

Construction and Application of Rapid Stormwater Filter Design Method Based on Rainfall Return Period

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Abstract: To address urban challenges such as waterlogging, water pollution, and water scarcity, this study proposes a design method for rapid rainwater filtration systems based on rainfall return periods. The objective is to purify stormwater and reduce pollutant loads through filtration. The physical design of the rapid filter must account not only for water quality treatment targets, filter media selection, and operational strategies, but also for factors such as rainfall intensity and catchment area. Rainfall intensity is determined by the return period. Using the Chicago Hydrograph Method, rainfall intensity is calculated for different return periods and design storm durations. This intensity, combined with the runoff coefficient and catchment area, is used to estimate the peak runoff rate, from which the minimum required cross-sectional area of the filter is derived. A case study conducted in Nanjing demonstrated that, across various return periods, the runoff flow from a given catchment area consistently peaked at 47 minutes after the onset of rainfall. This peak flow condition represents the maximum treatment demand on the filter, and thus serves as the basis for determining its physical dimensions. Under specified conditions—a 10-year return period, 120-minute storm duration, and a catchment area of 200 m²—the corresponding cross-sectional areas of the rapid filter were calculated for different filtration velocities ($v = 1, 2, 3, \text{ and } 4 \text{ mm/s}$). The results were 10.344 m², 5.172 m², 3.448 m², and 2.586 m², respectively. These findings provide a methodological reference for the design parameters of rapid rainwater filters, and contribute to the advancement of rooftop stormwater utilization technologies and the improvement of urban stormwater management systems in China.

Keywords: Roof runoff; Rapid stormwater filter; System design; Stormwater resource utilization

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1. Introduction

Water is fundamental to life, industrial activity, and ecosystems, playing a critical role in human development. Currently, approximately 400 cities in China are facing severe water scarcity. As a renewable resource with comparatively better quality than industrial wastewater and simpler treatment processes, rainwater represents an important alternative source, and its rational utilization is particularly significant. The main approaches to rainwater resource utilization include direct use, indirect use, and comprehensive application^[1]. Among these, collecting rainwater from rooftops and impermeable pavements is a primary method for direct use^[2], with collection efficiency influenced by factors such as local climate, roofing materials, and rainfall characteristics^[3]. Although China is actively promoting the “Sponge City” initiative, this

effort faces multiple challenges, including uneven spatiotemporal distribution of rainfall and an incomplete planning framework, which affect project performance and effectiveness^[4].

Rapid filter technology, which employs media such as quartz sand, can effectively remove pollutants from stormwater. It offers advantages such as high treatment efficiency, small footprint, and low operational costs, making it suitable for rooftop rainwater treatment. Studies have shown that the time-varying characteristics of rainfall are key factors influencing the performance of rainwater harvesting systems^[5]. While system design should holistically consider water demand and regional conditions, most existing research has focused on filter media selection and purification efficiency, with relatively limited attention given to the design of filter physical dimensions^[6]. To enhance system efficiency and reduce operational costs, this study establishes a design method for rapid filters based on rainfall return periods, using Nanjing as a case study. By systematically analyzing local meteorological and geographical conditions, a tailored technical solution is proposed, providing a valuable reference for rooftop rainwater resource utilization.

2. Design and calculation methods

Based on existing research, a composite filter medium consisting of anthracite and quartz sand exhibits favorable hydraulic conductivity. Therefore, this combination was selected for the rapid filter in the present study. The treated effluent meets the requirements specified in the Chinese national standard “GB/T 18920—2002: Water Quality Standard for Urban Miscellaneous Water Use.”

2.1. Rapid filter cross-sectional area design method

2.1.1. Chicago Hydrograph Method

In this study, the urban storm intensity formula serves as the fundamental basis^[7], with the Chicago Hydrograph Method—centrally derived from this formula—being employed for rainfall hyetograph development. The computational procedure is as follows: First, the average value of the rainfall peak position coefficient for storm events of equal duration is calculated using Equation (1). A weighted average of these values is then computed according to the corresponding storm durations, yielding a composite rainfall peak position coefficient.

$$1r = \frac{t}{T} \quad (1)$$

In the equations above:

t — Time to the rainfall peak (min)

