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EFFECTS OF RAINFALL ON REDUCTION OF URBAN NON-POINT SOURCE POLLUTION LOAD IN A LOW IMPACT DEVELOPMENT (LID) RESIDENCE COMMUNITY IN SHAANXI, CHINA

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Abstract

In order to study the influence of different rainfall processes on the total pollutant load of non-point sources and pollutant load reduction rate of the low-impact development facilities, this paper took a Low Impact Development (LID) community of Tianfuheyuan, Fengxi new city, Xixian new district in Shaanxi, China as an example, and constructed the storm water management model (SWMM) of the study area. The computed results demonstrate that the storm patterns have obvious effects on the pollutant load and its reduction. The effect trend is similar to the runoff and runoff control process by LID measures. With the increase of the return period, the total pollutant load increases and the pollutant load reduction rate decreases. That is, the higher the rainfall intensity is, the less pollutant the LID measures could mitigate. Compared with the return period of 1a, the total pollutant load increased by 74.36% – 248.26% and the pollutant load reduction rate decreased by 3.67% – 10.27%, respectively, when the return period is 2a – 10a. The rain peak location has slight impact on the urban non-point source pollution. Compared with the rain peak coefficient of 0.2, the total pollutant load is decreased by 2.24% – 6.95% and the pollutant load reduction rate is increased by 0.24% – 0.74%, respectively, when the rain peak coefficient is 0.3 – 0.6. This research can help understand the mechanism of the non-point source pollution mitigated by the LID measures, and plan or design the LID measures.

Key words: low impact development, non-point source pollution, pollutant load, runoff control, SWMM model

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1. Introduction

Non-point source pollution in urban areas refers to water pollution caused by urban roof, road surface and other ground pollutants entering rivers and lakes in a wide-area and dispersed form under the action of rainfall runoff leaching and scouring (Shen et al., 2020; Wang et al., 2010). Rainfall is the driving factor of urban non-point source pollution and runoff is the carrier of non-point source pollutant migration. Therefore, in a narrow sense, urban non-point source pollution refers to urban rainfall runoff pollution, which is the most important form of urban non-point source pollution (Zhang Y.Y. et al., 2006). The study on urban non-point source (UNPS) pollution in foreign cities started earlier. At present, rainfall runoff pollution is becoming more and more serious in China. SWMM (Storm Water Management Model) can dynamically simulate the occurrence, migration and discharge of non-point source pollution (Li et al., 2011; Qin et al., 2016).

Many researchers also studied urban non-point source pollution in different regions based on SWMM model. For example, Characklis and Wiesner (1997) studied the distribution of dissolved state and gel metal content in surface runoff by monitoring the

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water quality at the outlet of municipal drainage system in sunny and rainy days. Dietz (2007) found that green roofs can reduce runoff by 60-70% compared with traditional roofs. Hood et al. (2007) found that LID facilities could effectively reduce the runoff coefficient and significantly reduce the runoff under the condition of low rainfall intensity. Jiang et al. (2011) studied the effects of different precipitation on Total Suspended Solid (TSS) of urban rainfall runoff. Ma X.H. et al. (2012) studied the effects of different return periods on urban non-point source loads. Chen S. and Chen X.H. (2018) studied the influence of Low Impact Development (LID) (a storm management and nonpoint source pollution treatment technique for controlling storm runoff and pollution through decentralized, small-scale source control) measures on urban rainwater runoff pollution. However, there are few studies focusing on pollutant load (the amount of pollutant carried by a region or an environmental element) reduction by using LID under different rainfall processes.

Therefore, this paper investigates the impacts of the storms on the non-point source pollution in a LID residence community—Tianfuheyuan community in Shaanxi, China, through modelling the pollution-load reduction effect of LID measures under different storms with multifarious return periods and rain peak coefficients.

2. Material and methods

2. 1. Study area and data

The research area of this paper is Tianfuheyuan community in Fengxi new town, Xixian new area, and Shaanxi province. The area is located in the south of Xian yang city, with an average annual precipitation of about 520mm. Most precipitation in the summer comes in the form of heavy rains.

The study area covers an area of 3.67hm^2. It is a LID residence community (Fig. 1). Two LID measures (Fig. 2), i.e. rain garden and permeable pavement, are laid out, accounting for 7.92% and 14.34% area, respectively. A brief description of the terrain, hydrology and other data for the study area are listed in Table 1.

