quad (2)$$

Equation (2) yields Z , where Z greater than zero indicates an upward trend within the time sequence. Conversely, a descending trend becomes evident when Z is lesser than zero. Absolute values of Z equal to or surpassing 1.65, 1.96, or 2.56 signal the passing of trend tests, corresponding to confidence levels of 90%, 95%, and 99%, respectively.

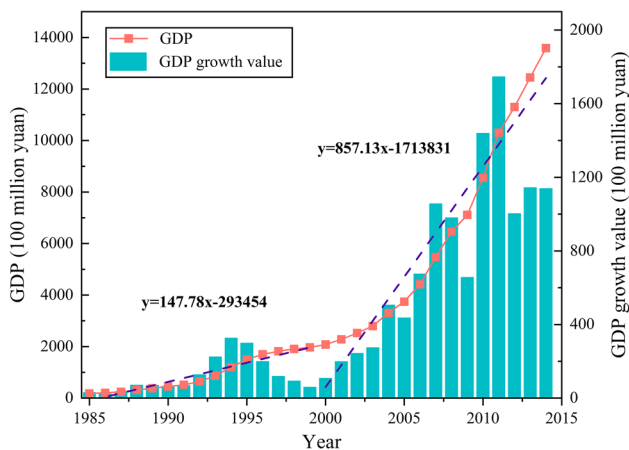


Fig. 2 GDP and its growth values in Guangxi from 1985 to 2014

2.3.3 Classification of urban and rural attributes of meteorological stations

Based on the percentage of impervious area (PIA) within a specified radius around the meteorological stations, the stations are categorized into urban and rural stations. The process is conducted as follows: (i) A circular buffer zone is established for each station based on GIS within a specified radius. Yao et al. (2022) discovered that the correlation coefficient between the EPI and the PIA was highest when the buffer circle radius ranged from 3 to 5 km. To account for the level of urban development in Guangxi and prevent buffer zones from overlapping with adjacent stations, a buffer circle radius of 5 km is selected for this study. (ii) The impervious area is identified, and the land use/land

Table 1 Eleven EPIs used in this study

Index type	Index name	Unit	Definition
Duration	CDD	d	Maximum consecutive days with daily precipitation < 1 mm
	CWD	d	Maximum consecutive days with daily precipitation ≥ 1 mm
	R10	d	Number of days with daily precipitation ≥ 10 mm
	R20	d	Number of days with daily precipitation ≥ 20 mm
	R50	d	Number of days with daily precipitation ≥ 50 mm
Magnitude	PRCPTOT	mm	Annual cumulative precipitation with daily precipitation ≥ 1 mm
	R95p	mm	Annual cumulative precipitation with daily precipitation > 95th percentile
	R99p	mm	Annual cumulative precipitation with daily precipitation ≥ 99th percentile
	RX1day	mm	Maximum daily precipitation in a year
	RX5day	mm	Maximum 5-day consecutive precipitation in a year
Intensity	SDII	mm/d	Annual total precipitation/number of precipitation days

cover data from the CLCD are utilized to calculate the PIA of the underlying surface within the buffer zone of each station. The PIA serves as an indicator of the urbanization level at the station's location (Yao et al. 2022). (iii) The urban and rural attributes of the stations are determined based on the PIA value. Stations with larger PIA values in their buffer zones correspond to higher levels of urbanization in the region (Liao et al. 2017; Lin et al. 2018, 2020). In this study, stations with a PIA exceeding 20% are classified as urban stations (with urban attributes) since a PIA of 20% is indicative of buffer zones with urban characteristics (Yang et al. 2017b); stations with a PIA below this threshold are classified as rural stations (with rural attributes).

2.3.4 A novel evaluation method for the urbanization effect on extreme precipitation

To evaluate the disparity in extreme precipitation between urban and rural areas, the EPI difference (EPID) was utilized:

$$EPID = EPI_{urban} - EPI_{rural} \quad (3)$$

where EPI_{urban} and EPI_{rural} are the EPI for the urban and rural areas, represented by urban stations and rural stations respectively.

Based on the growth of GDP in Guangxi (Fig. 2), the development of urban areas in Guangxi was categorized into two periods: the slow urbanization period (SUP; 1985–1999) and the rapid urbanization period (RUP; 2000–2014) (Yang et al. 2024). Mean EPID values were calculated for urban and rural stations during both periods, and the difference was defined as the potential urbanization effect (PUE) using the following equation:

$$PUE = EPID_{RUP} - EPID_{SUP} \quad (4)$$

where $EPID_{RUP}$ and $EPID_{SUP}$ represent the mean EPID values during the rapid and slow urbanization periods, respectively.