T — Total rainfall duration (min)

r — Rainfall peak position coefficient

Next, when establishing the hyetograph curve, the rainfall intensity i in the Chicago Hyetograph Method is defined as a function of time. The instantaneous rainfall intensity before the peak, $i(t_a)$, and the instantaneous rainfall intensity after the peak, $i(t_b)$, can be calculated using Equations (2) and (3), respectively.

$$i(t_b) = A[(1-n)t_b/r+b]/[t_b/r+b]^{n+1} \quad (2)$$

$$i(t_a) = A[(1-n)t_a/(1-r)+b]/[t_a/(1-r)+b]^{n+1} \quad (3)$$

Where: A , b , n — Constant parameters

Assuming a constant filtration rate in the rapid filter, its treatment capacity is determined by the cross-sectional area. During a rainfall event, the runoff flow rate (Q_{runoff}) varies continuously. For a given filtration rate, the required cross-sectional area of the filter changes accordingly with the fluctuating Q_{runoff} . This results in a dynamic relationship between Q_{runoff} , filtration rate, and the corresponding cross-sectional area, as illustrated in Figure 1. Therefore, to ensure

effective treatment of stormwater runoff throughout the entire rainfall event, the minimum required cross-sectional area must be calculated. The relationship among these variables is governed by the following equation:

$$Q_{\text{runoff}} = \psi \cdot F \cdot q \quad (4)$$

$$V_{\text{runoff}} = Q_{\text{runoff}} \cdot t \quad (5)$$

$$A = \frac{Q_{\text{runoff}}}{v} \quad (6)$$

$$A_{\text{design}} = \frac{Q_{\text{runoff_max}}}{v} \quad (7)$$

Where:

ψ — Rooftop runoff coefficient

F — Catchment area (m^2)

q — Storm intensity (mm/min)

v — Filtration velocity of the filter (mm/s)

A — Cross-sectional area of the filter (m^2)

A_{design} — Minimum required cross-sectional area of the filter (m^2)

The runoff coefficient (ψ) for rooftop rainwater was determined as 0.9 in this study. This value was established with reference to the Chinese national standard “GB 50015-2019: Standard for Design of Building Water Supply and Drainage,” and was systematically calculated by incorporating adjusted surface cover types based on this standard.

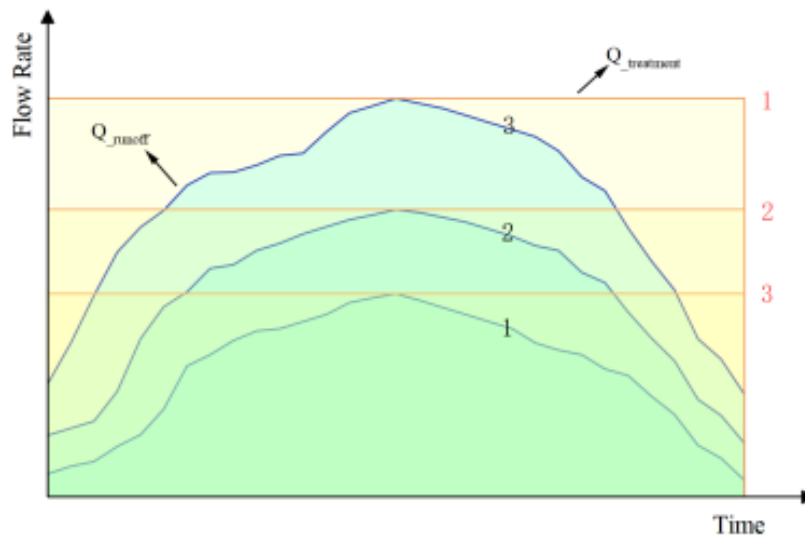


Figure 1. Schematic diagram of the relationship between runoff flow rate and treatment flow rate of the filter tank (1, 2, and 3 represent three corresponding groups of different runoff and treatment flow rates).

