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Article

Analysis of the Relationship between Extreme Rain Patterns and Maximum Runoff in Xuyi County Urban Area: Production Confluence of Urban Underlying Surface

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Abstract: The relationship between extreme rainfall and maximum runoff in Xuyi County, Huai'an City, Jiangsu Province, China was studied by using the Chicago rain pattern method, statistical analysis, and literature review. From 1957 to 2020, the average precipitation was 1015 mm with a fluctuating upward trend mainly in July-August which accounted for 40% of the total annual precipitation. The maximum evaporation occurred in June, accounting for 12.7% of the total annual evaporation. From 1957 to 2020, the average maximum daily precipitation was 45 mm, while the maximum precipitation was found as 233.2 mm on July 27, 1970. In the 120-minute rain pattern, the maximum precipitation coefficient was 0.4, and the rainfall intensity showed an unimodal distribution. The total annual runoff control rate increased from 60 to 95%, the corresponding design precipitation increased from 16.3 to 71.5 mm, and the growth rate of design precipitation became faster.

Keywords: Extreme rain pattern, Maximum runoff, Production confluence, Urban underlying surface, Xuyi County

1. Introduction

In nearly 70% of China's land area, different degrees of floods occur [1], because the high terrain in the west and low terrain in the east cause the rapid accumulation of floods in the downstream area. This is intensified by the flat terrain in the east, higher urbanization level, dense population, and developed economy [2,3]. Rapid urbanization has disrupted and destroyed the natural water cycle and the underlying surface. It also affects the production and confluence in river basin areas, leading to urban water problems and water management as unprecedented challenges [4,5]. Urbanization changes the regional microclimate [6] and the hydrological cycle of precipitation, evaporation, and runoff. Many scholars have hydrometeorologically and historically observed and established hydrological models of small urban catchments to study the changes in precipitation, evaporation, and runoff caused by rapid urbanization. The impact of urbanization on precipitation is revealed as the increase in the frequency of urban extreme precipitation with seasonal and regional characteristics. Urbanization changes the regional microclimate, the underlying surface of the city, and evaporation patterns [7–9]. Urbanization also influences runoff by changing the catchment path and the urban drainage system and alters the surface permeability coefficient, surface roughness coefficient, and groundwater level [10–12]. Urbanization changes the processes of runoff and confluence within the watershed. Traditional land use methods cannot effectively identify impervious surfaces that cause small runoffs [13–19]. The urban underlying surface was refined into six units according to the different hydrological response units and hydrological responses. Theories and methods were proposed to describe precipitation and confluence processes [20]. The mechanism of urban runoff production is important to study the relationship between extreme rainfalls and maximum runoffs in urban areas.

Based on theoretical analysis, data analysis, and model simulation methods, we analyzed the relationship between extreme rain patterns and maximum runoff in Xuyi County, China. With high-precision data, we analyzed the relationship between the annual changes in precipitation, evaporation, the maximum daily precipitation, the hourly and minutely change in precipitation, the design precipitation, and the total annual runoff control rate. The result provides an understanding of the complex urban underlying surface structure and such relationship between the extreme rainfall pattern and the maximum runoff at the scientific level and a reference for the planning and construction of urban water supply and drainage network.