The PUE indicator addresses the temporal variation effect of extreme precipitation, particularly during the SUP. It reflects the difference in EPID between urban areas during different development periods (Lin et al. 2020), providing a better understanding of the urbanization effect during the RUP (Sun et al. 2021). However, the PUE alone does not solely capture information about the urbanization effect and cannot be extracted from the precipitation attribute alone. Previous studies have utilized the UMR method to quantify the urbanization effect on extreme precipitation by comparing the difference trend between urban and rural anomaly sequences (sequences comprising anomaly values) with the trend of the urban sequence (Ren et al. 2008; Zhao et al. 2019; Lin et al. 2020; Pimonsree et al. 2022). Nevertheless, urban–rural differences may arise from diverse factors, and directly utilizing sequence differences may lead to an over-estimation of the urbanization effect.

Due to the expansion of impermeable surfaces caused by urban growth, local evaporation decreases, heat flux increases, and the water vapor boundary layer becomes more homogenized, significantly impacting local precipitation (Lu et al. 2019). Therefore, this study proposes a new method, the improved normalization method for the urbanization effect on extreme precipitation (INM-UUEP), to quantify the urbanization effect (UE) by incorporating the correlation coefficient α between urban extreme precipitation and impermeable surfaces as a weight with PUE, as shown in Eq. (5). The INM-UUEP establishes a connection with the underlying surface, providing a better understanding of the urbanization effects on extreme precipitation.

$$UE = \alpha \times PUE \quad (5)$$

$$\overline{UE}_{norm} = \frac{1}{n} \sum_{j=1}^n \left(\frac{UE_{ij} - UE_{min}}{UE_{max} - UE_{min}} \right) \quad (6)$$

where UE_{ij} represents the UE value of the j th EPI for the i th urban area, calculated as $\alpha * PUE_{ij}$, where PUE_{ij} is the PUE value of the j th EPI for the i th urban area; UE_{min} and UE_{max} represent the minimum and maximum values of UE for the j th EPI, respectively; n is the number of selected EPIs; \overline{UE}_{norm} is the normalized UE value within the range [0, 1]. A value closer to 1 indicates a stronger impact of urbanization on extreme precipitation. The significance test is conducted using a t-test. When $\overline{UE}_{norm} \geq 0.43, 0.71, \text{ or } 0.94$, it indicates a significant urbanization effect on extreme precipitation at the 0.1, 0.05, or 0.01 level, respectively.

3 Results

3.1 Spatial-temporal distribution characteristics of extreme precipitation in Guangxi

The EPI in Guangxi during the period from 1985 to 2014 was analyzed using the M–K test, revealing its interannual variation trend (Fig. 3). With the exception of CWD, the duration indices of the EPIs in Table 1 did not exhibit significant upward trends since 1985 [Fig. 3 (a) to (e)]. The magnitude indices of the EPIs showed a slightly upward trend,

but this trend was not statistically significant [Fig. 3 (f) to 3(j)]. However, the intensity index (SDII) demonstrated a significant upward trend, with precipitation increasing by 0.528 mm every 10 years ($p < 0.05$) [Fig. 3(k)]. Overall, extreme precipitation in Guangxi exhibited an upward trend, accompanied by a decrease in the number of consecutive rainy days and a significant increase in precipitation intensity.

To assess the spatial variation trends of the EPIs across Guangxi, the M–K test and inverse distance weighting interpolation (IDW) method were employed for 88 meteorological stations (Fig. 4). The results showed that CDD generally decreased in the northwest and increased in the southeast of Guangxi [Fig. 4(a)]. CWD, on the other hand, decreased at all stations [Fig. 4(b)]. The R10, R20, R50, and magnitude indices exhibited overall increasing trends across Guangxi [Fig. 4 (c) to 4(j)], with the southeast experiencing more pronounced increases and the northwest showing decreases. Significant increasing trends were primarily observed in highly urbanized areas, particularly in the central to northeastern parts, with the most significant increases occurring in Nanning, Liuzhou, and Guilin. However, areas with high values of extreme precipitation, such as Qinzhou, Beihai, and Fangchenggang, did not show significant increases. The SDII showed a significant upward trend at most stations [Fig. 4(k)], indicating a substantial rise in precipitation intensity across Guangxi. These findings suggest that extreme precipitation events have increased in Guangxi,

