Waterlogging risk assessment of the Beijing-Tianjin-Hebei urban agglomeration in the past 60 years

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Abstract
The risk of urban waterlogging is increasing with global climate change and rapid urbanization, especially for urban agglomeration like Beijing-Tianjin-Hebei (BTH) region. In this study, we obtain the urban waterlogging risk index of the BTH urban agglomeration and considering the hazard, exposure, and vulnerability factors, we assess waterlogging risks in the built-up area of the BTH for two periods (1961–1990 and 1991–2019). We analyze the economic and social data as well as the climate data from 149 meteorological observation stations in Beijing, Tianjin, and Hebei provinces. The results showed that for the two considered periods, the area with the lowest (level 1) waterlogging risk has decreased by nearly 50%, and the second-lowest (level 2) ones have increased by nearly 55%. Although the area higher risk has decreased by 17%, the difference among each city is quite large. Among them, the areas at level 3 have increased by 52% and 51% in Beijing and Handan, respectively. During the years 1991–2019, the areas with risks of level 3 and above have increased by 76% in the past 30 years. The areas with the highest risk level (level 4) of waterlogging in Beijing were mostly found in the downtown areas (Haidian, Chaoyang, Dongcheng, and Xicheng districts). This study provides a scientific background for urban waterlogging risk management and implementation of the national and regional strategy for the development of the BTH region.

1 Introduction

China is undergoing rapid urbanization. By the end of 2016, there were 88 large cities with over 1 million inhabitants in the country. The cities have dense population, concentrated assets, and are highly exposed and vulnerable to the risk of climate change (Zhai et al. 2018). In the context of climate change and urbanization, the changes and impacts of extreme precipitation in cities have attracted more and more attention (Li et al. 2015; Zhou et al. 2017; Bai et al. 2018; Gu et al. 2019). Due to the hardening of the underlying urban surface and poor drainage facilities, heavy rainfalls will increase the risk of urban waterlogging (Kaźmierczak and Cavan 2011; Wang et al. 2014; Yu et al. 2018a).

The Beijing-Tianjin-Hebei (BTH) region is one of the three fastest-growing megacity clusters in China, with an area of 216,000 km² and a population of 110 million, including 13 cities (Beijing, Tianjin, Shijiazhuang, Baoding, Tangshan, Langfang, Handan, Qinhuangdao, Zhangjiakou, Chengde, Cangzhou, Xingtai, and Hengshui). The precipitation in the BTH cluster is fluctuating each year and features with heavy rainstorm intensity (Zheng et al. 2019). Recent decades have witnessed the increase of the average temperature, the decrease of the annual precipitation, and the number of precipitation days (Zhai et al. 2005; Li and Ma 2011; Wang et al. 2020). More specifically, the frequency and intensity of extreme summer precipitation have increased (Zhang 2010; Liang et al. 2018). In particular, the hour-scale extreme heavy rainfall occurs more often, leading to prominent urban waterlogging problems (Yin et al. 2011; Yang et al. 2014; Song et al. 2014; Liang and Ding 2017).
For example, on July 21, 2012, the 18-h maximum rainfall in Beijing reached 460 mm, which caused serious urban flooding. The disaster covered 16,000 km², affected 1.9 million populations, left 79 people dead, and paralyzed the traffic (National Climate Center and (NCC) 2013). For the continuous global warming, the intensity of extreme precipitation events in the BTH urban agglomeration will further increase (Yu et al. 2018b; Shi et al. 2019) and will cause serious risks of urban waterlogging.

