



A Low-Return-Period Rainfall Intensity Formula for Estimating the Design Return Period of the Combined Interceptor Sewers

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Abstract

The design rainfall intensity and its return period of the combined interceptor sewer is an important factor affecting combined sewer overflow (CSO) occurrence. However, we often use the interceptor ratio (or interceptor multiple, n_0) to design the interceptor sewer, and its equivalent design return period is often ignored. In this study, a low return period rainfall formula modeling method was proposed to estimate this return period. First, a new rainfall event separation approach was especially developed, and the minimum interevent time (MIET) was set to time of concentration of the tributary area corresponding to the most downstream interceptor well. Second, a new rainfall intensity sampling algorithm, annual multi—event—maxima (AMEM) sampling algorithm, was put forward. For this sampling algorithm, several maxima of rainfall intensity should be sampled annually, and only one maximum is sampled for each rainfall event. In addition, the empirical frequency values of the above sampled rainfall intensities can be obtained according to the mathematical expectation formula (Weibull formula). After comparison, the lognormal distribution was selected for the theoretical probability density function. Finally, parameters of the low return period rainfall intensity formula were estimated using three-parameter Horner formula and MCMC (Markov Chain Monte Carlo) algorithm. A case study was conducted to demonstrate the proposed method based on the recorded rainfall data from a meteorological station in southwestern China and a combined sewer system. Results revealed that: (1) A MIET determination method was proposed according to independence of CSO events. (2) An annual multi-event-maxima (AMEM) sampling was proposed for collecting samples of the low return period rainfall intensity. (3) For the case study, the best-fit distribution for low return period rainfall intensity was lognormal distribution. (4) Resulted low return period rainfall intensity formula was provided.

Keywords The combined interceptor sewer · Return period · Threshold · Low return period rainfall intensity formula · The annual multi-event-maxima (AMEM) sampling · combined sewer overflow (CSO)

Abbreviations

AMEM Annual multi-event-maxima

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AMS	The annual maxima sampling
CC	Correlation coefficient
C_s	Coefficient of skewness
CSO	Combined sewer overflow
C_v	Coefficient of variation
MCMC	Markov Chain Monte Carlo algorithm
MIET	The minimum interevent time

1 Introduction

Combined sewer overflow (CSO) pollution was a challenge facing urban water environment managers across the globe (Andrés-Doménech et al. 2010; Passerat et al. 2011; Yu et al. 2013; Goore Bi et al. 2015; Rosin et al. 2021). In recent years, many cities in China have been affected by CSO pollution because point pollution, from the industrial wastewater and the domestic sewage, were dramatically improved by the Chinese ecological civilization practices.

For CSO polluted events, the drainage capacity of the combined interceptor sewer was a crucial parameter. Physically, CSO will occur when the actual outflow of the combined sewer exceeds the design inflow of the intercepted sewer. That is to say, mathematically, CSO will definitely occur when the design return period of the combined sewer is greater than that of the actual rainfall intensity. Design method of the combined sewer was similar to that of storm sewer. Its design drainage capacity and the equivalent return period is easy to obtain. In contrast, the design rainfall return period of the interceptor sewer is often ignored, because its design methodology is different from that of the combined sewer. In this context, it is of significance to calculate the equivalent return period of interceptor sewer.

In China, design of interceptor sewer is based on a design parameter-interceptor ratio (or interceptor multiple, n_0), which is the ratio of the intercepted storm flow and the average sanitary flow. If we know the average sanitary flow and select the interceptor multiple, design inflow of interceptor sewer can be calculated. However, from the perspective of the rainfall intensity, the equivalent design return period of this design inflow of interceptor sewer was normally ignored. Especially for CSO related issues, it is of significance for estimating the rainfall intensity threshold of CSO.

Currently, the commonly used rainfall intensity formula was for the purposes of storm sewer design. It is called as Intensity—Duration—Frequency (IDF) or Depth—Duration—Frequency (DDF) curve in many countries across the globe. This intensity formula is obtained based on the annual maxima sampling (AMS). It is suitable for occasions with a return period of more than 2 years. In contrast, design return period of interceptor sewer is much smaller, because its design flow is only $(n_0 + 1)$ times of the average sanitary flow ($n_0 = 2 \sim 5$). That is the reason why CSO occurs many times annually and their return periods are normally lower than half a year. In this context, a low return period rainfall intensity formula was needed for analysis of CSO and it was investigated in this study.