Bi et al. (2015) pointed out that the short-duration rainstorm in urban areas of Xi'an was relatively concentrated, with the single peak type in the majority, and the comprehensive rain peak coefficient was 0.35481. Cen et al. (1998) pointed out that the rain pattern of Chicago was an uneven design rain pattern based on the intensity-duration relationship. The flood peak was not affected by the duration, and the rain intensity process was easy to determine. In the large return period, people pay more attention to the waterlogging problem rather than the water quality problem, so the small return period has more practical significance for the water quality model (Cai et al., 2017). Regarding the design storm, a Chicago-type design storm is applied in this work. The storm intensity formula of Xi'an (Hou et al., 2017) is given by Eq. (1):

$$q = \frac{2210.87(1 + 2.915 \lg P)}{(t + 21.933)^{0.974}} \tag{1}$$

where: q represent the intensity of rainstorm, L/ (s · hm^2); P represent the return period, a; t represent the duration of rainstorm, min.

When considering the return period, the storm with the return periods of 1a, 2a, 3a, 5a, 10a and the peak coefficient of 0.4 respectively are used. When investigating the rain peak coefficients, they are set as 0.2, 0.3, 0.4, 0.5, 0.6 respectively with the return period of 2a. For all cases, the storm duration is assumed as 120min. The design storms are shown in Fig. 3.

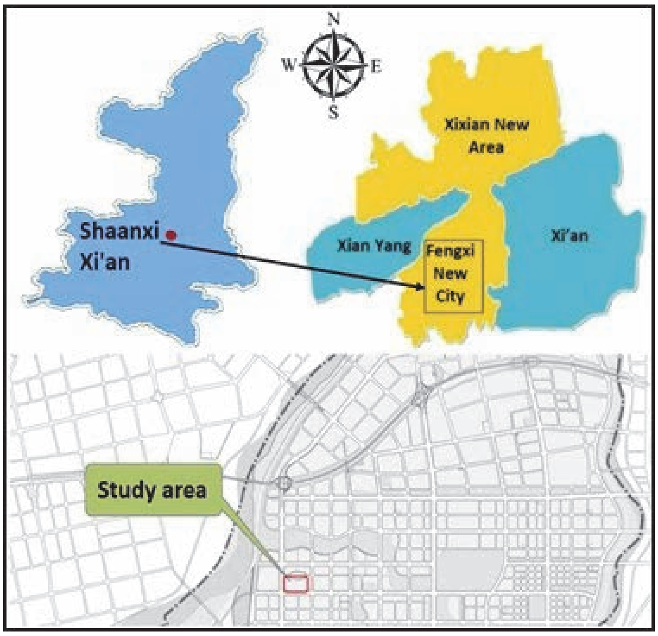


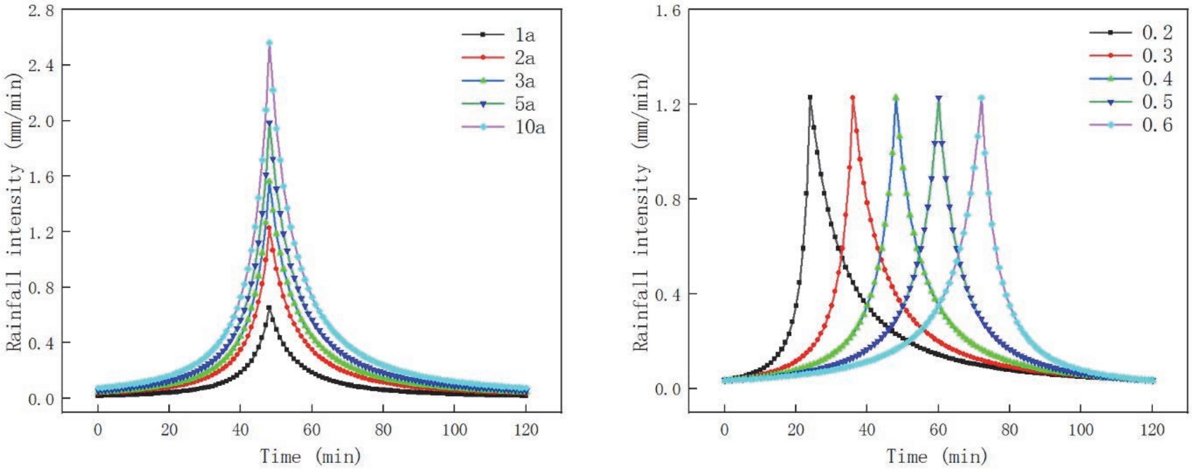
Fig. 1. Location of the study area

(a) (b)

