Characteristics of temporal and spatial evolution of rainfall under the influence of urbanization—A case study of the Beijing-Tianjin-Hebei region

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Abstract: With rapid urbanization in recent years, the frequency of extreme rainfall events has increased in major cities around the world during the flood season, and the social and economic losses caused by heavy rainfall are becoming increasingly serious. In this context, it is necessary to study the changes in rainfall during the urbanization stage, in the Beijing-Tianjin-Hebei region, the economic capital region of China. Based on the rainfall data from 197 rain gauge stations for the period 1960 to 2019, linear regression, moving average, and SURFER spatial analysis were used to analyze the temporal and spatial characteristics of rainfall in the Beijing-Tianjin-Hebei region, and compare the difference in rainfall between the mountainous areas and plains, during the flood season. The results show that (1) the overall duration of rainfall in each region of Beijing-Tianjin-Hebei exhibit a downward trend, and the overall spatial performance gradually decreases from east to west. (2) The mountainous areas in the Beijing-Tianjin-Hebei region are prone to light and moderate rainfall events; the plains are more prone to rainfall events at levels above moderate rain, especially rainstorms and heavy rain events; the probability of light and moderate rainfall events in the suburbs is close to that of the urban areas, but the probability of rainfall events at levels above heavy rain is less than that of the urban areas; the probability of rainfall events of all levels in the outer suburbs is higher. (3) Increase in rainfall in urban areas compared to the southern suburbs is greater than when compared with the northern suburbs which are at different stages of urbanization, but the effect of urbanization on rainfall is also reflected in the comparison between the urban areas and the northern suburbs. (4) With increasing urbanization, the built environment in the mountainous areas and plains of the Beijing-Tianjin-Hebei region has continued to grow, and the original underlying surface conditions have changed. Because the urbanization process is faster in the urban areas than in the suburbs, the changes to the underlying surface conditions lead to greater increase in rainfall in urban areas during the

flood season compared to the suburbs; the urban areas are also more prone to rainfall events at levels above heavy rain. Studying the rainfall trend and its driving forces in the Beijing-Tianjin-Hebei region during the flood season is expected to increase understanding of the cause and mechanism of urban runoff and waterlogging, leading to the adoption of corresponding preventive measures and formulation of policies to cope with the continuous changes.

Keywords: Urbanization, Flood season, Rainfall characteristics, Beijing-Tianjin-Hebei region of China