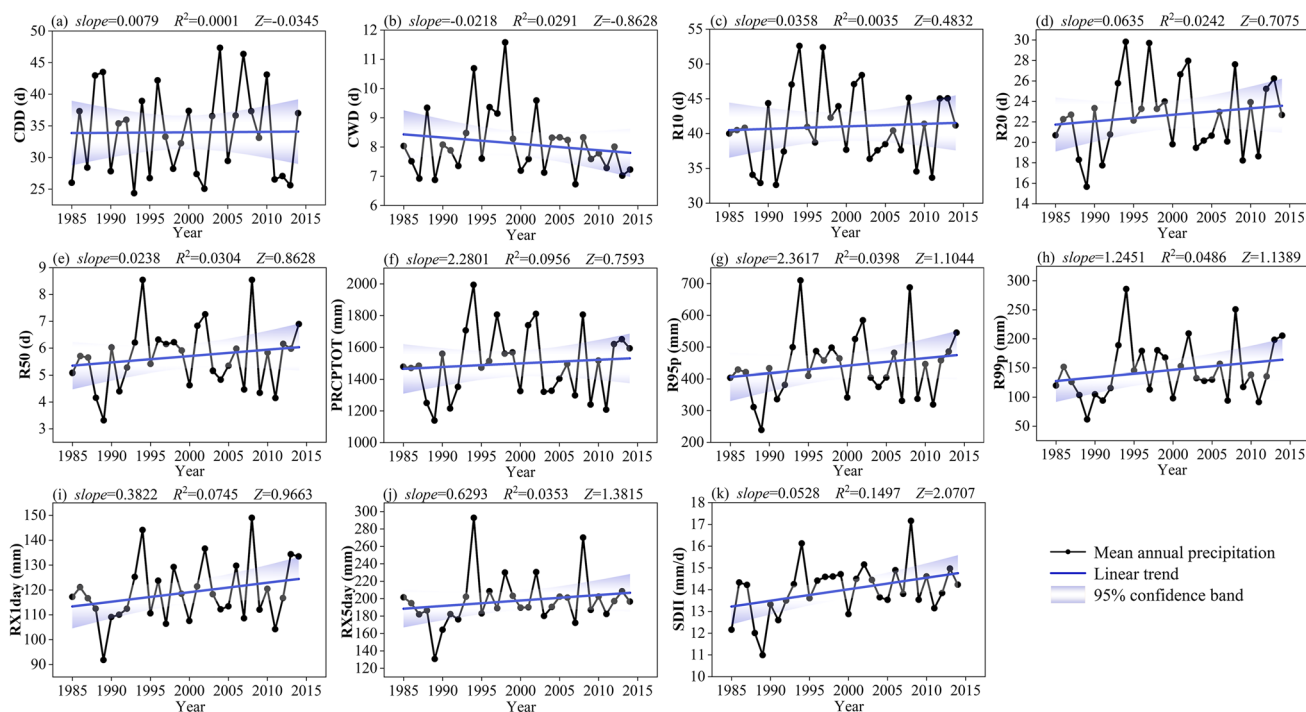


Fig. 3 Inter-annual variations in extreme precipitation in Guangxi from 1985 to 2014

