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Impact of urbanization on variability of annual and flood season precipitation in a typical city of North China

Peijun Li, Depeng Zuo, Zongxue Xu, Xiaoxi Gao, Dingzhi Peng,
Guangyuan Kan, Wenchao Sun, Bo Pang and Hong Yang

ABSTRACT

Urbanization plays an important role in a global change, but there are few studies that combine land use with topography and precipitation. The urbanization in Jinan, a typical city of North China, between the 1980s and 2005 was analyzed by transition matrix analysis, and the topographic effects on land use changes were explored considering altitude, slope, and aspect. The temporal trends and abrupt changes of annual and flood season precipitation for the last 60 years were detected by multiple nonparametric detection methods, and the precipitation indices were adopted to characterize the frequency and intensity of precipitation. The relationship between urbanization and precipitation was finally investigated by grey correlation analysis. The results showed that land use structure in Jinan experienced a dramatic change during recent decades due to the urbanization process, the conversion of cropland to forest, and the protection of spring in Jinan. The land use types that closely related to mankind's activities and living behaviors were more concentrated in areas with lower altitude and slope, and detected more significant changes. The significant abrupt changes of precipitation generally occurred in 1989 and concentrated in urban areas and southern mountainous areas with high increment. The increase of flood season precipitation was more significant in the central urban region with a maximum increasing rate of 39.52%, and the increase in the number of storm and precipitation days was also obvious. The precipitation indices in the flood season were more closely related to changes in farmland and settlements affected by urbanization with a maximum correlation coefficient of 0.75. These findings illustrate the impact of urbanization on the variability of precipitation and support that the changes in the urban underlying surface have a certain effect on the surface energy balance.

Key words | abrupt change, land use change, North China, precipitation, topographic effects, urbanization

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HIGHLIGHTS

- A significant urbanization process has undergone in Jinan during recent decades.
- Flood season precipitation showed a more significant upward trend during the last 60 years.
- The rainstorm days, precipitation amount, and the probability of heavy rain in urban areas have significantly increased.

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- The precipitation indices in the flood season were more closely related to changes in farmland and settlements affected by urbanization.

INTRODUCTION

The urbanization process is generally accompanied by the rapid succession of underlying surface (Mahmood *et al.* 2014), resulting in changes of topography, thermal dynamic conductivity, and hydraulic permeability (Oke 1982), which in turn have an impact on the urban hydrological cycle, such as an increase in regional precipitation and local extreme precipitation, particularly in downwind suburban areas (Pathirana *et al.* 2014; Yu *et al.* 2018). Urbanization not only exacerbates the flood response, but also increases the frequency of heavy rains (Zhang *et al.* 2018). The Metropolitan Meteorological Experiment (METROMEX) confirmed that the urban heat island circulation can trigger and enhance convective weather, such as thunderstorms, heavy precipitation, and strong storms, which especially has a significant impact on urban downwind areas (Changnon 1979). Furthermore, studies in Netherland showed that extreme precipitation in urban areas is more intense compared with rural areas, which have a vital connection with the urbanization process (Golroudbary *et al.* 2017).

There are kinds of methods for investigating the impact of urbanization on regional precipitation. For statistical methods, Lu *et al.* (2019) applied four nonstationary generalized extreme value models to evaluate the impact of urbanization on extreme precipitation in the Yangtze River Delta metropolitan region, which found that urban expansion could increase the magnitudes of extreme precipitation and its recurrence levels under different return periods. Zhu *et al.* (2019) analyzed hourly precipitation data in Beijing Municipality during the period of 2011–2015 using the circular statistical analysis and the grange causality test technique, which indicated that impacts of urbanization on precipitation varied with different types of urbanization. In addition, the climate model and the land surface model are the alternative methods for exploring the impact of urbanization on regional precipitation. Wang *et al.* (2018) coupled the Weather Research and Forecasting (WRF) model with a single-layer urban canopy model (UCM) to assess the impact of extensive urbanization on regional precipitation across the Beijing–Tianjin–Hebei region of China, which showed that extensive urbanization considerably decreased precipitation over and downwind of Beijing city.

Other studies focused on the separation of climate change and urbanization on precipitation at different spatial scales. Gu *et al.* (2019) separated potential contributions of urbanization and climate change to precipitation trends in China at national, regional, and local scales using a 'trajectory'-based method, which concluded that climate change was the principle factor for variations of precipitation, while urbanization generally has a greater effect on total precipitation than precipitation extremes. Whether the effect of urbanization on precipitation is increasing or decreasing is still controversial, and some studies have even reached the opposite conclusion. The precipitation in the urban downwind direction was suppressed in the study of major urban areas and industrial facilities areas, because the addition of ice nuclei and cloud condensation nuclei reduced the conversion efficiency of cloud water to rainwater (Rosenfeld 2000; Givati & Rosenfeld 2004). Moreover, a decrease in surface water storage and in water vapor supply to the upper atmosphere may also lead to a decrease in precipitation in urban areas. The impacts of heat island effect and aerosol emissions on precipitation may be insufficient, compared with the impact of changes in the hydrological characteristics of the underlying surface (Kaufmann *et al.* 2007; Wang *et al.* 2018).

However, most of the research focused on the five precipitation gauging stations located in the Xiaoqing River basin, occupying only a quarter of the total area of the study area, which is not enough to comprehensively reflect the spatial heterogeneity of precipitation in the whole of Jinan. Therefore, more detailed information on the relationship between land use change and precipitation in the study area should be further investigated. In this study, a variety of

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methods were used to analyze the spatial pattern and temporal trend of precipitation and the changes of land use types in Jinan during the last 60 years, and the relationship between land use change and precipitation variation in the study area was explored. This study tried to reveal the evolution law between the two environmental variables and point out the issues that need to be faced in the development, utilization, and protection of water and soil resources, which is of great significance for further urban development and the coordination of the water and environment.

STUDY AREA AND DATA DESCRIPTION

Study area

Jinan, the capital of Shandong Province, is located in the Midwest of Shandong Province, the downstream region of the Yellow River Basin and on the eastern edge of the North China Plain (116°11′–117°44′ E, 36°01′–37°32′ N) (Figure 1). The area under the jurisdiction of the Jinan municipal administrative area is 8,151 km^2, including seven districts and two counties. The terrain is high in the south and low in the north. The terrain is complex and can be divided into three zones: the north is near the Yellow River area, the middle is the piedmont plain area, and the south is the hilly mountain area. There are many rivers in Jinan, mainly the Yellow River and the Xiaoqing River. Jinan belongs to the sub-humid continental monsoon climate and has obvious monsoon characteristics, with an annual average temperature of 14.3 °C and an annual average precipitation of 648.0 mm (Zuo *et al.* 2018). The precipitation is extremely uneven, and the inter- and intra-annual variability is strong (Chang *et al.* 2018). In summer, the average precipitation in various regions is more than 400 mm, which concentrates 60% of the annual precipitation. The average number of precipitation days in July is about 15 days, and the number of rainstorm days with

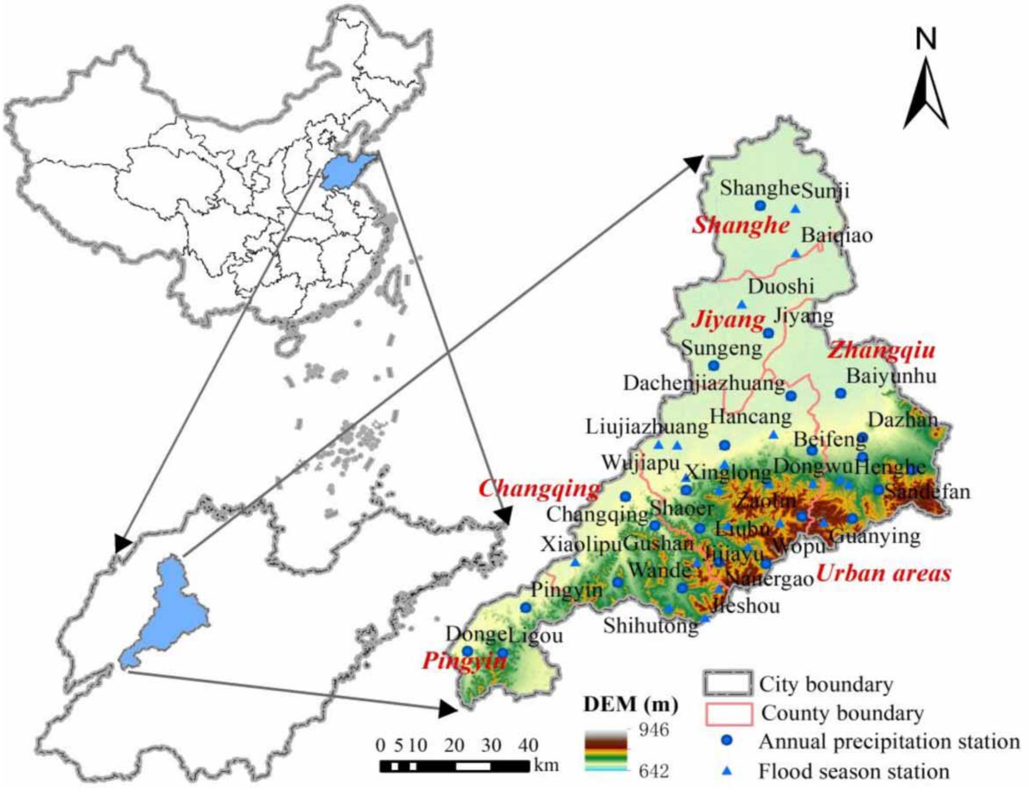

Figure 1 | Digital elevation model (DEM) and locations of precipitation gauging stations in Jinan.

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daily precipitation above 50 mm is concentrated in July and August, accounting for 70% of the number of rainstorm days throughout the year.