Introduction

The urban development process inevitably changes the original topography, which directly affects the dynamics of the underlying surface characteristics of the city (Han S et al., 2019). At the same time, increase in population leads to higher building density and increased emission of various waste and hot gases into the atmosphere; the thermodynamic properties of the underlying surface and the atmosphere above the city, as well as the characteristics of the condensation nuclei caused by cloud formation in the atmosphere change accordingly (D.-P. Häder et al., 2011), directly affecting rainfall. While the economic capital region of China, the Beijing-Tianjin-Hebei region, has experienced rapid urbanization in recent years, heavy rainfall during flood seasons and extreme rainfall events have become more frequent; the resulting urban runoff and waterlogging have caused increasing social and economic losses. Studying the rainfall trend and its driving forces in the Beijing-Tianjin-Hebei region during the flood season is of great significance for understanding the cause and mechanism of urban runoff and waterlogging, so that corresponding preventive measures can be adopted (Zhang S et al., 2018; Yu M et al., 2020; Zhang Y et al., 2014). With regard to the impact of urbanization on rainfall characteristics, many scholars in China and abroad have conducted research from different perspectives (Liu J et al., 2019; Yin J et al., 2020; Shastri H et al.,2019; Luong et al., 2020). Research methods mainly include comparative analysis based on observation data, satellite data analysis, and the numerical model method (Zhong S et al., 2015; El Alfy M,2016; Miao S et al., 2011).The advantage of a comparative study method based on observational data is that it can remove the influence of climate system variability. With advancements in science and technology, the satellite data analysis method has also been well developed in recent years, and the analysis results have become increasingly reliable. (Chen Z et al., 2015; Deng S et al., 2018; Liu H et al., 2020; Okonkwo C et al., 2013). The numerical model refers to the use of numerical meteorological models or theoretical physical models to analyze the characteristics of regional rainfall. This method is based on individual case analyses. The basic idea is to select several rainfall events that can represent the general mechanism of regional precipitation, and use sensitive numerical values. The experiment records the changes in the simulated element field, and on this basis, analyzes the influence mechanism from a synoptic perspective (Liu Y-Y et al., 2020). Compared with the method of comparative analysis of urban and suburban areas based on observational data, the advantage of the numerical model method is that it can explain the mechanism of urbanization affecting rainfall to a certain extent. The disadvantage is that the representativeness of regional climate characteristics is limited in case analysis; the generalization is weak, the calculation cost is high, and the accuracy of the model itself adds certain amount of uncertainty to the simulation results. Niyogi et al. analyzed the impact of urbanization on summer rainfall using meteorological data from 1958 to 2008 for eastern United States, and found that urbanization has a promoting effect on rainfall (Niyogi D et al., 2017). Zhang L explained the main driving factors that control the spatial pattern of surface water in China on three scales (watershed, 1 km buffer zone, and custom area). Compared with other types of land, the responsibility coefficient in the spatial water quality model for cities and farmland is higher, which indicates that both urbanization and crop production have a serious impact on surface water quality, and is accompanied by the dilution effect of rainfall on all spatial scales (Zhang L et al., 2019). Kumar S studied the seasonal and regional differences in extreme rainfall events, and their contribution to global precipitation (Kumar S et al., 2019). Al Saleem developed a method based on the influence of current urbanization and industrialization on precipitation in the Kingdom of Saudi Arabia (KSA), to investigate the impact of changes in rainfall on the adequacy of drainage infrastructure capacity of KSA's Medina (AlSaleem et al., 2018). Bonneau J performed weekly sampling of rainfall and base flow to obtain stable isotope water in two nearby streams, and assessed the impact of urbanization on groundwater sources of streams (Bonneau J et al., 2018).Prakash et al used remote sensing satellite data to analyze monthly rainfall and flow in the Ganga-Brahmaputra river system in India during 2003–12. They observed that rapid industrialization, urbanization, and population growth may have an impact on land and water resources, and emphasized the potential for application of earth observation satellite data in hydrological exploration (Prakash et al., 2014). Schütte S outlined the link between urbanization and hydrological flow response in the sub-humid study area. In terms of hydrological flow response, the urban characteristics namely the increase in impervious area and the potential return of water as drinking water through diversion from outside the catchment area have been identified. By using a daily time-step process based on the ACRU model, a method was developed to model urban response scenarios with urban characteristics as variables (Schütte S et al., 2017). In most previous studies, the focus of research was mainly the impact of urbanization on annual rainfall. However, an increasing number of studies show that urbanization has a more significant impact on rainfall during the flood season, especially in China's economic capital region. In recent years, the level of urbanization has increased rapidly; the distribution of rainfall in the Beijing-Tianjin-Hebei region during the year is also very uneven. Rainfall in the flood season accounts for 70% to 80% of the annual rainfall, therefore, analysis of rainfall changes during the flood season can better reflect the impact of urbanization on rainfall. On the other hand, owing to the limited conditions considered in many research processes, the number of representative rain gauge stations selected for the comparison of urban and suburban rainfall characteristics is too small, resulting in reduced research accuracy. This study uses the actual rainfall data from 197 rain gauge stations in the Beijing-Tianjin-Hebei region for the flood season, for the period 1960–2019, to analyze the temporal and spatial evolution characteristics of rainfall in the region and to study the impact of urbanization on rainfall, with the aim of suggesting measures for rainwater management and flood prevention in urban areas during the flood season.

1 Study area, data and methodology

1.1 Regional overview

The Beijing-Tianjin-Hebei region includes the cities of Beijing and Tianjin, and the Hebei Province, and is bounded by the Taihang Mountain to the west and Bohai Bay to the east, with high terrain in the northwest and north, flat terrain in the south and east, and is located in a temperate semi-humid, semi-arid continental monsoon climate zone. The northwest-southeast trending Yanshan-Taihangshan mountain system gradually transitions into a plain toward the southeast, from the high elevations in the northwest. Due to the large variations in the topography and landforms of the Beijing-Tianjin-Hebei region, analysis of the rainfall characteristics of the region during the flood season and study of the impact of urbanization on the rainfall characteristics necessitated dividing the Beijing-Tianjin-Hebei region into the following two research sub-areas based on physical geography and socioeconomic development: the mountainous area in the northwest and the plains in the southeast. The spatial location of these divisions is shown in Figure 1.

