



A Method for Calculating the Design Volume of the Initial Rainwater Storage tank

Xingpo Liu¹ · Keer Wei¹

Received: 14 June 2024 / Accepted: 28 August 2024
© The Author(s), under exclusive licence to Springer Nature B.V. 2024

Abstract

Construction of the initial rainwater storage tank is crucial for managing urban first-flush pollution. Initial rainwater storage tank is designed to maximize pollutant capture efficiency while minimizing storage volume requirement. Considering the random nature of rainfall process, a method is proposed for determining the design volume of initial rainwater storage tank with its specific design return period. First, rainfall events were obtained by dividing the original rainfall series, setting the minimum inter-event time (MIET) as the emptying time of storage facilities. The rainfall events for design purpose were selected from the above rainfall events according to three indicators (the initial rainfall amount, maximum rainfall intensity of the specified period, and antecedent dry periods (ADP)). Then the annual multi-event-maxima (AMEM) method was used for the sampling of initial rainfall period on the basis of the selected rainfall events. Second, samples were arranged in descending order and the empirical frequency of the samples was calculated according to the mathematical expectation formula (Weibull formula). Thus, the theoretical probability distribution function was estimated based on Markov Chain Monte Carlo (MCMC) algorithm and the initial rainfall intensity formula was obtained according to the Horner formula. Finally, for the targeted catchment and the selected return period, the initial rainfall intensity can be calculated setting the initial period equals to overland time of concentration. Afterward, the design rainfall amount (design volume) can be obtained by the initial rainfall intensity, the initial period, initial loss and the catchment area. It was concluded that: (1) A method for the initial rainfall intensity sampling and the initial rainfall intensity formula were proposed for design volume of the initial rainwater storage tank. (2) The return period of the design volume can be taken into consideration in this method. (3) The proposed method is suitable for scenarios of collecting urban first-flush pollutants from small urban catchments.

Keywords First-flush pollution · The initial rainwater storage tank · Design volume · Return period · The initial rainfall intensity formula · Urban catchment

✉ Xingpo Liu
stormmodel@163.com

¹ College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, P.R. China

Abbreviations

ADP	Antecedent dry periods
AMEM	Annual multiple rainfall event maximum method
IDF	Intensity-duration-frequency
MCMC	Markov Chain Monte Carlo
MIET	The minimum inter-event time

1 Introduction

The initial rainfall-runoff pollution (or the first-flush pollution) is one of the major causes of urban non-point source pollution and urban water pollution (Wang et al. 2021). The initial rainwater storage tank is a commonly used measure to deal with this sort of problem (Costa et al. 2021; Mamun et al. 2020; Maniquiz-Redillas et al. 2022).

For design of the initial rainwater storage tank, a fundamental question is how to determine the effective and rational design volume to capture more runoff pollutants with the smaller volume. Several design methods were employed in the past decades. Empirical (or direct) method was the commonly used method across the globe. It is calculated based on the average initial rainfall depth and area of catchment. Merely the design value of the initial rainfall depth varies in different countries or regions. For example, 12–15 mm was used as the empirical values in the United Kingdom (Andoh and Iwugo 2002), 0.5 (for scenarios with the first-flush effect) or directly 1 inch in the United States (Andrle 2005; Wang 2008), and 4–8 mm in China (Xu et al. 2005). Particularly in Shanghai, 11 mm is recommended as minimum of the initial rainfall interception standard for the combined sewer system and 5 mm for the separate sewer system according to “Shanghai Urban Rainwater Drainage Plan (2020–2035)” (Zhang et al. 2022). In some cases, the runoff coefficient was also taken into consideration (often referred to as the method of empirical formula) (Chen and Adams 2005). Another method is the cumulative probability method. It is calculated by the runoff volume corresponding to the rainfall event with 90% probability (Andoh and Iwugo 2002). This method was commonly used in the United States and the United Kingdom. In addition, the hydrological and hydraulic simulation models (e.g. Stormwater management model (SWMM)) are normally used when the actual rainfall, discharge and water quality data are available (Si et al. 2022; Shi et al. 2021).

In summary, there were several methods for calculating the design volume of the initial rainwater storage tank across the globe. However, the design level (or design return period) of design volume was normally ignored or vague for the current literatures. This makes it difficult for designers to optimize the design volume parameters, resulting in design schemes that are either too large or too small. In this context, taking the randomness of rainfall processes into consideration, a new method was proposed for calculating the design volume of the initial rainwater storage tank.

2 Methodology

The proposed method of this study should be based on the long-term recorded rainfall series of the target region. It includes several steps such as rainfall event division (or separation), selection of the initial rainfall events, sampling of the initial rainfall intensity, the calculation of the empirical and the theoretical frequency of the initial rainfall intensity, the initial rainfall intensity formula, and determination of design scenarios (including design return period, the initial loss, overland time of concentration, area of the catchment studied) and calculation of design volume. The flowchart of this study is shown in Fig. 1. Figure 2 illustrates the design background or scenario of the initial rainwater storage tank.

2.1 Rainfall Event Division Method

The operation process of the initial rainwater storage tank is related to rainfall event. Therefore, rainfall event division is necessary for its design. For rainfall event division, the determination of the minimum inter-event time (MIET) is the question in point. In practice, in order to improve the efficiency of the initial rainwater storage tank, we often expect that it can play the greater role to deal with more pollutants or rainfall events. In this context, the emptying time of the tank was an important factor for selecting MIET. This enables that it can play the maximum role and generate maximum benefits in the two successive rainfall events. On the other hand, the determination of MIET should also take production and accumulation process of the surface pollutants into consideration. Therefore, the selection of rainfall events for design purpose is illustrated in the next step.