Recently, urban waterlogging risks have been extensively studied (Saeed et al. 2010; Li et al. 2015; Hu 2016; Wang et al. 2017, 2018). Various problems have been considered ranging from urban rainwater runoff modeling to the development of urban waterlogging simulation system (Li et al. 2002) and the two-dimensional hydraulic evaluation model (Xie et al. 2018). However, most of the researchers focused on assessing the waterlogging risks in a single city. The same problem for multiple cities at the regional scale was commonly addressed using the data from the weather station located in a given urban area. This approach could not reflect the spatial difference in the urban waterlogging risk at the regional scale (Zheng et al. 2018; Sun et al. 2020). Therefore, there is currently a gap for a regional-scale urban waterlogging risk assessment system featuring high spatial resolution and even fewer studies on waterlogging risks and changes in the BTH urban agglomeration.

This paper addresses the problem mentioned above for the urban built-up BTH area. More specifically, we consider hourly precipitation, daily precipitation, and 5-day continuous precipitation as the hazard factors of a rainstorm and waterlogging, population density and GDP per unit area as exposure indicators, and adaptability to heavy rainfall and waterlogging such as drainage network density, vegetation coverage, and river network density as vulnerability indicators. The waterlogging risks in the built-up area of the BTH urban agglomeration during the two periods of 1961–1990 and 1991–2019 were assessed, aiming to reveal the changes of waterlogging risk in the past 60 years. Thus, we aimed to provide scientific background for the implementation of the national and regional strategy for the coordinated development of the BTH region.

2 Data and methods

2.1 Data

The meteorological data used in this paper came from 149 meteorological observation stations in the BTH region provided by the National Meteorological Information Center of the China Meteorological Administration. The hourly and daily precipitation data from 1961 to 2019 (Fig. 1) have undergone quality control and uniformity inspection (Ren et al. 2012).

The population and GDP grid data at 1 km resolution of the BTH region in 2015 came from the Data Center for Resources and Environmental Sciences of Chinese Academy of Sciences (http://www.resdc.cn/Default.aspx). We developed the population and GDP grid data at 1 km resolution of the BTH region in 1990 (Fu et al. 2014) based on the population and GDP statistics of the BTH region from China City Statistical Yearbook 1991, and referring to the data processing method of the Data Center for Resources and Environmental Sciences of Chinese Academy of Sciences.

The spatial distribution of land use and river network density data of 2015 in 13 cities of the BTH came from Tsinghua University with a spatial resolution of 30 m (http://data.ess.tsinghua.edu.cn), and drainage data including pipeline length and vegetation coverage area was obtained from the China City Statistical Yearbook 2016.

2.2 Methods

2.2.1 Normalization method

To normalize all the factors considered in this study, we used the following expression (Sun et al. 2020):

$$I = 5 + \frac{(X_i - X_n)}{\sigma}$$  \hspace{1cm} (1)

where $I$ is the normalized value, $X_i$ is the value of the $i$th factor, $X_n$ is the mean value of this factor, and $\sigma$ stands for its standard deviation.

2.2.2 Waterlogging risk index

Waterlogging refers to the phenomenon of a stagnant water disaster in an urban area due to heavy rainfall or continuous precipitation (Chen et al. 2012); in recent years, urban rainstorm waterlogging has occurred frequently around the world, especially in developing countries such as China (Yu et al. 2018a, b). We followed IPCC AR5 (IPCC 2014) and used a three-determinant risk model. We consider hazard, exposure, and vulnerability as model parameters and accounted for the recently suggested method of Sun et al. (2020). The resulting equation for waterlogging risk assessment is:

$$R = H \times E \times (10 - A)$$  \hspace{1cm} (2)

here, $H$ is the hazard index, $E$ is the exposure index, and $A$ is the adaptability index.

The waterlogging risk was divided into four grades according to the standard deviation ($\sigma$) ranging from 1 to 4, with values from low to very high, respectively. The standards were set as follows:
low risk (level 1): \( R \leq R_a - 0.5\sigma \);
moderate risk (level 2): \( R_a - 0.5\sigma < R \leq R_a + 0.5\sigma \);
high risk (level 3): \( R_a + 0.5\sigma < R \leq R_a + \sigma \);
very high risk (level 4): \( R > R_a + \sigma \).