1.2 Data

The data used in this article include daily data from 197 rain gauge stations in the Beijing-Tianjin-Hebei region from 1960 to 2019 as well as data on population and Gross Domestic Products (GDP), with high data accuracy and completeness, for 1978 to 2018; the distribution of rain gauge sites is shown in Figure 2.

The rainfall data for the Beijing-Tianjin-Hebei region for 1960 to 2019 are obtained from the National Meteorological Station, and the data for population and GDP for 1960 to 2018 from the "Beijing Statistical Yearbook," "Tianjin Statistical Yearbook," and "Hebei Economic Yearbook."

The rainfall data are listed in Table 1. The data for some rain gauge stations are missing; however, the total missing data are less than 5% which is low considering the long time span and the large number of stations. More than 36% of the non-measured rain gauge stations in the study area since 1960, and the remaining missing data are only counted in quantity. For the stations with missing data, the data are substituted with values obtained using the Kriging interpolation method. Finally, the area controlled by each station is divided by the Tyson polygon. Each area contains 3 complete sequences of stations, and the rain gauge stations in different regions are more representative of the region they are in. Therefore, the data can be used to analyze the rainfall changes in the Beijing-Tianjin-Hebei region.

1.3 Research methods

In this study, the urbanization process of the Beijing-Tianjin-Hebei region is evaluated and presented based on population, socio-economic development, and land use data. Statistical methods are combined with the SURFER spatial analysis function to analyze the temporal and spatial variability of rainfall in the Beijing-Tianjin-Hebei region during the flood season. Finally, the impact of urbanization on the rainfall characteristics during the flood season for mountainous areas and plains is compared; the changes in the urban flood season rainfall characteristics at different stages of urban development are also studied. A paired two-sample analysis of the average is also used to test whether the rainfall differences between the plains and mountainous areas are significant.

2 Analysis of Results

2.1 Analysis of urbanization process

The level of urbanization is generally measured by the urbanization rate and the proportion of urban population in the total population. The urbanization rate for each year is calculated from the population data of Beijing-Tianjin-Hebei for 1978–2018; the urbanization process of the Beijing-Tianjin-Hebei region is divided into four stages based on GDP data. In the first stage from 1978 to 1988, the urbanization rate for the Beijing-Tianjin-Hebei region was lower than 48%, with 42% in 1982; the average annual GDP growth for Beijing was 3.156 billion yuan, and that for Tianjin was 1.8258 billion yuan. In the second stage from 1989 to 1999, the urbanization rate for the region was between 48% and 53% with 49.52% in 1990; the average annual GDP growth for Beijing and Tianjin were 25.06 billion yuan and 12.894 billion yuan, respectively. In the third stage from 2000 to 2010, the urbanization rate of the Beijing-Tianjin-Hebei region grew rapidly, with the urbanization rate between 53% and 70%, the average annual growth rate in GDP being 112.288 billion yuan for Beijing and 76.418.9 billion yuan for Tianjin. During the fourth stage from 2011 to 2018, the urbanization rate of the Beijing-Tianjin-Hebei region basically remained above 70%; the average annual GDP growth for Beijing was as high as 198.480 billion yuan, and the average annual GDP growth for Tianjin was 118.323 billion yuan.

2.2 Analysis of rainfall characteristics

Based on the rainfall data from each station during the flood season, the rainfall changes in the mountainous areas and plains during the flood season were obtained. As seen in Figure 4(a), the linear regression results show that the rainfall in each area during the flood season follows a downward trend from 1960 to 2019, but there is a slight difference in the decline rate in the two regions. In the plains, the rainfall decline rate is 3.35 mm/a, whereas the rainfall in the mountainous area declines relatively slowly, with a decline rate of 2.06 mm/a. The 5-year moving average data of rainfall in the mountains and plains show, as is evident from Figure 4(b), that the internal variation of rainfall in the mountainous areas and plains of the Beijing-Tianjin-Hebei region from 1960 to 2019 is basically the same, exhibiting a characteristic change from high to low; the 1960s to the mid-1970s, and the early 1990s belonged to periods of high rainfall, while the 1980s and the period after 2000 belonged to periods of low rainfall.