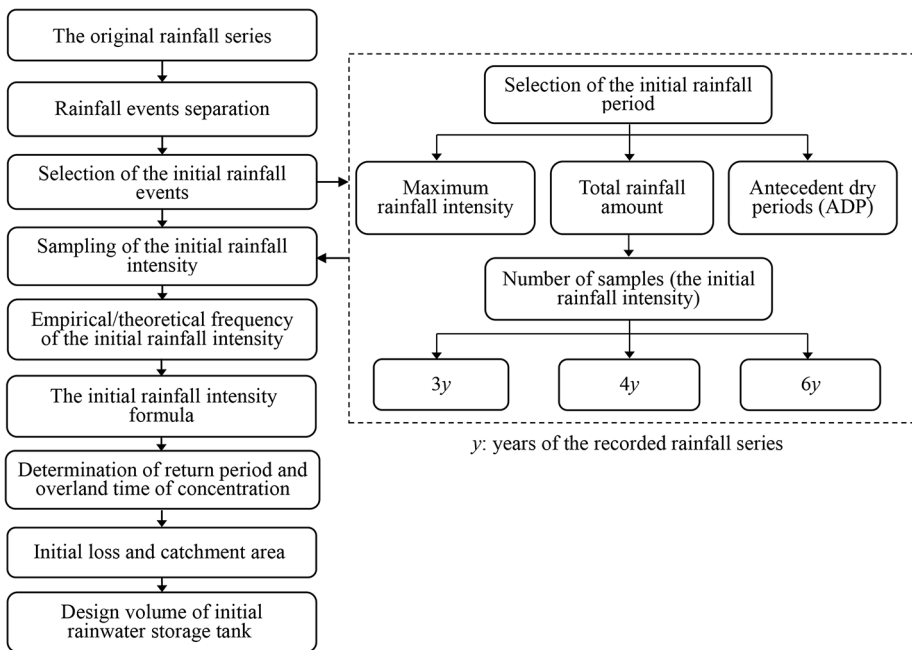


Fig. 1 Flowchart of this study

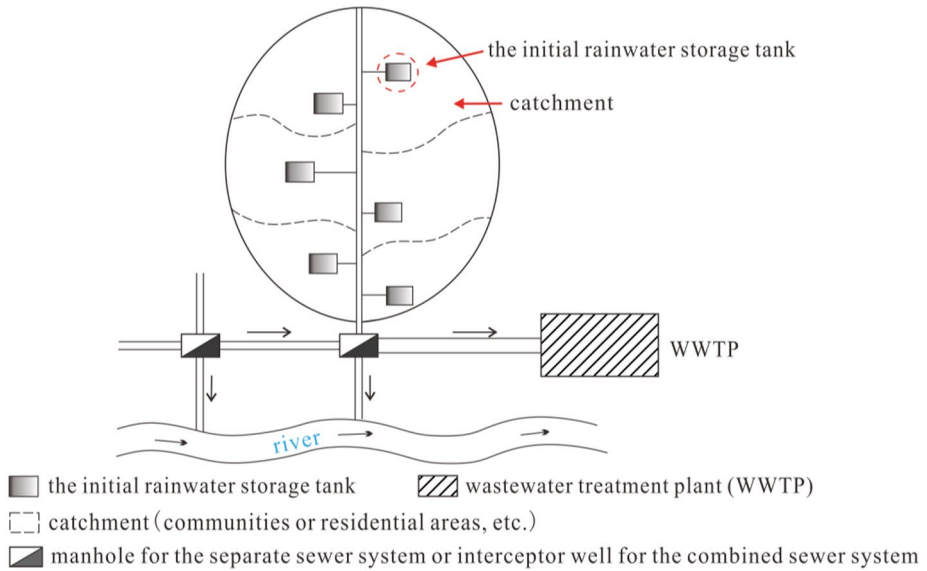


Fig. 2 Design scenario of the initial rainwater storage tank

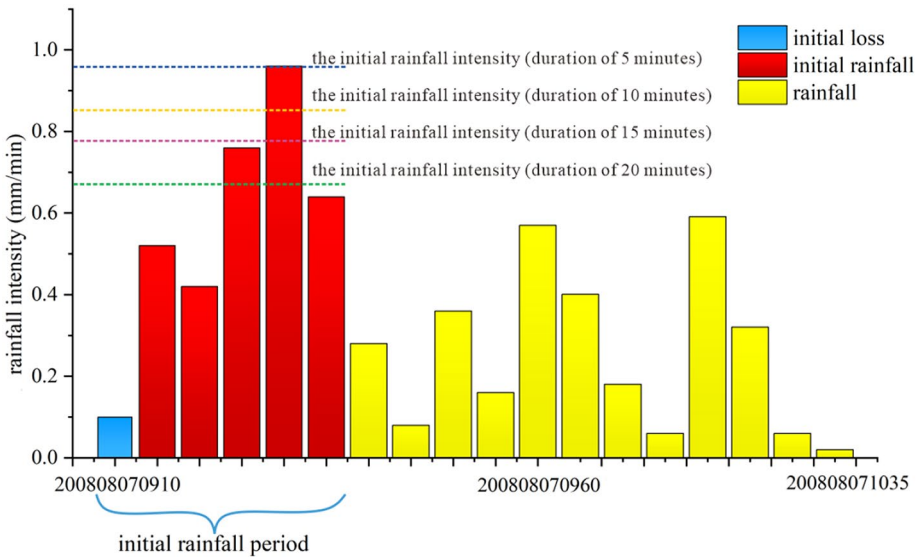


Fig. 3 Sampling procedure of the initial rainfall intensity

2.2 Selection Method of the Initial Rainfall Events

As mentioned above, not all the divided rainfall events are suitable for design purposes. It is expected that the more first-flush pollutants can be collected with the smaller volume. Therefore, the capture quantity and efficiency of the targeted pollutants should be empha-

sized here. According to these principles, the initial (or design) rainfall events (rainfall events used for this design purpose) should be selected firstly. Generally, the washing and concentration processes of the first-flush pollutants are related to rainfall intensity, rainfall amount and antecedent dry periods (ADP), and so on (Gnecco et al. 2005). For instance, ADP affects pollutants accumulated before the rainfall event, while the rainfall intensity and the rainfall amount affect hydrograph of pollutants flushed (Zhang et al. 2018). Therefore, the three indicators, rainfall intensity, rainfall amount and ADP, were used for selection of the design rainfall events (or the initial rainfall events).

2.3 Determination Method of the Initial Rainfall Period

Next, the initial rainfall period should be sampled from the initial rainfall events. First, the span of the initial period is crucial for the design. If it is too longer, we cannot catch the concentrated part of the pollutant hydrograph and overestimate the design volume. Otherwise, we cannot collect most of the pollutants from the whole catchment and underestimate the design volume. In addition, determination of the initial rainfall period should consider the processes of the initial loss of the catchment, such as filtration, retention and detention, and so on. Apparently, it is also relevant to the detailed conditions of the catchments. For simplicity, the overland time of concentration of the catchment can be used to determine the initial rainfall period. Here, the overland time of concentration is the time that surface runoff flows from the most remote point of the catchment to its outlet.

