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Study of risk and early warning index of rainstorm waterlogging in Wuhan City

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Abstract. In the present study, rainfall thresholds creating waterlogging and a waterlogging risk map were established by analyzing waterlogging monitoring and rainfall observation data in Wuhan City from 2011 to 2016. The study found that 1) Wuhan City rainstorm waterlogging occurred during the summer months, mostly in June and July, accounting for 90% of the total waterlogging; 2) Waterlogging generally occurred along the rivers and lakes near low-lying areas; 3) The longest continuous waterlogging time was greater than 10 h and the deepest water depth was 2 m; 4) The greater the cumulative rainfall over 24 h, 12 h, 6 h, or 3 h, the more severe the waterlogging was; 5) The thresholds of continuous 24 h rainfall of mild, moderate, and severe waterlogging in Wuhan City were 123, 163, and 196 mm, respectively, while 12 h cumulative rainfall thresholds were 86, 145, and 187 mm, respectively. The 6 h cumulative rainfall thresholds were 68, 113, and 135 mm, respectively, and 3 h cumulative rainfall thresholds were 40, 74, and 94 mm, respectively. If the city's drainage capacity increases, the cumulative rainfall of waterlogging warning indicators will also need to be adjusted.

1. Introduction

Rainstorms are the major meteorological disaster in China because heavy rainfall can lead to flooding, urban waterlogging, landslides, and other derivative disasters [1]. Wuhan City is located in the middle reaches of the Yangtze River, Yangtze River, and Han Jiang River, as well as near dozens of large and small lakes. In Wuhan City the average annual rainfall is approximately 1200 mm, which is mainly concentrated during the summer months [2]. Owing to the concentration of rainfall and low-lying aspect of the city, there is frequent flooding in Wuhan City, which has a great impact on the population's production and everyday life. City waterlogging is in China, India and other emerging developing countries in the process of urbanization problems [3].

At present, there are three main methods for assessing the risk of urban waterlogging disasters. The first method is studying the history of disaster statistics [3]. Using mathematical statistics, analysis of historical disaster data can be undertaken to determine the patterns of disaster development, establish the statistical model of disaster occurrence probability and its influencing factors, and then estimate the possible losses caused by future disasters [4-6]. This method is simple to calculate and does not require detailed geographical background data. However, at present, because of limited historical observation data, it has limitations in its application. The second method is the index system method. Based on the characteristics of the disaster system, a certain index system is selected, the indicators are established, and the process of regional disaster risk can be obtained. The accuracy of this method for calculating results is low and, therefore, has fewer applications [7-12]. The third method is the hydrological hydraulics model and simulation method. By setting the different frequency rainstorm scenarios, using the numerical simulation of the basin production and flooding model and the flood evolution model, the flooding range, flooding depth, and flooding of urban floods caused by heavy rain in different scenarios can be predicted. This method requires a large amount of data, the calculation is more complex, and therefore the practical application is less. The establishment of an urban waterlogging disaster index system, as well as a risk assessment and early warning system is required from an urban waterlogging disaster research point of view [13-15].

In the present study, the waterlogging monitoring data and rainfall observation data for Wuhan City between 2011 and 2016 are utilized to study the temporal and spatial distribution characteristics of waterlogging in Wuhan City, and the relationship between waterlogging and rainfall is analyzed. Based on this rainfall threshold and waterlogging risk map, this city waterlogging warning can be utilized to provide a reference. On this basis, it is possible for the city to have a reference for a future waterlogging warning system.

2. Data and methodology

2.1. Data

The data used in the present study are from waterlogging monitoring points and rainfall observations in Wuhan City from 2011 to 2016. The spatial layout of the waterlogging monitoring points and the multi-element automatic meteorological observation stations are shown in figure 1.