2.2. Design of the Required rapid filter cross-sectional area based on return period

2.2.1. Design storm intensity

Nanjing, located in the southwestern part of Jiangsu Province within the middle and lower reaches of the Yangtze River, is selected as the case study area. The region experiences a humid northern subtropical climate, characterized by distinct seasonal variations and abundant rainfall. Precipitation is particularly concentrated from June to August, accounting for approximately 50% of the annual total. Seasonal distribution of rainfall generally follows the pattern: summer > spring > autumn > winter^[8]. According to the “Nanjing Storm Intensity Formula (Revised) Reference Table,” the storm intensity

formula for Nanjing is given by Equation (7) as follows:

$$q = \frac{10716.700(1+0.837\lg P)}{(t+32.900)^{1.011}} \quad (7)$$

Where:

q — Design storm intensity (mm/min)

P — Return period (years)

t — Rainfall duration (min)

This study employs the Chicago Hyetograph Method^[9], which is derived from the storm intensity formula, to generate design storm hyetographs. The rainfall peak position coefficient (r) for Nanjing's urban area was adopted as 0.39, based on the findings of Ni et al.^[10] who calculated this value using precipitation data from 1982 to 2015. Considering the short concentration time characteristic of urban core areas, the design storm duration was set at 120 minutes. Design rainfall intensities for different return periods were subsequently generated using the aforementioned parameters, as illustrated in Figure 2.

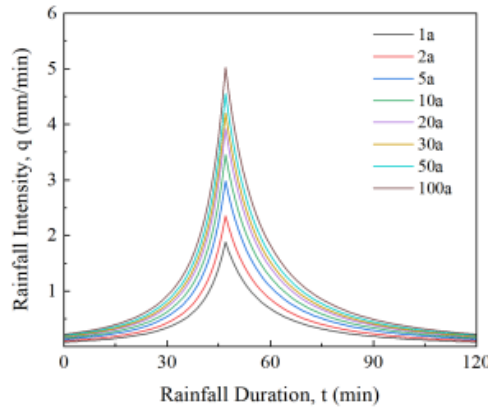


Figure 2. Nanjing short calendar time, Chicago rain type (120 min).

2.2.2. Design rainfall runoff, treatment flow, and rapid filter cross-sectional area

The design short-duration storm hyetograph was developed in accordance with the “Technical Guidelines for Formulating Urban Storm Intensity Formulas and Determining Design Storm Hyetographs,” utilizing the Chicago Hyetograph Method. This method constructs a single-peaked hyetograph based on the storm intensity formula, where the design rainfall intensity follows a typical unimodal curve, initially increasing before decreasing^[7]. The required cross-sectional area of the rapid filter is primarily determined by the runoff flow rate and the filtration velocity. To thoroughly investigate how the required cross-sectional area varies under different conditions, this study assigned specific parameter values for the return period, runoff coefficient, catchment area, and filtration velocity. The rooftop runoff coefficient (ψ) was set at 0.9. Return periods (P) were selected as 1, 2, 5, 10, 20, 30, 50, and 100 years, and catchment areas (F) were chosen as 50 m², 100 m², 200 m², 300 m², and 500 m². Filtration velocities (v) were set at 1, 2, 3, and 4 mm/s. By analyzing and calculating different parameter combinations, the corresponding required cross-sectional areas of the rapid filter under multiple scenarios were determined.

3. Results and discussion

3.1. Rainfall process and runoff flow rate based on different return periods

As shown in Figure 3, the variation in runoff flow rate (Q_{runoff}) aligns with the design rainfall intensity pattern, characterized by an initial increase followed by a decrease, peaking at 47 minutes before gradually declining. The

maximum treatment capacity of the rainwater filter must accommodate this peak runoff flow rate; otherwise, overflow measures are required for system protection. Consequently, the physical dimensions of the rapid filter should be designed based on the treatment capacity corresponding to this maximum runoff flow rate. The peak rainwater flow rate increases with higher return periods, indicating that greater return periods correspond to greater peak runoff rates.