In addition, the initial rainfall period can also be determined based on the percentage of pollutants flushed, which is related to the rainfall intensity and the amount of pollution (Zhang and Wang 2016). It can be expressed as the following Eq.

$$\frac{L - L_0}{t - t_0} = \frac{\Delta L}{\Delta t} = \frac{dL}{dt} = -ki(t)L \tag{1}$$

$$i = \frac{A_1(1 + C \lg P)}{(t + b)^n} \tag{2}$$

$$\int_0^t \frac{1}{L} dL = \int_0^t -ki(t) dt \tag{3}$$

$$\ln \frac{L_t}{L_0} = \frac{-A_1(1 + C \lg P)k}{1 - n} [(t + b)^{1-n} - b^{1-n}] \tag{4}$$

$$t_I = \sqrt[1-n]{\frac{(1 - n) \ln L_p}{-A_1(1 + C \lg P)k} + b^{1-n}} - b \tag{5}$$

where i is the initial rainfall intensity (mm/min), P ($=1/F$) is the return period (a), t_1 is the initial rainfall period (minute), A , C , b , n are the local parameters of the catchment, L is the amount of residual pollutant, L_t is the amount of residual pollutant at time t , L_0 is the initial amount of residual pollutant on the surface, k is the average reduction coefficient, and $L_p = \frac{L_t}{L_0}$ is the percentage reduction of the pollutant.

2.4 Sampling Method of the Initial Rainfall Intensity

The annual multi-event-maxima method (AMEM) was used for the sampling of the initial rainfall intensity method in this work (Liu et al. 2023). The sampling process is as follows:

- (1) Select the first X minutes of each rainfall event as the initial rainfall period. Normally, it can be set as 5, 10, 15, 20, 25–30 min according to catchment conditions.
- (2) M initial (or design) rainfall events are selected every year according to three indicators (initial rainfall amount, maximum rainfall intensity during the initial rainfall period, and ADP). If y years of rainfall records are available, ($y \times M$) rainfall events will be collected.
- (3) Sample the maxima of the average rainfall intensity for each rainfall duration (5, 10, 15, 20, 30 min are often used) during the initial rainfall period (X minutes) according to AMEM sampling principles.
- (4) Arrange the above samples of all the rainfall durations in the descending order, respectively.
- (5) The first $(3 \sim 6) \times y$ samples of the initial rainfall intensity for every rainfall duration will be used for the subsequent analysis.

Figure 3 depicts the sampling method of the initial rainfall intensity.

2.5 Calculation Method of the Empirical / Theoretical Frequency Curve

After sampling, the initial rainfall intensities can be obtained for different rainfall durations and sorted in descending order. Next, their empirical frequency values can be calculated according to the Weibull formula, as shown below:

$$F = \left(\frac{m}{n+1} \right) \times 100\% \quad (6)$$

where m is the serial number of the corresponding initial rainfall intensity, n is the total number of samples, and F is the empirical frequency of the initial rainfall intensity.

The pairs of the initial rainfall intensity and the corresponding empirical frequency can then be used to plot the empirical frequency curve. According to the empirical frequency curve, the theoretical frequency function or curve can be acquired. Normally, the lognormal, exponential, Gumble, and Pearson type III (P-III) distribution functions and several parameter optimization methods such as method of moments, the least square method, and Markov Chain Monte Carlo (MCMC), can be used for this purpose (Deng 1996; Zalina et al. 2002).

2.6 Extrapolation Method of the Initial Rainfall Intensity Formula

Similar to storm sewer design, the framework of rainfall intensity formula can be also applied to calculate the initial rainfall intensity. Hence, the three-parameter Horner formula (Eq. (7) and Eq. (2)) was used and its parameters can be estimated through the optimization algorithms.

$$i = \frac{A}{(t + b)^n} \quad (7)$$

where i is the initial rainfall intensity (mm/min), t is the initial rainfall period (minute), and A , b , n are the local parameters.

2.7 Calculation Method of Design Volume of the Initial Rainwater Storage Tank

For the catchment studied, four parameters (design return period, the initial rainfall period, the initial loss and area of the catchment) should be determined before the calculation of design volume. First, area of catchment can be calculated through the geographic information tools. Generally, it should not exceed a few hectares. It is noted that the area of waters should be excluded from the total area of the catchment. Second, the design return period is relevant to the investment of the project and should be optimized through the cost effectiveness analysis. It is clear that this return period is different from that of the storm sewers. Third, the initial loss of the catchment can be estimated according to the empirical data or hydrological tools (SCS-CN method, Horton infiltration method, Green-Ampt method, etc.). For the current short duration rainfall-runoff issues, evaporation is often ignored. For the pervious area, depression and infiltration should be taken into consideration while for the impervious area, depression sometimes is significant. Finally, the initial rainfall period (t) is an important parameter in the initial rainfall intensity formula. Here, the overland time of concentration of the catchment studied is recommended to calculate the initial rainfall period.

When values of the above four parameters are obtained, the initial rainfall intensity can be acquired according to the initial rainfall intensity formula. Thus, the rainfall depth during the design duration can be calculated as: rainfall depth = the initial rainfall intensity \times the design duration. Finally, design volume can be obtained, that is, design volume = (rainfall depth - the initial loss) \times area of the catchment.

2.8 Study Data

The recorded rainfall data used in this study were obtained from an urban meteorological station in southwestern China. They span ten years from 1 January 2008 to 31 December 2017, with the temporal resolution of 5 min.

3 Results of this Study

3.1 Results of Rainfall Event Division

In this study, the rainfall statistical analysis software (RSAS) was used to separate rainfall events (Liu et al. 2023). The emptying time of the initial rainwater storage tank is 3 h; therefore, MIET was set as 3 h. According to the results of the rainfall event division, the 10-year original rainfall series were divided into 694 rainfall events, as shown in Table 1.

Table 1 Statistics of the total amount of rainfall events when MIET=3 h

MIET (hour)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
3	70	56	74	64	66	77	62	68	70	87	694

3.2 Results of the Selection of the Initial Rainfall Events

After rainfall event division, several rainfall events were selected from the above 694 rainfall events for design purposes. Normally, overland time of concentration of urban catchment (several hectares) is less than 30 min (According to Standard for design of outdoor wastewater engineering of China (GB50014-2021), it is about 5~15 min). Therefore, the initial 30 min of each rainfall event was used as the initial rainfall period in this work. Next, the three indicators (total rainfall amount, maximum rainfall intensity and ADP) were used to identify the selected rainfall events. Finally, a total of 80 rainfall events (8 rainfall events annually) were selected for the further study. Statistics of the selected rainfall events were shown in Table 2.