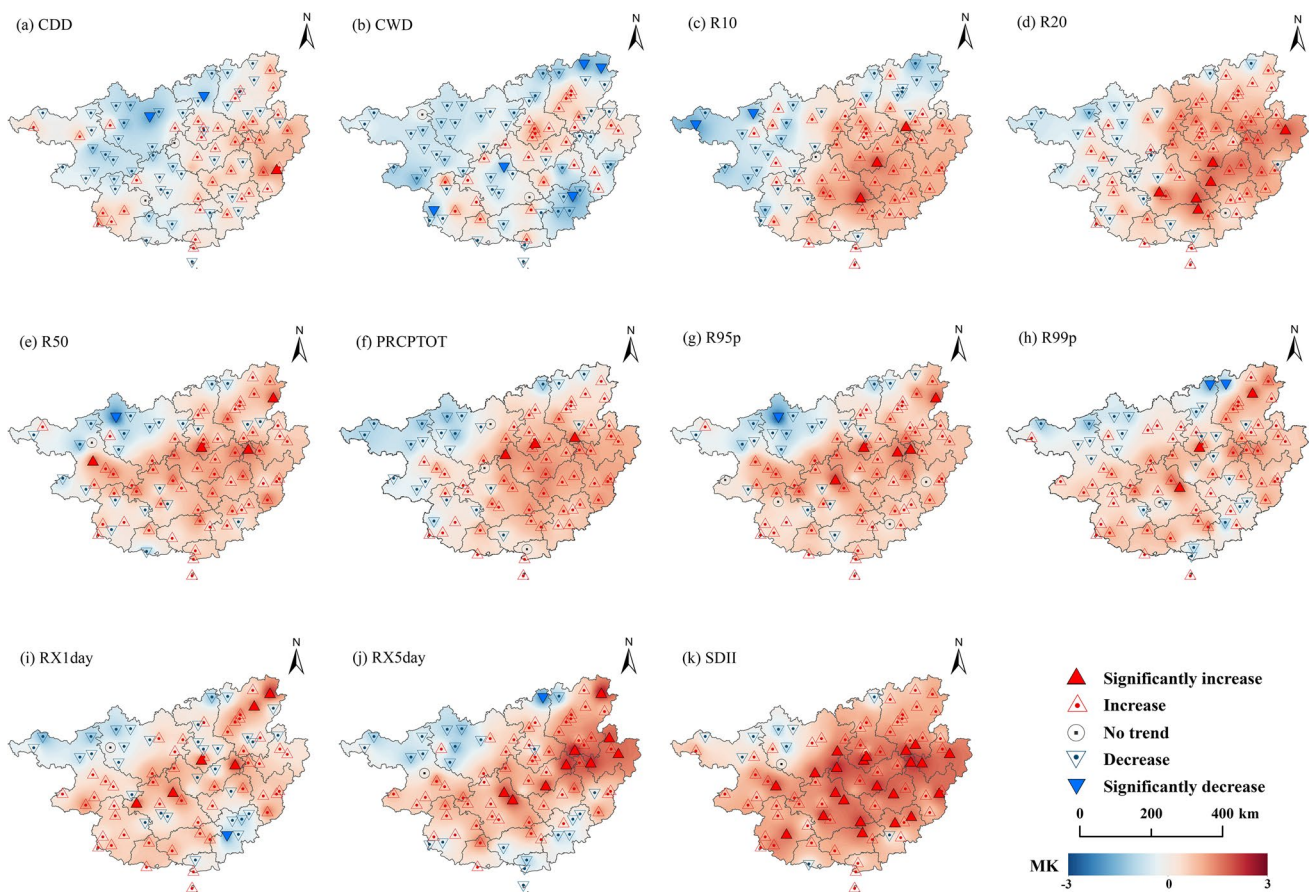


Fig. 4 Spatial trends of EPIs in Guangxi from 1985 to 2014

particularly in the highly urbanized areas in the central and eastern regions. The distribution patterns of areas with high PRCPTOT, R50, R95p, R99p, RX1day, RX5day, and SDII were relatively consistent, indicating a higher likelihood of extreme precipitation events occurring in areas with high total precipitation.

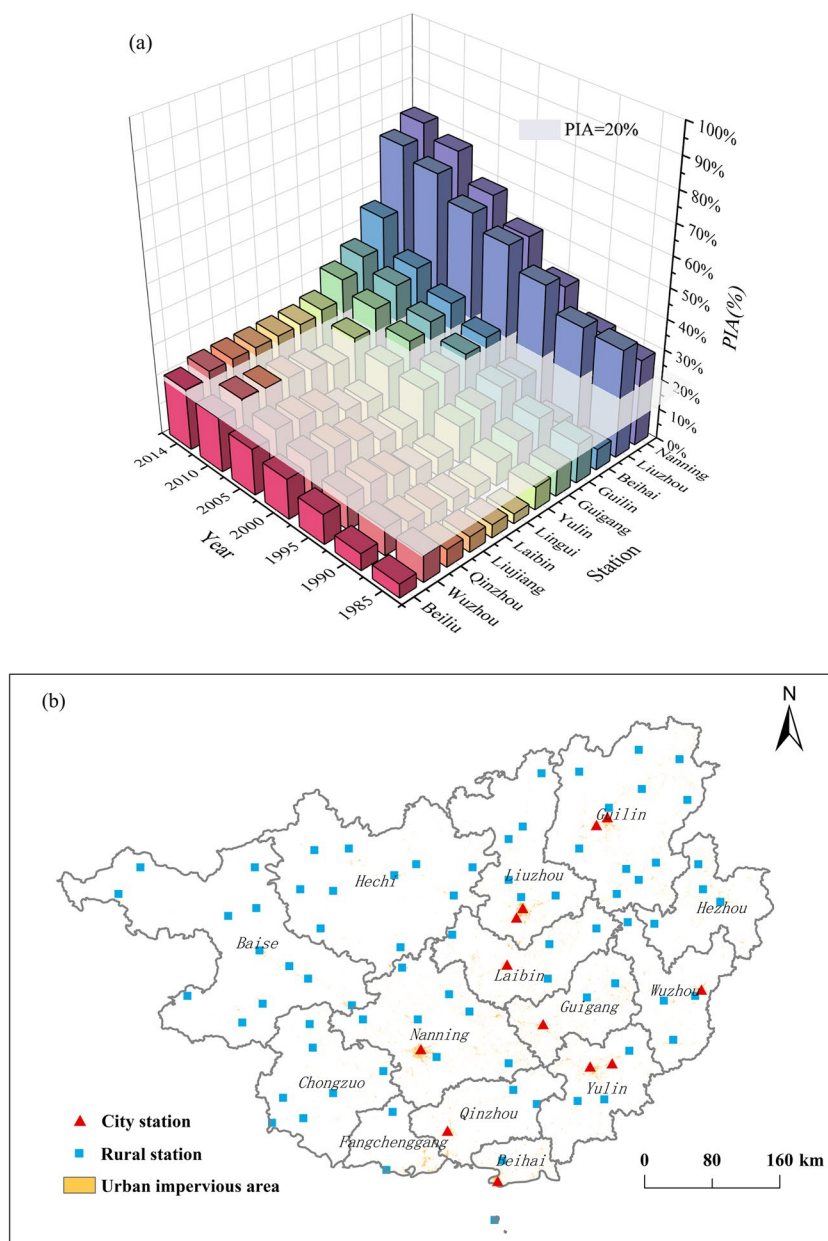
3.2 Differences in extreme precipitation between urban and rural areas in Guangxi

In this study, the CLCD data was utilized to select 88 meteorological stations. These stations were categorized into urban and rural areas based on the impervious surface proportion within their buffer zones, as indicated in Fig. 5. Notably, the pace of urbanization in Guangxi was gradual. Prior to 2000, only four urban meteorological stations existed in Nanning, Liuzhou, Beihai, and Guilin [Fig. 5(a)]. However, urbanization rapidly accelerated thereafter, resulting in a total of 12 urban meteorological stations by 2014 (Fig. 5), in line with the GDP development presented in Fig. 2. The distribution of urban stations was primarily concentrated in the eastern and central regions of Guangxi, indicating higher levels of urbanization compared to the western

areas. Figure 4 illustrates that urban stations predominantly occupied regions characterized by frequent and significantly increased extreme precipitation events, which suggests the influence of urbanization on extreme precipitation to some extent.