The rest of this study is organized as follows: Sect. 2 gives a detailed introduction to the basic principles and flowchart of the proposed method. Section 2.1 introduces the scheme of rainfall event separation; Sect. 2.2 introduces the annual multi-event-maxima (AMEM) sampling method; Sect. 2.3 introduces the frequency curve (or distribution) selection and Sect. 2.4 introduces the parameter optimization of rainfall intensity formula based on

MCMC (Markov Chain Monte Carlo) algorithm. In Sect. 3, a case study is elaborated to demonstrate the feasibility of the new method. Finally, findings of our work are summarized in Sect. 4.

2 Methodology

A flowchart for obtaining the low return period rainfall intensity formula was proposed based on the recorded rainfall data, as shown in Fig. 1. It consists of four parts: rainfall event separation, rainfall intensity sampling, frequency curve selection and parameter estimation of rainfall intensity formula.

2.1 Rainfall Events Separation (or Division) Method

Actually, the return period of the interceptor sewer is relevant to the CSO frequency. When the return period of the interceptor sewer is higher, the CSO frequency is relatively lower and vice versa. A CSO event is triggered by a rainfall event that return period of its maxima rainfall intensity is higher than that of the interceptor sewer. Therefore, to calculate the return period of the interceptor sewer, it is necessary to conduct rainfall event division firstly. An ideal rainfall event should be completely continuous

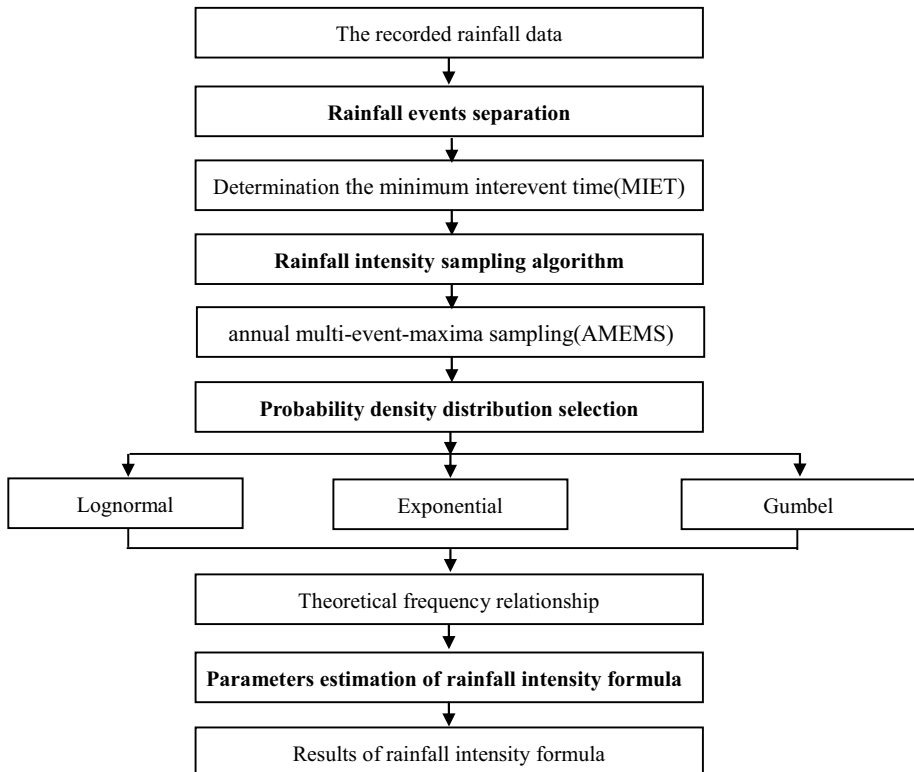


Fig. 1 Flowchart

rainfall process and independent of other rainfall events in the meantime (Jean et al. 2018; Li et al. 2019). Hence, it is very important to determine the appropriate interevent time between the two rainfall events. If this parameter is set too small, the two rainfall events do not meet the requirement of statistical independence. Conversely, it breaks the integrity of a continuous rainfall process (or a rainfall event). Currently, a very popular method to determine the interevent time was based on the assumption of coefficient of variation (C_v) of rainfall event intervals equals to 1 (Restrepo-Posada and Egelson 1982). It was assumed that the prior distributions of rainfall characteristics (rainfall interval, rainfall depth and rainfall duration) are all the exponential distribution. In this study, not only the independence of rainfall events, but also the independence of the two adjacent CSO events should be ensured from the statistical perspective. In view of this requirement, runoff or flow from the two adjacent rainfall events, should not overlap or meet in the combined system (On this occasion, CSO frequency can be clearly defined and quantified). According to this principle, a rainfall event separation method was proposed accordingly. It can be explained as follows: the minimum interevent time (MIET) between the two rainfall events should be greater than or equal to the time of concentration (t_c) of the studied tributary area (or the time of concentration from the most downstream interceptor well), as shown in Fig. 2a, b.