3.3 Results of the Initial Rainfall Intensity Sampling

On the basis of the 80 design rainfall events mentioned above, the initial rainfall intensity for different durations (5, 10, 15, 20, 25, 30 min) were calculated and arranged in the descending order, respectively. Furthermore, the annual multi-sampling method were used for sampling of the initial rainfall intensity and calculation of the empirical frequency. Here, $(3\sim 6) \times y$ ($y=10$ in this study) samples were collected and three schemes (30, 40, 60 sets) were investigated for the different durations. Results were shown in Table 3.

3.4 Results of the Theoretical Frequency Curve Selection

Based on the results of the empirical frequency of the initial rainfall intensity, the theoretical probability distribution was investigated. In this study, the exponential, Gumbel and lognormal distributions were compared and three schemes were discussed respectively, as shown in Figs. 4, 5, and 6. According to coefficient of determinability (R^2), the lognormal distribution was the best-fit one, as shown in Table 4.

3.5 Results of the Initial Rainfall Intensity Formula

According to results of the theoretical frequency distribution, the initial rainfall intensity formula was obtained. The local parameters (A_1 , C , b , n) of the initial rainfall intensity formula were estimated using the Markov Chain Monte Carlo (MCMC) algorithm. Results were shown in Table 5. The corresponding intensity-duration-frequency (IDF) curves were shown in Fig. 7. It was found that when $t=15$ min and $P=0.5$ a, the initial rainfall intensities of the three schemes were 0.706, 0.711, and 0.707 mm/min, respectively, which means that the difference between them was less than 1%. Therefore, the number of samples was insignificant on the initial rainfall intensity. In the next steps, the sampling scheme of 60 sets was used for illustration.

Table 2 Statistics of the selected rainfall events (for the initial 30 min)

Number of rainfall event	Total rainfall amount (mm)	ADP (hour)	Maximum rainfall intensity for different durations (mm/min)					
			5	10	15	20	25	30
1	21.8	52.25	1.080	1.020	0.853	0.830	0.820	0.727
2	17.9	16.67	0.960	0.860	0.787	0.720	0.700	0.597
3	11.4	28.00	1.120	0.780	0.633	0.520	0.448	0.380
4	8.4	46.75	0.540	0.490	0.427	0.355	0.320	0.280
5	6.7	47.50	0.580	0.510	0.393	0.315	0.256	0.223
6	6	260.42	0.360	0.240	0.227	0.220	0.200	0.200
7	5.5	108.00	0.240	0.220	0.213	0.200	0.184	0.183
8	5.1	129.08	0.420	0.380	0.307	0.245	0.204	0.170
9	17.5	47.25	1.240	1.010	0.800	0.685	0.632	0.583
10	16.2	128.08	1.420	1.220	1.040	0.800	0.644	0.540
...
40	2.9	48.42	0.160	0.150	0.120	0.095	0.088	0.097
41	22.7	37.68	1.380	1.220	1.140	1.025	0.896	0.757
42	17.9	78.17	1.200	1.070	0.980	0.810	0.692	0.597
43	12.8	10.75	0.960	0.800	0.633	0.580	0.500	0.427
44	6.6	67.50	0.520	0.450	0.353	0.290	0.260	0.220
45	6.6	16.00	0.380	0.290	0.247	0.255	0.248	0.220
46	6	14.08	0.480	0.470	0.380	0.295	0.236	0.200
47	5.3	121.17	0.560	0.400	0.313	0.255	0.212	0.177
48	4.7	97.32	0.300	0.230	0.220	0.200	0.180	0.157
49	28.7	51.00	1.440	1.380	1.307	1.195	1.116	0.957
50	20.3	13.43	1.200	1.080	0.980	0.915	0.804	0.677
...
70	11.2	76.18	0.960	0.830	0.627	0.485	0.436	0.373
71	7.4	73.25	0.540	0.500	0.353	0.295	0.288	0.247
72	7.2	10.58	0.560	0.440	0.327	0.300	0.280	0.240
73	51.8	16.42	2.440	2.350	2.240	2.100	1.964	1.727
74	22.5	181.67	1.580	1.150	0.987	0.850	0.812	0.750
75	11.3	47.68	1.340	1.050	0.733	0.555	0.452	0.377
76	11.1	15.08	0.760	0.580	0.527	0.475	0.432	0.370
77	7.8	27.92	0.520	0.440	0.407	0.350	0.300	0.260
78	7.7	63.42	0.800	0.730	0.507	0.385	0.308	0.263
79	7.3	26.40	0.460	0.420	0.313	0.315	0.272	0.243
80	4.8	10.33	0.260	0.190	0.173	0.160	0.168	0.160

3.6 Results of Design Volume of the Initial Rainwater Storage Tank

For the calculation of design volume of the initial rainwater storage tank, four parameters (design return period, overland time of concentration, the initial loss and the area of the catchment) are necessary. In this study, the design scenarios for an urban catchment were shown in Table 6.

Based on the initial rainfall intensity formula below, the initial rainfall intensity was obtained from Eq. (8). Then the rainfall amount (in rainfall depth, H) can be calculated as rainfall depth = the initial rainfall intensity \times the design duration (eq. (9)), then design vol-