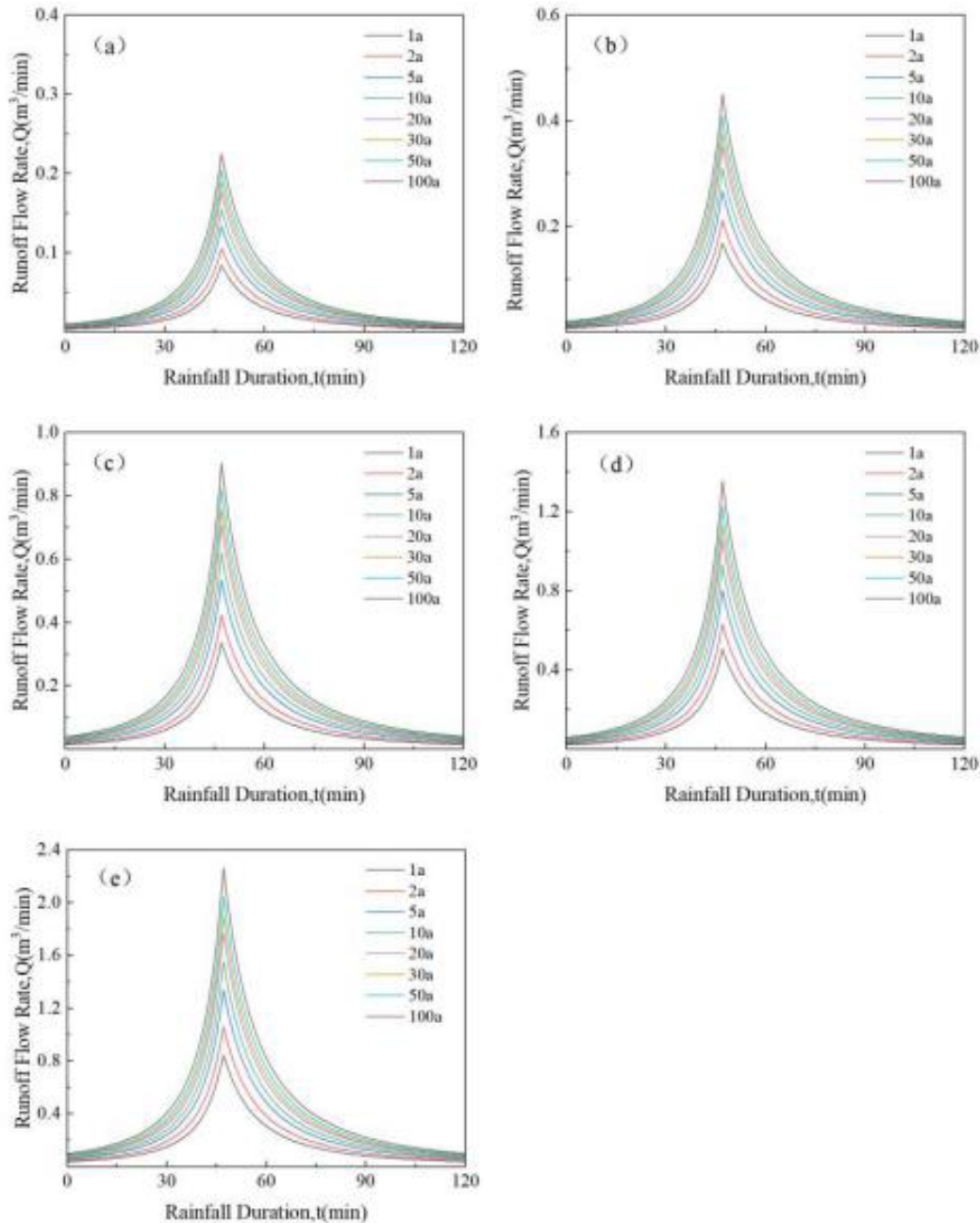


Figure 3. Changes in runoff flow at different catchment areas (a, b, c, d, and e represent catchment areas $F = 50, 100, 200, 300$, and 500 m^2 , respectively).

3.2. Variation trend of rapid filter cross-sectional area with rainfall duration

Based on the preceding analysis, when the rainwater runoff flow rate determines the treatment capacity, the required cross-sectional area of the rapid filter is primarily governed by the runoff flow rate and the filtration velocity. The design cross-sectional area of the filter should correspond to the maximum area required at the time of peak runoff flow, which occurs

at the 47-minute mark in this case. As illustrated in Figure 4, the required cross-sectional area varies dynamically over time, with its minimum value increasing at higher return periods and reaching a maximum at the flow peak. Thus, the cross-sectional area required at this specific moment is defined as the design area (A_{design}). For a given catchment area, the size of the rapid filter decreases as the filtration velocity increases, a relationship influenced by properties of the filter media such as particle size and material composition.

As shown in Figure 4 (a) (filtration velocity $v = 1 \text{ mm/s}$), at the 47-minute peak rainfall moment, the required cross-sectional area increases from 2.8155 m^2 to 7.5285 m^2 as the return period rises from 1 year to 100 years. In contrast, Figure 4 (d) indicates that at a filtration velocity of 4 mm/s , the maximum required cross-sectional areas at the 47-minute mark are 0.7039 m^2 and 1.8821 m^2 for the same return periods. Therefore, for a fixed catchment area, both the rainfall return period and the filtration velocity significantly influence the required cross-sectional area of the rapid filter.