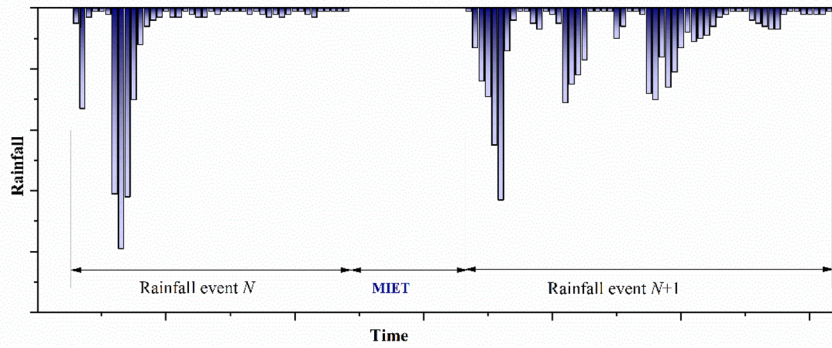
Time of concentration is a commonly used parameter for storm sewer design. For the interceptor sewers concerned in the actual project, their times of concentration can be obtained from the existing storm sewer design data or completion archives. Otherwise, these values should be re-calculated according to the local storm sewer design manuals. For instance, time of concentration (t_c) equals to t_1 plus t_2 . Here, t_1 is the inlet time to the point where the runoff enters the combined sewers (or overland runoff time), t_2 is the time of flow in the closed combined sewers to the studied interceptor well or sewer flow time.

2.2 Rainfall Intensity Sampling Method

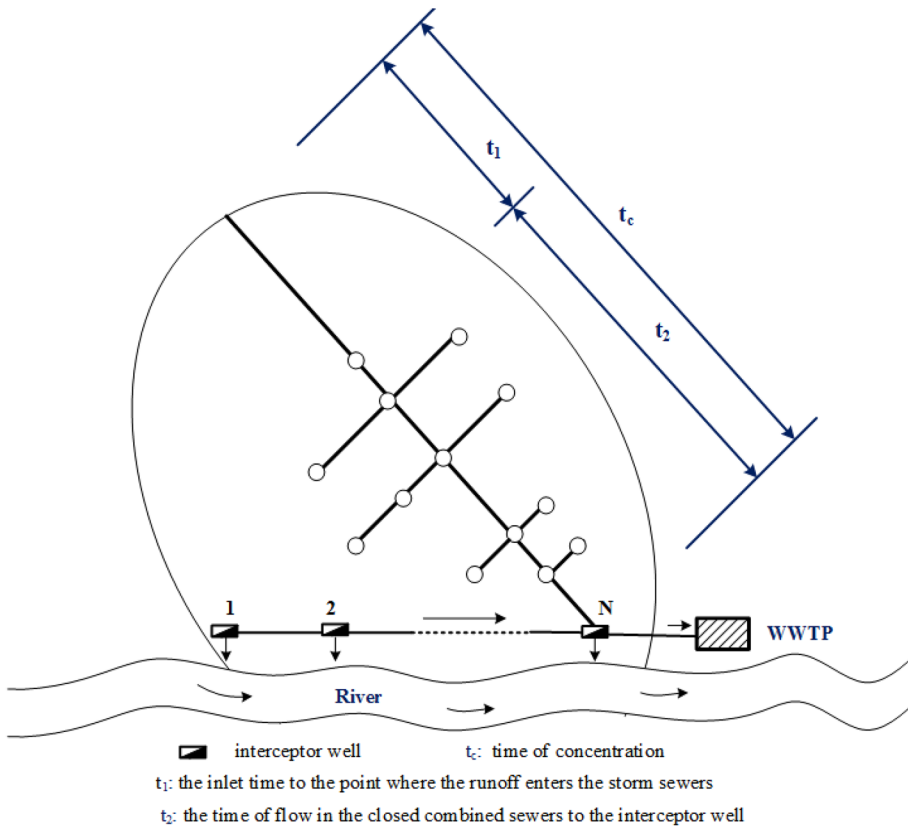
Currently, there are many methods used for rainfall intensity sampling, such as the annual maxima (AM) sampling, the annual multi-sampling, and so on. They are suitable for the different applications with the varied return period spans respectively (Ahmad et al. 2019). Table 1 presents the relationship between the sampling methods and their applicable ranges of return period.