Table 3 The empirical frequency of the initial rainfall intensity

Number	Rainfall duration (minute)						Empirical frequency (%)		
	5	10	15	20	25	30	30 sets	40 sets	60 sets
1	2.440	2.350	2.240	2.100	1.964	1.727	3.23	2.44	1.64
2	2.300	1.850	1.823	1.770	1.468	1.227	6.45	4.88	3.28
3	2.180	1.770	1.607	1.405	1.216	1.033	9.68	7.32	4.92
4	2.040	1.770	1.567	1.360	1.204	1.027	12.90	9.76	6.56
5	1.980	1.730	1.547	1.195	1.116	0.957	16.13	12.20	8.20
6	1.580	1.380	1.307	1.175	0.948	0.803	19.35	14.63	9.84
7	1.440	1.220	1.140	1.025	0.896	0.757	22.58	17.07	11.48
8	1.420	1.220	1.040	0.915	0.820	0.750	25.81	19.51	13.11
9	1.380	1.190	1.020	0.890	0.812	0.727	29.03	21.95	14.75
10	1.380	1.150	0.987	0.850	0.804	0.690	32.26	24.39	16.39
11	1.340	1.080	0.980	0.830	0.784	0.677	35.48	26.83	18.03
12	1.300	1.080	0.980	0.825	0.736	0.647	38.71	29.27	19.67
13	1.280	1.080	0.940	0.810	0.700	0.600	41.94	31.71	21.31
14	1.260	1.070	0.913	0.805	0.696	0.597	45.16	34.15	22.95
15	1.260	1.050	0.900	0.800	0.692	0.597	48.39	36.59	24.59
16	1.240	1.020	0.853	0.770	0.688	0.583	51.61	39.02	26.23
17	1.240	1.010	0.800	0.720	0.644	0.583	54.84	41.46	27.87
18	1.200	0.940	0.787	0.685	0.632	0.540	58.06	43.90	29.51
19	1.200	0.920	0.733	0.680	0.572	0.497	61.29	46.34	31.15
20	1.120	0.900	0.713	0.585	0.556	0.487	64.52	48.78	32.79
21	1.080	0.860	0.700	0.580	0.528	0.443	67.74	51.22	34.43
22	1.020	0.850	0.687	0.580	0.500	0.430	70.97	53.66	36.07
23	1.020	0.830	0.673	0.565	0.472	0.427	74.19	56.10	37.70
24	1.000	0.810	0.673	0.555	0.456	0.400	77.42	58.54	39.34
25	0.960	0.800	0.640	0.530	0.452	0.383	80.65	60.98	40.98
26	0.960	0.780	0.633	0.525	0.448	0.380	83.87	63.41	42.62
27	0.960	0.760	0.633	0.520	0.440	0.377	87.10	65.85	44.26
28	0.940	0.750	0.627	0.515	0.436	0.373	90.32	68.29	45.90
29	0.940	0.740	0.620	0.515	0.432	0.370	93.55	70.73	47.54
30	0.900	0.740	0.600	0.505	0.432	0.370	96.77	73.17	49.18
31	0.880	0.730	0.580	0.485	0.428	0.367		75.61	50.82
32	0.860	0.710	0.580	0.485	0.428	0.367		78.05	52.46
33	0.840	0.700	0.567	0.475	0.416	0.357		80.49	54.10
34	0.820	0.700	0.533	0.475	0.408	0.340		82.93	55.74
35	0.800	0.650	0.527	0.465	0.372	0.327		85.37	57.38
36	0.760	0.640	0.520	0.445	0.364	0.313		87.80	59.02
37	0.760	0.600	0.507	0.415	0.364	0.310		90.24	60.66
38	0.740	0.580	0.507	0.410	0.360	0.303		92.68	62.30
39	0.740	0.560	0.507	0.390	0.344	0.290		95.12	63.93
40	0.740	0.530	0.480	0.385	0.336	0.280		97.56	65.57
41	0.660	0.520	0.427	0.385	0.320	0.280			67.21
42	0.640	0.510	0.420	0.355	0.308	0.263			68.85
43	0.600	0.500	0.407	0.350	0.300	0.260			70.49
44	0.600	0.490	0.407	0.325	0.288	0.247			72.13
45	0.580	0.480	0.400	0.315	0.280	0.243			73.77
46	0.580	0.470	0.393	0.315	0.272	0.240			75.41
47	0.560	0.470	0.380	0.315	0.272	0.240			77.05

Table 3 (continued)

Number	Rainfall duration (minute)						Empirical frequency (%)		
	5	10	15	20	25	30	30 sets	40 sets	60 sets
48	0.560	0.450	0.360	0.300	0.268	0.230			78.69
49	0.560	0.440	0.353	0.295	0.260	0.223			80.33
50	0.540	0.440	0.353	0.295	0.256	0.223			81.97
51	0.540	0.440	0.347	0.290	0.252	0.220			83.61
52	0.540	0.440	0.340	0.280	0.248	0.220			85.25
53	0.540	0.420	0.333	0.275	0.248	0.213			86.89
54	0.520	0.420	0.333	0.275	0.236	0.210			88.52
55	0.520	0.400	0.327	0.275	0.236	0.207			90.16
56	0.500	0.400	0.327	0.270	0.232	0.203			91.80
57	0.480	0.390	0.320	0.260	0.228	0.200			93.44
58	0.460	0.390	0.313	0.260	0.224	0.200			95.08
59	0.460	0.380	0.313	0.255	0.220	0.200			96.72
60	0.420	0.380	0.307	0.255	0.220	0.197			98.36
...			
75	0.300	0.230	0.220	0.200	0.180	0.157			
76	0.260	0.220	0.213	0.200	0.172	0.153			
77	0.260	0.210	0.187	0.195	0.168	0.143			
78	0.240	0.190	0.173	0.160	0.164	0.137			
79	0.220	0.190	0.153	0.150	0.140	0.127			
80	0.160	0.150	0.120	0.095	0.088	0.097			

ume can be obtained, that is, design volume (V) = (rainfall depth - the initial loss) \times area of the catchments (eq. (10))

$$i = \frac{19.278(1 + 0.9534 \lg 0.25)}{(15 + 15.2947)^{0.8711}} \approx 0.42(\text{mm}/\text{min}) \tag{8}$$

$$H = i \times t = 0.42 \times 15 = 6.3(\text{mm}) \tag{9}$$

$$V = (H - i_L) \times A = (6.3 - 3) \times 4 = 13.2(\text{m}^3) \tag{10}$$

4 Discussions

In this work, a new method was proposed for calculating the design volume of the initial rainwater storage tank. Currently, the deterministic method is often used for rainwater storage tank design. For this design methodology, only one invariable design volume result is offered for the specific initial rainwater storage tank. However, the actual rainfall process is random process. Therefore, the probability and statistical theory should be introduced to cope with this issue. In this manner, the deterministic design method is only for the average design scenarios. Moreover, from the perspective of individual infrastructure design, it is necessary to provide the information of design level. Thus, the appropriate design level (or