Here, \( R \) is the waterlogging risk level, and \( R_a \) is the average value of \( R \).

### 2.2.3 Hazard index

We adopted a maximum of 1 h, 1 day, and 5 continuous days precipitation as the waterlogging hazard factors. Since most of the precipitation data from the meteorological stations in the BTH region covered the last 60 years and considering the uncertainty of the return period calculation, we used
the common practice adopted for the extreme climate studies. More specifically, we calculated the hazard index for every 20 years (Kharin et al. 2013; Sillmann et al. 2013). The hazard assessment was divided into two periods from 1961 to 1990 and from 1991 to 2019, to analyze the variation characteristics under climate change. The maximum precipitation in 1 h, 1 day, and 5 days for these two periods once in every 20 years were calculated using the generalized extreme value distribution (GEV) method (Chen et al. 2010). Then, the normalized hazard index was given by:

\[ D = 0.2 \times H_{1h} + 0.6 \times H_{1d} + 0.2 \times H_{5d}, \]

where \( D \) is the hazard index, \( H_{1h} \), \( H_{1d} \), and \( H_{5d} \) stand for the maximum precipitation in 1 h, 1 day, and 5 days once in every 20 years. The weights of different hazard factors were scored by subject matter experts. The hazard index referred to the risk level of waterlogging and was divided into four levels: low, medium, high, and very high, ranging from 1 to 4.

2.2.4 Exposure index

The spatial data from the BTH region for the year 2015 was processed, and the resolution was scaled up to 1 km using the Arcmap resampling method (Wang et al. 2016). The grid data population and GDP were obtained, combining with the population and economic data for the years 1990 and 2015. The normalized exposure indices in 1990 and 2015 were determined from (Sun et al. 2020):

\[ E = 0.5 \times P + 0.5 \times G \]

where \( P \) and \( G \) are the grid population and grid economic factors, respectively.

The exposure index was divided into four levels: low, medium, high, and very high according to the risk level of waterlogging, ranging from 1 to 4.

2.2.5 Adaptability index

The vulnerability was characterized by the index of the city’s adaptability to rainstorm and waterlogging. The adaptability to rainstorm and waterlogging comprehensively considered the density of urban drainage pipe network, vegetation coverage, and river network density.

The drainage network density and vegetation coverage rate of the built-up area were spatialized based on the urban drainage pipeline length and vegetation coverage in the Statistical Yearbook 2015, combined with the grid distribution data. Based on the land usage data at 30-m resolution in 2015, the river network density information was resampled to a 1 km grid.

Expert scoring (Burton et al. 2002) showed that all these three factors played a positive role in urban waterlogging and had the same contribution rate. The density of drainage pipe network, vegetation coverage, and river network density were all normalized and divided into four levels of the low, medium, high, and very high, ranging from 1 to 4. The equal weight sum method was adopted to obtain the urban waterlogging adaptability index given by:

\[ A = (D + V + R)/3, \]

where \( D \), \( V \), and \( R \) stand for the density of drainage pipe network, the vegetation coverage rate, and the density of the river network.

The adaptability index was divided into four levels, low, medium, high, and very high, ranging from 1 to 4.

3 Results

3.1 Hazard

3.1.1 One-hour precipitation distribution

In the past 60 years, the distribution of 1-h precipitation, \( H_{1h} \), in the BTH decreased from southeast to northwest. For most areas in the south of the Taihang Mountains, it exceeded 60 mm, while the northern areas generally had less than 50 mm. The comparison of time periods 1961–1990 and 1991–2019 revealed that the percentage of \( H_{1h} \) over 60 mm increased significantly in Beijing, northern Tianjin, northern Shijiazhuang, and southern Qinhuangdao, while decreasing in Baoding (Fig. 2). More specifically, the maximum \( H_{1h} \) in Beijing has increased from 72.8 to 96.8 mm (33.0%) and the average \( H_{1h} \) increased from 54.5 to 61.9 mm (13.6%). At the same time, the maximum \( H_{1h} \) in Baoding decreased from 93.1 to 76.0 mm. This change in short-time heavy precipitation was likely caused by the urban heat islands that enhanced the vertical mixing of urban water vapor. In particular, the strong convective system was split in the upwind direction of the city and merged in the downwind one. The latter increased heavy precipitation in the urban and downwind directions (Zhang et al. 2009, 2014; Yang et al. 2017).