2. Research Area

Xuyi County is located in the Yangtze River Delta region, southwest of Huai'an City in Jiangsu province, China, and at 32°N and 118°E. In the northeast, there is low-lying with many plains, while in the southwest, there is higher-lying with low mountains and hills. The terrain presents a ladder-like slope, and the elevation difference is about 223 m (Fig. 1). Xuyi County has a variety of landforms, including low mountains, hills, and plains. In addition, there are rivers and lakes in Xuyi County. The Huai River flows through Xuyi County, and the northern part of the county is bordered by Hongze Lake. Xuyi County has two regional rivers—the Huaihe River and the river-entering waterway, as well as several streams. In Xuyi County, Hongze Lake, Qili Lake, Maoer Lake, and Sishan Lake are located. The water area of the county is about 428 km^2, of which the river and lake area is about 295 km^2 and the reservoir and pond area is about 133 km^2. The water area accounts for 5.43% of the total area of the county. Xuyi County is located in the transition zone between the north subtropical and the warm temperate zones with a humid monsoon climate. Xuyi has four distinct seasons and a hot summer when the highest temperature reaches 39 °C. It is cold in winter, and the lowest temperature is as low as −12 °C. Precipitation is high and concentrated in July-September. Due to the impact of the monsoon climate, the distribution of precipitation throughout the year is not uniform which causes floods in the densely populated area. Thus, it is necessary to simulate patterns of precipitation in case studies. Considering the regional water resource management, it is required to plan and construct a sponge city with the implementation and transformation of the results. In this study, we collected the data from a domestic meteorological station of the National Meteorological Administration (No. 58138), located at 32.98°N, 118.52°E and at an altitude of 40.8 m.

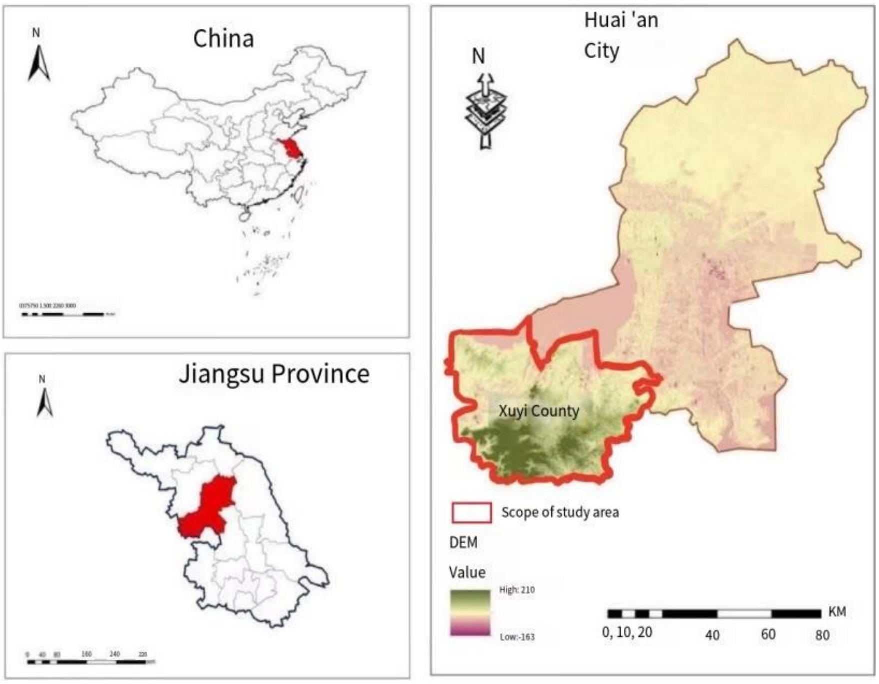

Fig. 1. Overview of research area.

3. Data and Methods

3.1. Data Sources

The main research data included topography, precipitation, evaporation, and other data. The digital elevation model (DEM) of Huai'an city was obtained from the geospatial data cloud (www.gscloud.cn). Daily precipitation data for 64 years from 1957 to 2020 was obtained from the Xuyi Meteorological Observation Station. Hourly precipitation data from January to December for 11 years from 2011 to 2021 were included with the minute precipitation data from 2011 to 2021.

3.1.1. Sample selection of extreme precipitation data

From the hourly and minute precipitation data from 2011 to 2021, extreme precipitation data samples were selected. Considering the duration of each precipitation event, all extreme precipitation data in different periods were reviewed. Then, all the selected events were sorted by the total precipitation. According to the standards of the meteorological department, extreme precipitation was defined as the total precipitation of over 16 mm in an hour, over 30 mm in 12 hours, and over 50 mm in 24 hours. The daily precipitation of ≥50 mm was regarded as extreme precipitation in this study. According to regulations, the definition of precipitation is a rainfall of >0.1 mm in an hour. When analyzing the diurnal variation of extreme precipitation, the maximum precipitation in an hour of ≥16 mm was recorded as extreme precipitation.