Compared with flooding events or storm sewer design scenarios, return period of the combined interceptor sewer is lower than half a year. Therefore, a new rainfall intensity sampling algorithm, AMEM sampling algorithm, was developed based on the rainfall event separation results. The sampling process is as follows:

- (a) Select a rainfall duration to be analyzed;
- (b) Corresponding to the current rainfall duration, calculate the maxima of (average) rainfall intensity for each rainfall event;
- (c) M maxima were selected annually in the descending order. Note, only one maximum can be selected for each rainfall event to ensure the statistical independence. Suppose there are N years of rainfall data. At this time, $M * N$ maxima will be collected.
- (d) Sort the $M * N$ data in descending order, and then select the first half of the data. $M/2 * N$ data (maxima) can be sampled.
- (e) Continued to select another rainfall duration and replicate step (a)~(d).



(a) Rainfall event division



(b) Time of concentration of the most downstream interceptor well

Fig. 2 MIET calculation principle in this study

Table 1 Relationship between the sampling methods and their return period ranges

Sampling methods	Annual maxima sampling (AMS)	Annual multi-sampling	Annual multi-event-maxima (AMEM) sampling
Return period ranges (year)	≥ 2	[0.5, 2]	< 0.5
Scenarios	storm sewer design or flooding prevention purposes	storm sewer design with the insufficient rainfall records	Combined interceptor sewers or other CSO facilities

In general, the selected rainfall duration can be 5, 10, 15, 20, 30, 45, 60, 90, 120 min. If sizes of the urban catchments studied are very big, 150 or 180 min can also be considered.

2.3 Frequency Curve Selection Method

After AMEM sampling, a number of rainfall intensities for different rainfall durations can be selected. Then these rainfall intensity values are sorted in the descending order, and their corresponding empirical frequency values can be calculated according to Weibull formula (Weibull 1939), shown as follows:

$$F = \frac{m}{n+1} \times 100\%$$

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

Later, the empirical frequency curve can be plotted by rainfall intensity—frequency pairs. Currently, hydrologists prefer to use the specific mathematical probability density distribution functions to summarize the empirical frequency features of rainfall intensity, such as lognormal distribution, Gumble distribution and Pearson type III (P-III) distribution (Yilmaza et al. 2014). This mathematical probability density distribution is normally referred to as the ‘theoretical’ frequency distribution (It is a relative concept. Actually, we will never know the true distribution). Based on the plotted empirical frequency graph, the best fitting frequency curve can be determined in terms of physical causality or statistics. Thus, the theoretical frequencies of rainfall intensities can also be obtained.

2.4 Parameter Estimation Method for Rainfall Intensity Formula

In China, three—parameter Horner rainfall intensity formula was generally used to represent the relations between rainfall intensity, rainfall duration and rainfall frequency for storm sewer design. In this study, the above relationships were similar. Therefore, the mathematical form of the low return-period rainfall intensity formula is the same as that of storm sewer design and Horner formula is still used here, shown as below.

$$i = \frac{A}{(t+b)^n} \text{ or } i = \frac{A_1(1+C \lg P)}{(t+b)^n}$$

where i is the rainfall intensity (mm/min), P ($=1/F$) is the return period (a), t is rainfall duration (minute), and A, A_1, C, b, n are the local parameters. In this study, t is equal to the time of concentration.

As mentioned earlier, the relationship between rainfall intensity (i) and the theoretical frequency (F) or return period (P) can be determined by the theoretical frequency curve (probability density distribution function). Meanwhile, the maxima of rainfall intensity corresponding a rainfall duration (e.g. 5, 10, 15, 20, 30, 45, 60, 90, 120 min) can be analyzed according to the recorded rainfall series in real applications (Zhang et al. 2016). On this occasion, data of i, t , and P should be collected for all the interceptor sewers for parameters (A, A_1, C, b, n) estimation. Several methods (including moments method, maximum likelihood estimation, MCMC method) can be used to calculate the local parameters of low return-period rainfall intensity formula (Liu et al. 2021).