2.3 Analysis of characteristics of rainfall of different levels

According to the rainfall classification of the China Meteorological Administration, rainfall is divided into the following 6 levels: light rain (daily rainfall < 10 mm), moderate rain (daily rainfall between 10 mm & 25 mm), heavy rain (daily rainfall between 25 mm & 50 mm), rainstorms (daily rainfall between 50 mm & 100 mm), heavy rainstorms (daily rainfall between 100 mm & 200 mm), and extremely heavy rainstorms (daily rainfall ≥ 200 mm).Considering that the frequency of extreme heavy rain is relatively small, this study combines the heavy rainstorm and the extremely heavy rainstorm into one category namely the heavy rainstorm. Two indicators namely rainfall frequency and level of rainfall in the flood season were chosen, and the corresponding data from 197 rain gauge stations were obtained to analyze the change characteristics of rainfall during the flood season in the Beijing-Tianjin-Hebei region, and a box diagram showing the occurrence frequency of different levels of rainfall in each region was drawn (Figure 5). It can be seen in Figure 5 that mountainous areas are more prone to precipitation events than plains. Mountainous areas are more prone to light rain events, and the frequency of heavy rain events increases from the base of the mountain to the plains. By analyzing the height and abnormal points of the box charts, we found that the variation in intervals of light rain and moderate rain in the two regions are relatively stable, with fewer abnormal values, while heavy rain and heavy rainstorm have more abnormal values, indicating regional variations in the occurrence of different levels of rainfall. The analysis also indicates that rainfall events above heavy rain are more volatile, and are more likely to fluctuate when affected by other factors.

2.4 Impact of urbanization on rainfall during the flood season

Climatic factors are the main factors leading to changes in rainfall. The moving-average results in Figure 4(b) show that rainfall in the mountainous areas and plains of the Beijing-Tianjin-Hebei region has obvious chronological changes, and the transition trends in the mountains and plains are consistent. The reason is that mountains and plains fall within the same large-scale climate circulation system so that the impact of meteorological factors on mountains and plains is basically the same. Based on the urbanization stages described in section 2.1, the impact of urbanization on the rainfall characteristics of the flood season was analyzed through the horizontal comparison of rainfall in mountainous areas and plains and the longitudinal comparison of rainfall during the flood season in different urbanization stages, and the double accumulation curve of rainfall in the mountainous areas and plains during the flood season was drawn. As shown in Figure 6, with the development of urbanization, the slopes of the two curves deviate from the 1:1 line to varying degrees. The slope of the double cumulative curve in the plains is greater than that of the 1:1 line, indicating that the rainfall increase trend for the flood season in the plains is greater than that in the mountainous area (significantly, through $\alpha=0.05$ significance level). Based on the time distribution characteristics of rainfall in mountainous areas and plains, the time and space distribution map of annual average rainfall from 1960 to 2019 was plotted, as shown in Figure 7. In 1960, the distribution of rainfall centers in Beijing-Tianjin-Hebei was not obvious; in 1970, the center of low rainfall (rainfall < 300 mm) gradually transitioned from the mountains to plains; in 1980, there were 3–4 rainfall centers in the plains with rainfall greater than 600 mm; in 1990, the rainfall centers in the plains continued to expand; in 2010, the rainfall centers were concentrated in the coastal zone of the eastern plain, with significant rainfall reduction in the transition zone between the mountain and the plain; in 2019, the distribution of rainfall greater than 50 mm corresponds with the distribution of cities or urban areas in Beijing-Tianjin-Hebei, and the urban "rain island effect" is clearly visible .

2.5 Correlation analysis of urbanization and rainfall

Combining the rainfall changes in the various stages of urbanization described in section 2.1, and comparing the urban rate and rainfall data for the Beijing-Tianjin-Hebei region, as shown in Figure 8, it can be observed that for the period 1970–1980, rainfall decreased as the city developed. During the period 1980–1995, there was an overall slow increase in rainfall with urban development; from 1995 to 2019, as the urban rate continued to increase, rainfall shows a decreasing trend, but the overall decrease rate is slower than the rate before 1980. Combining this with the impact of urbanization on rainfall during the flood season described in section 2.4, it can be seen that there is little change to the built environment in the pre-urbanization stage, with little change in the built environment. In the later stages of accelerated urbanization, rainfall has decreased over most areas of the region, but the effect of increasing rainfall in the cities has slowed down the decrease in rainfall for the region as a whole.