3.1.2. Statistical Analysis

We calculated the design precipitation using the total annual runoff control rate in Xuyi County. The daily precipitation data of Xuyi County from 1957 to 2020 were sorted in ascending order. After deleting the invalid data (precipitation of ≤2mm), 1349 effective daily precipitation data were obtained. The analysis was conducted with Microsoft Excel.

3.1.3. Chicago Rain Pattern Method

The Chicago rain pattern method was used to determine the precipitation pattern of Xuyi County by calculating the position coefficient of the maximum precipitation. All extreme precipitation data were divided at 5-minute intervals. Then, we divided precipitation peak times by precipitation duration to calculate the maximum precipitation coefficient of all extreme precipitation data. Then, the average maximum precipitation coefficient in the same duration was calculated. The weighted average of the maximum precipitation coefficients of different precipitation durations was calculated to obtain a *r*-value. The extreme precipitation intensity was calculated. The data were selected by using the annual maximum method, and then Pearson type III distribution was used for the frequency analysis. We adopted the Gauss-Newton method to calculate the parameters of the formula of extreme precipitation intensity. In the Chicago rain pattern method, the extreme precipitation intensity formula was used. Using the formula, the cumulative and average precipitation in different precipitation periods were obtained with corresponding recurrence periods.

4. Results and Discussion

4.1. Interannual and Intra-annual Variation of Precipitation

4.1.1. Interannual Variation

The trend in precipitation from 1957 to 2020 is shown in Fig. 2. The average annual precipitation in Xuyi County was 1015 mm, and the precipitation was concentrated from June to September. The precipitation in the period accounted for 63% of the total annual precipitation. The interannual variation of precipitation in Xuyi County varied greatly. The highest annual precipitation was observed in 1991 at 1757.1 mm, while the minimum precipitation was found in 1978 at 497.0 mm. The difference between the highest and lowest precipitation was 3.5 times, showing a large inter-annual change. From 2011 to 2021, annual precipitation increased slightly.

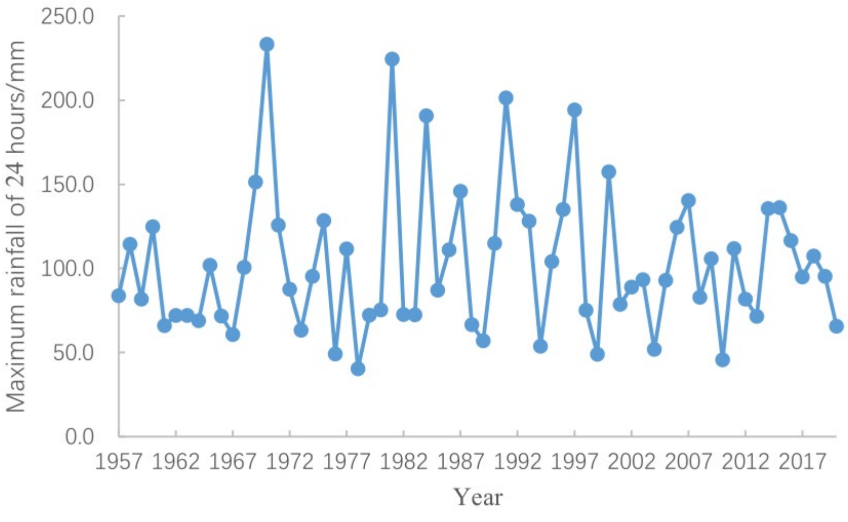

Fig. 2. Annual precipitation change in Xuyi County from 1957 to 2020.