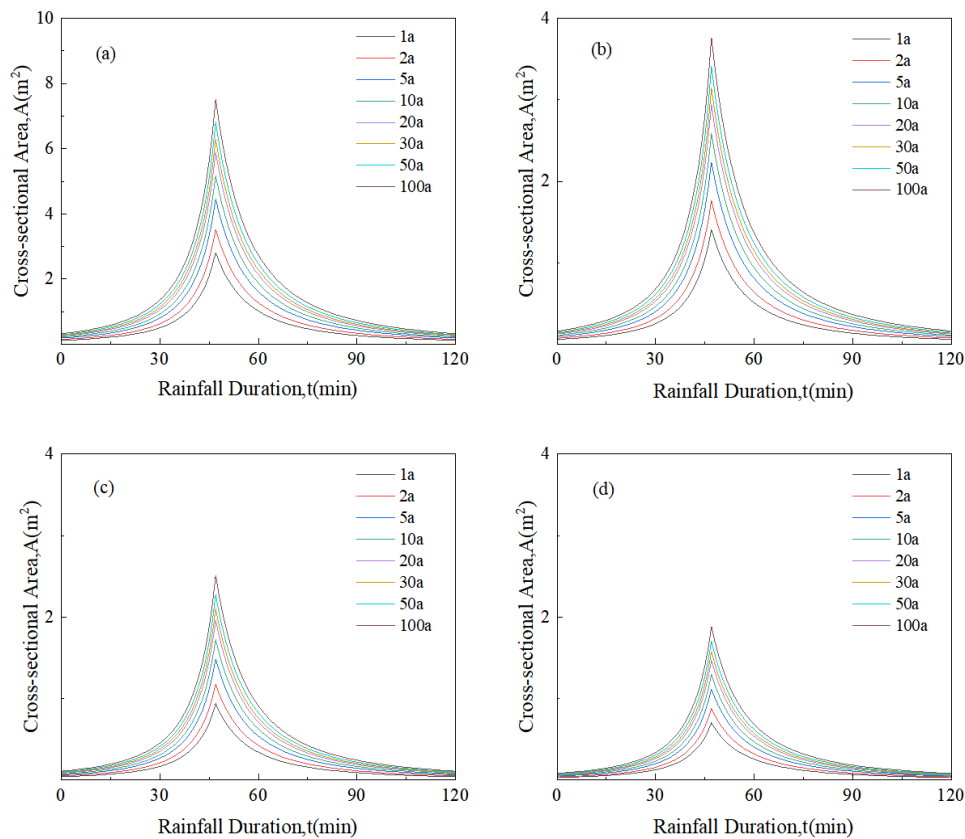


Figure 4. Variation of required cross-sectional area with rainfall calendar time for different filtering rates in filter cells ($F = 100 \text{ m}^2$).

3.3. Quantitative analysis of the minimum cross-sectional area under different conditions

Figure 5 illustrates the relationship between the required cross-sectional area of the filter and the filtration rate under different catchment areas and rainfall return periods. As shown, for a given catchment area, the required design area (A_{design}) gradually decreases as the filtration velocity increases. Furthermore, at a constant filtration velocity, larger catchment areas correspond to increased A_{design} values across all conditions. Comparing Figures 5 (a) to Figure 5 (e), under a return period of 10 years and a filtration velocity of 2 mm/s , the required A_{design} values for catchment areas of 50 m^2 and 500 m^2 are 1.293 m^2 and 12.93 m^2 , respectively. These results demonstrate that both catchment area and filtration velocity significantly influence the sizing of rapid filters, with larger areas requiring proportionally larger filter dimensions while higher filtration velocities allow for more compact designs.