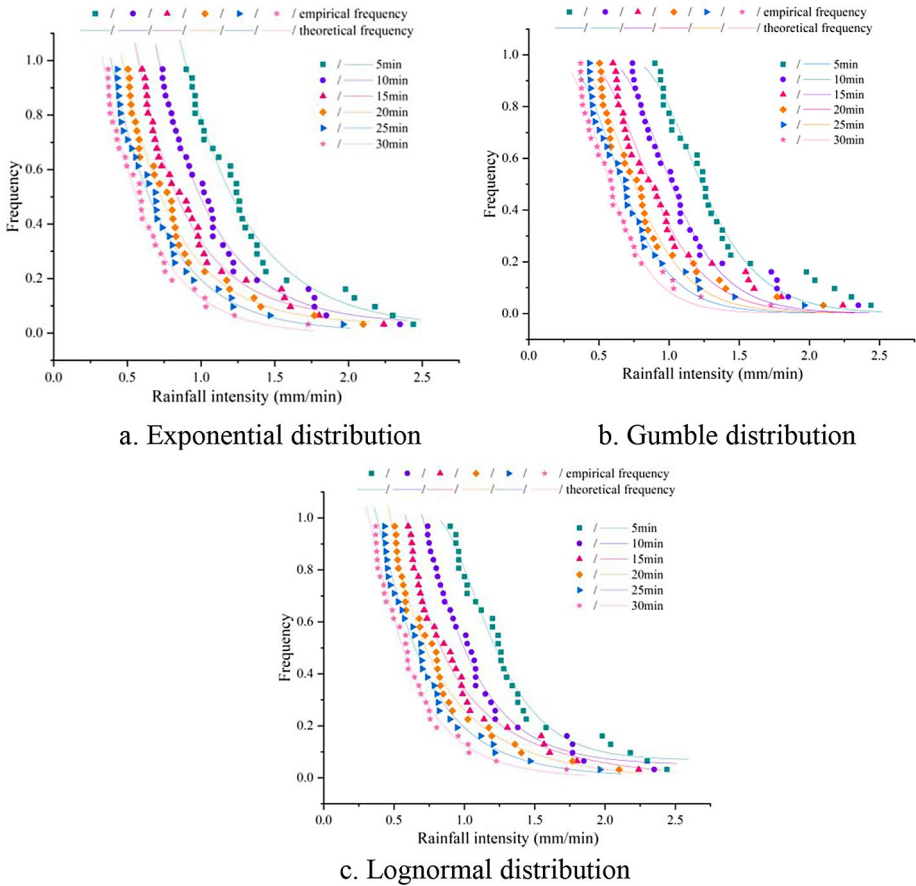


Fig. 4 Comparison of the theoretical distribution curves (30 sets of samples)

design return period) can be determined based on the investment and functional requirements of the project.

Actually, there are many purposes for the rainwater storage tank design, such as urban flooding mitigation, rainwater collection for water resource utilization, and so on. Here the function of the initial rainwater storage tank is to collect more pollutants from surface runoff and prevent pollution of the receiving waters. Therefore, the first-flush effect is the fundamental design principle in order to collect more pollutants with the most economical volume. In this sense, the size of the targeted urban catchment cannot be too large to ensure the existence of the first-flush effect for the initial surface runoff process. Normally, several hectares are suitable for urban catchment delineation. In the real world, there are often a number of similar catchments within the urban drainage districts (or watersheds). To abate this category of the non-point source pollution from the catchments, a number of the initial rainwater storage tanks should be designed and constructed. In this context, the initial rainfall intensity formula is necessary for guiding their designs. Under the design framework of the initial rainfall intensity formula, the suitable design parameters, such as overland time

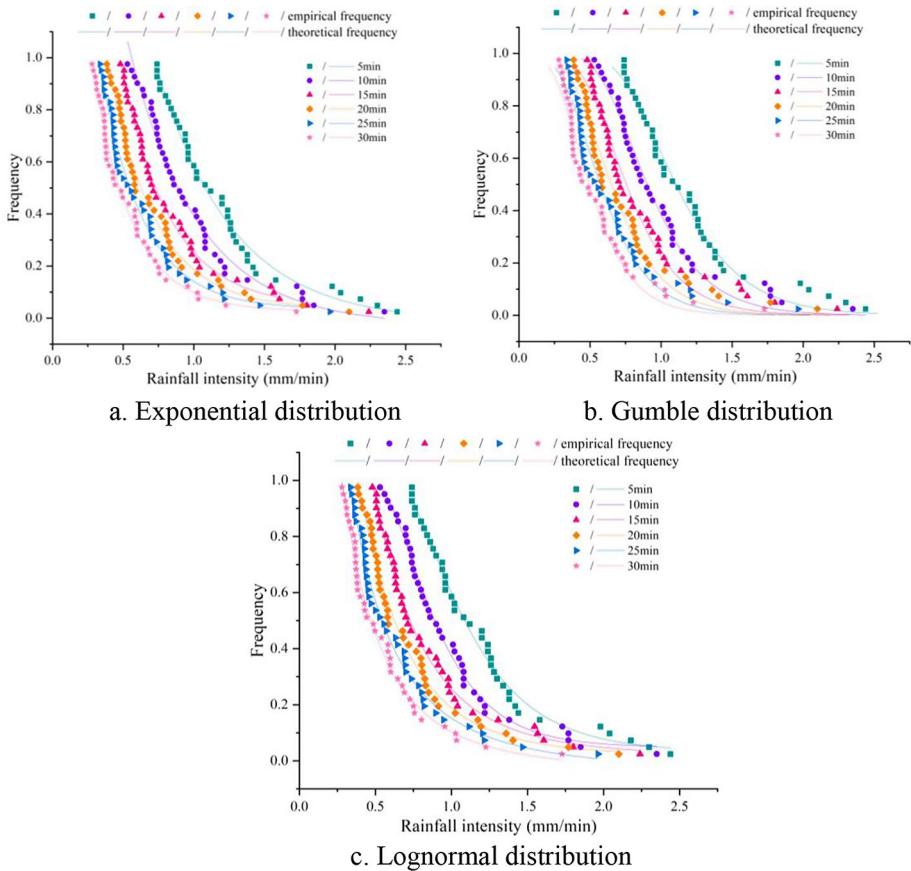


Fig. 5 Comparison of theoretical distribution curves (40 sets of samples)

of concentration, the initial loss, the catchment area, can be determined or calculated by designers according to the detailed conditions of the targeted catchment.