According to statistics, the urban built-up area of Jinan is expanded by 57.94 km^2 during the period of 1986–2000 (Jiang *et al.* 2003). With the rapid economic and social development, human activities in Jinan have significantly intensified. According to the results of the sixth national census in 2010 (http://www.stats.gov.cn), the permanent resident population of Jinan is 6.184 million, which is an increase of 892,300 compared with 10 years ago, with a growth rate of 15.07%. With the processes of urbanization, population growth and economic development, land use patterns have also undergone tremendous change. Under the influence of the drastic changes in underlying surface conditions during the recent decades, large- and medium-sized cities in China have suffered from rainstorm flood and waterlogging, in which Jinan is a typical case (Hammond *et al.* 2015; Cheng *et al.* 2017).

Data description

The land use type data of the study area in 1980s and 2005 were provided by the National Science and Technology Foundation Platform Project 'Data-Sharing Network of Earth System Science' (www.geodatda.cn). The daily precipitation data at 47 gauging stations during the period of 1950–2016 were collected for further analysis, which was provided by the Jinan Hydrology Bureau. The locations of the precipitation gauging stations are shown in Figure 1, in which 23 flood season gauging stations were mainly used to study the spatiotemporal variability of precipitation in the flood season; the remainder of the gauging stations for annual precipitation monitoring was adopted for abrupt change detection and trend analysis of precipitation. The missing data of the precipitation series were filled by neighboring stations through the linear regressive method, in which all the correlation coefficients $R^2 > 0.8$, which indicates that the filled series can satisfy the quality requirements for this study. Furthermore, the economic and social statistics-related administrative regions in the Statistical Yearbook were also used in this study.

METHODOLOGY DESCRIPTION

To analyze the relationship between urbanization and precipitation in Jinan, urban areas (including municipal districts of Licheng, Shizhong, Tianqiao, Lixia, and Huaiyin), suburban areas (Zhangqiu and Changqing districts), and rural areas (including Jiyang, Shanghe, and Pingyin) were divided based on GDP levels and distance from the urban core. In exploring the topographic effects on the characteristics of spatial distribution of land use types, a sampling point was set at each 0.01 km^2 in the study area, and a scatter plot was drawn based on the attributes of sampling points. The areas of each land use type were calculated at 50 m increments of elevation and 1° increments of slope.

Land use transition matrix

Land use transition matrix is derived from the quantitative analysis of system state and state transition in system analysis. The matrix reflects the land use dynamic process information of the mutual transformation between the beginning and end of a certain period at a certain area. It can be used to characterize the structural characteristics of land use change and show the trend and direction of various land-based transformations in a concrete and comprehensive way (Lu *et al.* 2020). The general formula is shown in Table 1, in which P_{11}–P_{nn} is the transfer area between different land use types A_1–A_n during the period from T_1 to T_2. S_{n1} and S_{n2} indicate the n-type area in the land use period T_1 and the period T_2, respectively.

Table 1 | The description of land use transition matrix

	T_2				
T_1	A_1	A_2	…	A_n	Total
A_1	P_{11}	P_{12}	…	P_{1n}	S_{11}
A_2	P_{21}	P_{22}	…	P_{2n}	S_{21}
…	…	…	…	…	…
A_n	P_{n1}	P_{n2}	…	P_{nn}	S_{n1}
Total	S_{12}	S_{22}	…	S_{n2}	Total area

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Temporal trend and abrupt change detection methods

Nonparametric Mann–Kendall test method

The Mann–Kendall method is a nonparametric statistical test method used to calculate the changing characteristics of hydro-meteorological factors (Mann 1945; Kendall 1975). Its advantage is that the sample does not need to follow a certain regular distribution and will not be disturbed by a small number of abnormal values. It is simple to calculate and suitable for type variables and order variables.

For a time series x with n sample sizes, construct an ordered sequence:

$$s_k = \sum_{i=1}^{k} r_i \quad k = 2, 3, \cdots, n \tag{1}$$

in which

$$r_i = \begin{cases} +1 & x_i > x_j \\ 0 & x_i \le x_j \end{cases} \quad (j = 1, 2, \cdots, i) \tag{2}$$

Assuming the time series are random and independent, the defined statistics are as follows:

$$\mathrm{UF}_k = \frac{[s_k - E(s_k)]}{\sqrt{\mathrm{Var}(s_k)}} \quad (k = 1, 2, \cdots, n) \tag{3}$$

where $\mathrm{UF}_1 = 0$, $E(s_k)$ is the mean of the cumulative number s_k, and $\mathrm{Var}(s_k)$ is the variance of the cumulative number s_k.

$$\begin{aligned} E(s_k) &= \frac{n(n-1)}{4} \\ \mathrm{Var}(s_k) &= \frac{n(n-1)(2n+5)}{72} \end{aligned} \tag{4}$$

Given the significance level α is 0.05, check the normal distribution table to determine the critical value $u_{0.05} = \pm 1.96$. Repeat the above process in reverse order of time series, while making $\mathrm{UB}_k = -\mathrm{UF}_k$, $k = n$, $n-1$, …, 1, $\mathrm{UB}_1 = 0$, and draw a sequence curve diagram of UF_k and UB_k. If the value of UF_k or UB_k is greater than 0, it indicates that the sequence is increasing, and conversely, it indicates a decreasing trend. When the value of UF_k or UB_k exceeds a critical straight line, it indicates that the upward or downward trend is significant. If two curves appear at the intersection point, and the point appears between the critical lines, then the moment corresponding to the point is the start time of the abrupt changes (Zuo *et al.* 2016).

Nonparametric Pettitt test method

The Pettitt method is also a kind of nonparametric test method, which directly uses the order column to detect mutation points (Petitt 1979). For a time series x with n sample sizes, construct an ordered sequence:

$$r_i = \begin{cases} +1 & x_i > x_j \\ 0 & x_i = x_j \\ -1 & x_i < x_j \end{cases} \quad (j = 1, 2, \cdots, i) \tag{5}$$

If

$$k_{t_0} = \mathrm{Max}|s_k| \quad (k = 2, 3, \cdots, n) \tag{6}$$

The time corresponding to t_0 is the start time of the abrupt changes.

$$P = 2\exp\left(\frac{-6k_{t_0}^2}{n^3 + n^2}\right) \tag{7}$$

If $P \le 0.5$, the detected abrupt changes are considered to be statistically significant.

Moving *T*-test method

The basic test idea of the moving *T*-test is to deal with the problem of whether there is a significant difference between the mean values of the two subsequences in the climate series. When the difference between the mean values of two subsequences exceeds a certain level of significance, it is considered that the mean value has changed qualitatively at this moment.

For a time series x with n samples, a moment is selected as the reference point, and the samples of x_1 and x_2 in the two subsequences before and after the reference point define the statistics t for n_1 and n_2, respectively:

$$t = \frac{\overline{x_1} - \overline{x_2}}{s \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{8}$$

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in which

$$s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 - n_2 - 2}} \tag{9}$$

where s_1^2 and s_2^2 are the variances of the two subsequences.

To improve the reliability of the calculation results and avoid the shift of abrupt changes caused by the length of the subsequence, the experimental comparison was performed by changing the length of the subsequence for several times. Finally, the value of n_1 and n_2 was selected as 7 and the confidence level α was set as 0.05. Therefore, the critical value $u_{0.05} = \pm 2.18$ is determined.

Grey relational analysis

Grey relational analysis (GRA) is a dynamic correlation analysis method that quantitatively describes the strength, size, and order of the relationship between factors (Tan & Deng 1995). During the development of the system, if the trends of the two factors are consistent, the correlation between the two factors is higher; otherwise, it is lower. When performing data analysis, x_0 is set to be the reference sequence and x_i is set to be the comparison sequence. Dimensionless is calculated by means of the mean method, which is transformed into a pure number sequence x_0' and x_i'. The absolute value of the corresponding point difference constitutes the difference sequence, and the maximum difference and the minimum difference between the two sequences are identified. The grey correlation coefficient formula is as follows:

$$\xi_{0i(k)} = \frac{\min\limits_{i}\min\limits_{k} |x'_{0(k)} - x'_{i(k)}| + \xi \cdot \max\limits_{i}\max\limits_{k} |x'_{0(k)} - x'_{i(k)}|}{\Delta_{0i(k)} + \xi \cdot \max\limits_{i}\max\limits_{k} |x'_{0(k)} - x'_{i(k)}|} \tag{10}$$

in which, ξ is the resolution coefficient, $1 > \xi > 0$. ξ takes values according to different background requirements.

A correlation degree is calculated as follows:

$$\gamma_{0i} = \frac{1}{N}\sum_{k=1}^{N} \xi_{0i(k)} \tag{11}$$

in which γ_{0i} is the correlation degree. The greater the grey correlation degree, the closer the geometric curve shape is, which shows that the development and change of the two factors are closer.

RESULTS AND ANALYSIS

Changes in land use types from 1980s to 2005

Spatiotemporal variation of land use types

From the point of view of spatial distribution, the maps of land use type in Jinan for the periods of the 1980s and 2005 are shown in Figure 2. Farmland dominates the land use types in Jinan, reaching about 65% of the total area, mainly distributed in the northern and central plains affected by the terrain. The southern mountainous area is characterized as higher altitudes, the main land use types of which are forests and grasslands. The main stream of the Yellow River runs through Jinan flowing from the central region to the northeast. The main urban area of Jinan City is located in the middle. The evolution of construction land was characterized as an increase of urban area from east to west and an expansion of suburban area in the northwest and the southern mountainous areas.