3 Results of the Case Study

3.1 Study Data

The recorded rainfall data from January 1, 2008 to December 31, 2017 was used in this case study, which are obtained from a urban meteorological station located in Sichuan province of southwestern China. The temporal resolution of the recorded rainfall data is 5 min, as shown in Fig. 3. It was used for calculation of the low-return period rainfall intensity formula.

A combined sewer system was used for validation and verification of the resulted rainfall intensity formula, as shown in Fig. 4. Design data of the combined interceptor sewers, including design flows and times of concentration, were from the completion archives and listed in Table 2.

3.2 Rainfall Statistical Analysis Software

A rainfall statistical analysis software was especially developed to separate rainfall events and obtain their statistics, such as the total number of rainfall events, average rainfall intensity of each rainfall event, the maximum of (average) rainfall intensity for the specific duration, and so on.

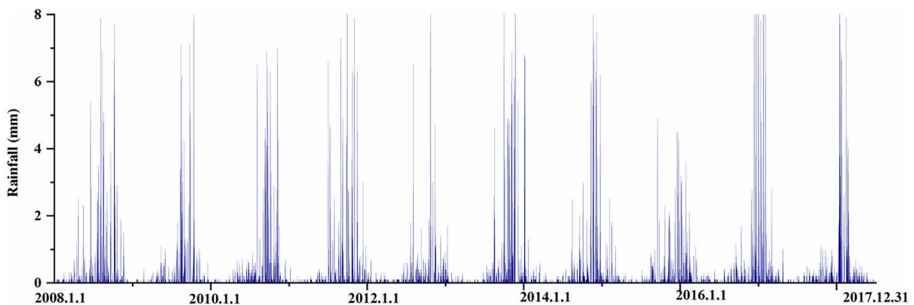


Fig. 3 The recorded rainfall data of the case study (2008/01/01–2017/12/31)



Fig. 4 The combined sewer system for the case study

3.3 Results

3.3.1 Results of MIET Uncertainty Evaluation

In order to evaluate the impact of MIET on the rainfall event separation, three schemes of MIET (1, 2 and 3 h) were studied, respectively. Results were compared with the total amounts and rainfall depths of rainfall events, as shown in Table 3.

First, it reveals that the total amount of rainfall events decreases from 754 to 694 when MIET increases from 1 to 3 h. Meanwhile, variability of the total amount of rainfall events was -5.84% when MIET increases from 1 to 2 h, and -2.25% when MIET increases from 2 to 3 h.

In addition, it terms of mean rainfall depth, variability was 0.9% when MIET increases from 1 to 2 h, and 0.32% when MIET increases from 2 to 3 h. Meanwhile,

Table 2 Design data of the combined sewer system

Number of link	Design areal unit flow(L/(s·hm ²))	Design time of concentration(minute)	Resulted return period (year)
3–2	3.55	34.34	0.080
2–1	4.44	47.65	0.084
1–0	6.28	66.25	0.093

Table 3 Statistics of total amounts, rainfall depth of rainfall events for different MIET values (unit: mm)