In addition, it is important to improve the usage efficiency of the initial rainwater storage tank to optimize its design volume. From this perspective, the annual multi-event-maxima (AMEM) method was selected for sampling purpose. Therefore, the maxima of the design return period of the initial rainfall intensity formula is half an year. In the meantime, the emptying time is another factor for the optimal design. Normally, it is relevant to the rainwater discharge or treatment conditions. Given the fact that the production and accumulation of surface pollutants often require a longer period of time, the case study in this article is only for the reference of methodology and the larger MIET are recommended for the actual application purpose.

In summary, we always expect to achieve better (economic, efficient, effective, rational) design schemes of the initial rainwater storage tank. For this sake, further theoretical research, more experiments and applications are equally important for the the mitigation of the first-flush pollution from the separate or combined sewer system.

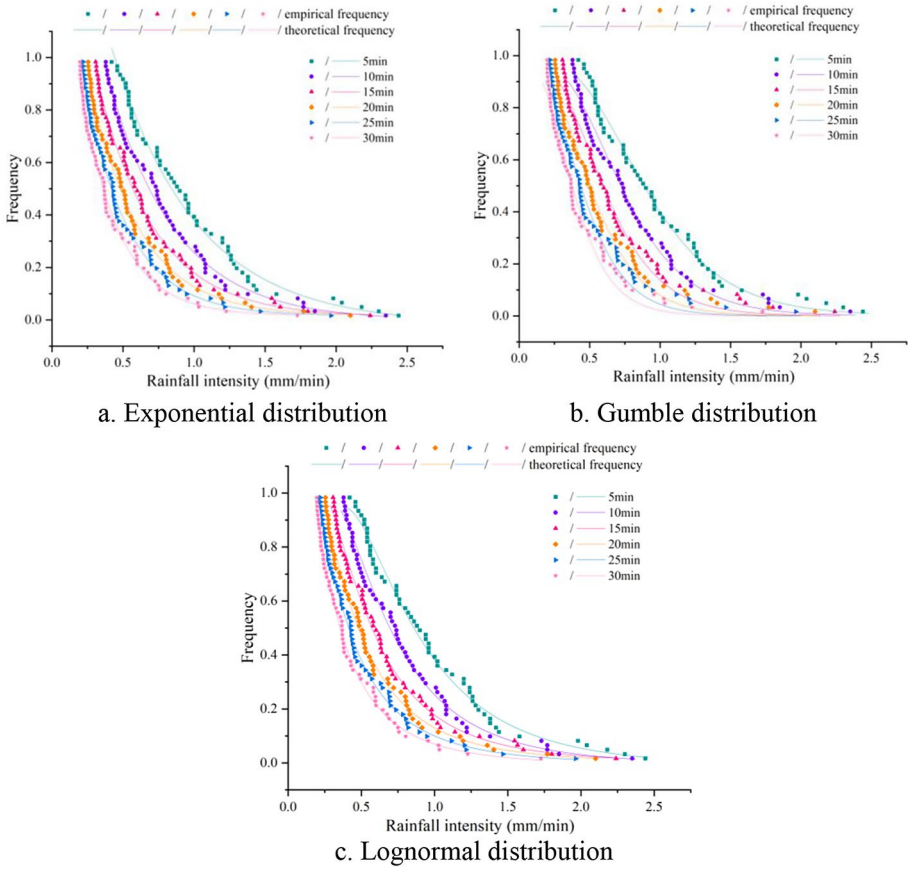


Fig. 6 Comparison of theoretical distribution curves (60 sets of samples)

Table 4 Comparison of the theoretical frequency distributions

Schemes	Distributions	R^2						Mean
		5	10	15	20	25	30	
30 sets	Exponential	0.97427	0.98716	0.98627	0.97896	0.98267	0.98372	0.98218
	Gumbel	0.97523	0.96894	0.97261	0.96149	0.96395	0.97771	0.96999
	Lognormal	0.97677	0.98713	0.98759	0.97826	0.98159	0.98273	0.98235
40 sets	Exponential	0.98571	0.98168	0.99288	0.98568	0.98459	0.98611	0.98611
	Gumbel	0.98324	0.9851	0.96874	0.96369	0.96175	0.96469	0.97120
	Lognormal	0.98867	0.9925	0.99298	0.98564	0.9852	0.9863	0.98855
60 sets	Exponential	0.98947	0.9925	0.99511	0.99485	0.99543	0.99494	0.99372
	Gumbel	0.9856	0.98275	0.98161	0.97641	0.97145	0.96724	0.97751
	Lognormal	0.99061	0.99229	0.99502	0.99447	0.99525	0.99504	0.99378

Table 5 Comparison of the initial rainfall intensity formula for different schemes

30 sets of samples	40 sets of samples	60 sets of samples
$i = \frac{20.5893(1+0.9406 \lg P)}{(t+16.4211)^{0.882}}$	$i = \frac{22.8668(1+0.9244 \lg P)}{(t+16.4073)^{0.9111}}$	$i = \frac{19.278(1+0.9534 \lg P)}{(t+15.2947)^{0.8711}}$

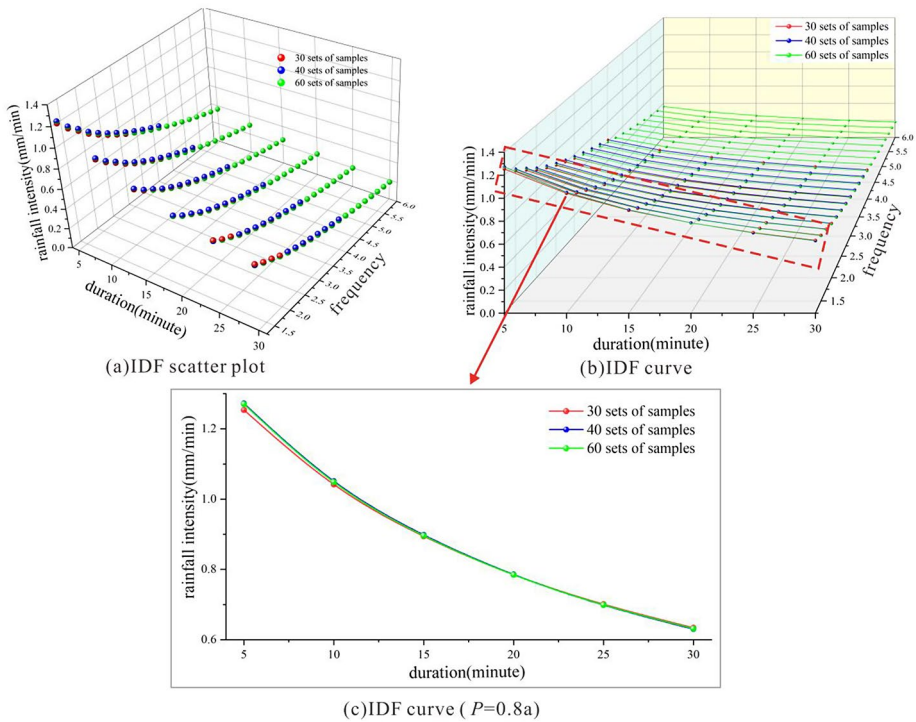


Fig. 7 IDF curve for the initial rainfall intensity

Table 6 Four parameters for the case study

design return period (P)	overland time of concentration (t)	the initial loss (i_L)	area of the catchment
0.25 a	15 minutes	3 mm	4 hectares