From 1981 to 2020, the average daily temperature in the four seasons around Hongze Lake showed an overall increase. It was colder in springs and summers before the 1990s, while autumn and winter became shorter. Compared with other seasons, winter became warmer, and low temperatures were found in early winters. The length of the period with abnormal temperatures in winter was similar in that of spring and summer. The daily minimum temperature increased. In spring and summer, the temperature was lower before the 1990s, and it was low in only one winter season. The level of the daily maximum temperature in the four seasons was lower than the average minimum temperature. The abrupt high temperatures in summer, autumn, and winter were found to be higher than the daily average and the daily minimum temperature.

4.1.2. Annual Variation of Precipitation

The monthly precipitation changes for 64 years are presented in Fig. 3. Extreme precipitations occurred from May to October but mainly were observed from July to August, especially in July. In July, the average precipitation was 238.3 mm which accounted for about 24% of the total annual precipitation. In August, the precipitation was 167.7 mm, which accounted for about 17% of the total annual precipitation. The combined precipitation in July and August accounted for about 40% of the total annual precipitation. The lowest precipitation in Xuyi County occurred in winter, and the total precipitation in December was 22.9 mm The amount of precipitation in July and August was greater than that of evaporation. The difference between precipitation and evaporation in July was the most prominent. In the other months, the evaporation was greater than the precipitation.

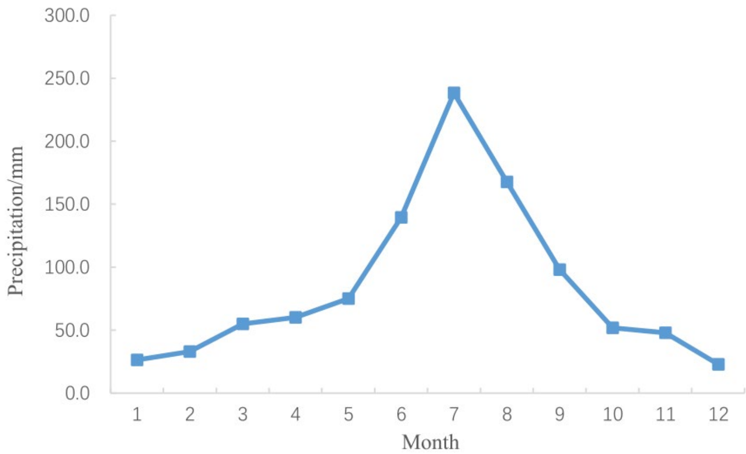

Fig. 3. Change curve of monthly precipitation in Xuyi County from 1957 to 2020.

4.2. Inter-Annual Variation of Maximum Daily Precipitation

The average value of the maximum daily precipitation in XuYi County from 1957 to 2020 was about 45 mm. The highest daily precipitation was observed on July 2, 1970, at 233.2 mm. The maximum daily precipitation on June 16, 1978, was the lowest at 40.4 mm (Fig. 4).

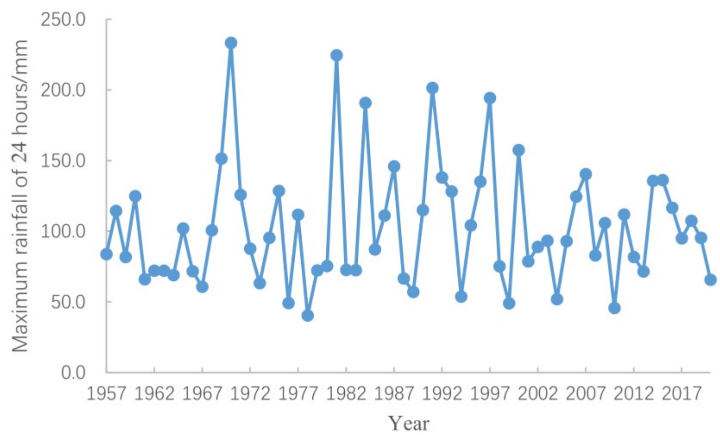

Fig. 4. Change curve of the maximum daily precipitation in Xuyi County from 1957 to 2020.