3.1.2 One-day precipitation distribution

Unlike 1-h distribution, the daily one, \( H_{1d} \), exceeding 150 mm remarkably decreased from 1961–1990 to 1991–2019 time period. Moreover, regional distribution has also changed. Previously (1961–1990), heavy rains mainly distributed in Tianjin, Tangshan, Qinhuangdao, Cangzhou, Hengshui, eastern Langfang, central Baoding, southwestern Chengde, eastern Handan, and most parts of...
Xingtai. However, in the years 1991–2019, the distribution has changed for southern Beijing, most part of Tianjin, Langfang, Cangzhou, Qinhuangdao, western Shijiazhuang, northeastern Baoding, western Xingtai, and western Handan (Fig. 3). In the past 30 years, the maximum $H_{1d}$ in the BTH decreased from 270.6 to 229.0 mm (18.2%), but the one in Beijing increased from 198.8 to 229.9 mm (15.6%). Moreover, the maximum $H_{1d}$ of Tangshan has decreased from 270.6 to 179.6 mm (50.7%) along with that of Shijiazhuang, Baoding, and Zhangjiakou. At the same time, 1-day maximums for Qinhuangdao, Tianjin, Chengde, Cangzhou, and Hengshui have dropped dramatically.

3.1.3 Five-day precipitation distribution

Similar to 1-day distribution, the area with precipitation above 250 mm for 5-day one, $H_{5d}$, in the BTH region has decreased significantly from 1961–1990 to 1991–2019.
Moreover, the maximum $H_{5d}$ of the area has also decreased from 540.1 to 354.7 mm (52.3%). In particular, except for Shijiazhuang, where maximum $H_{5d}$ has increased from 315.2 to 354.7 mm (15%), it has decreased for all other cities, with the largest decrease occurred in Tianjin (from 521.6 to 251.0 mm or by 107.8%). The decrease of continuous precipitation in the BTH may be related to the weakening of the East Asian summer monsoon, which reduced the water vapor flux into Northern China from the southern border, and the southward shift of the subtropical high (Hao et al. 2011).

### 3.1.4 Hazard index

The risk index can be calculated from formula (3) after normalizing $H_{1h}$, $H_{1d}$, and $H_{5d}$. The corresponding results are shown in Fig. 5 and demonstrate that the risks for Zhangjiaokou and northern Chengde were at risk level 1 during both

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**Fig. 4** Maximum 5-day precipitation in 20-year return period of the BTH for a 1961–1990 and b 1991–2019 time periods.

**Fig. 5** Hazard intensity for a 1961–1990 and b 1991–2019 time periods. It was measured once in every 20 years. Numbers in legend correspond to hazard intensity levels.
time periods. The areas with level 3 risk and above during the 1961–1990 time period included Qinhuangdao, Tangshan, Tianjin, Cangzhou, Hengshui, western Xingtai, eastern Handan, and central Baoding. The areas with level 4 risks were located in Qinhuangdao, Tangshan, and other places. The situation has changed for the time period of 1991–2019. In particular, the areas with level 3 risk and above were mainly in Beijing, Tianjin, western Shijiazhuang, Qinhuangdao, Langfang, Cangzhou, the eastern Tangshan, western Handan, and western Xingtai. Among them, the areas with level 4 risk included southern Beijing, western Tianjin, western Shijiazhuang, southern Cangzhou, and western Xingtai. This is consistent with the spatial distribution characteristics of maximum 1-h precipitation, maximum 1-day precipitation, and maximum 5-day precipitation during two periods. Compared to the time period from 1961 to 1990, the risk indices of Beijing, Shijiazhuang, and Langfang have increased significantly in the past 30 years (by 41%, 42%, and 35%, respectively). At the same time, the risk indices of Tangshan and Hengshui have decreased significantly (by 29% and 21%, respectively, Table 1).