Fig. 2. LID measures: (a) Permeable pavement, (b) Rain garden

Table 1. Data sources for the model

The data type	***Name***	***Method applied***
Network data	Node elevation, Buried depth, Pipe diameter, Pipe length	CAD drawings
Underlying surface data	Land use type, Catchment area and Slope	CAD drawings
Rainfall data	Rainfall, Rainfall intensity, Rainfall duration	Rainfall data measured by weather stations
Hydrological model data	Parameters of infiltration, Impermeable proportion and Volume of depression	Rate constant
Water quality model data	Cumulative function, Scour function, Cleaning removal rate	SWMM user manual and reference water quality model parameters in similar areas



(a) (b)

Fig. 3. Design storms with different: (a) return periods and (b) rain peak coefficients

2.2. Numerical model

In this paper, SWMM model software was used as a rainfall runoff simulation tool. SWMM model includes hydrological process simulation, hydraulic process simulation and water quality process simulation. It is a rainfall runoff model based on hydrodynamics. The hydrological hydrodynamic module includes surface runoff and pipeline runoff. SWMM first divides the study area into several sub catchment areas, and calculates surface runoff and catchment respectively in each catchment area. The study area includes three types of land use: permeable area, impervious area with hollow storage and impervious area without hollow storage. SWMM model provides a variety of production and flow simulation methods for selection. The infiltration models in the surface runoff process include Horton formula method, Green-Ampt formula method and SCS-CN method. In the Horton model, the infiltration decreases exponentially from the initial maximum rate to the minimum rate during the whole long-term rainfall time. Horton model is more suitable for urban areas among them and has few undetermined parameters, so it is adopted for further calculation.

The nonlinear reservoir method is used to solve Manning formula and continuity equation simultaneously in the surface confluence process.