Year	Total amounts									Maximum			Minimum			Mean			Median					
	1 h			2 h			3 h			1 h	2 h	3 h	1 h	2 h	3 h	1 h	2 h	3 h	1 h	2 h	3 h			
	77	71	70	82.1	82.2	82.2	82.2	82.2	82.2	2	2	2	2	2	2	2	2	2	12.57	13.98	14.21	6.6	7.1	7.1
2008	77	71	70	82.1	82.2	82.2	82.2	82.2	82.2	2	2	2	2	2	2	2	2	2	12.57	13.98	14.21	6.6	7.1	7.1
2009	61	59	56	66.1	66.1	66.1	66.1	66.1	66.1	2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	10.67	11.41	12.13	5.2	6.3	6.5
2010	81	75	74	95	96.7	96.7	96.7	96.7	96.7	2	2	2	2	2	2	2	2	2	10.83	11.90	12.18	5.2	5.7	5.9
2011	74	65	64	83.3	83.3	83.3	83.3	83.3	83.3	2	2	2	2	2	2	2	2	2	12.42	14.47	14.85	6.6	7.2	7.3
2012	71	69	66	43.5	44.2	44.2	44.2	44.2	44.2	2	2	2	2	2	2	2	2	2	7.55	8.13	8.61	4.3	4.4	4.65
2013	83	80	77	169.3	169.4	169.4	169.4	169.4	169.4	2	2	2	2	2	2	2	2	2	15.11	15.99	16.72	6.9	6.35	6
2014	68	61	62	105	105	105	105	105	105	2	2	2	2	2	2	2	2	2	12.19	13.89	13.85	4.85	5.7	5.55
2015	73	70	68	84.8	124.3	124.3	124.3	124.3	124.3	2	2	2	2	2	2	2	2	2	10.94	11.59	12.10	5.6	5.75	5.8
2016	73	72	70	79.3	79.9	79.9	79.9	79.9	79.9	2	2	2	2	2	2	2	2	2	12.25	12.69	13.19	7.4	7.4	7.55
2017	93	88	87	108.4	108.4	108.4	108.4	108.4	108.4	2	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	9.39	10.19	10.37	4.7	4.7	4.7
Total (2008–2017)	754	710	694	169.3	169.4	169.4	169.4	169.4	169.4	2	2	2	2	2	2	2	2	2	11.39	12.42	12.82	5.4	6.03	5.95
Variability (%)	/	-5.84	-2.25	/	0.06	90.61	/	0	0	0	0	0	0	0	0	0	0	0	/	0.90	0.32	/	11.67	1.33

Table 4 The empirical frequency results of rainfall intensity (unit: mm/min)

No	Rainfall duration(mm)											Empirical frequency (%)	Theoretical frequency (%)
	5	10	15	20	30	45	60	90	120	150	180		
1	2.440	2.230	2.040	1.670	1.727	1.396	1.088	0.753	0.578	0.527	0.563	2.44	2.950
2	2.300	1.850	1.847	1.640	1.330	1.236	1.032	0.744	0.563	0.477	0.442	4.88	5.280
...
39	1.120	0.910	0.787	0.660	0.580	0.458	0.370	0.250	0.214	0.191	0.163	95.12	99.200
40	1.080	0.900	0.740	0.645	0.577	0.444	0.370	0.246	0.214	0.189	0.162	97.56	99.600
...	1.542	1.305	1.137	1.010	0.869	0.717	0.583	0.448	0.335	0.287	0.263
Cv	0.226	0.243	0.280	0.273	0.309	0.335	0.311	0.333	0.305	0.304	0.351
Cs	0.974	0.866	1.102	0.732	1.056	1.152	1.054	0.492	0.787	1.041	1.117
Cs / Cv	4.310	3.562	3.934	2.678	3.423	3.440	3.388	1.478	2.583	3.424	3.185

for the median value, variability was 11.67% when MIET increases from 1 to 2 h, and 1.33% when MIET increases from 2 to 3 h. It is the same results for the the minimum.

In summary, according to the above results for different MIET scenarios, it can be found that most of the statistical indicators rarely changes when MIET equals to 2 h and 3 h. In addition, time of concentration of urban downtown catchment is generally not more than 2 h (except for mega-cities). Therefore, 2 h were selected to carry out the later work.

3.3.2 Results of Rainfall Intensity AMEM Sampling

First, rainfall statistical analysis software (RSAS) was used to obtain the maximum rainfall intensity of rainfall event for different rainfall durations (5, 10, 20, 30, 45, 60, 90, 120 and 180 min). For each rainfall duration, a total of 710 rainfall intensity samples can be obtained.

Second, the first 8 maxima of each year were selected as candidate samples. Thus, there are 80 candidate samples derived from the 10-year recorded rainfall data for the specific duration. Later, 80 candidate samples were sorted in the descending order and the first 40 data were selected as the final samples. Finally, according to Weibull formula, the empirical frequency of each rainfall intensity can be calculated for different durations, as shown in Table 4.