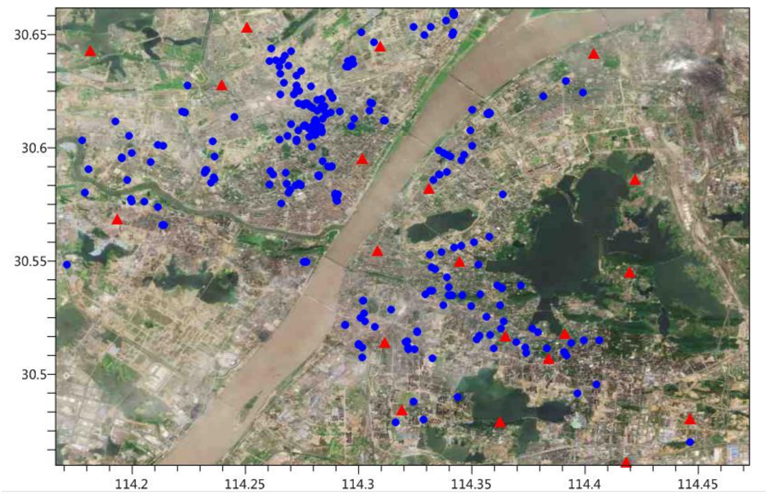

Figure 1. Spatial distribution of waterlogging monitoring points (blue dots) and meteorological observation stations in Wuhan (red triangles).

Waterlogging monitoring data were obtained from the Wuhan Municipal Water Affairs Bureau and included the location of waterlogging points, waterlogging times and the depths of waterlogging. The waterlogging point is not an isolated point in space, rather it represents a community, or a culvert, or it might even be a crossing. In Wuhan City, there are 258 waterlogging monitoring points. The time of waterlogging is not accurate to the minute; it is only a rough record of the occurrence of waterlogging and the approximate end time. The depth of the water is accurate to 0.1 m and only the maximum depth of a waterlogging process is recorded.

The rainfall observation data was obtained from the Wuhan Meteorological Bureau, which records the hourly rainfall and is accurate to 0.1 mm. In Wuhan City, there are 12 multi-element automatic meteorological observation stations.

2.2. Analysis methods
First, based on the waterlogging monitoring data during the period from 2011 to 2016, the waterlogging distribution map of Wuhan city was established. Second, the cumulative rainfall and precipitation intensity characteristics of typical waterlogging were analyzed, and the corresponding relationship between waterlogging and rainfall established, and the threshold value of rainfall determined. Finally, a comprehensive analysis of waterlogging distribution and rainfall threshold was completed, which resulted in the establishment of a waterlogging risk map for Wuhan City.

3. Results and discussion

3.1. Waterlogging characteristics
Statistics showed that during 2011–2016 Wuhan City had a total of 32 waterlogging processes caused by rainfall, which equated to an average of 5.3 times a year. Because of the East Asian monsoon climate present in Wuhan City, the heavy rainfall occurred mainly during the summer months; therefore, the waterlogging caused by this precipitation occurred in June and July, which accounted for 90% of the total number of waterloggings.

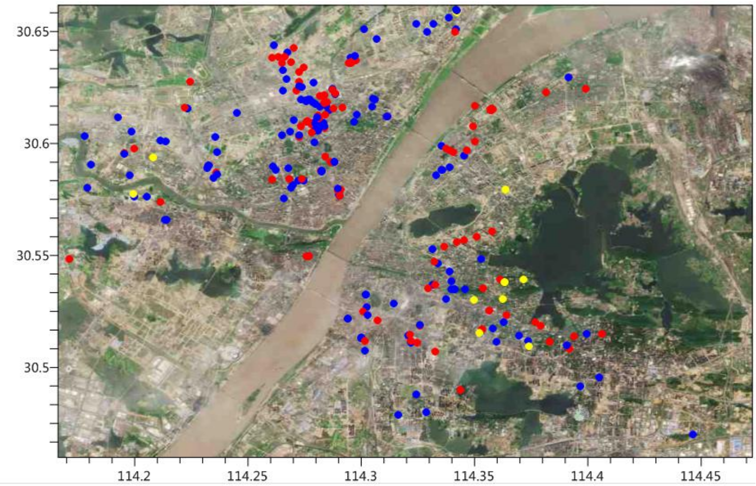

Figure 2. The waterlogging situation synthesis map in Wuhan City (yellow dots: the maximum water depth ≥ 1.0 m, blue dots: the maximum water depth < 0.5 m, and red dots: the maximum water depth ≥ 0.5 m and <1.0 m).

Figure 2 is based on the 32 waterlogging processes obtained from the Wuhan City waterlogging map and shows the location of possible waterlogging in Wuhan City and the maximum possible waterlogging depth. The different colored dots represent the positions of the waterlogged points, which are relatively fixed and are divided into three grades based on the waterlogging depth (i.e., > 1.0 m, 0.5–1.0 m, and <0.5 m). For each waterlogging point, the maximum waterlogging depth was selected from the 32 waterlogging processes and classified to the corresponding level. Figure 2 demonstrates that waterlogging in Wuhan City generally occurs along the rivers and lakes near low-lying areas. In addition, the intersection of two or more streets, culverts, and overpasses are also prone to waterlogging and the lower the terrain, the greater the possible waterlogging depth.