Figure 6 displays the disparities in average EPI values between urban and rural stations during periods of rapid and slow urbanization in Guangxi. Compared to the SUP, upward trends were observed in most indices, except for the CWD index in urban areas and the CWD, R10, R20, and PRCPTOT indices in rural areas. On the other hand, during the RUP, the overall trend exhibited higher EPI values in urban regions compared to rural regions. In the SUP, urban stations showed significant differences from rural stations solely in the R20, R50, PRCPTOT, RX1day, and RX5day indices. Conversely, in the RUP, the disparity between urban and rural stations increased overall. Specifically, the R50, R95p, R99p, and RX1day indices of urban areas experienced significantly greater increases compared to rural areas. However, the increases in urban areas for the R10, R20, and RX5day indices were relatively weak. This implies that the acceleration of urbanization has heightened precipitation extremes, leading to more frequent occurrences

Fig. 5 Classification results of urban and rural stations in Guangxi. (a) Urban station variation process; (b) Spatial distribution of urban and rural stations in 2014



of extreme precipitation events in urban areas. It is important to note that while the PRCPTOT index decreased in rural stations during the RUP, there was a certain extent of increase observed in urban stations.

3.3 Urbanization effects on extreme precipitation in Guangxi

In order to explore the potential impacts of urbanization, a selection was made of nine cities and their respective urban meteorological stations (Fig. 5). To better emphasize the influence of urbanization on extreme precipitation, six representative EPIs (PRCPTOT, R50, R95p, R99p, RX1day, and SDII) were chosen based on the findings from Fig. 6.

These EPIs were utilized in the calculation of the PUE using Eq. 4, and the results were presented in Fig. 7. In most of the nine cities, positive PUE values are observed, indicating an increase in extreme precipitation due to urbanization in these areas, which is consistent with the findings of Sun et al. (2021). Among these urban regions, Liuzhou exhibits the highest PUE values for most indices, except for SDII, suggesting that it is considerably impacted by urbanization in terms of extreme precipitation. Nanning displays high overall PUE values, with the exception of the RX1day index, indicating significant influence of urbanization on extreme precipitation in Nanning, except for RX1day. Beihai, Guilin, Guigang, Yulin, and Wuzhou generally exhibit positive PUE values, indicating that urbanization has to

Fig. 6 Mean EPIs of urban and rural stations during rapid and slow urbanization periods

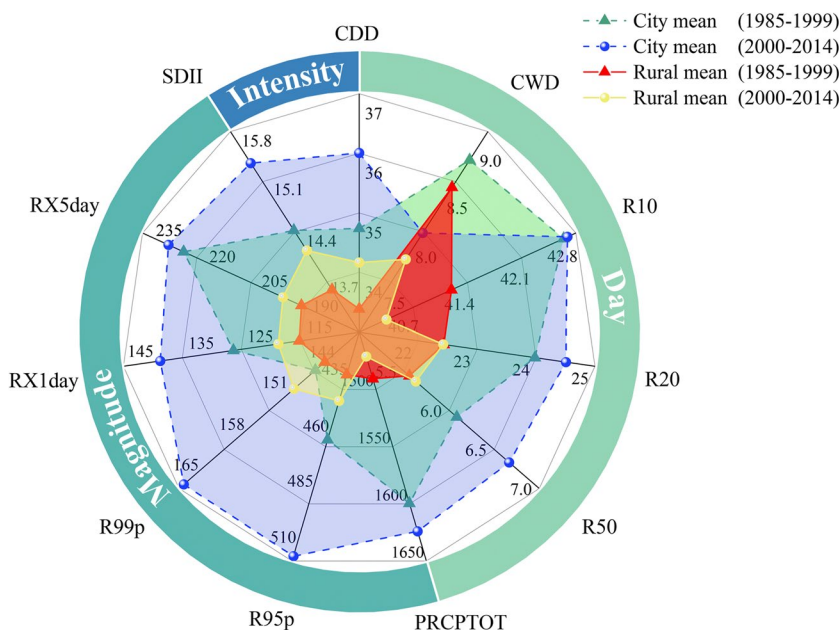


Fig. 7 Potential urbanization effect values on extreme precipitation in nine cities with urban meteorological stations in Guangxi