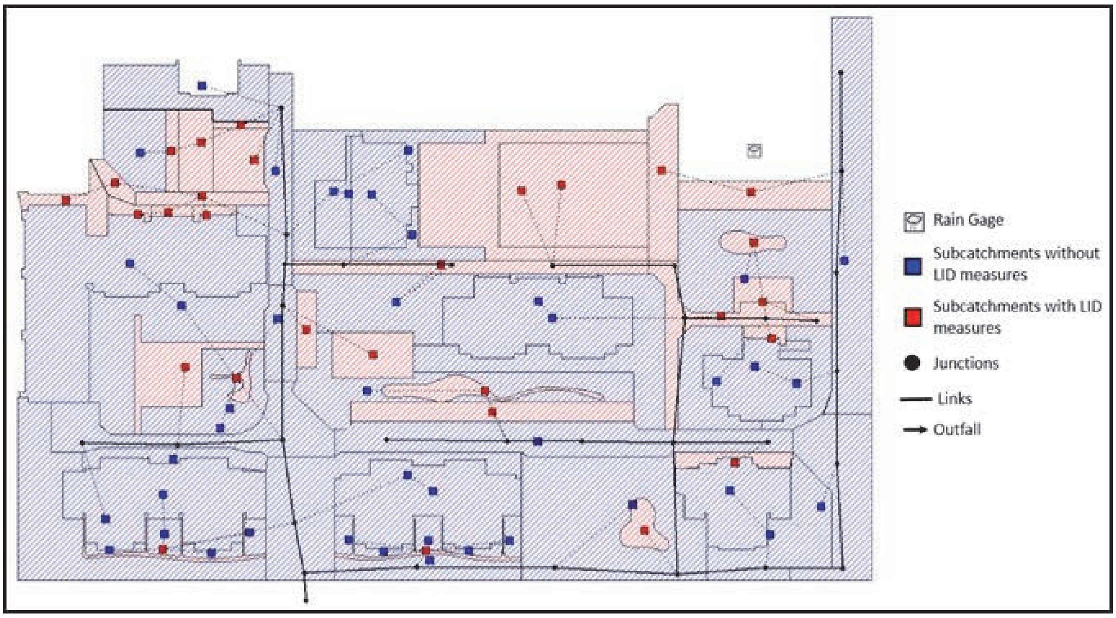


Fig. 4. Study area generalization diagram

The nonlinear reservoir method assumes that the relationship between soil storage and outflow is nonlinear, and each sub-catchment area is treated as a nonlinear reservoir, whose capacity is the storage of the largest depression. Surface runoff occurs only when the water depth of the reservoir exceeds that of the largest depression. The outflow is calculated by manning formula. In SWMM model, three calculation methods of steady flow, motion wave and dynamic wave are provided for pipeline confluence. The steady flow method is the simplest of the three algorithms, it assumes that the flow is uniform and constant in each calculated time step. The method of motion wave include the calculation of the flow continuity equation and the momentum conservation equation by simplifying the momentum equation of each pipeline. The two methods are simplified methods with high computational efficiency but with general application effect. The dynamic wave method is based on the complete one dimensional Saint-Venant flow equation. It has the most accurate result in theory and the best application effect (Ren et al., 2010; Zhang M.L. et al., 2007). In this paper, the dynamic wave method is adopted.

The water quality module defines the accumulation model and scour model of various surface pollutants according to the functional area or land use type to simulate the growth, scour, transportation and treatment process of pollutants in surface runoff. This paper adopts the saturation function accumulation model and the exponential function erosion model (Chen et al., 2013; Huber et al., 1995; Mei et al., 2017; Xu, 2014). Water quality parameters selected four representative storm water runoff pollutants, namely TSS, COD, TN and TP, as simulation objects. Yuan et al. (2011) showed that various pollutants mainly adhered to solid particles, and COD, TN and TP had a good correlation with TSS. Therefore, TSS was taken as an example for this study. For the study case, the model firstly divides the research area into several sub-catchment zones, generalizes the pipe network, and then selects the appropriate flow direction according to the actual terrain, through the process of production-catchment and pipe network catchment, and finally carries out simulated monitoring at the exit. LID measures were arranged in the study area according to the low-impact development layout drawings provided by the Fengxi new town management committee, and the study area is divided into three land use types green space, roads, houses, area accounted for 39.89%, 22.77% and 15.09% respectively. The model has 71 sub-catchment zones, 31 nodes, 31 sections of rainwater pipe network, and 1 outlet in the southwest. The generalization diagram of LID situation model is shown in Fig. 4.

2.3. Parameter calibration and model validation

Hydrological and hydrodynamic parameters were determined according to the measured rainfall runoff data of Fengxi new town on August 20 and September 9, 2017. The calibration results of main hydrological parameters are shown in Table 2. The research area is relatively small and the space change is not large, so the slope of each sub-catchment area is set as 0.5% according to the average slope, and the underlying surface parameters of the same attribute are set as the same. Hydrodynamic parameters were determined according to the measured rainfall runoff data of Fengxi new town on August 20 and September 26, 2017. The calibration results of main hydrological parameters are shown in Table 2.

Due to the lack of measured water quality monitoring data in this research area, the water quality parameters were obtained by referring to the research data in the same area (Ma et al., 2017), as shown in Table 3. The rainfall, runoff and measured discharge data on September 16, 2017 and September 26, 2017 were used to verify the model. The comparison between simulated data and monitoring data is shown in Fig. 5.