3.2. The relationship between waterlogging and precipitation
The present study revealed that if the actual occurrence of waterlogging monitoring points that accounted for the proportion of total waterlogging monitoring points reached 40% (103 waterlogging points), as a large range of waterlogging processes, then from 2011 to 2016 waterlogging processes occurred a total of seven times over a wide range in Wuhan City (table 1).

Table 1. Waterlogging duration, maximum depth, and number of waterlogged spots in Wuhan City from 2011 to 2016 ("d" represents the depth of water, unit: m).

Case	Date	Waterlogging duration (h)	Maximum depth (m)	Number of waterlogged spots			
				total	d≥1.0	0.5≤d<1.0	d<0.5
1	June 8, 2011	4	1.6	236	17	107	112
2	June 27, 2012	1	0.6	105	0	42	63
3	July 12, 2012	4	1.6	234	17	104	113
4	June 6, 2013	2	0.7	167	0	76	91
5	July 6, 2013	12	2.0	258	23	141	94
6	July 23, 2015	11	2.0	258	21	144	93
7	July 5, 2016	11	2.0	258	22	143	93

It can be seen from table 1 that the longest waterlogging time of the seven waterlogging processes lasted approximately 12 h, the minimum waterlogging time was only 1 h, and the maximum waterlogging depth exceeded 2 m. In addition, case 5 had the widest range of waterlogging and the most serious waterlogging, with all 258 monitoring points experiencing waterlogging, and 64% of the maximum waterlogging points greater than 0.5 m depth. Twenty-three waterlogging points had a maximum water depth of greater than 1.0 m. The waterlogging situation for case 6 was similar to case 5. Case 2 had the least number of waterlogging spots, with less than half the monitoring spots experiencing waterlogging, and the maximum waterlogging depth was less than 1 m. The same was true for the waterlogging situation in case 4. Case 1 and case 3 had similar waterlogging situations, with 92% of monitoring points experiencing waterlogging. The number of monitoring points with water depth of greater than 1.0 m was less than that of case 5, case 6, and case 7.

3.2.1. Rainfall characteristics during waterlogging. It can be seen from figure 1 that there is not a one-to-one relationship between the automatic weather station and waterlogging monitoring point. In the present study, the most recent rainfall observation data from the location of the stained water point represents the amount of rainfall at that waterlogging point. If there are several automatic weather stations closer to a point of waterlogging, then the maximum rainfall observed was taken from these automatic weather stations to represent the amount of rainfall at this waterlogging point. Finally, the rainfall per hour takes the maximum value of the observed rainfall at all weather stations.

Table 2 shows the cumulative rainfall for different hourly periods for the seven cases. The cumulative rainfall for 24 h is the sum of the hourly rainfall from 00:00 (UTC) to 23:00 (UTC). The accumulated rainfall of 12 h is the maximum of the sum of the hour-by-hour rainfall for 12 consecutive hours from 00:00 (UTC) to 23:00 (UTC), and so on. From table 2 it can be seen that the minimum value of the cumulative rainfall of the seven cases is 122.9 mm and the maximum value is 251.9 mm over a 24 h period.

Comparing the cumulative rainfall from 12 h to 24 h, the ratios of the former to the latter are 85%, 70%, 98%, 89%, 94%, 95%, and 86% for the seven cases. The maximum cumulative rainfall of 12 h is the main contributor to the 24 h total rainfall. Similarly, the maximum cumulative rainfall of 6 h is the main contributor to the maximum accumulated rainfall of 12 h, and the maximum accumulated rainfall of 3 h is the main contributor to the 6 h maximum accumulated rainfall. This indicates that the rainfall in these seven cases is extremely uneven in time distribution.

Table 2. Hourly cumulative rainfall data of waterlogging in Wuhan City from 2011 to 2016.