	Nanning	Beihai	Liuzhou	Guilin	Guigang	Laibin	Qinzhou	Yulin	Wuzhou
PRCPTOT	118.3	25.6	142.6	43.5	58.3	-71.8	-49.7	22.1	12.7
R50	1.0	-0.4	1.3	0.3	0.3	-0.3	-0.5	-0.1	0.4
R95p	91.9	62.0	150.2	2.9	12.6	-45.3	-86.5	-12.5	32.3
R99p	19.3	18.3	126.8	4.6	-13.5	-52.3	-23.0	19.2	-4.2
RX1day	-4.5	13.2	39.1	8.3	-16.1	-9.6	4.5	12.6	6.6
SDII	1.5	0.5	1.1	-0.1	-0.3	-0.3	-0.5	0.2	0.4

some extent increased extreme precipitation in these locations. Conversely, Qinzhou displays negative PUE values for all indices except for RX1day, while Laibin exhibits negative PUE values overall, suggesting that urbanization does not significantly enhance extreme precipitation in these two urban areas.

Correlation coefficients were calculated between the impervious surface area and urban EPI in each city, and by utilizing Eqs. 5 and 6, the UE and its normalized results were derived. These results were presented in Figs. 8 and 9. The normalized UE value (UE_{norm}) for Liuzhou is 0.818 (significant at 0.05), with the UE for R99p and R95p surpassing that of all other cities, indicating that urbanization has a significant impact on extreme precipitation in Liuzhou compared to the other cities. Nanning, with a UE_{norm} value

of 0.619 (significant at 0.1), ranks second, displaying the highest UE values for PRCPTOT and SDII among all cities. This suggests that urbanization greatly contributes to the increase in total precipitation and precipitation intensity in Nanning. Beihai and Wuzhou experience a moderate impact from urbanization on extreme precipitation, albeit not significant, with one index showing negative UE values. The impact of urbanization on extreme precipitation in Guigang, Guilin, and Yulin is minor, with some indices exhibiting positive but low UE values, while PRCPTOT in Guigang being the most affected. Laibin and Qinzhou predominantly display negative UE values, with UE_{norm} values approaching zero, indicating a lack of significant urbanization effects on extreme precipitation in these regions.

Fig. 8 Urbanization effect values on extreme precipitation in various cities in Guangxi ("/" means no urbanization effect)

	Nanning	Beihai	Liuzhou	Guilin	Guigang	Laibin	Qinzhou	Yulin	Wuzhou
PRCPTOT	92.9	16.8	80.2	/	36.4	/	-44.1	-18.2	10.5
R50	0.7	-0.2	1.0	0.1	0.1	0.0	-0.1	0.0	0.4
R95p	63.7	45.4	112.5	0.3	4.8	/	-16.6	-6.9	25.8
R99p	10.6	2.4	94.7	0.5	-2.9	/	-14.7	6.7	-2.1
RX1day	-2.6	3.6	25.8	2.1	-9.9	/	3.0	/	2.6
SDII	1.3	0.3	0.7	0.0	-0.1	-0.1	-0.2	0.1	0.3

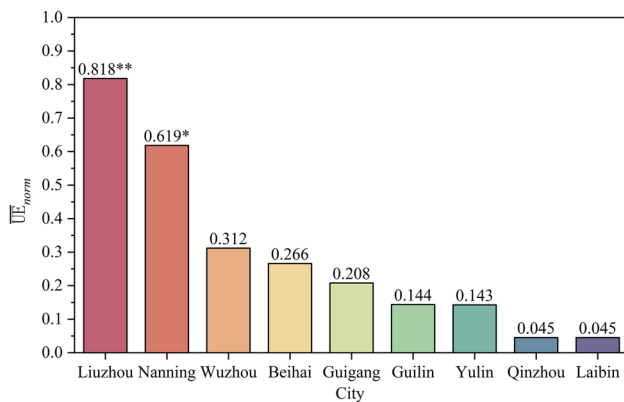


Fig. 9 Normalized urbanization effect values on extreme precipitation in various cities in Guangxi (“*” and “**” indicate significant effects at the 0.1 and 0.05 significance levels for urbanization effects in urban areas, respectively)

4 Discussion

4.1 Factors influencing the urbanization effect on extreme precipitation

The spatial–temporal evolution of extreme precipitation in Guangxi exhibits distinct regional variations resulting from regional characteristics, climatic driving factors, and the process of urbanization (Nie et al. 2012). Apart from CWD, the interannual distribution of EPIs in Guangxi shows an increasing trend, with SDII significantly rising (Fig. 3), similar to the mechanism observed in the urban agglomeration of the Yangtze River Delta (Yao et al. 2022). In China, extreme precipitation in the northern regions has been found to be decreasing (Zhao et al. 2019), while the precipitation intensity and frequency of extreme precipitation events in the southern regions have significantly increased (Fu et al. 2024). These changes probably be attributed to the weakening of the Asian monsoon, leading to increased moisture transport in South China and the Pearl River Basin (Zhao et al. 2024). The decrease in CWD and the increase in CDD indicate an enhanced drought trend in Guangxi. Spatially, the regions with high values of both total and extreme precipitation in Guangxi overlap (Fig. 4), indicating that regions experiencing an enhanced trend in total precipitation are likely to undergo more frequent extreme precipitation events (Zhai et al. 2005).