5 Conclusions

In this study, a new method is proposed based on the initial rainfall intensity formula to calculate the design volume of the initial rainwater storage tank for collecting the first-flush pollutants at the source of the catchments or sub-catchments. It is a stochastic design framework different from the current deterministic method, and the design level (return period) can be selected according to the requirements and demands of the decision-makers, planners or designers, and so on. It includes several steps such as rainfall event division, selection of the initial rainfall events, sampling of the initial rainfall intensity, the calculation of the empirical and the theoretical frequency of the initial rainfall intensity, the initial rainfall intensity formula and determination of design scenarios. First, rainfall events

were obtained by dividing the original rainfall series, setting MIET as the emptying time of storage tank. The rainfall events for design purpose were selected from the above rainfall events according to three indicators (the initial rainfall amount, maximum rainfall intensity of the specified period, and ADP). Then AMEM method was used for the sampling of initial rainfall period (the initial X minutes) on the basis of the selected rainfall events. Second, samples were arranged in descending order and the empirical frequency of the samples was calculated according to the mathematical expectation formula (Weibull formula). The theoretical probability distribution function was estimated based on the MCMC algorithm and the initial rainfall intensity formula was obtained according to the three-parameter Horner formula. Finally, for the targeted catchment and the selected return period, the initial rainfall intensity can be calculated setting the initial period equals to overland time of concentration. Afterward, the design rainfall amount (design volume) can be obtained by the initial rainfall intensity, the initial period, initial loss and the catchment area. It was concluded that: (1) A method for the initial rainfall intensity sampling and the initial rainfall intensity formula were proposed for design volume of the initial rainwater storage tank. (2) The return period of the design volume can be taken into consideration in this method. (3) The proposed method is suitable for scenarios of collecting urban first-flush pollutants from small urban catchments.

Acknowledgements we are very grateful to the editors and anonymous reviewers for their insightful suggestions and comments on this paper.

Data availability The authors confirm that some data are available from the corresponding author on reasonable request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing Interests Authors declare no conflict of interest.

References

- Andoh RY, Iwugo KO (2002) Sustainable urban drainage systems: a UK perspective *Global Solutions for Urban Drainage*. 1–16. https://www.stormwatercenter.net/Manual_Builder/Sizing_Criteria/Water%20quality/Options%20for%20Water%20Quality%20Volumes.htm. accessed on 26 July 2024
- Andrle SJ (2005) *Iowa Drainage Law Manual*. Center for Transportation Research and Education (CTRE) of Iowa State University. <https://intrans.iastate.edu/research/completed/iowa-drainage-law-manual-tr-497/>. accessed 26 July 2024
- Chen J, Adams BJ (2005) Analysis of storage facilities for urban stormwater quantity control. *Adv Water Resour* 28(4):377–392
- Costa MEL, Carvalho DJ, Koide S (2021) Assessment of pollutants from diffuse pollution through the correlation between rainfall and runoff characteristics using EMC and first flush analysis. *Water* 13(18):2552
- Deng P (1996) Establishment and application of mathematical model for storm sampling and frequency distribution. *Water Wastewater Eng* 22(2):5–9 (in Chinese)
- Gnecco I, Berretta C, Lanza L, La Barbera P (2005) Storm water pollution in the urban environment of Genoa, Italy. *Atmos Res* 77(1–4):60–73

- Liu X, Ouyang C, Zhou Y (2023) A low-return-period rainfall intensity formula for estimating the design return period of the combined interceptor sewers. *Water Resour Manage* 37(1):289–304
- Mamun AA, Shams S, Nuruzzaman M (2020) Review on uncertainty of the first-flush phenomenon in diffuse pollution control. *Appl Water Sci* 10(1):53
- Maniquiz-Redillas M, Robles ME, Cruz G, Reyes NJ, Kim L-H (2022) First flush stormwater runoff in Urban catchments: a bibliometric and comprehensive review. *Hydrology* 9(4):63
- Shi L, Liu H, Xi C, Zhang Z (2021) The initial rain water storage tank volume determination and pollution interception efficiency based on the SWMM model and computer software analysis. *J Phys: Conf Ser* 1992(2):022044
- Si S, Li J, Jiang Y, Wang Y, Liu L (2022) The response of runoff pollution control to initial runoff volume capture in sponge city construction using SWMM. *Appl Sci* 12(11):5617
- Wang M (2008) The theoretical research on design of rainwater tanks. Beijing University of Technology. (in Chinese)
- Wang Z, Gao J, Du Z, Zhang Y, Lai X (2021) Simulation of interception capacity of Nanhe initial rain storage tanks. In: *IOP Conference Series: Earth and Environmental Science*, 787(1):012138
- Xu G, Chen C, Lin W, Lu S (2005) Study on Pollution Control of Overflow from Initial Rainwater Storage Tank. *China Water&Wastewater* (08):19–22. (In Chinese)
- Zalina MD, Desa MNM, Nguyen V, Kassim AHM (2002) Selecting a probability distribution for extreme rainfall series in Malaysia. *Water Sci Technol* 45(2):63–68
- Zhang Q, Wang X (2016) Research and quantitative analysis of initial rainwater. *Water Wastewater Eng* 52(S1):38–42 (in Chinese)
- Zhang P, Cai Y, Wang J (2018) A simulation-based real-time control system for reducing urban runoff pollution through a stormwater storage tank. *J Clean Prod* 183:641–652
- Zhang Y, Chen Y, Zhang L (2022) Research on long-series rainfall characteristics of some drainage system based on initial rainwater interception standard. *Environ Eng* (02):25–27. (in Chinese)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.