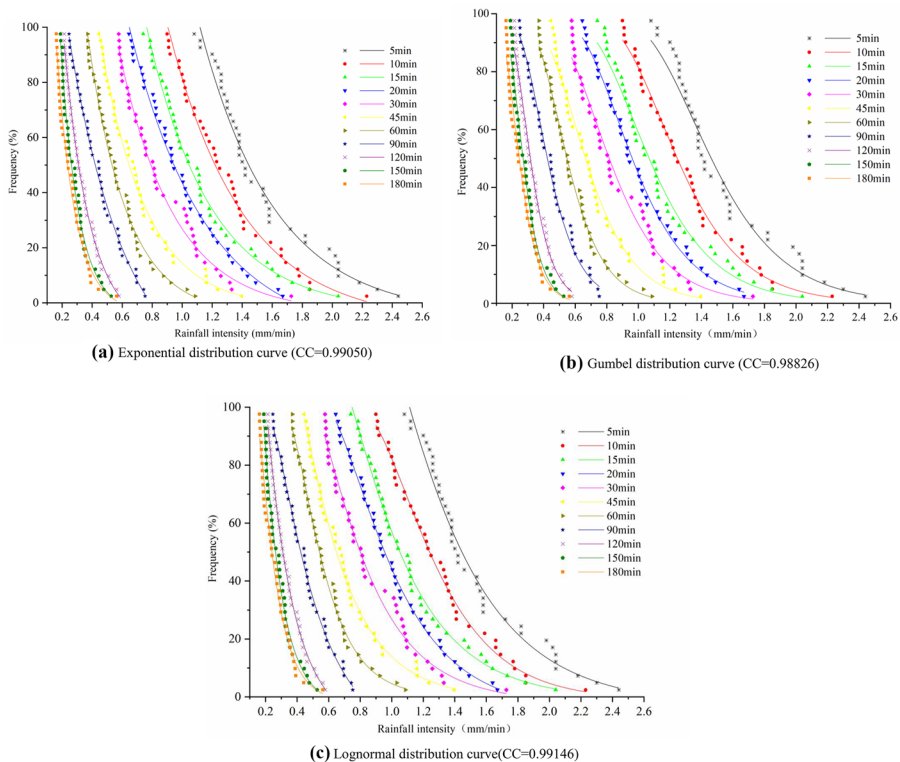


Fig. 5 Comparison of theoretical distribution curves and empirical frequency scatter data

Table 5 Comparison of the theoretical frequency distributions

Rainfall duration (minute)	CC										Mean	
	5	10	15	20	30	45	60	90	120	150		180
Exponential	0.98418	0.98735	0.99426	0.99479	0.9851	0.99313	0.99135	0.99447	0.99672	0.98742	0.98675	0.99050
Gumbel	0.97695	0.99208	0.9886	0.99548	0.98414	0.98767	0.99363	0.9884	0.99244	0.98456	0.98749	0.98826
Lognormal	0.98418	0.99209	0.99495	0.99693	0.9852	0.9933	0.99485	0.99434	0.99655	0.98695	0.98671	0.99146

3.3.3 Results of Frequency Curve Selection

In this study, the exponential distribution, lognormal distribution, Gumbel distribution were used for frequency curve analysis. For each distribution, eleven empirical frequency curves can be plotted for every rainfall duration, as shown in Fig. 5a–c. Moreover, the least square method was used to estimate parameters of the probability density distribution function. Correlation coefficient (CC) was selected as the fitness indicator. It was found that the lognormal distribution was the best-fit one and selected for the calculation of the theoretical frequency of rainfall intensity, as shown in Table 5. Figure 6 presents relationship curves between rainfall intensity, rainfall duration and return period. They can be called as IDF curves for low return periods.

3.3.4 Results of Rainfall Intensity Formula

Based on the above data of the theoretical frequency, rainfall duration and rainfall intensity, MCMC algorithm was used to estimate the local parameters (A_1, C, b, n) of rainfall intensity formula. Resulted rainfall intensity formula for low return period scenarios was shown as follows:

$$i = \frac{28.2852(1 + 0.882 \lg P)}{(t + 28.662)^{0.921}}$$

where i, P, t are the areal unit sanitary flow (or equivalent rainfall intensity), return period, and time of concentration. of the interceptor sewer, respectively.