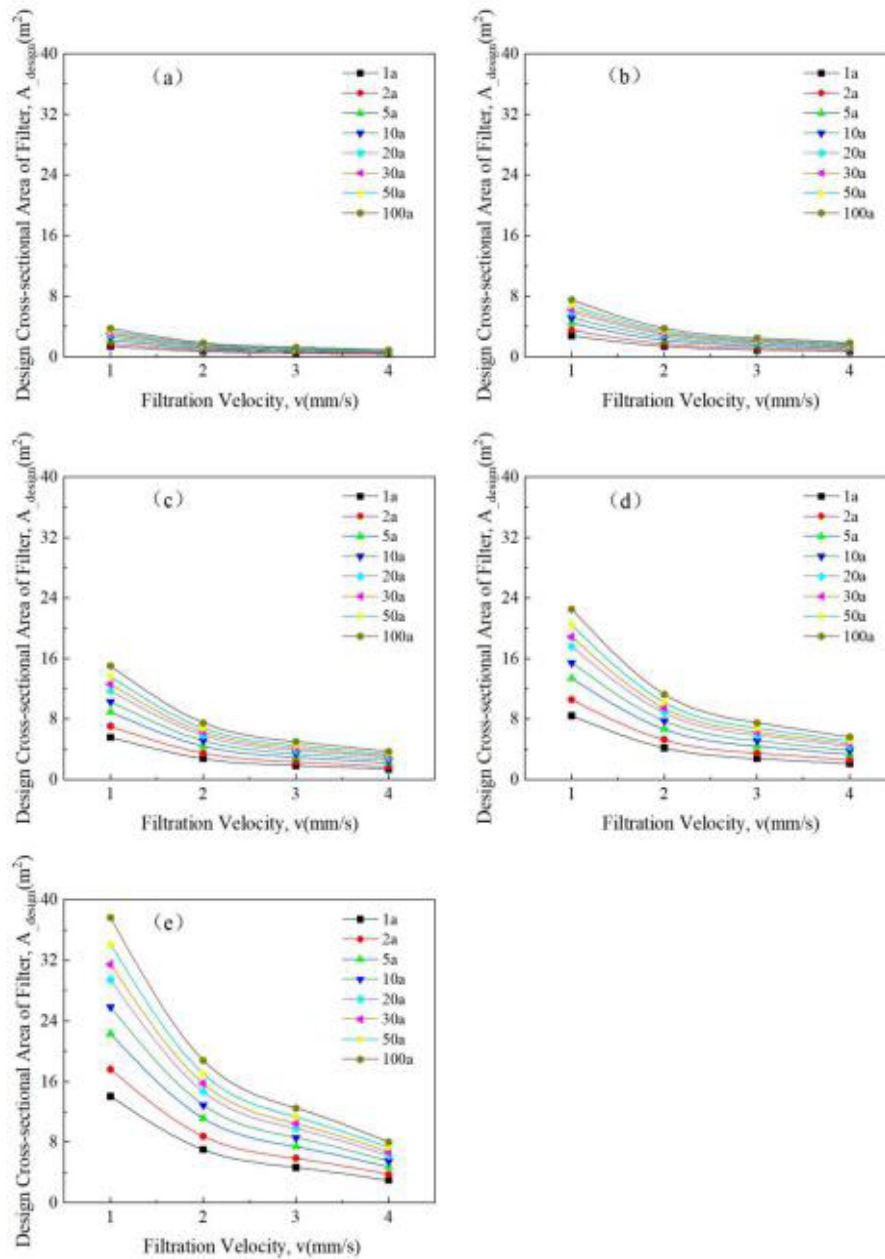


Figure 5. Changes in cross-sectional area of filter cell design for different confluence areas (a, b, c, d, and e represent catchment areas $F = 50, 100, 200, 300$, and 500 m^2 , respectively).

Figure 6 illustrates the relationship between the required design cross-sectional area (A_{design}) and the catchment area under different filtration velocities ($v = 1, 2, 3, 4 \text{ mm/s}$) and across different return periods.