3.2 Exposure index

To reveal the dynamics of changes in exposure index for urban built-up areas of BTH, we selected the years 1990 and 2015 as the representatives of the two periods (1961–1990 and 1991–2019) and analyzed it. As shown in Fig. 6, in 1990 and 2015, the areas of Beijing, Tianjin, and Qinhuangdao had level 4 exposure and demonstrated more than 11.2% increase. Among them, the areas of Beijing and Tianjin at level 3 exposure risk and above increased from 25.2% and 22.5% in 1990 to 47.3% and 38.2% in 2015, respectively. At the same time, the exposure for Tangshan, Zhangjiakou, and Chengde decreased from 17.8%, 12.7%, and 18.7% in 1990 to 3.5%, 2.7%, and 0.4% in 2015, respectively. The exposure of other cities was relatively low. It can be seen that the development of the BTH urban agglomeration came in line with the concentration of population, capital, and materials in the megacities of Beijing and Tianjin. Among the changes in the average exposure index of each city, Beijing had the largest increase of 32%.

3.3 Vulnerability index

The waterlogging vulnerability index in the built-up areas of the BTH comprehensively considered drainage pipe network density, vegetation coverage, and river network density. Since these factors have not changed significantly in recent decades, we used the 2015 value or the urban waterlogging vulnerability assessment.

According to the density of the drainage pipe network in the built-up areas of the BTH, the drainage capacity was analyzed. The results showed that the drainage capacities of Beijing, Baoding, Zhangjiakou, Qinhuangdao, and other places were at level 1 risk, the drainage capacity of Tianjin was at level 4 risk, and the drainage capacities of other cities were between level 2 and level 3 (Fig. 7a). The urban vegetation coverage rate for all 13 cities in BTH had level 1 risk, and that of the surrounding area was between level 1 and level 3 (Fig. 7b). The density of river network in BTH urban built-up area at 1 km grid demonstrated that the majority of the cities were at level 1, while some areas of Tianjin and Cangzhou featured level 4 (Fig. 7c).

The urban waterlogging adaptability index in the BTH was calculated using formula (5). As can be seen from Fig. 8, the higher adaptability of the area resulted in lower waterlogging vulnerability. More specifically, Tianjin city had the highest waterlogging adaptability with level 3 and above, covering 99.9% for all areas. Handan city had the second-highest waterlogging adaptability, between third and