3 Conclusion

Based on the rainfall data from 197 rain gauge stations in the Beijing-Tianjin-Hebei region during the flood season for 1960 to 2019, this paper uses linear regression, moving average and other mathematical statistical methods combined with SURFER, to study the characteristics of the rainfall during the flood season, in the mountains and plains of the region from the perspectives of time and space. The comparative method studies the impact of urbanization on the rainfall characteristics of the Beijing-Tianjin-Hebei region during the flood season, and draws the following main conclusions:

(1) The rainfall in the Beijing-Tianjin-Hebei region shows a downward trend in the flood season, as a whole. The rainfall has the fastest decline in mountainous areas, and the slowest in urban areas; spatially, the overall rainfall distribution in the Beijing-Tianjin-Hebei region in each period shows a decreasing trend from east to west. Considering different levels of rainfall in the flood season, light rain and moderate rain events are most likely to occur in mountainous areas, while rainfall events of moderate or higher intensity are more likely to occur in the plains. Heavy rain and heavy storm events are also more likely to occur in the plains.

(2) Compared with the southeast plain, the rainfall in the mountainous area during the flood season is greater during different stages of urbanization, but the effect of urbanization on increasing rainfall is also reflected in the difference in rainfall between the plains and the mountainous area.

(3) With increasing urbanization, the area of the built environment in the plains and mountainous towns of the Beijing-Tianjin-Hebei region has continued to increase, and the original underlying surface conditions have changed; as the urbanization process in the plains is faster than in mountainous areas, these changes are greater in the plains. The rainfall in the urban areas during the flood season is greater than that in the suburbs owing to this reason; the urban areas are also more prone to rainfall events at levels above heavy rain.

In summary, with the development of cities, the rainfall in the plains of the Beijing-Tianjin-Hebei region has become greater than that in the mountains, with the plains more prone to heavy rain or rainstorm events. The reasons may be as follows: during urbanization, large areas that include natural vegetation and lakes are replaced by impervious surfaces and buildings. The thermal reflectivity of roads and buildings is low; solar radiation absorbed by the ground surface causes the surface temperature to rise rapidly, and second, the underlying surface of the plains serves as low-level air. The ground with its stored heat, is the main heat source of the city; the stored heat is transported outwards through turbulent exchange as longwave radiation, and absorbed by the atmosphere in contact with the surface. Due to urban development, the concentration of CO_2 and pollutant particles in the atmosphere has increased, resulting in a significant increase in the absorption rate, resulting in an urban. The rate of temperature increase of urban areas is significantly higher than that of the suburbs, forming an urban "heat island." Studies have shown that during the different stages of urban development, the temperature in the plains and mountainous areas of the Beijing-Tianjin-Hebei region showed an overall upward trend, with the temperature increase in the cities significantly higher than that in the suburbs; the area and intensity of the "heat island effect" are gradually increasing. The thermal expansion of air due to the urban "heat island effect" causes an increase in the upward air movement, forming a regional low-pressure center near the ground in the urban area; this causes the cooler air from the suburbs to gradually converge to the urban area, forming an urban "heat island circulation." The occurrence of "heat island circulation" produces instability in the urban air stratification, and the resulting updraft can induce wet convection under good thermal conditions, thereby forming precipitation. In addition, studies have shown that the effect of urban heat island circulation is conducive to the generation of local weak precipitation processes, increasing urban precipitation intensity and extending precipitation duration; this increases the probability of short-duration heavy precipitation in urban areas and triggers the urban "rain island effect." Therefore, the plains should pay attention to early warnings of heavy rainfall events during the flood season, improve flood design standards, ensure unhindered operation of flood drainage facilities, and introduce measures to reduce the social and economic losses caused by urban floods.

The Beijing-Tianjin-Hebei region has a relatively small number of rainstorms and heavy rain events during the flood season, especially heavy rain of which there are no rainfall events in most years. In future studies, numerical climate models can be used to select typical rainfall events to analyze the impact of heavy rain and rainstorms on urbanization more accurately, to provide valuable suggestions for urban flood prevention and disaster mitigation.

Availability of data

In this paper, we mainly used the rain gauge stations data, population data, and GDP data to support the findings of this study were supplied by the National Meteorological Information Center (http://data.cma.cn/) under license and so cannot be made freely available.

Author contributions

Xu Chengcheng and Lu Chuiyu designed research; Lu Chuiyu performed research; Xu Chengcheng analyzed data; Wang Jianhhua contributed to interpretation of results; Lu Chuiyu contributed to algorithm development; and Xu Chengcheng wrote the paper.

Competing interests

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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