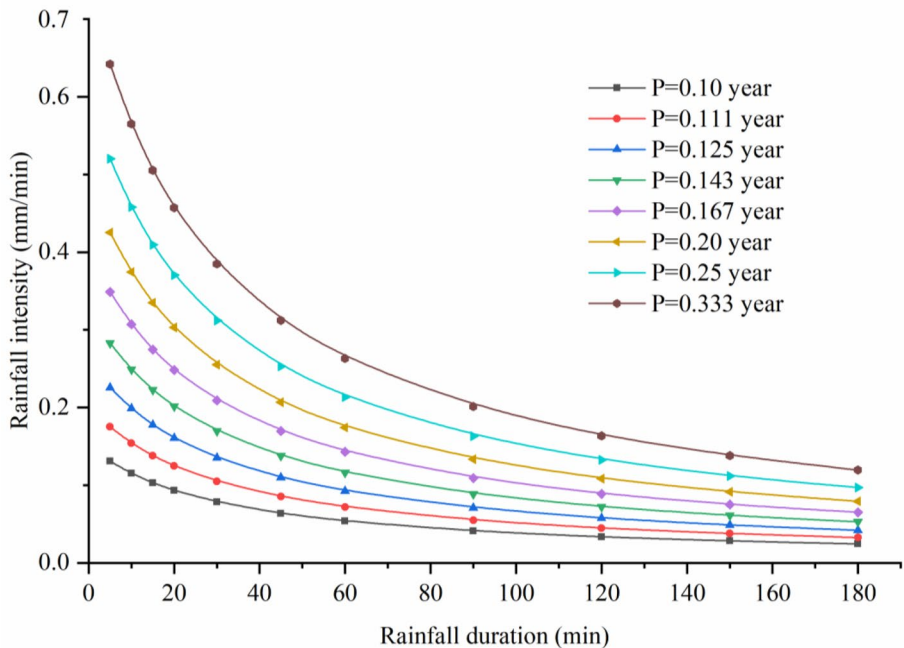


Fig. 6 IDF curves for low return periods

To demonstrate the applicability of the formula, it was used for a combined sewer system to calculate the return periods of the interceptor sewers. Results were shown in Table 2. It revealed that this formula is effective for interceptor sewers.

4 Discussions and Conclusions

In this work, a low- return- period rainfall intensity formula was proposed for the combined interceptor sewers. According to this formula, the equivalent return period (P) of the existing interceptor sewers can be estimated. Here, as the two known parameters, t and i can be obtained according to the completed sewer design archives (Table 2). In addition, this formula can also be used for design scenario of the new interceptor sewer. Design areal unit flow (i) can be acquired based on the formula according to the specified design return period (it is normally related to the CSO control standard) and the corresponding time of concentration. Under this circumstance, as the unknown parameter, the design interceptor ration (n_0) can be calculated according to the design areal unit flow, the local population density and sewage discharge quota of the contributing catchment.

More importantly, this formula can also be utilized for calculating the threshold of CSO from the perspective of the interceptor sewer (or well). As mentioned above, design rainfall intensity of the combined interceptor sewers can be viewed as one of thresholds for occurrence of CSO events. If occurrence of CSO can be judged, CSO frequency can be estimated accordingly. From this standpoint, this formula is helpful to estimate CSO frequency. As we know, CSO spill frequency is one of the important indicators for controlling CSO. Hence, this formula can be employed for design of CSO abatement facilities to meet the requirement of the specific CSO frequency standards.

In addition, thresholds of CSO occurrence at the different interceptor wells are varied and this formula provide us an appropriate approach to calculate their return period thresholds. Currently, observation method is used in many studies for estimation of these thresholds and a large number of monitoring tasks should be carried out in wet weather. This formula offer us a theoretical pathway to estimate one of the critical thresholds of CSO and only few data are needed.

Nowadays, CSO frequency standard has been applied in more and more cities (Lau et al. 2002; Mailhot et al. 2015). The low return period rainfall intensity formula offers an approach to establish the relationship between interceptor ratio, the areal unit sanitary flow, time of concentration, design drainage capacity, return period of the interceptor sewers and CSO frequency.

Author Contributions Xingpo Liu designed the study, co-wrote the the initial draft of the manuscript and made revisions to the draft. Chenmeng Ouyang performed the research and co-wrote the initial draft of the manuscript. Yuwen Zhou contributed to the revisions.

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Availability of Data and Materials The authors confirm that some data are available from the corresponding author on reasonable request.

Declarations

Ethics Approval This paper has neither been published nor been under review for publication elsewhere.

Consent to Participate The authors have participated in the preparation of this paper for publication in the *Water Resources Management*.

Consent to Publish The authors declare their consent to publication of the manuscript in “*Water Resources Management*” journal.

Competing Interests Authors declare no conflict of interest.


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