4.3. Hourly and Minutely Precipitation Pattern

4.3.1. Precipitation Changes in Minute

The precipitation pattern reflects the distribution of precipitation intensity. The precipitation pattern is not evenly distributed over time, and the intensity changes over time. In extreme precipitation, precipitation intensity over time is called the rainfall pattern. The extreme precipitation intensity reflects the precipitation trend of a region and is an important basis for the design and construction of urban drainage and flood control projects. The extreme precipitation intensity is as follows.

$$q = 19.205(1 + 0.665lg\ \mathrm{P})/(t + 19)^{0.758} \quad (1)$$

where q is rainstorm intensity (unit: m^3/s); P is the recurrence period of designed rainfall (unit is a); t is the confluence time (in min).

The precipitation pattern has been researched with different methods to establish the short-duration model such as the the Chicago rain pattern, Huff rain pattern, asymmetric triangle rain, and SCS rain pattern methods. The Chicago rain pattern method is recommended by the Ministry of Housing and Urban-Rural Development and the China Meteorological Administration to calculate the short-duration extreme precipitation pattern. This method is simple, efficient, and easily applied. Therefore, we used the Chicago rain pattern method to study the short extreme precipitation rain pattern in Xuyi County. To determine the rain pattern, the extreme precipitation intensity was calculated using the maximum precipitation position coefficient (r-value). Then, we obtained the design precipitation of Xuyi County. Based on the extreme precipitation intensity, we determined the r-value of the maximum precipitation coefficient. Based on the minute precipitation data from 2011 to 2021, the maximum precipitation coefficient of the extreme precipitation was calculated to be 0.4 at an interval of 5 min. After the r value was determined, the 120-minute rain pattern was calculated (Table 1).

Table 1. Xuyi 120min model rain pattern (mm/min).

Duration /min	**Recurrence Period /a**				
	1	**2**	**3**	**5**	**10**
5	0.17	0.21	0.23	0.25	0.29
10	0.20	0.23	0.26	0.28	0.32
15	0.22	0.27	0.29	0.32	0.37
20	0.26	0.31	0.34	0.38	0.43
25	0.31	0.37	0.41	0.45	0.51
30	0.38	0.46	0.50	0.56	0.63
35	0.50	0.60	0.66	0.74	0.84
40	0.73	0.87	0.96	1.06	1.21
45	1.26	1.51	1.65	1.83	2.08
50	1.62	1.94	2.12	2.36	2.68
55	1.02	1.22	1.34	1.49	1.69
60	0.73	0.87	0.96	1.06	1.21
65	0.56	0.67	0.74	0.82	0.93
70	0.46	0.55	0.60	0.67	0.76
75	0.38	0.46	0.50	0.56	0.63
80	0.33	0.40	0.43	0.48	0.55
85	0.29	0.35	0.38	0.42	0.48
90	0.26	0.31	0.34	0.38	0.43
95	0.23	0.28	0.31	0.34	0.39
100	0.21	0.25	0.28	0.31	0.35
105	0.20	0.23	0.26	0.28	0.32
110	0.18	0.22	0.24	0.26	0.30
115	0.17	0.20	0.22	0.25	0.28
120	0.16	0.19	0.21	0.23	0.26

The maximum 120-minute design precipitation in Xuyi County was 54.9 mm in one year, 65.8 mm in two years, 72.1 mm in three years, and 80.1 mm in five years. The maximum 120-minute design precipitation in one year was 90.9 mm. According to the Chicago rain pattern method (r = 0.4), 120-minute short-duration rain patterns in different recurrence periods in XuYi County were analyzed, and the results are shown in Table 1 and Fig. 5.