The changes in various land use types between the two periods are calculated in Figure 3. The land use structure of Jinan experienced a great change from 1980s to 2005, in which settlements and farmland saw the most obviously change. The area of settlements increased 173.26 km^2 with a growth rate of 18.5%, while the area of farmland decreased 190 km^2. The period from the 1980s to 2005 was the period when the 'Administrative Measures for the Urban Planning of Jinan City' were promulgated and implemented. The sharp increase in the settlement area indicates that Jinan's urbanization is advancing rapidly, which reflects the impact of urbanization and population growth on land resources. It can be seen from the Annual Statistical Yearbook of Jinan in 2005 that Jinan's per capita GDP was 1,263 yuan in 1985, and dramatically reached to 31,606 yuan in 2005, with an increase of 25 times. The economy of Jinan rapidly developed during this period, and the level of urbanization gradually increased, which is in line with the trend of land use change.

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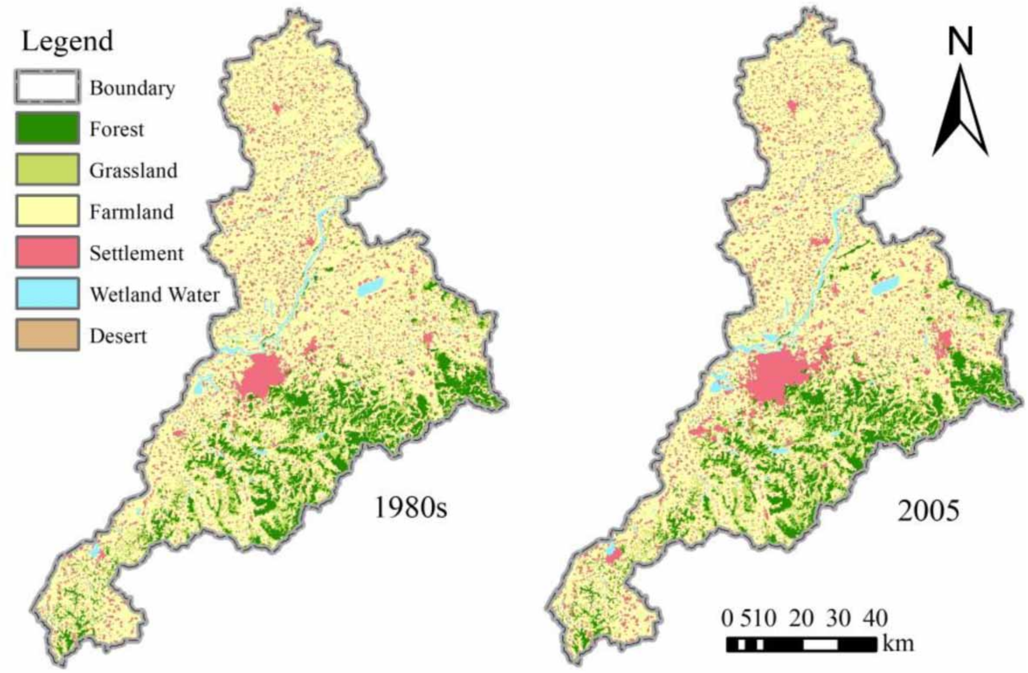

Figure 2 | The spatial distributions of land use types in Jinan during the periods 1980s and 2005.

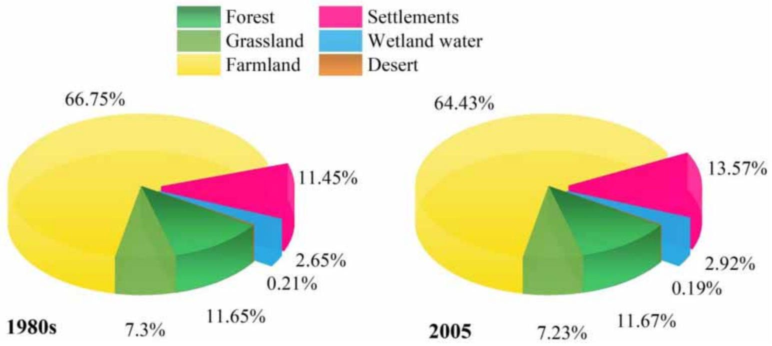

Figure 3 | Proportions of land use types in Jinan during the periods 1980s and 2005.

Forests are the second most dominant type of land use following farmland, which showed an overall growth trend during the study period, from 952.56 km^2 in the 1980s to 954.12 km^2 in 2005, increasing 0.16%. The area of wetlands and water showed an upward trend during the study period, and the growth rate was second only to settlements, reaching 10.12% with a total increase of 21.92 km^2. Grassland and desert areas showed a slight decline with little change overall. The changes in land use types during the study period were not only affected by natural factors such as topography, landforms, and hydrology, but also social development and human activities.

Transition matrix of land use types

The land use transition matrix of Jinan from 1980s to 2005 in Table 2 explains how the land use types changed in detail. The transferred area of settlement accounted for 17.36% of the total transferred area of all land types in the study area; the increased area accounted for 32.83% of the total increased area of all land use types. The increased

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Table 2 | Transition matrix of land use changes in Jinan from the 1980s to 2005 (km^2)

	2005						
1980s	**Forest**	**Grassland**	**Farmland**	**Settlements**	**Wetland water**	**Desert**	**Total**
Forest	806.96	58.22	79.22	9.62	2.04	0.29	956.34
Grassland	71.81	441.41	74.10	8.67	1.57	0.14	597.70
Farmland	75.22	87.82	4,887.42	344.98	57.47	3.74	5,456.65
Settlements	2.75	3.36	181.63	741.70	6.40	0.46	936.30
Wetland water	0.84	1.11	39.29	3.89	168.11	0.05	213.30
Desert	0.38	0.26	4.51	0.55	0.11	11.11	16.92
Total	957.95	592.19	5,266.15	1,109.41	235.72	15.79	8,177.21

area of settlement was 1.89 times the transferred area, and the growth rate of which was significantly faster than other land use types. More than half of the increased settlement came from the conversion of farmland. The settlement area converted from farmland reached 345.04 km^2, accounting for 60.62% of the total transferred area of farmland, which reflects the rapid development of urbanization in Jinan and the impact of population growth on land resources. The transferred area of farmland was 1.5 times the increased area of farmland.

The area of wetland and water showed an upward trend during this period, and the increasing rate of 10% ranked only second to settlements. During the research period, Jinan invested billions of dollars in the treatment and restoration of rivers and lakes under the jurisdiction of the municipal government, which not only improved the water quality, but also expanded the water area, reflecting that the 'spring city' has put considerable effort into ecological protection and restoration. With the issuance and promotion of the 'Jinan City Ecological Restoration and Urban Remediation Pilot', the government implemented the ecological restoration and protection of water and paid more attention to the surrounding ecological greening of river banks and reservoir areas. It is expected that the wetland and water area will maintain steady growth in the future. The transferred area of forest is not much different from the increased area, with an overall increase less than 0.1%. Among the newly added areas, the land use types were shifted mostly from farmland, accounting for 50% of the total new increased area of forest, reflecting the impact of environmental protection policies such as returning farmland to forests on land use structure in Jinan City.

Topographic effects on land use changes

The scatter plot was used to explore the topographic effects on the characteristics of spatial distribution of land use types (Figure 4). At the altitude of 400–600 m, the distribution of forests on each aspect and slope was relatively uniform, while that was concentrated in the areas with the west aspect at the altitude of 150–250 m. The grassland was generally distributed around 200 m, which had a good adaptability to slope and aspect. The distribution of cultivated land characterized as that where most was located in the areas with a slope of 0–4° and an altitude of about 0 m. Water bodies were mostly distributed in low-lying areas with a slope of 0–5° and an altitude of about −50 m, and most of the settlements were located in the areas of 0–10° and 50–100 m. The distribution of desert was relatively loose, which was less affected by topographic factors.

The area statistics of land use types according to aspects are shown in Figure 5. The distributions of farmland and water body were less affected by the aspect, showing a strong adaptability of aspect. Compared with 1980s, the area of farmland with easterly aspect had decreased significantly, while the area of water body had an overall increase, especially for SW aspect. In the 1980s, settlements were mainly oriented toward westerly aspect, while that tended to expand to easterly aspect in 2005. Most of the forest land was located on W and NW aspect, which had decreased from the 1980s to 2005. The desert on westerly and southerly aspects showed a significant decrease trend, which experienced an obvious shift