During the RUP, urban areas in Guangxi had larger values of the EPIs, indicating that cities experienced more intense and frequent extreme precipitation events compared to rural areas. The process of urbanization may have accelerated the occurrence of extreme precipitation in urban areas. The impact mechanism of urbanization on extreme precipitation is complex and depends on various factors. Common pathways discussed in existing research

include the increase in anthropogenic heat (AH) due to urbanization, changes in land properties, and aerosol emissions. The AH releasing from buildings, transportation, and human activities alters the radiation balance in urban areas, promoting the formation of Urban Heat Islands (UHIs) (Zhang et al. 2010; Fu et al. 2024). The UHI induces heating in the lower atmosphere strengthens vertical motion over urban areas, enhancing water vapor transport and upward convergence, triggering more intense convection and increasing short-term extreme precipitation intensity (Vittal et al. 2013; Gu et al. 2019; Liu et al. 2022). The process of urbanization, accompanied by changes in land cover, greatly alters surface characteristics such as soil moisture, roughness, and albedo in urban areas (Wang et al. 2017; Luo and Lau 2019; Luo et al. 2023). The formation of dense building clusters creates urban canopy layers (Zhang et al. 2010), significantly increasing surface roughness and reducing wind speed (Li et al. 2018; Liu et al. 2023; Qiao et al. 2023), leading to changes in the movement paths of air masses, and enhancing mechanical turbulence and low-level convergence in urban areas (Kishtawal et al. 2010; Li et al. 2021; Fu et al. 2024), which can exacerbate convective extreme precipitation (Zhang et al. 2018; Yan et al. 2020). Furthermore, aerosols emitted by urban activities can influence precipitation by altering the heating profile, cloud, and microphysical processes in the urban area (Han et al. 2023; Guo et al. 2024). On the one hand, an increase in aerosol loading reduces the efficiency of cloud droplet collision and coalescence, thereby suppressing the precipitation frequency of shallow clouds (Xiao et al. 2023). On the other hand, aerosols can enhance the growth of cloud droplets through condensation and transform them into ice crystals through updrafts, thickening the cloud body, promoting the development of strong convection, triggering thunderstorms, and generating convective heavy precipitation (Andreae et al. 2004; Cao et al. 2021; Feng et al. 2023). This study indicates that the urbanization effect on extreme precipitation in Nanning and Liuzhou is significantly higher than that in other cities (Fig. 9). The two cities have the highest urbanization rates in Guangxi, and the expansion of impervious surfaces in cities has altered the regional radiation balance, promoted local heat circulation, exacerbated the UHI effect, making urban areas significantly warmer than surrounding rural areas. The additional heat may trigger convection earlier, leading to intense upward motion and water vapor transport (Yang et al. 2017a; Yao et al. 2018; Pimonsree et al. 2022). Additionally, the construction of urban buildings in the expanding cities slows down wind speeds, causing microscale circulation changes. The reduction in urban heat island circulation and urban wind speeds will enhance regional convective extreme precipitation. Liuzhou exhibits a stronger urbanization effect compared to Nanning,

possibly due to Liuzhou being the largest industrial city in Guangxi, where significant aerosol emissions affect atmospheric radiation and cloud microphysical processes, promoting the occurrence of extreme precipitation.

Currently, research of the impacts of urbanization on extreme precipitation in the southern region of China mainly focuses on large urban clusters such as the Pearl River Delta and the Greater Bay Area in Guangdong Province, Hong Kong, and Macau. Driven by the UHI, the local convection and the land-sea circulation are strengthened. The urbanization has significantly enhanced extreme precipitation in the Greater Bay Area, as well as that in the Pearl River Delta region (Wu et al. 2019; Hu et al. 2021, 2023). Guangxi, adjacent to Guangdong, shares similar geographical and climatic conditions to Guangdong. However, this study indicates that urbanization has limited influence on extreme precipitation in most cities in Guangxi. It is because the cities in Guangxi are dispersed and the urbanization process there is slow, without forming large urban clusters. The precipitation in some cities is mainly driven by regional climate factors.

Due to the influence of geographical location and climatic conditions on urbanization at both local and regional scales, changes in precipitation amount and intensity in urban areas are dynamic and complex (Lin et al. 2020; Konduru et al. 2023). Pei et al. (2018) showed that urbanization could significantly impact extreme precipitation under monsoon conditions; while Zhang et al. (2009), Zhao et al. (2019), and Lin et al. (2020) suggested that the influence of urbanization on extreme precipitation events was not significant, even leading to a reduction in extreme precipitation. The contribution of urbanization to regional precipitation may be inhibited by topography and climate, leading to higher variability in local precipitation (Sun et al. 2021). Guilin has a relatively high level of urbanization, but its impact on extreme precipitation is weak (Fig. 9). As a tourist city, Guilin with low industrial pollution, high vegetation coverage, and few high-rise buildings is minimally affected by urbanization. Moreover, the northern part of Guilin is one heavy rainfall center of Guangxi, which weakens the local urbanization impact. Cities like Wuzhou, Laibin, Guigang, and Yulin have relatively low urbanization rates, and therefore, the urbanization effects there are not significant. Extreme precipitation in these regions is primarily governed by regional climate factors.