| Table 1 Hazard, exposure, adaptation, and risk indices for major in the BTH during 1961–1990 and 1991–2019 time periods |
|-----|-----|-----|-----|-----|-----|-----|
| Indices | 1961–1990 | 1991–2019 | 2015 |
| Hazard | Exposure | Risk | Hazard | Exposure | Risk | Adaptation |
|---|---|---|---|---|---|---|
| Beijing | 1.95 | 2.02 | 2.46 | 2.75 | 2.67 | 2.67 | 1.76 |
| Tianjin | 3.29 | 2.10 | 1.99 | 3.14 | 2.69 | 1.90 | 4.00 |
| Shijiazhuang | 2.12 | 2.16 | 2.02 | 3.01 | 2.21 | 2.15 | 2.27 |
| Tangshan | 3.78 | 1.94 | 2.54 | 2.70 | 2.03 | 1.87 | 2.45 |
| Qinhuangdao | 3.99 | 2.06 | 2.75 | 3.43 | 2.10 | 2.44 | 1.56 |
| Handan | 2.64 | 2.01 | 1.76 | 2.88 | 2.10 | 1.93 | 3.14 |
| Xintai | 2.65 | 1.85 | 1.84 | 2.85 | 2.02 | 1.90 | 2.42 |
| Baoding | 2.20 | 1.96 | 1.88 | 2.25 | 2.01 | 1.84 | 2.00 |
| Zhangjiakou | 1.01 | 1.61 | 1.04 | 1.04 | 1.40 | 1.00 | 1.90 |
| Chengde | 1.50 | 1.83 | 1.08 | 1.43 | 1.33 | 1.19 | 1.87 |
| Cangzhou | 2.94 | 1.61 | 1.79 | 3.21 | 1.90 | 1.82 | 2.69 |
| Langfang | 2.44 | 1.64 | 1.49 | 3.29 | 2.04 | 2.01 | 2.74 |
| Hengshui | 3.02 | 1.65 | 1.86 | 2.39 | 1.99 | 1.49 | 2.40 |
fourth grade covering 63.4% of all areas (Fig. 8). Most of the other cities had lower adaptability to waterlogging, mostly between levels 1 and 2 grade. In average, for the adaptability index by city, Tianjin had the highest score, followed by Handan, while Qinhuangdao had the lowest, followed by Beijing (Table 1).

3.4 Waterlogging risk

The BTH urban waterlogging risk index was calculated from formula (2) including hazard, exposure, and urban vulnerability indexes during the two time periods (from 1961 to 1990 and from 1991 to 2019). The waterlogging risk assessment grade is shown in Fig. 9.

The average waterlogging risk index for each city demonstrated that Qinhuangdao had the highest waterlogging risk for the years 1961–1990 (2.75), followed by Tangshan (2.54) and Beijing (2.46). Moreover, Beijing had the highest waterlogging risk for the 1991–2019 time period (2.67), followed by Qinhuangdao (2.44) and Shijiazhuang (2.15).

At the same time, Zhangjiakou, Chengde, and Hengshui had the lowest risks for both time periods (Table 1). Compared
to the previous 30 years, the areas at level 1 waterlogging risk in BTH cities have decreased except for Zhangjiakou, Tangshan, Chengde, and Hengshui, and the total area at level 1 risk of BTH has decreased by 50% (Table 2). Except for Zhangjiakou, Chengde, and Hengshui, the area at level 2 risk in other cities had increased, and the total area at level 2 has increased by nearly 55%. Although the areas at level 3 risk and above have been reduced by 17%, the waterlogging risk varied greatly among cities, while Beijing had the largest increase in the area at level 3 and above, accounting for 76%. The areas at level 4 risk increased most significantly in Beijing and Handan (by 52% and 51%, respectively). From 1991 to 2019, the areas at level 3 risk and above in the BTH were mainly found in Beijing, Shijiazhuang, Tianjin, Qinhuangdao, Handan, and Xingtai, while from 1961 to 1990, they were mainly concentrated in Beijing, Tangshan, Tianjin, Shijiazhuang, Baoding, and Cangzhou.

The changes in waterlogging risks for BTH cities were analyzed in the context of global climate change and urbanization. It revealed that the risk of waterlogging for Beijing had increased the most. More specifically, comparing the time periods from 1961 to 1990 and from 1991 to 2019, the areas at level 1 waterlogging risk in Beijing decreased from 29.8 to 1.1%, and that at level 2, level 3, and level 4 risks increased...
from 46.0, 4.7, and 19.4 to 56.3, 13.0, and 29.4, respectively. In the past 30 years, areas in Beijing at level 4 waterlogging risk were mostly found in Haidian, Chaoyang, Dongcheng, and Xicheng districts. The latter was mainly due to the high hazard and exposure (Fig. 10). Compared to the time period from 1961 to 1990, the waterlogging risks in Shunyi, Tongzhou, Daxing, and Fangshan districts have increased. These districts were the fastest developing districts in Beijing over the past 10 years, with the exposure index changed from level 2 to level 3 or 4, and the hazard also increased from levels 1 and 2 to levels 3 and 4.