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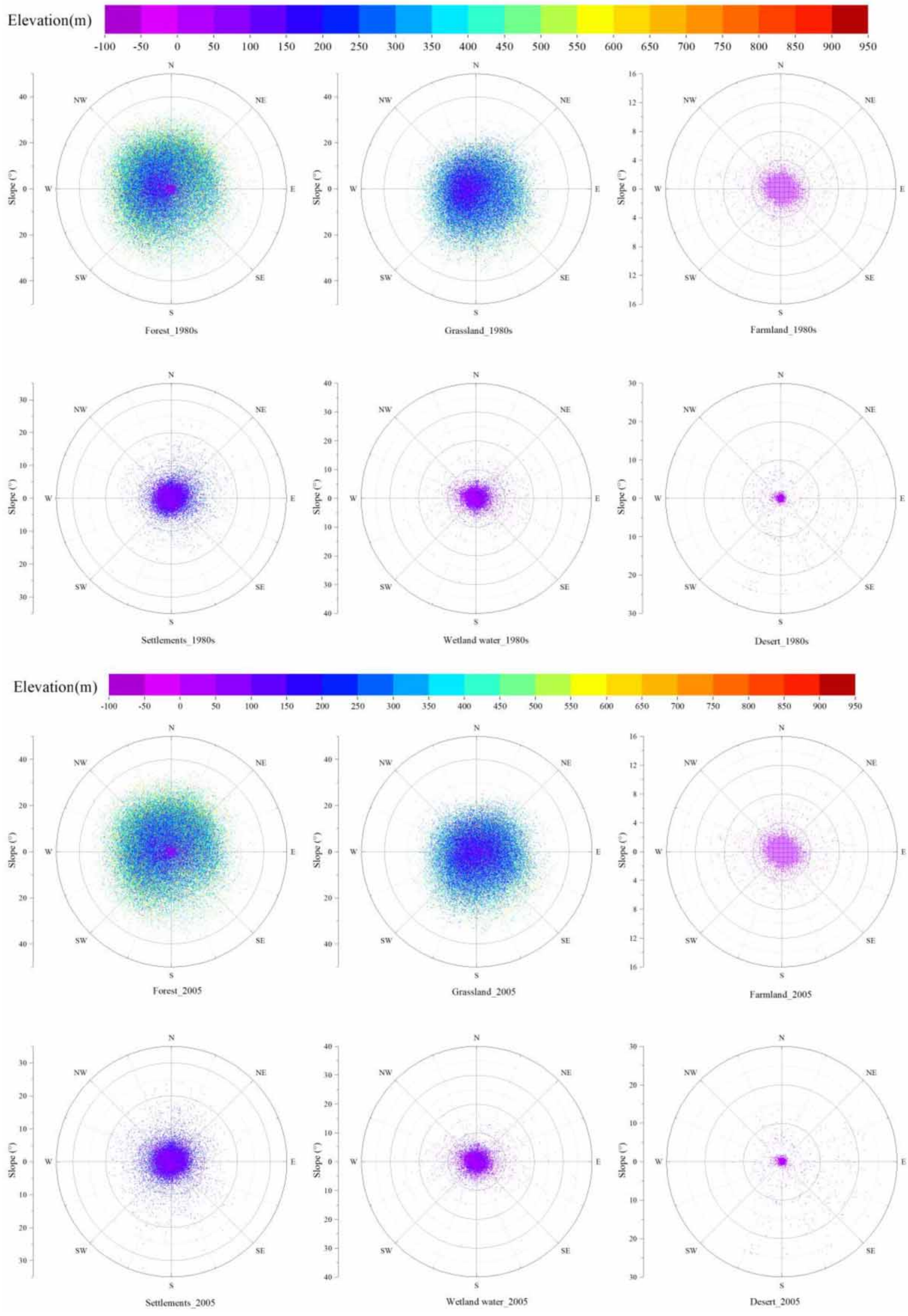

Figure 4 | The distributions of land use types on various aspects and elevations in Jinan during the periods 1980s and 2005.

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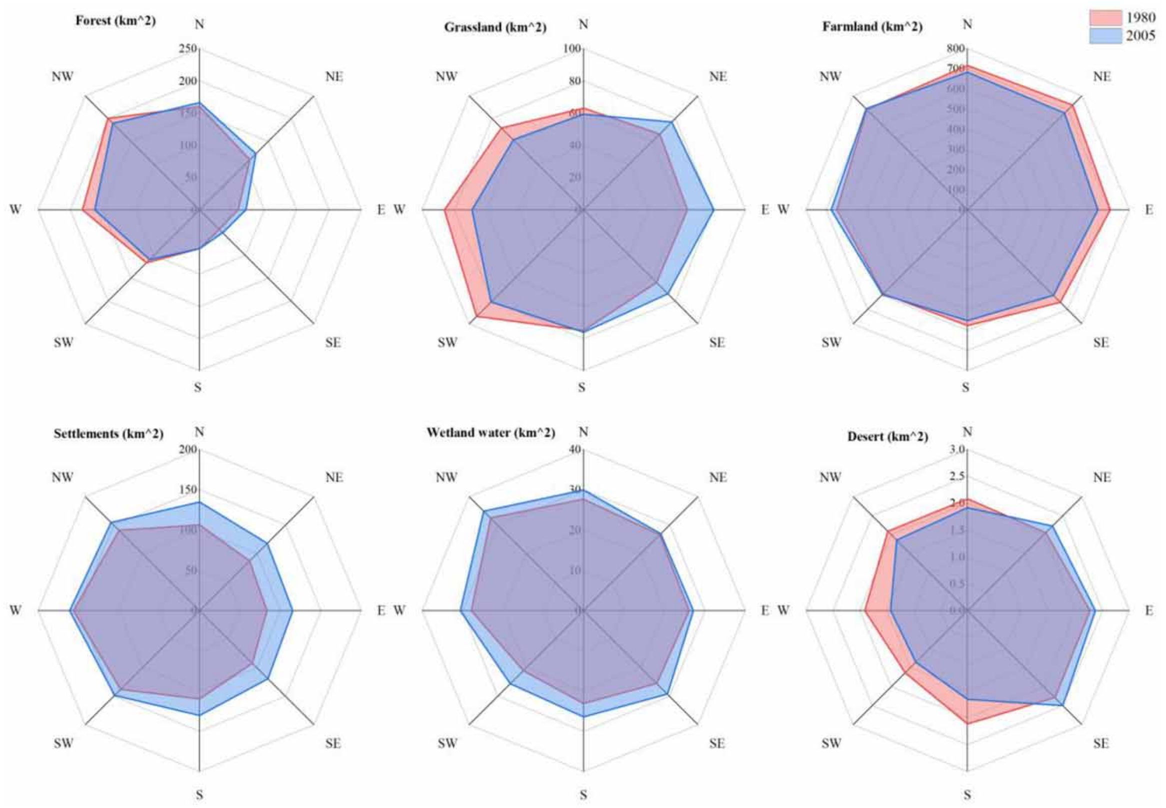

Figure 5 | Land use changes on different aspects in Jinan during the periods 1980s and 2005.

from westerly aspect to easterly aspect. The area of grassland in westerly aspect significantly decreased during the study period, while that in easterly aspect significantly increased.

With the rise of elevation, the area of each land use type increased first and then decreased (Figure 6). Most areas of farmland, settlements, wetland and waters, and deserts were concentrated at 0 m, which are the land use types closely related to human activities. Forests were mostly distributed at the elevation of 250–350 m, while the peak value of the grasslands area appeared at the elevation of about 200 m. The two types of land use were mostly distributed in mountainous and hilly areas, and their topographic effect was less than that on the other four types. Compared with the 1980s, the area of forest increased by nearly 30% at the elevation of 0 m, while the area of farmland decreased by 108.17 km^2, showing the effect of the Grain for Green Project in the study area. Jinan has implemented the Regulations of Forest Resources Protection and Management since 2000, which severely cracked down on deforestation and encouraged the conversion of cropland to forest. Compared with 2000, the forest coverage increased from 19.7 to 24.1% in 2005, which is consistent with the results reflected in the figure. The area of settlements significantly increased in the elevation belt of 0–150 m, which was also transformed from farmland, indicating an obvious urbanization process. Wetland and waters and deserts were generally distributed in low-lying areas, which was strongly constrained by elevation. Compared with the 1980s, the area of wetland and waters greatly increased at the elevation of 0 m, while that of deserts significantly decreased at the same elevation, indicating a considerable improvement of the eco-environment in the study area during recent decades.

As for the slope effect on land use changes, the distributions of forest and grassland were still different

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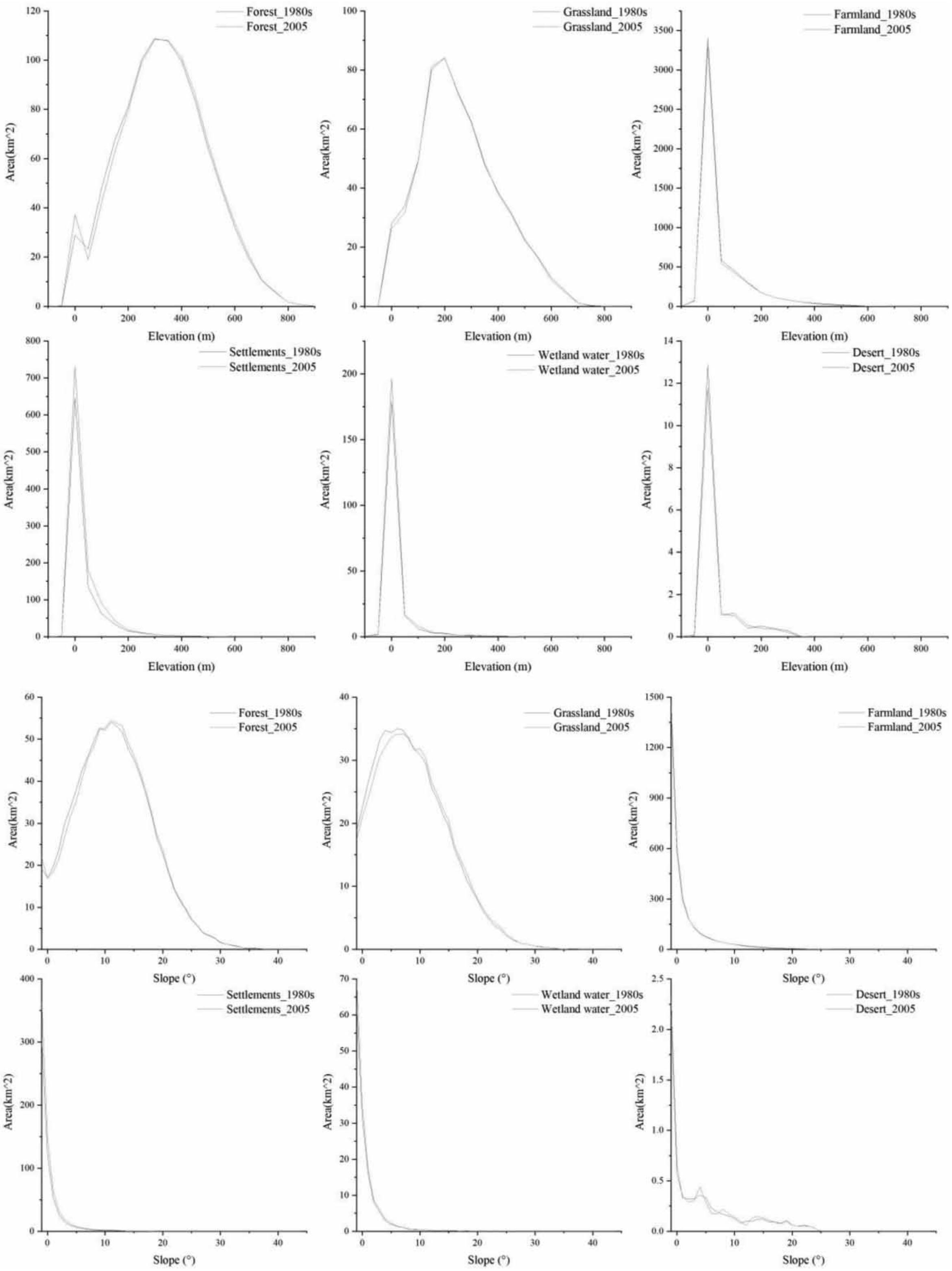

Figure 6 | Land use changes at different elevations and slopes in Jinan during the periods 1980s and 2005.