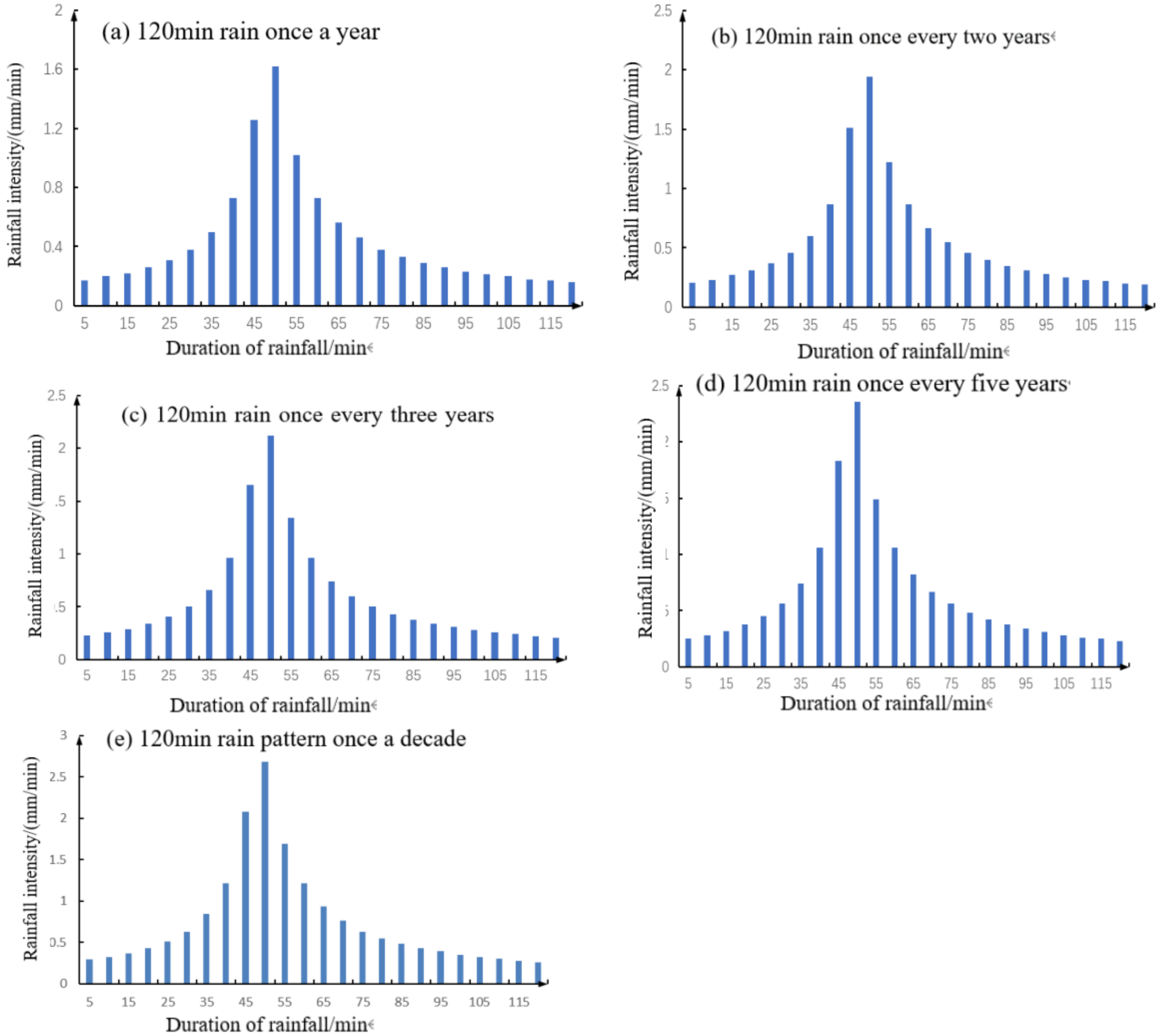

Fig. 5. 120-minute rain pattern in Xuyi County.

4.3.2. Hourly Extreme Precipitation

By using the data of extreme precipitation in Xuyi Station from 2011 to 2021, the maximum annual precipitation of 1, 3, 6, and 24 hours were obtained as shown in Fig. 6 and Table 2.