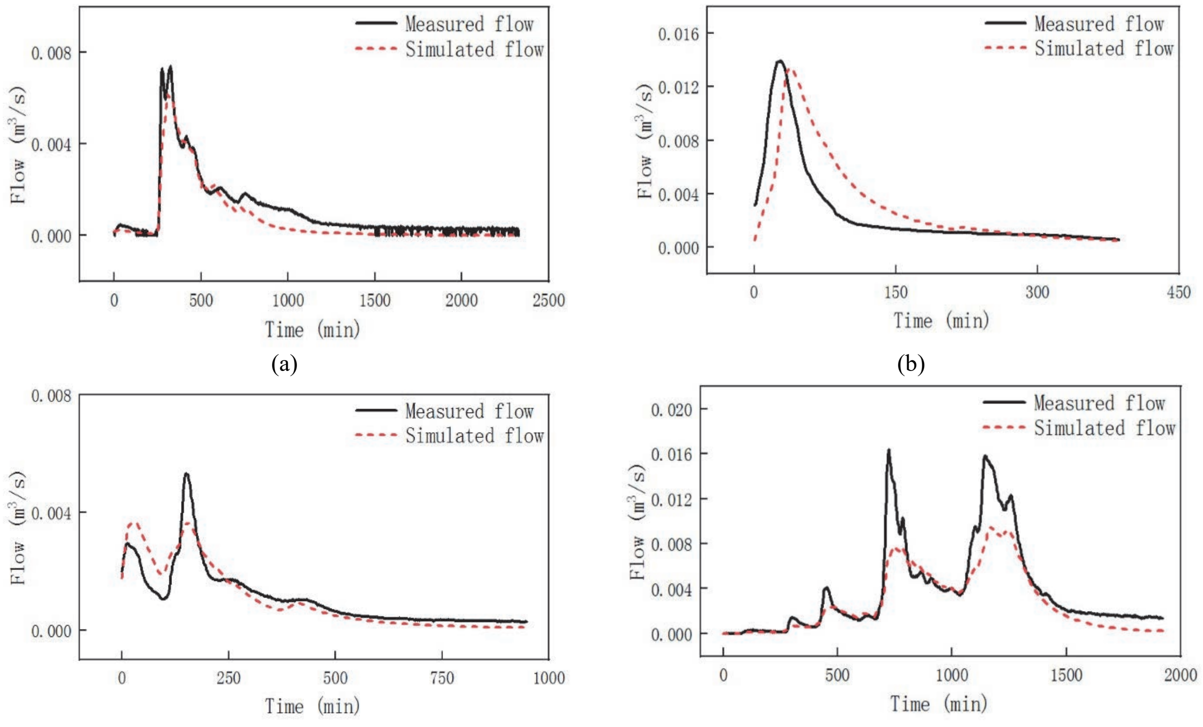
In this paper, Nash-Sutcliffe efficiency coefficient (E_{ns}) is used to evaluate the simulation performance of the model. The values of E_{ns} close to 1 indicates that the model has high credibility and good simulation effect (Liu et al., 2018).

Table 2. Hydrodynamic parameters of the model

	Name	*Unit*	*Reference range*	*Calibration results*
Subcatchment area	N-Imperv	/	0.001-0.015	0.0045
	N-Perv	/	0.100-0.300	0.200
	S-Imperv	mm	1-3	3
	S-perv	mm	3-10	7
Horton model	Max Rate	mm/h	10.0-100.0	24.5
	Min Rate	mm/h	0.0-10.0	3.1
	Decay Constant	L/h	0-7	5
Pipe	Roughness	/	0.001-0.400	0.013

Table 3. Water quality parameters of the model

Land use type	*Parameters of TSS*		
Building	Cumulative process parameter	Maximum cumulant /(Kg · ha)	140
		Half full and total time /d	10
	Erosion process parameter	Scouring coefficient	0.009
		Flushing index	0.400
Greenbelt	Cumulative process parameter	Maximum cumulant /(Kg · ha)	120
		Half full and total time /d	10
	Erosion process parameter	Scouring coefficient	0.090
		Flushing index	0.200
Road	Cumulative process parameter	Maximum cumulant /(Kg · ha)	130
		Half full and total time /d	8
	Erosion process parameter	Scouring coefficient	0.008
		Flushing index	0.500



(a) (b)

(c) (d)

Fig. 5. The computed and measured discharge at the outlet of the southwest: (a)August 20, 2017, (b) September 9, 2017, (c) September 16, 2017, (d) September 26, 2017

The E_{ns} of the four rainfall events on August 20, September 9, September 16 and September 26, 2017 were 0.49, 0.87, 0.80 and 0.76 respectively. Therefore, it can be considered that the hydrodynamic parameters of the SWMM model are reasonable and the reliability of the model constructed is high.