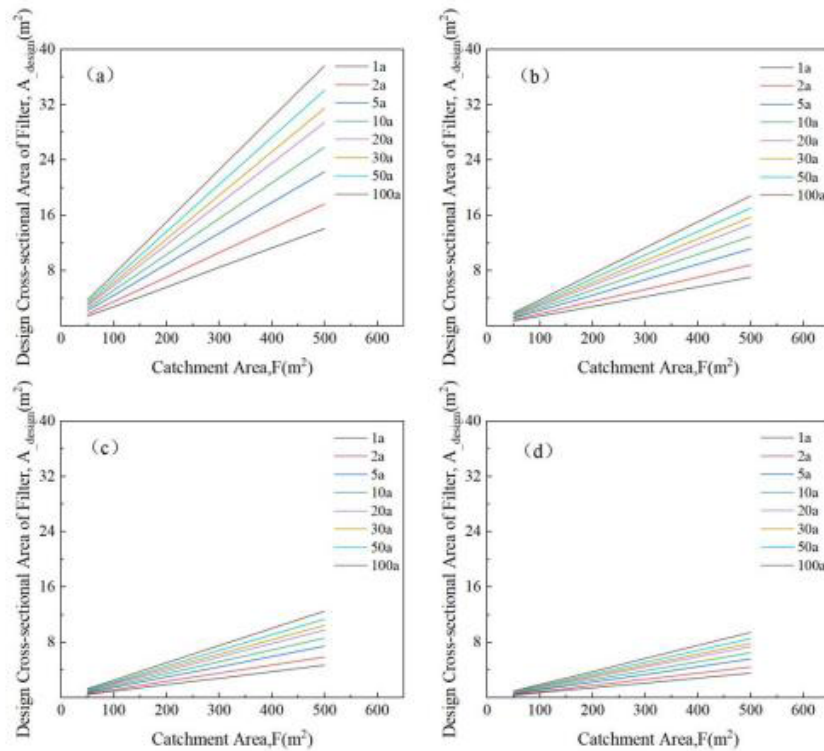


Figure 6. Changes in cross-sectional area of filter cell design for different filtration rates (a, b, c, and d represent filtration velocities $v = 1, 2, 3,$ and 4 mm/s, respectively).

Depending on the specific context of the study area and the intended application scenarios, appropriate values for parameters such as the return period (P), catchment area (F), and filtration velocity (v) can be selected. Using the design method presented in this study, the corresponding design cross-sectional area (A_{design}) of the rapid filter can be determined for any such combination.

4. Conclusion

This study developed a design framework for determining the cross-sectional area of rapid filters based on rainfall return periods and the Chicago Hyetograph Method, with a case application in Nanjing validating the approach. The methodology involves calculating rainfall intensity using the Chicago Hyetograph Method for specified return periods and storm durations, then determining the runoff flow rate by incorporating the runoff coefficient and catchment area, which ultimately defines the required filter design area. Case study results for Nanjing indicate that both the runoff flow rate and volume exhibit a unimodal distribution pattern, with their peak values increasing with higher return periods. The physical dimensions of the filter should be determined according to the treatment capacity required at the maximum runoff flow rate. The necessary filter area decreases with higher filtration velocities but increases with larger catchment areas.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Li P, Qian H, 2018, Water Resources Research to Support a Sustainable China. *International Journal of Water Resources Development*, 34(3): 327–336.
- [2] Zhou J, Pang Y, Wang H, et al., 2023, Review of Urban Rainwater Harvesting Development in China. *Water Resources and Hydropower Engineering*, 54(5): 61–74.
- [3] Liang W, 2014, Current Status and Research Progress of Urban Rainwater Collection and Utilization. *Industrial Water & Wastewater*, 45(3): 6–9.
- [4] Mao J, Xia B, Zhou Y, et al., 2021, Effect of Roof Materials and Weather Patterns on the Quality of Harvested Rainwater in Shanghai, China. *Journal of Cleaner Production*, 279: 123419.
- [5] Haque M, Rahman A, Samali B, 2016, Evaluation of Climate Change Impacts on Rainwater Harvesting. *Journal of Cleaner Production*, 137: 60–69.
- [6] Peng J, He S, Chen L, et al., 2021, Filtration Performance and Operation Effect of Fine Sand Filter Media. *China Water & Wastewater*, 37(1): 40–45.
- [7] Feng C, Mi N, Wang X, et al., 2015, Analysis of Road Runoff Pollutants in Southern City Based on the Typical Rainfall. *Ecology and Environmental Sciences*, 24(3): 418–426.
- [8] Mao Y, Wu H, Pei H, et al., 2012, Climate Features of Summer Rainfall in Nanjing During Recent 50 Years. *Journal of the Meteorological Sciences*, 32(6): 646–652.
- [9] Xu C, Jing Y, Chen W, 2018, The Ascertain and Application on Urban Design Rainfall Pattern. *Henan Science and Technology*, 2018(5): 159–160.
- [10] Ni Z, Li Q, Du F, et al., 2019, Study on Design of Rainstorm Pattern Based on Short Duration in Nanjing City. *Journal of Water Resources and Water Engineering*, 30(2): 57–62.

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