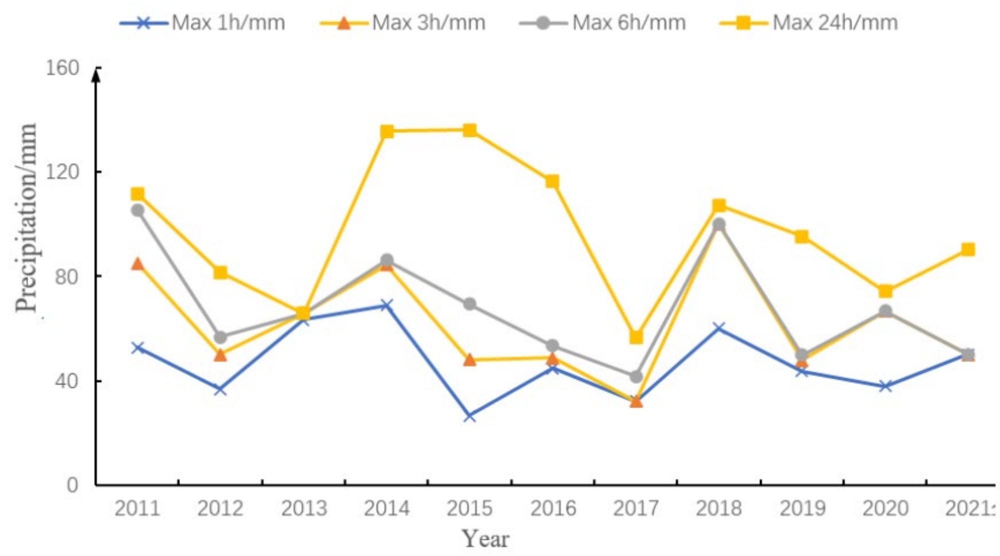

Fig. 6. Maximum annual precipitation of Xuyi Station from 2011 to 2021.

The shorter the duration, the smaller the variation and fluctuation in precipitation. The changes in the maximum precipitation in 1, 3, 6, and 24 hours became larger.

Table 2. Xuyi station 2011–2021 maximum 1, 3, 6, 24 hours rainfall statistical table.

Year	Max. 1 hour /mm	Max 3 hours /mm	Max 6 hours /mm	Max. 24 hours /mm
2011	52.9	85.2	105.6	111.8
2012	36.8	50.2	56.8	81.7
2013	63.5	65.9	65.9	65.9
2014	69.1	84.6	86.4	135.7
2015	26.5	48.1	69.5	136.2
2016	44.9	48.7	53.5	116.6
2017	32.1	32.1	41.6	56.5
2018	60.2	100.3	100.4	107.5
2019	43.7	47.9	49.8	95.3
2020	38	66.7	66.7	74.3
2021	50.1	50.1	50.1	90.3

4.4. Relationship between Annual Runoff and Design Precipitation

The annual runoff control rate is important for the sponge city planning and construction. The total annual runoff control rate refers to the percentage of the total annual precipitation controlled by the infiltration, evaporation, transpiration, and storage of rainwater. The rate is used to ensure the safety of urban drainage and avoid flood disasters by discharging water [21,22]. According to the analysis method in the Technical Guide for Sponge City Construction -- Construction of Rainwater System for Low-Impact Development (Trial), the daily precipitation data from 1957 to 2020 in Xuyi County were analyzed to obtain the relationship between the total annual runoff control rate and the designed precipitation in Xuyi County (Fig. 7).