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from the other four land use types, similar to the elevation effect on land use changes. As the slope increased, the areas of forest and grassland first increased and then decreased, and the peak values of area appeared in the regions with slope of 10° and 5°, respectively, which showed a strong suitability of the two land use types in the regions with relatively large slopes. Compared with the 1980s, the areas of forest and grassland below 10° significantly decreased in 2005. Farmland, settlements, and wetland and waters were mainly concentrated in the flat areas with slopes of -1–2°, due to the fact that areas with slopes exceeding 5° are unsuitable for construction and farming activities. The area of desert was small and scattered with stochastic distribution. Generally speaking, as the slope increases, the areas of various land use types that are closely related to mankind's producing activities and living behaviors will gradually decrease, while the distribution of land use types that are less disturbed by humans gradually has the advantage, showing a transition process from artificial ecosystems to natural ecosystems.

Spatiotemporal variability of flood season and nonflood season precipitation

Spatial patterns of flood season and nonflood season precipitation

Based on the daily precipitation data at 24 gauging stations in Jinan during the period of 1966–2016, the spatial distributions of average annual and flood season precipitation are shown in Figure 7. Both spatial patterns are characterized as decreasing from southeast to northwest and southwest. The maximum average annual precipitation is 759.54 mm at the Zaolin Station in the southern mountainous area, while the minimum value is 557.39 mm at the Baiyunhu Station in the east. The maximum value of the average precipitation during the flood season appeared at the Wupu Station, also located in the southern mountainous area, reaching 579.58 mm, while the minimum value appeared at the Baiyunhu Station with 408.48 mm.

The annual and flood season precipitation in mountainous areas is generally higher than that in the plain areas.

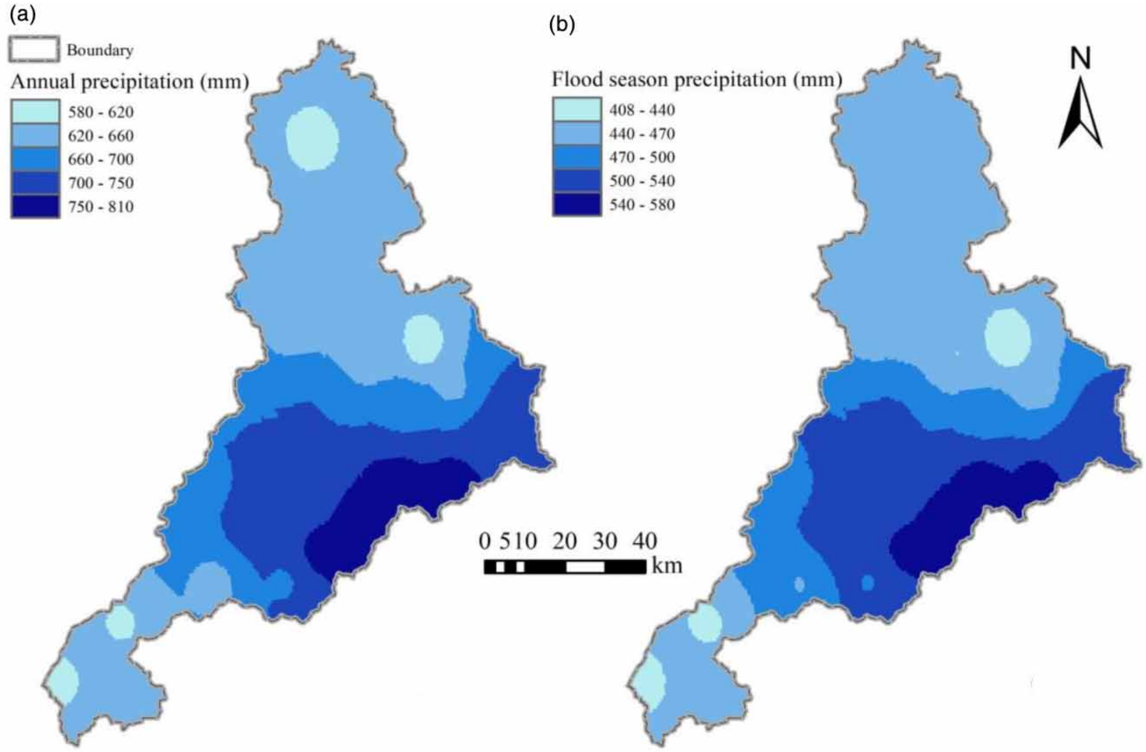

Figure 7 | The spatial distributions of average AP and flood season precipitation in Jinan.

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The settlements in concentrated areas are mostly in areas with relatively less precipitation. Compared with the characteristics of the terrain in the study area, the spatial distribution of average annual and flood season precipitation in Jinan has a significant relationship with the topography.

Abrupt changes of the flood season and nonflood season precipitation

To comprehensively analyze and validate the abrupt changes of flood season and nonflood season precipitation in Jinan during the period of 1966–2016, the widely used nonparametric Mann–Kendall test method, the Pettitt test method, and the moving *T*-test method were adopted to detect the abrupt changes of flood season and nonflood season precipitation at 47 gauging stations in the study area. The comparison between the abrupt change detection results obtained by the three different methods showed that the annual precipitation at all stations exhibited an upward trend. The abrupt change points generally occurred in the 1960s, 1989, and 2002, among which most abrupt change points in 1989 were detected at the significance level 0.05 (Figure 8). Most sites of the detected mutations are concentrated in the urbanized areas of central Jinan and the southern mountainous areas, corresponding to the strong change of land use structure during the rapid development of Jinan.

Changes in precipitation between pre-change and post-change point periods

According to the results of the abrupt change detection of precipitation, the study period was divided into two sub-periods: Period I: 1966–1989 (before the change point) and Period II: 1990–2016 (after the change point). The spatial variabilities in the differences between the pre-change and post-change points for annual precipitation in the study area are calculated and shown in Figure 9(a). For the spatial variability of flood season precipitation, the recorded data from the 23 flood season stations were incorporated to improve the spatial heterogeneity, which is shown in Figure 9(b). Since the rainfall stations in the central city are mostly flood season stations, the flood season data can well reflect the actual precipitation distribution.

The annual and flood season precipitation in the study area have significantly increased during the post-change point period with different extents. The increase of annual precipitation and flood season precipitation were similar in spatial distributions. The increasing rates of the annual and flood season precipitation in the eastern and southwestern plain regions were relatively low with less than 10%, while the increasing rate of that in the central urban region and southern mountain was relatively high. Especially for the Liujiazhuang Station close to the central city, the average flood season precipitation increased from

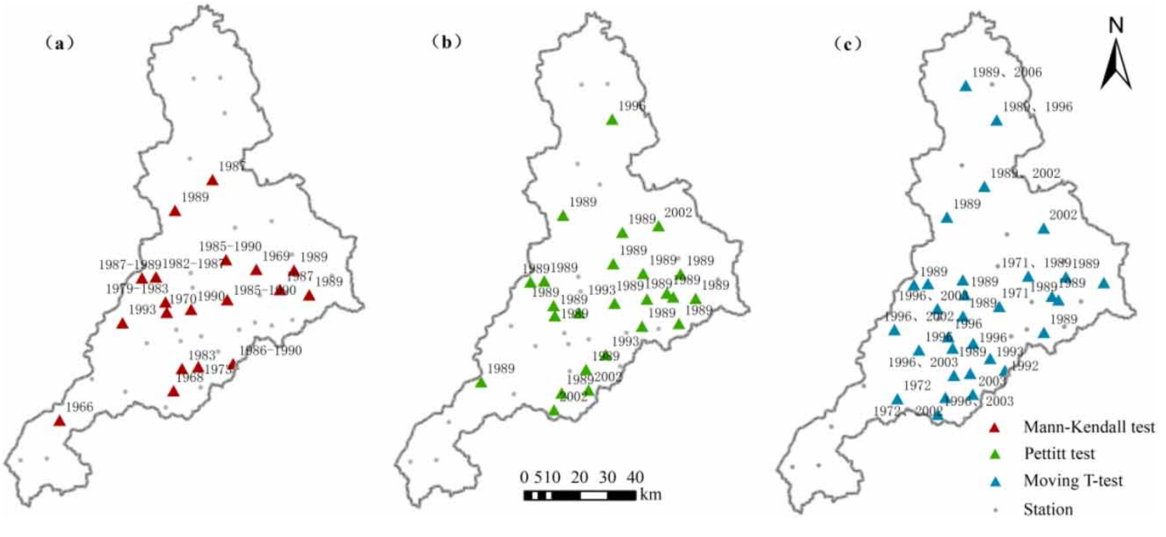

Figure 8 | The abrupt change points of annual and flood season precipitation in Jinan.