Case	Date	Maximum cumulative rainfall (mm)			
		24 h	12 h	6 h	3 h
1	June 8, 2011	170.7	145.2	112.6	74.0
2	June 27, 2012	122.9	85.9	68.4	39.7
3	July 12, 2012	162.8	159.0	138.8	91.0
4	June 6, 2013	124.3	111.2	76.5	61.2
5	July 6, 2013	251.9	237.8	156.0	126.3
6	July 23, 2015	195.5	186.5	144.6	108.8
7	July 5, 2016	241.5	206.8	134.7	93.6

However, in case 2 and case 4, although the cumulative rainfall after 24 h is very similar, the maximum cumulative rainfall in other periods is relatively dissimilar, especially for the maximum cumulative rainfall at 3 h. This shows that the rainfall time of case 4 is more concentrated.

3.2.2. The relationship between waterlogging and rainfall intensity. In the present study, we selected the smallest, medium, and largest of the continuous 24 h cumulative rainfall from table 2 as typical examples to analyze the relationship between the degree of waterlogging and rainfall intensity. These were case 2, case 1, and case 5, respectively. Figure 3 shows the hourly rainfall distribution for these three typical cases.

It can be seen from figure 3 that the 24 h rainfall of the three typical cases was reflected in the multi-peak form. Case 1 had four peak rainfall values (figure 3(a)), which appeared at 02:00, 09:00, 14:00, and 16:00. The rainfall was very small within 6 h after the first peak (1 h rainfall <5 mm). From the second peak to the third peak within 8 h, the rainfall did not stop and gradually increased, with the cumulative rainfall of 8 h being 134.2 mm (accounting for 79% of the total 24 h rainfall). This shows that the rainfall at this stage was not only relatively large, but was also very concentrated. Waterlogging occurred at 13:00, with the third and fourth peak rainfall, at which point the waterlogging increased, the depth of waterlogging increased, and led to a waterlogging time of 6 h.

Case 2 had three peaks of rainfall (figure 3(b)), which appeared at 6:00, 10:00, and 23:00. The first and second peaks occurred after a total of 5 h and a cumulative rainfall of 55.9 mm (45% of the total 24 h rainfall) and resulted in waterlogging. However, since the rainfall was very small within approximately 10 h after the second rainfall peak, the duration of waterlogging was only 1 h. The third rain peak did not cause waterlogging. Comparing case 1 and case 2, it was found that case 2 did not only have small cumulative rainfall but it was also scattered, with 30% of the rainfall (3rd rainfall peak) not contributing to waterlogging. Therefore, the waterlogging point of case 2 is less than that of case 1, and the waterlogging time is much shorter than that of case 1.

Case 5 (figure 3(c)) had three peak rainfall values, which appeared at 12:00, 17:00, and 23:00. The three peaks lasted for 11 h and the cumulative rainfall was 237.8 mm (94% of the total 24 h rainfall). During this 11 h, the rainfall was constant, and 1 h maximum rainfall reached 58.6 mm. This shows not only that the cumulative rainfall was very large and the rainfall was very concentrated, but the rainfall intensity was also very large. Waterlogging was at a peak after the first rainfall. With the second and third peak rainfalls, the waterlogging point increased rapidly, the depth of waterlogging significantly increased, the maximum water depth was 2 m, and the waterlogging time was more than 12 h.