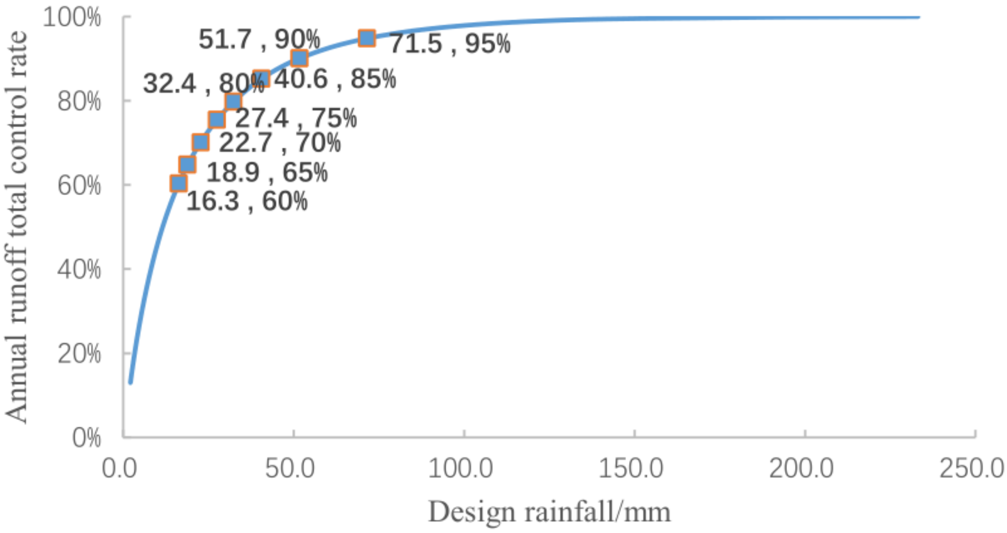

Fig. 7. Scatter diagram of design precipitation corresponding to the total annual runoff control rate in Xuyi County.

The design precipitation corresponds to the eight annual total runoff control rates (60, 65, 70, 75, 80, 85, 90, and 95%) (Table 3).

Table 3. Design precipitation to the annual total runoff control rate in XuYi County.

Total annual runoff control rate /%	60%	65%	70%	75%	80%	85%	90%	95%
Design precipitation /mm	16.3	18.9	22.7	27.4	32.4	40.6	51.7	71.5

The eight control rates of 60, 65, 70, 75, 80, 85, 90, and 95% corresponded to the design precipitation of 16.3, 18.9, 22.7, 27.4, 32.4, 40.6, 51.7, and 71.5 mm. With the improvement of the total annual runoff control rate in XuYi County (from 60 to 95%), when the control rate was increased by 5%, the corresponding design precipitation increased to 2.6, 3.8, 4.7, 5, 8.2, 11.1, and 19.8 mm. By increasing the total annual runoff control rate, the design precipitation was increased, and the rate increased more. The greater the total annual runoff control rate, the better the urban stormwater management. A moderate control rate must be considered to effectively prepare for stormwater and reduce the investment in large-scale facilities.

4. Conclusion

The hydrological data, the change in precipitation duration, and the extreme precipitation pattern in Xuyi County of Huaian City were studied using the Chicago rain pattern method. From 1957 to 2020, the average annual precipitation in Xuyi County was 1015 mm with an increase. The precipitation was concentrated in July-August, accounting for 40% of the total annual precipitation. The average annual evaporation was 1335 mm, and the evaporation in June was the largest, accounting for 12.7% of the total evaporation. The average annual maximum daily precipitation was 45 mm, of which the precipitation on July 27, 1970, reached the maximum in 64 years at 233.2 mm. The precipitation on June 16, 1978, was the lowest in 64 years at 40.4 mm. The Chicago rain pattern method was used to study the short-duration precipitation pattern, and the maximum precipitation position coefficient was 0.4. During the 120-minute precipitation, the precipitation intensity presented a "single peak type" distribution. With the increase of the total annual runoff control rate from 60 to 95%, the corresponding design precipitation increased from 16.3 to 71.5 mm, and the design precipitation increased more. The annual runoff total control rate can be used for construction as a key assessment index for sponge city construction. It is important to predict corresponding extreme rainfall for sponge city planning, design, and simulation [23–26]. Therefore, the relationship between extreme rain patterns and annual runoff total control rate must be understood for sponge cities [27–31]. In general, the larger the historical rainfall data, the better the representativeness of the data, and the more accurate the annual runoff total control rate. The influence of changes in the trends of long rainfall series on the total annual runoff control rate is still required to be studied. With abrupt changes or trend changes in the historical rainfall data, the rainfall characteristics are affected by "negative" data. The accuracy of the calculation results of the total annual runoff control rate is affected, too. Therefore, it is necessary to select representative historical data and identify the periodic changes in rainfall characteristics.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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