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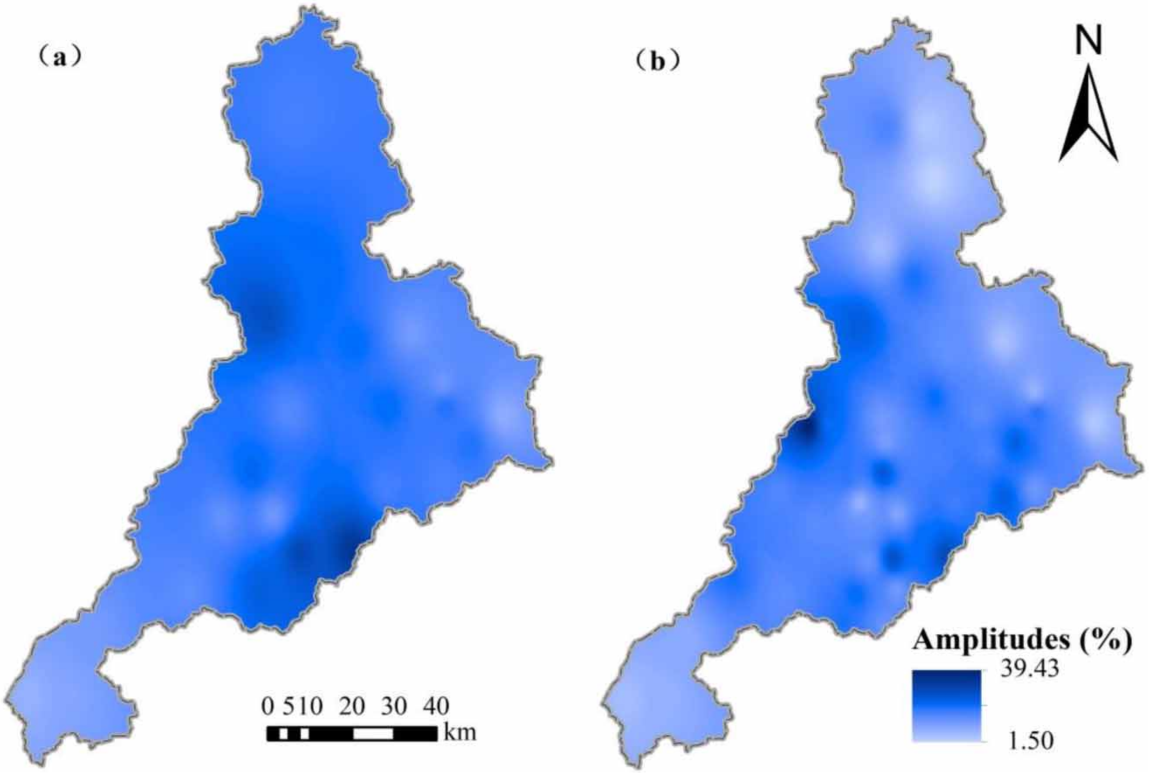

Figure 9 | The amplitudes of annual (a) and flood season (b) precipitation during the pre-change and post-change periods in Jinan.

370.4 to 516.8 mm, which indicates that Jinan faced considerable risk from flood disasters during the flood season in the central urban region over recent years.

To comprehensively study the characteristics of the variability of precipitation, two more indices, number of precipitation days and precipitation intensity, were adopted for further analysis. The daily rainfall above 50 mm is counted as an indicator of storm intensity. To avoid the impact of the initial year difference, the precipitation data of each site from 1980 to 2016 were selected for further analysis.

As can be seen from Figure 10, the number of precipitation days throughout the year and flood season in each rainfall station generally showed an increasing trend. The spatial distribution of average annual precipitation days is similar to that of precipitation days in the flood season. The stations with a larger increase of annual precipitation days were mostly concentrated in the southern mountainous areas, and the Nanergao Station increased from 55.8 to 77.4 days. In the flood season, the stations with a larger increase were concentrated in the urban areas of central Jinan. The Xiaolipu Station, located near the central urban area, increased from 22 to 33.5 days. The increase in the number of storm days throughout the year is obvious, and the annual precipitation generally increased, which is shown in Figure 11. The proportion of rainstorm days at most stations has increased at different rates during the flood season, and the stations with larger increases are concentrated in central Jinan. The largest increase of rainstorm days was at the Guanying Station in the southern mountainous region. The proportion of heavy rain in the flood season increased from 3.1 to 7%, and the proportion of heavy rain in the Xinglong Station, located in the central urban area of Jinan, also increased by nearly 4%. The increase in the number of precipitation days at stations close to the urban area was significantly higher than the flood season, and the increase in precipitation indices during the flood season was also significantly higher than that of the whole year. It can be inferred that the threat of flood disasters to the urban area of Jinan continues to

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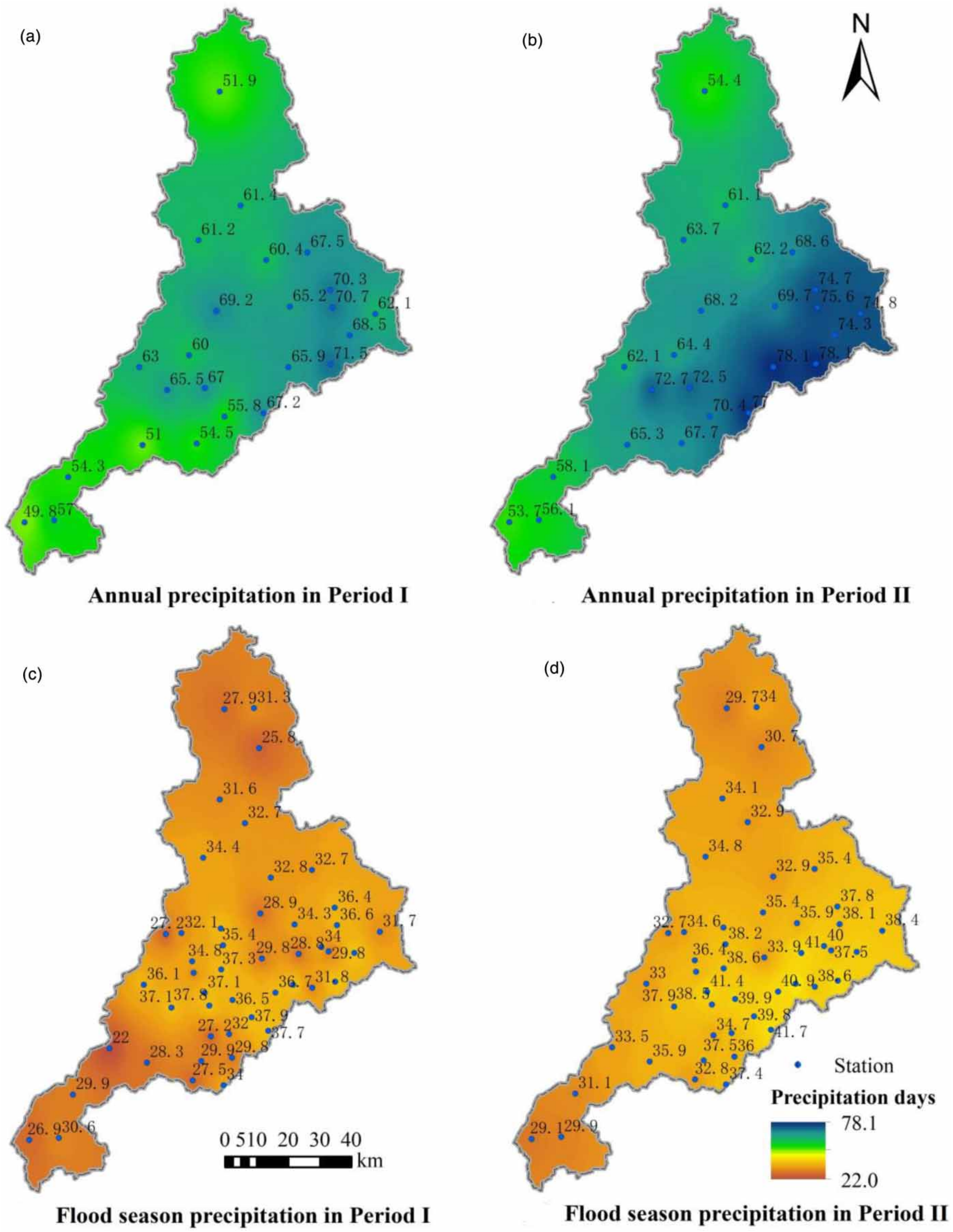

Figure 10 | The changes of annual and flood season PDs during the pre-change and post-change periods in Jinan.