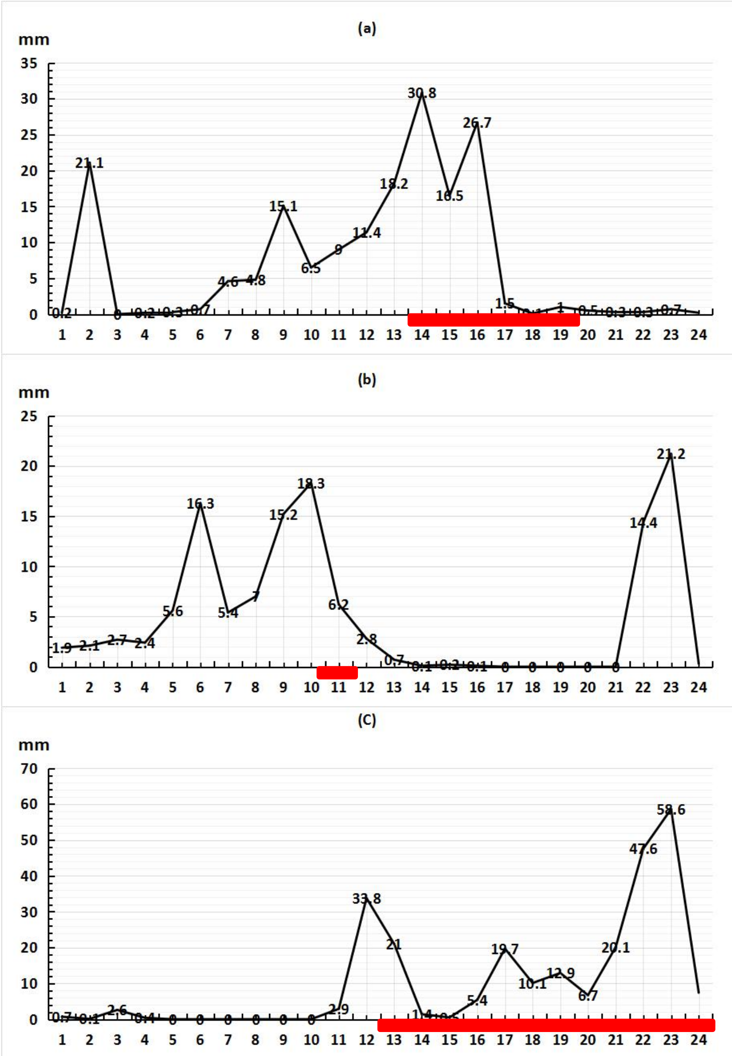

Figure 3. Typical case of hourly rainfall distribution, a: June 8, 2011(case 1); b: June 27, 2012 (case 2); and c: July 6, 2013 (case 5) (X-axis is time, unit: h; Y-axis is rainfall, unit: mm. The red rectangle represents the duration of waterlogging).

In summary, as the cumulative rainfall for 24 h, 12 h, 6 h, and 3 h increased, the more serious was the waterlogging. Waterlogging occurred after the cumulative rainfall reached a certain level because the runoff and confluence takes some time. In addition, the duration of waterlogging was not only related to the cumulative rainfall, but also to the urban drainage capacity.

3.3. The rainfall threshold for waterlogging

Based on results in table 1, the seven cases were divided into three grades (mild, moderate, and severe) according to the waterlogging condition. Case 2 and case 4 were mild waterlogging; case 1 and case 3 were moderate waterlogging; and case 5, case 6, and case 7 were severe waterlogging. For each level of waterlogging, first, the minimum value of the maximum cumulative rainfall for 24 h, 12 h, 6 h, and 3 h was selected for the threshold of rainfall that might lead to waterlogging (table 3). Then, the place where waterlogging occurred in each of the cases was recorded as was the maximum waterlogging depth of each waterlogging site. Finally, the actual waterlogged spots and their maximum waterlogging depth were plotted on the city map, resulting in a waterlogging risk map (figure 4).