4 Conclusion and discussion

We have investigated the combined influence of global climate change and urbanization on 13 cities in Beijing, Tianjin, and Hebei provinces for the past 60 years. We have found that Beijing, Tianjin, Shijiazhuang, Qinhuangdao, Handan, and Xingtai have become cities with the levels 3 and 4 waterlogging risks. Among them, Beijing has the highest risk of waterlogging. The areas at level 3 and above have accounted for 62% of the total area of the BTH region and demonstrated an increase of 76%. The areas at level 4 risk have been mainly
concentrated in major urban areas such as Haidian, Chaoyang, Dongcheng, and Xicheng districts. Compared to the 1961 to 1990 time period, the areas at level 1 risk have decreased by nearly 50%. In particular, the areas at level 2 risk have increased by nearly 55% and that ones at level 3 and above have decreased. However, the variations in each city were quite different. Among them, the areas at level 4 risk have increased by 52% and 51% in Beijing and Handan, while that in Tangshan and Baoding have decreased significantly.

In recent decades, the rapid urbanization process of the BTH region has changed its original natural landscape and ecosystem. With the fast-growing of economic and social exposure and the short-time rainfall intensity, the problem of urban waterlogging for the BTH urban agglomeration has become particularly important. In particular, the planning, design, safety operation, and maintenance of megacities have become very challenging. For example, the built-up area in Beijing has increased from 239 in the early 1980s to 1400 km² now (Tan et al. 2018), leading to the decrease of the density of natural river networks. At the same time, the newly built pipeline network has a low level of fortification that speeds up the surface convergence. Additionally, Beijing’s economic and social exposure has also increased notably. In 2015, Beijing’s total population reached 21.7 million, and its GDP reached 2.3 trillion yuan, twice and 45 times that of 1990, respectively. In addition, global climate change caused a remarkable increase in the 1-h and 1-day rain intensity, leading to an increase of the waterlogging risk in Beijing. Therefore, it is necessary to implement the BTH-coordinated development strategy and relieve Beijing’s non-capital functions. In the future development plan of the BTH region, the changes in short-time precipitation intensity caused by climate change should be considered. Moreover, the infrastructure construction standards of urban drainage should be improved, and the drainage pipeline networks should be carefully arranged. Moreover, the scientific approach to the utilization of vegetation coverage and improvement of the city’s adaptability to extreme rainstorms are required. Finally, the enhancement of urban resilience and reduction of the waterlogging risks caused by rainstorms should also be done.

In this paper, a quantitative assessment of the urban waterlogging risk in the BTH region was conducted at the kilometer-grid scale, considering hazard, exposure, and vulnerability factors. However, the formation mechanism of urban waterlogging is complex, especially in the context of global climate change. The impact of urbanization on the hazard of waterlogging needs to be further studied. Finally, this study has several limitations. In particular, the density of urban drainage network can only be assigned to grid points belonging to the same administrative area through statistical yearbook data and the actual drainage capacity of each network point, and the impact on terrain has not been considered.

Author contribution Yujie Wang contributed to this paper by performing analyses and drafting the paper. Jianqing Zhai performed analyses by calculating the hazard factors, exposure indicators, adaptability, and risk level to heavy rainfall and waterlogging in the BTH urban agglomeration. Lianchun Song conceived the study and modified the complete research and manuscript.

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Availability of data and material All data that support the finding of this study are available as follows. The population and GDP grid data in 2015 are available at http://www.resdc.cn/Default.aspx; the spatial distribution of land use and river network density data are available at http://data.ess.tsinghua.edu.cn, and the meteorological data and other data used in this paper are available from the author (Jianqing Zhai; zhaijq@cma.gov.cn) upon reasonable request.
Conflict of interest The authors declare no competing interests.

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