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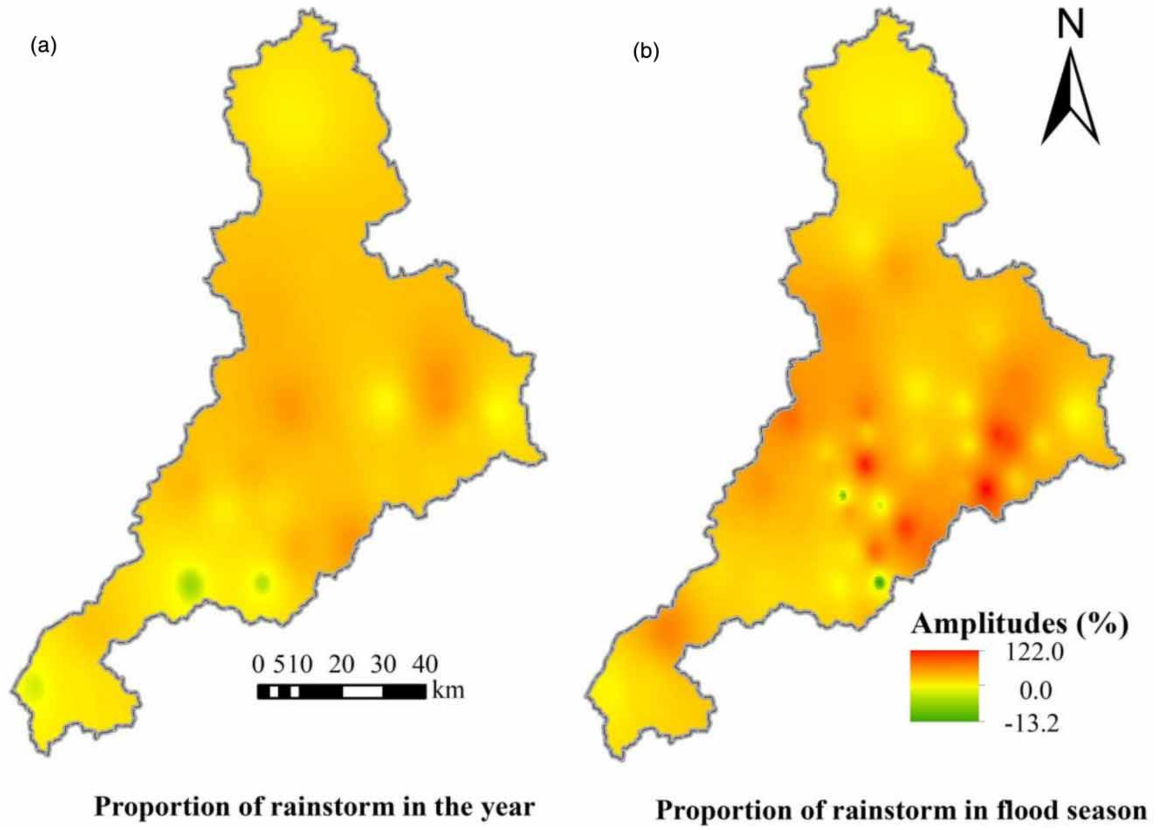

Proportion of rainstorm in the year

Proportion of rainstorm in flood season

Figure 11 | The amplitudes of rainstorm proportion during the pre-change and post-change periods in Jinan.

increase after the abrupt change year. The analysis of the precipitation days and precipitation intensity showed a significant increasing trend for annual and flood season scales, which indicates that beside the total amount, the frequency and intensity of precipitation in the study area also increased to some extent.

Impact of urbanization on precipitation

The arithmetic average of each index in the region is calculated to obtain the variabilities of land use types and precipitation indices between the pre-change point and post-change point periods (Figure 12). Six precipitation indices, including annual precipitation (AP), precipitation days (PDs), rainstorm days (RDs), AP in the flood season (AP_F), PDs in the flood season (PD_F), and RDs in the flood season (RD_F), were adopted in this study to describe the characteristics of precipitation. AP describes the variabilities from rainfall amount, PD describes the variabilities from frequency, and RD describes the variabilities from intensity.

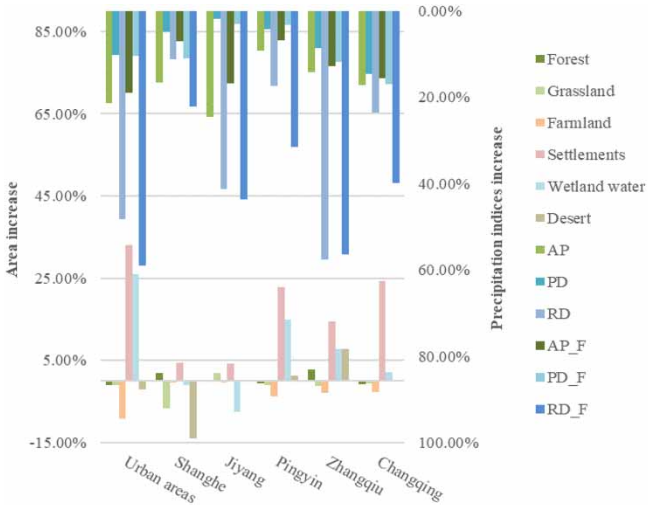

Figure 12 | The relationship between precipitation indices and land use changes in different regions of Jinan.

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As can be seen from Figure 12, the increase of settlement in the urban area is the largest with an increasing rate of 33.01%, followed by wetland water area with an increase of 25.94%, while the farmland in the urban area showed a significant decrease of 9.13%. The increase of urbanization is highest in the urban area, followed by suburban areas. According to the statistics of the Statistical Yearbook of Jinan City in 2005, the GDP per capita in the urban area is 44,805.6 yuan, Zhangqiu district is 22,483.6 yuan, Changqing district is 22,117.6 yuan, and Pingyin, Jiyang, and Shanghe counties are 20,992.6, 15,991.7, and 12,483.3 yuan, respectively. The level of per capita GDP in each region is consistent with the increase in the land use type of settlements, indicating that the socioeconomic development is generally corresponds to the land use change.

Precipitation indicators show that the growth rates of various precipitation indices in the urban area were generally the most significant. Among them, the number of rainy days in the flood season increased by 58.95%, and the amount of precipitation in the flood season increased by 18.96%. Compared with the average value of other areas in Jinan, the number of rainy days in the central district increased by 15.38%, and the probability of heavy rains increased by 4.73%, showing typical characteristics of the 'rain island effect'. The number of rainy days increased by 14.48% in Changqing District, while the number of heavy rains increased by 57.61% in Zhangqiu District. Although the settlement area of Pingyin has increased significantly, the actual urbanized area is relatively small, resulting in little impact on precipitation. As for some stations in the south of Jiyang, precipitation indicators are generally affected because they are closer to the central urban area.

In order to further explore the relationship between land use types and precipitation factors, GRA was used to calculate the correlation coefficient in each area. The indicators were firstly listed in order of the economic level of each district from the largest to the smallest, and dimensionless was then carried out, taking the indicator of urban area as the initial value. The calculation results after dimensionless processing are shown in Figure 13. The changes in land use and precipitation indices in different administrative areas were well synchronized, with a range of correlation coefficients between 0.5 and 0.75. Changes in the settlement had the greatest impact on AP_F, with a correlation coefficient of 0.75, while grassland and desert had the least impact on AP_F, with a correlation coefficient of 0.5. The fluctuation of RD_F was directly related to the changes of cultivated land and settlements, with correlation coefficients of 0.73 and 0.7, respectively, while the lowest correlation occurred in the grassland area. Wetland and water, and settlements had a greater impact on PD than other land use types, and the changes in desert were less synchronized with that in PD. Generally speaking, the precipitation indices associated with the flood season in the study area were more closely related to land use changes. Changes in farmland and settlements affected by urbanization were more closely related to precipitation indices.

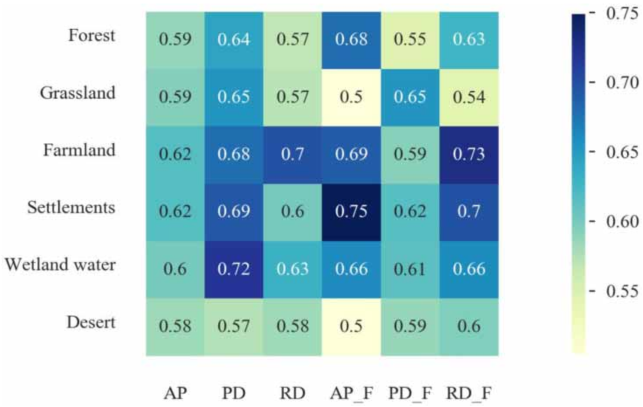

Figure 13 | Grey correlation analysis of precipitation indices and land use changes in Jinan.

The above analysis shows that in the context of further development of the urban economy and society and drastic changes in land use types, the precipitation in urban areas during the flood season is more significantly affected compared with other regions. This phenomenon may be the result of a combination of the heat island effect, the blocking effect, and the condensation effect (Mohammad *et al.* 2019).

DISCUSSION

Different statistical test methods have their own advantages and disadvantages, and the cross-verification of the results obtained by the three abrupt change test methods in this study could minimize the instability and maximize the rationality of the determination of the abrupt change point. In previous studies, it was found that the change in reflection or absorption of solar radiation on the urban

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underlying surface has a certain effect on the surface energy balance, which is one of the physical mechanisms by which land use changes affect regional precipitation (Oke 1982; Arnfield 2003). Moreover, studies in Beijing and Tokyo showed that the increase of surface impermeable area ratio makes the local evaporation decrease, the sensible heat flux increases, and the water vapor mixing in the boundary layer becomes more uniform, which affects the development of the local weather system (Zhang *et al.* 2009; Souma *et al.* 2013). There are some previous studies on simulating the impact of land use change on rainfall. For example, the WRF model and UCM are recently used in the field; however, it requires large amounts of computing resources. More sophisticated models with long-term simulations are required in the future to simulate the specific spatial correlation between land use change and precipitation (Miao *et al.* 2011; Wang *et al.* 2018).

Through the research, it could be found that the distribution of cultivated land had a significant relation with the requirements of crop growth and the convenience of cultivation, which was obviously controlled by the topographic factors. In addition to urbanization, the transferred area of farmland is also affected by environmental protection policies such as returning farmland to forest and returning farmland to lake. It is important to note that our study focused on the local recycled precipitation instead of large-scale advected precipitation which is beyond the scope of this study but deserves further research. For example, Daniels *et al.* (2016) indicated that the impact of land use change on summer precipitation in the Netherlands was smaller than that of climate change, but it cannot be ignored. Similar findings were found in the Beijing–Tianjin–Hebei region, about 11% of the reduction of the total precipitation was caused by the decrease of local recycled precipitation induced by urbanization, while the remainder 89% was caused by the reduction of large-scale advected precipitation (Li *et al.* 2017). It remains a great challenge to clearly elucidate the independent effects of land use change on climate.