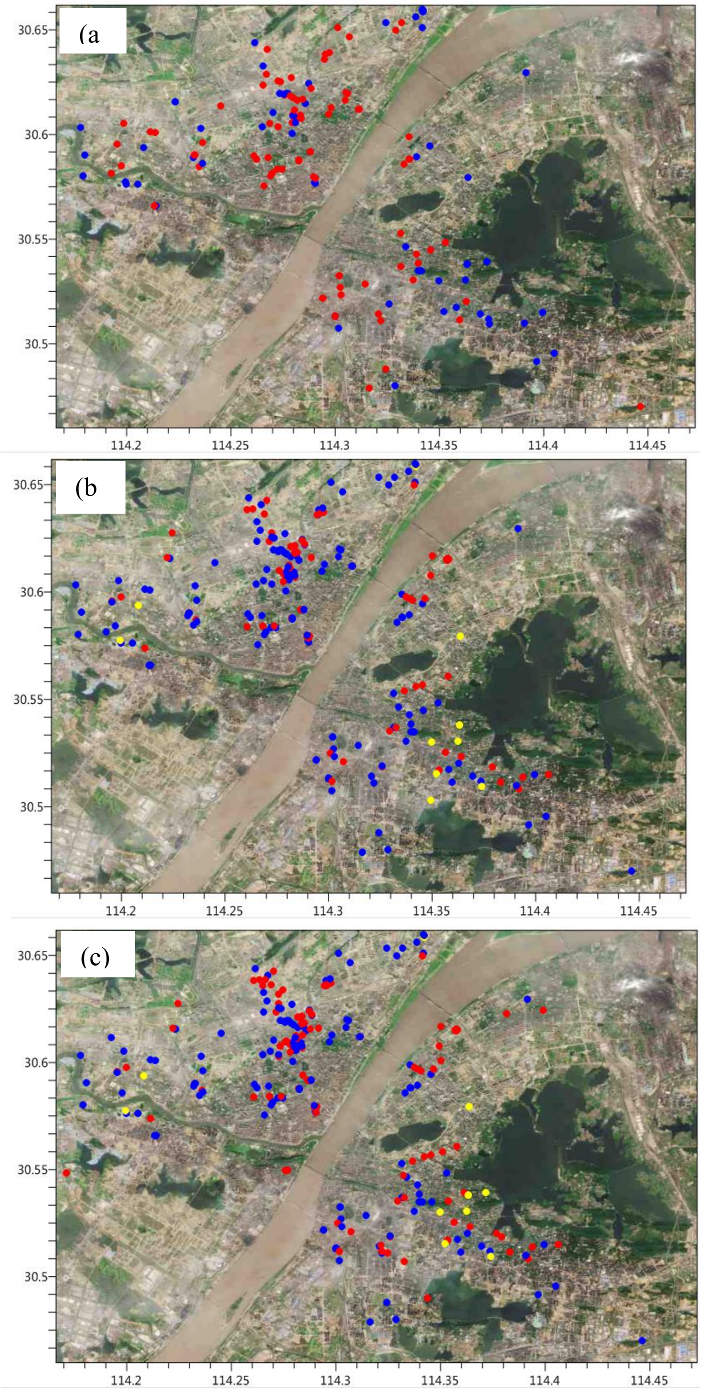

Figure 4. Wuhan City waterlogging risk map. a, Mild waterlogging; b, Moderate waterlogging; and c, Severe waterlogging. (Yellow dots: maximum water depth ≥ 1.0 m, blue dots: maximum water depth <0.5 m, and red dots: maximum water depth ≥ 0.5 m and <1.0 m).

If the accumulated rainfall in a given period reaches the thresholds in table 3, the possible waterlogging situation can be seen from figure 4. For example, if the maximum cumulative rainfall of 3 h is 38 mm, it can be seen from table 3 that there might be mild waterlogging in the future, the longest water duration would be 2 h, a maximum water depth of 0.7 m, and the specific waterlogging point and waterlogging depth can be seen in figure 4(a). Based on the future possible rainfall obtained from table 3 the corresponding waterlogging level can be determined and then, from figure 4, an estimated possible waterlogging point and waterlogging depth.

Table 3. Precipitation threshold of waterlogging in Wuhan City.

Waterlogging grade	Cumulative rainfall index (mm)				Maximum waterlogging depth (m)	Longest duration of waterlogging (h)
	24 h	12 h	6 h	3 h		
Mild	123	86	68	40	0.7	2
Moderate	163	145	113	74	1.5	5
Severe	196	187	135	94	2.0	10

4. Conclusions

In the present study, using data from waterlogging monitoring points and rainfall observations in Wuhan City from 2011 to 2016 and based on the relationship between waterlogging characteristics and rainfall, the threshold value of rainfall caused by waterlogging was established. The main conclusions are as follows:

- Rainfall during the summer months causes waterlogging in Wuhan City, on average 5.3 times a year with June and July having the most rainfall. This accounts for 90% of the total number of waterloggings. Waterlogging occurs generally along rivers and lakes near low-lying areas, the longest continuous waterlogging time is greater than 10 h, and the deepest water depth is 2 m.
- The degree of waterlogging is not only related to the cumulative rainfall, but also to the time distribution of rainfallalong with rainfall intensity. In general, as the cumulative rainfall for 24 h, 12 h, 6 h, and 3 h increases, the more severe the waterlogging is.
- The thresholds of continuous 24 h rainfall for mild, moderate, and severe waterlogging in Wuhan City are 123, 163, and 196 mm respectively, 12 h cumulative rainfall thresholds are 86, 145, and 187 mm, respectively, 6 h cumulative rainfall thresholds are 68, 113, and 135mm respectively, and 3 h cumulative rainfall thresholds are 40, 74, 94 mm, respectively.

Since there are only six years of data, the sample size is small, which means it is not possible to run further correlation analysis on this data. Therefore, the above conclusions need to continue to be complemented and improved upon in future studies. In addition, if the city’s drainage capacity increases, the cumulative rainfall of waterlogging warning indicators also needs to be adjusted.

Acknowledgments

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