3. Results and discussion

3.1. Impact of the return periods on pollutant load reduction

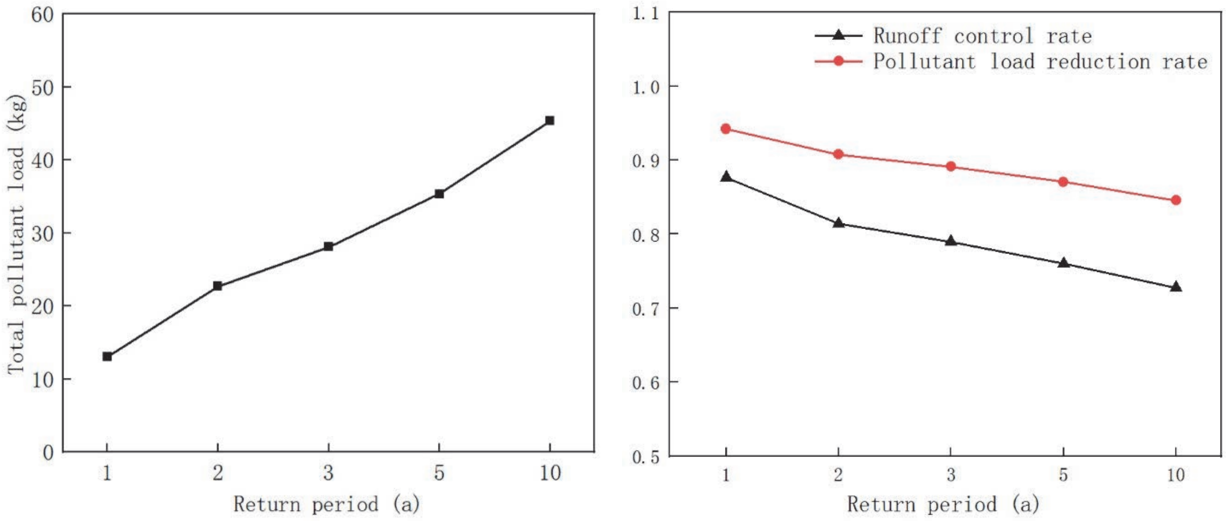
As shown in Fig. 6, the total pollutant load was 13.02kg – 45.34kg within the return period of 1a – 10a. Compared with the return period of 1a, the total pollutant load with the return period of 2a – 10a increased by 74.36% – 248.26%, the total pollutant load is positively correlated with rainfall intensity, and the greater the rainfall intensity, the greater is the pollutant discharge. This is because the rainfall intensity increases, the runoff is large, and also the runoff scour of pollutants is larger. This also leads to the decrease of pollutant load reduction rate (the proportion of the controlled amount of pollutants in the site to the total pollutant load) with the increase of return period.

When the return period 1a increased to 10a, the runoff control rate (the proportion of controlled rainfall in the site to total rainfall) decreased from 87.64% to 72.73%, and the pollutant load reduction rate decreased from 94.21% to 84.54%. Compared with the return period of 1a, the runoff control rate and pollutant load reduction rate of 2a – 10a respectively decreased by 7.14% – 17.02% and 3.67% – 10.27%. The reduction range of runoff control rate was 3.47% – 6.75% higher than that of pollutant load reduction rate.

This indicates that the variation trend of pollutant load reduction rate and runoff control rate is the same. With the increase of return period, both decrease by a similar range, indicating a good correlation between the two. When conducting correlation analysis on the two variables of runoff control rate and pollutant load reduction rate, Pearson correlation coefficient was 0.997 by SPSS analysis, which was close to 1. This means that there is a conspicuous correlation between them. This is because the carrier of pollutant transport is runoff formed by rainfall. The reason why the runoff control rate and pollutant load reduction rate of this residential area are relatively high is that the layout area of LID measures in this residential area is 22.26%, the green area 39.89%, and the impervious area 37.86%. Both LID measures and green areas have good effects on runoff control and pollutant reduction.

3.2. Impact of the rain peak coefficients on pollutant load reduction

As shown in Fig. 7, the total pollutant load decreased from 23.66kg to 22.01kg within the range of 0.2 – 0.6 rain peak coefficient. Runoff control rate and pollutant load reduction rate were 81.17% – 81.72% and 90.36% – 91.03%, respectively. Within the range of rain peak coefficient 0.2 – 0.6, with the increase of rain peak coefficient, the total pollutant load decreased, and the runoff control rate and pollutant load reduction rate increased, but the change was not obvious. Compared with the rain peak coefficient of 0.2, the total pollutant load decreased by 2.24% – 6.95% when the rain peak coefficient was 0.3 – 0.6, and the runoff control rate and pollutant load reduction rate increased by 0.13% – 0.68% and 0.24% – 0.74%.