CONCLUSIONS

In this study, the impact of urbanization on annual and flood season precipitation was qualitatively analyzed from the spatial pattern and temporal trends of precipitation and the changes of land use types in Jinan during the last 60 years. Conclusions can be summarized as follows:

1. The land use types in Jinan experienced great changes during the period 1980–2005, in which settlements and farmland were the most obvious changing types. The area of settlements converted from farmland accounted for 60.6% of the total transfer area of farmland, reflecting the rapid development of urbanization in Jinan and the impact of growing population on land resources. It is worth mentioning that the growth rate of wetland water in Jinan ranked only second to the settlements, which reflects the great efforts for ecological protection and restoration.
2. The distribution of land use was characterized as a certain terrain gradient under the influence of topographic factors. In lower altitude and slope areas, settlements, farmland, and wetland and water were more concentrated, which are closely related to mankind's producing activities and living behaviors. The forest and grassland show a strong adaptability of higher altitudes and steeper slopes, accounting for a larger proportion of land use types in the areas. The influences of aspect on the distribution of various land use types were not obvious.
3. The spatial pattern of precipitation in Jinan is generally characterized as decreasing from southeast to northwest, which is mainly affected by monsoon and topography. The temporal variability of precipitation is obvious, and the intra-annual distribution is uneven. The average AP and flood season precipitation in Jinan showed an overall increasing trend. The significant abrupt change point of precipitation generally occurred in 1989 detected by three methods. The growth rate of precipitation in eastern and western regions was relatively low, while that in the central urban region was relatively high. The frequency and intensity of precipitation in Jinan also increased significantly.
4. Compared with other regions, the urban region with the largest area of settlements produced the largest increase of precipitation especially for the post-change period, and the water and wetland area have also increased significantly. The increase of the number of RDs and the

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amount of precipitation during the flood season in the urban area were much higher than that in other areas. The changes in land use and precipitation indices in different administrative areas were well synchronized. The precipitation indices in the flood season were more closely related to changes in farmland and settlements affected by urbanization with a maximum correlation coefficient of 0.75. The results obtained in this study are of great significance for the further urban development and the coordination of the water and environment.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (National Science and Technology Foundation Platform Project 'Data-Sharing Network of Earth System Science' (www.geodatda.cn)).

REFERENCES

Arnfield, A. J. 2003 Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* **23** (1), 1–26.

Chang, X., Xu, Z., Zhao, G., Cheng, T. & Song, S. 2018 Spatial and temporal variations of precipitation during 1979–2015 in Jinan City, China. *Journal of Water and Climate Change* **9** (3), 540–554.

Changnon, S. A. 1979 Rainfall changes in summer caused by St. Louis. *Science* **205** (4404), 402–404.

Cheng, T., Xu, Z., Hong, S. & Song, S. 2017 Flood risk zoning by using 2D hydrodynamic modeling: a case study in Jinan city. *Mathematical Problems in Engineering* 5659197.

Daniels, E., Lenderink, G., Hutjes, R. & Holtslag, A. 2016 Relative impacts of land use and climate change on summer precipitation in the Netherlands. *Hydrology and Earth System Sciences* **20** (10), 4129–4142.

Givati, A. & Rosenfeld, D. 2004 Quantifying precipitation suppression due to air pollution. *Journal of Applied Meteorology* **43** (7), 1038–1056.

Golroudbary, V. R., Zeng, Y., Mannaerts, C. M. & Su, Z. B. 2017 Detecting the effect of urban land use on extreme precipitation in the Netherlands. *Weather and Climate Extremes* **17**, 36–46.

Gu, X., Zhang, Q., Singh, V. P., Song, C., Sun, P. & Li, J. 2019 Potential contributions of climate change and urbanization to precipitation trends across China at national, regional and local scales. *International Journal of Climatology* **39** (6), 2998–3012.

Hammond, M. J., Chen, A. S., Djordjevic, S., Butler, D. & Mark, O. 2015 Urban flood impact assessment: a state-of-the-art review. *Urban Water Journal* **12** (1 SI), 14–29.

Jiang, L. G., Nie, X. H. & Liu, E. F. 2003 Analysis on the spatial structure of urban land use in Jinan city. *Economic Geography* **23** (1), 70–73 (in Chinese).

Kaufmann, R. K., Seto, K. C., Schneider, A., Liu, Z., Zhou, L. & Wang, W. 2007 Climate response to rapid urban growth: evidence of a human-induced precipitation deficit. *Journal of Climate* **20** (10), 2299–2306.

Kendall, M. G. 1975 *Rank Correlation Methods*, 4th edn. Charles Griffin, London, UK.

Li, X., Zhang, X., Zhang, L. & Zheng, J. 2017 The varied impacts of land use/cover change on summer precipitation over eastern China. *Geographical Research* **36**, 1233–1244.

Lu, M., Xu, Y., Shan, N., Wang, Q., Yuan, J. & Wang, J. 2019 Effect of urbanization on extreme precipitation based on nonstationary models in the Yangtze River Delta metropolitan region. *Science of the Total Environment* **673**, 64–73.

Lu, D., Gao, G., Lu, Y., Xiao, F. & Fu, B. 2020 Detailed land use transition quantification matters for smart land management in drylands: an in-depth analysis in northwest China. *Land Use Policy* **90**, 104356.

Mahmood, R., Pielke, R. A. S., Hubbard, K. G., Niyogi, D., Dirmeyer, P. A., Mcalpine, C., Carleton, A. M., Hale, R., Gameda, S., Beltran-Przekurat, A., Baker, B., Mcnider, R., Legates, D. R., Shepherd, M., Du, J., Blanken, P. D., Frauenfeld, O. W., Nair, U. S. & Fall, S. 2014 Land cover changes and their biogeophysical effects on climate. *International Journal of Climatology* **34** (4), 929–953.

Mann, H. B. 1945 Non-parametric test against trend. *Econometrical* **13**, 245–259.

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Miao, S., Chen, F., Li, Q. & Fan, S. 2011 Impacts of urban processes and urbanization on summer precipitation: a case study of heavy rainfall in Beijing on 1 August 2006. *Journal of Applied Meteorology and Climatology* **50** (4), 806–825.

Mohammad, P., Goswami, A. & Bonafoni, S. 2019 The impact of the land cover dynamics on surface urban heat island variations in semi-arid cities: a case study in Ahmedabad city, India, using multi-sensor/source data. *Sensors* **19** (17), 3701.

Oke, T. R. 1982 The energetic basis of the urban heat-island. *Quarterly Journal of the Royal Meteorological Society* **108** (455), 1–24.

Pathirana, A., Denekew, H. B., Veerbeek, W., Zevenbergen, C. & Banda, A. T. 2014 Impact of urban growth-driven land use change on microclimate and extreme precipitation – a sensitivity study. *Atmospheric Research* **138**, 59–72.

Petitt, A. N. 1979 A non-parametric approach to the change point problem. *Applied Statistics* **28**, 125–135.

Rosenfeld, D. 2000 Suppression of rain and snow by urban and industrial air pollution. *Science* **287** (5459), 1793–1796.

Souma, K., Tanaka, K., Suetsugi, T., Sunada, K., Tsuboki, K., Shinoda, T., Wang, Y., Sakakibara, A., Hasegawa, K., Moteki, Q. & Nakakita, E. 2013 A comparison between the effects of artificial land cover and anthropogenic heat on a localized heavy rain event in 2008 in Zoshigaya, Tokyo, Japan. *Journal of Geophysical Research-Atmospheres* **118** (20), 11600–11610.

Tan, X. & Deng, J. 1995 Grey relational analysis: a new method for multivariate statistical analysis. *Statistical Research* **11** (3), 46–48 (in Chinese).

Wang, J., Feng, J. & Yan, Z. 2018 Impact of extensive urbanization on summertime rainfall in the Beijing region and the role of local precipitation recycling. *Journal of Geophysical Research-Atmospheres* **123** (7), 3323–3340.

Yu, M., Miao, S. & Zhang, H. 2018 Uncertainties in the impact of urbanization on heavy rainfall: case study of a rainfall event in Beijing on 7 August 2015. *Journal of Geophysical Research-Atmospheres* **123** (11), 6005–6021.

Zhang, C. L., Chen, F., Miao, S. G., Li, Q. C., Xia, X. A. & Xuan, C. Y. 2009 Impacts of urban expansion and future green planting on summer precipitation in the Beijing metropolitan area. *Journal of Geophysical Research-Atmospheres* **114**, D02116.

Zhang, W., Villarini, G., Vecchi, G. A. & Smith, J. A. 2018 Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. *Nature* **563** (7731), 384.

Zhu, X., Zhang, Q., Sun, P., Singh, V. P., Shi, P. & Song, C. 2019 Impact of urbanization on hourly precipitation in Beijing, China: spatiotemporal patterns and causes. *Global and Planetary Change* **172**, 307–324.

Zuo, D., Xu, Z., Yao, W., Jin, S., Xiao, P. & Ran, D. 2016 Assessing the effects of changes in land use and climate on runoff and sediment yields from a watershed in the Loess Plateau of China. *Science of the Total Environment* **544**, 238–250.

Zuo, D., Cai, S., Xu, Z., Li, F., Sun, W., Yang, X., Kan, G. & Liu, P. 2018 Spatiotemporal patterns of drought at various time scales in Shandong Province of Eastern China. *Theoretical Applied Climatology* **131** (1–2), 271–284.

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