Research has found that urbanization has a negative effect on extreme precipitation in developed coastal areas in China (Lin et al. 2020). The urban dry island (UDI) effect in cities reduces atmospheric humidity, limits water vapor transport, and decreases convective activity (Lin et al. 2020). Additionally, coastal winds and topography may also play important roles in shaping local precipitation and could suppress the contribution of urbanization (Sun et al. 2021). Qinzhou and Beihai are both located in the southern coastal region of

Guangxi. In recent years, the urbanization process in the two cities has been rapid, but the urbanization effects on extreme precipitation there are not significant, possibly due to the influence of the UDI and coastal climate. Other factors such as the number of meteorological stations, research methods, and time series selection may influence the study results (Song et al. 2014; Sun et al. 2021).

4.2 Applicability of the INM-UEEP

The UMR method, commonly used in developed cities or urban clusters, has limited application in underdeveloped areas like Guangxi (Zhao et al. 2019; Lin et al. 2020). This limitation arises from its reliance on sequence trends for analysis, which may not effectively identify urbanization effects in regions with subtle changes in urban–rural sequences (Zhao et al. 2019). To overcome this, the INM-UEEP method proposed in this study considers underlying surface changes and different urban development stages. By extracting the urbanization effect from the varying values of urban and rural sequences, it enables a direct evaluation (Fig. 8). The INM-UEEP demonstrates good applicability in underdeveloped urban areas, such as Wuzhou and Yulin, despite the uneven level of urbanization in Guangxi.

In contrast, the traditional UMR method lacks a unified evaluation standard and performs poorly in comparative studies of multiple regions (Lin et al. 2020; Pimonsree et al. 2022). In contrast, the INM-UEEP comprehensively evaluates the urbanization effects on multiple indicators across different regions. This quantitative comparison allows for assessing the degree of urbanization impact on extreme precipitation, providing valuable insights for formulating flood control measures in different cities of Guangxi.

It is important to note that this study solely focuses on the urbanization effect on extreme precipitation. However, climate change can either enhance or mitigate urbanization effects in different regions (Chapman et al. 2017; Lin et al. 2020). Therefore, future extreme precipitation predictions may be subject to underestimation or overestimation due to the interaction between urbanization and climate change. Further research is necessary to investigate the urbanization effects resulting from climate change.

5 Conclusions

The evaluation of urbanization effects on extreme precipitation in Guangxi has received limited attention in previous studies, making this analysis a significant contribution. To assess these effects, this study utilized the M–K method to analyze the spatial–temporal trends of extreme precipitation over the past 30 years in Guangxi. In addition, the study incorporated the impact of urban underlying surface

changes and considered differences in 11 EPIs between urban and rural meteorological stations at different time periods. To overcome the shortcomings of traditional studies that lack unified evaluation standards, a novel evaluation method called the INM-UEEP was proposed. The study produced several conclusions:

Firstly, from a temporal perspective, all the EPIs, except for CWD, exhibited an overall upward trend since 1985. Among these, SDII showed a significant increase, passing the 0.05 significance level test. From a spatial distribution standpoint, most of northwestern Guangxi experienced a descending trend in EPIs, while the southeast showed an increasing trend. The central and northeastern parts, characterized by higher levels of urbanization, exhibited significant increases in EPIs, with the most pronounced increases observed in Nanning, Liuzhou, and Guilin.

Secondly, at the regional scale, urbanization had a greater impact on increasing EPIs in urban areas compared to rural areas during the RUP from 2000 to 2014. Specifically, the indices R50, R95p, R99p, and RX1day, which represent extreme precipitation, demonstrated that urban areas had larger overall EPI values compared to rural areas during the RUP.

Thirdly, based on six selected EPIs (PRCPTOT, R50, R95p, R99p, RX1day, and SDII), the study revealed significant and greater urbanization effects on extreme precipitation in the Liuzhou and Nanning regions compared to other urban regions. Beihai and Wuzhou experienced moderate urbanization effects, while Guigang, Guilin, and Yulin displayed relatively low values of urbanization effects. Notably, Laibin and Qinzhou exhibited almost no detectable urbanization effects on extreme precipitation, suggesting that extreme precipitation in these areas was largely unaffected by urbanization.

Authors' contributions Jingyi Huang wrote the original draft under the supervision of Prof. Xungui Li. Prof. Xungui Li was responsible for coming up with the new methodology and proofreading the draft. Formal analysis was performed by Yi Tian. Data curation was performed by Meiqing Yang. Visualization was performed by Jian Sun, Qiyong Yang and Shaobo Wang.

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Data availability Data will be available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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