(a) (b)

Fig. 6. Simulation results under different return periods: (a) total pollutant load, (b) runoff control rate and pollutant load reduction rate

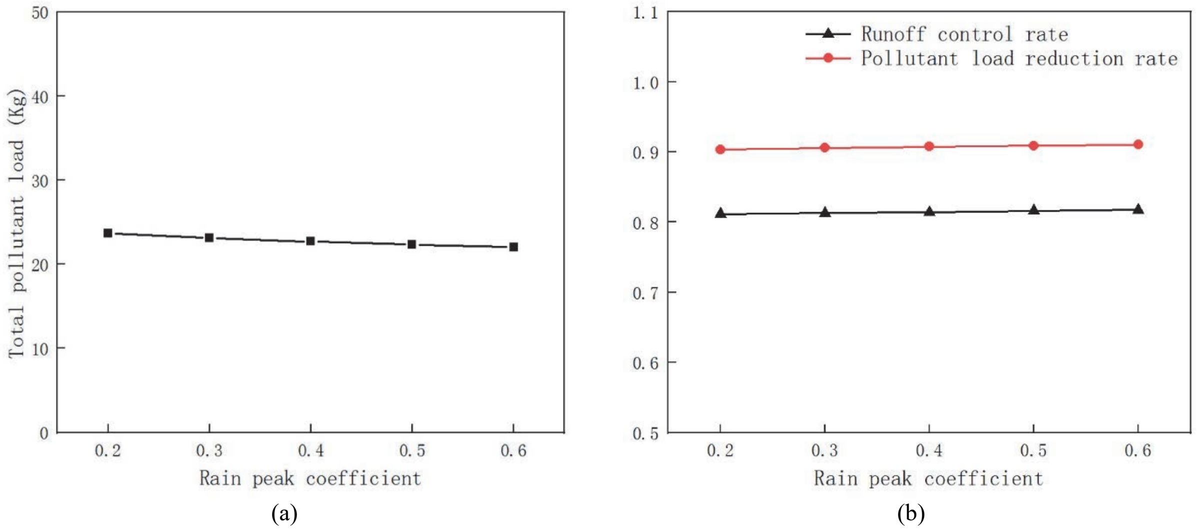


Fig. 7. Simulation results under different rain peak coefficients: (a) total pollutant load, (b) runoff control rate and pollutant load reduction rate

This is because the total amount of rainfall is basically the same due to different rain peak coefficients, which may affect the pollutant load at different moments in the rainfall process, but does not affect the total amount of pollutant load in the whole process. This is consistent with the research conclusion of Cai et al. (2017) when the rain-peak coefficient only affects the peak and peak time of pollutant concentration, and has little influence on the final stable pollutant concentration.

Similarly, pollutant load reduction rate and runoff control rate have the same change trend and the change range is similar. Increasing of rain peak coefficient lead to a slight change of the two parameters mentioned above. Pearson correlation coefficient was 0.976 by SPSS analysis, which was close to 1. This means that there is a conspicuous correlation between them.

4. Conclusions

Taking a LID residential community in Xixian new area of Shaanxi province as an example, this paper studies the influence of different rainfall processes on the total pollutant load of non-point sources and pollutant load reduction rate by using SWMM. The following conclusions are based on a small scale in a specific region. The model parameters are selected according to the geographical and meteorological conditions of northwest China. For example, the storm design is based on the characteristics of local short-duration storm concentration and the design storm type is limited.

In different design storms, the return period has obvious effect on pollutant load and its reduction, while the rain peak coefficient has little influence on it. The effect trend is similar to the runoff and runoff control process by LID measures.

When the return period increases from 1a to 10a, the total pollutant load increases from 13.02kg to 45.34kg, with a maximum increase of 248.26% compared with the return period of 1a, and the pollutant load reduction rate decreases from 94.21% to 84.54%, with a maximum decrease of 10.27%. This means that, when rainfall intensity increases, the pollutant discharge increases, and the reduction effect of LID on pollutants weakens. When the rain peak coefficient increases from 0.2 to 0.6, the total pollutant load decreases, but the maximum reduction is 6.95% compared with the rain peak coefficient of 0.2, and the pollutant load reduction rate increases, but the maximum increase is less than 1%. The pollutant discharge and the reduction effect of LID measures on pollutants are largely unaffected by the rain peak coefficient.

This research reveals the effects of rainfall patterns on rainfall runoff pollution under the LID measures, providing a reference for planning and assessment of the LID measures. The future work is planned to collect more systematically measured data for non-point source pollution in urban LID area, in order to investigate more reliable effects of LID measures on reducing non-point source pollutions.

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