Evaluation model of LID facilities based on the influence of water resource value

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ABSTRACT

Low-impact development (LID) facilities can not only effectively control rainwater runoff and its pollution, but also enhance the value of urban water resources in water systems. Current studies usually pay more attention to the effect of pollution control indicators, and there are few reports on the evaluation of LID facilities from the perspective of enhancing the value of water resources. Taking the Maluan Bay area of Haicang, Xiamen as an example, an evaluation model of water resource value was established based on the SWMM software and the pollution loss model. From the perspective of economic quantification, the value of water resources brought by three types of LID facilities, such as green roofs, permeable pavement and infiltration gallery, under rainfall conditions in different recurrence intervals was simulated and calculated. In the single rainfall event of 1–10a recurrence interval, the water resource value brought by the green roofs is 679.14–787.49 RMB/hm^2, the permeable pavement is 79.07–383.37 RMB/hm^2 and the infiltration gallery is 825.45–1,021.79 RMB/hm^2. The results show that the value of water resources brought by the three types of LID facilities decreases with the increase of rainfall recurrence interval.

Key words: low-impact development (LID), pollution loss model, SWMM software, water resource value

HIGHLIGHTS

- Evaluation of LID facilities from the perspective of enhancing the value of water resources.
- Establish a water resource value evaluation model for LID facilities based on the SWMM software and the pollution loss model.
- The evaluation model can quantify the economic benefits of the pollution interception effect of LID facilities.

1. INTRODUCTION

The purpose of building sponge city is to control rainfall–runoff and pollution through scattered and small-scale LID facilities at the source, carry out water-sensitive urban design (Morison & Brown 2011) to form a sustainable urban drainage system (Kändler *et al.* 2020; Mbanaso *et al.* 2020) and return to the natural hydrological cycle (Lu *et al.* 2015; Latifi *et al.* 2019). Since the pilot project of sponge city construction was launched in China in 2015, a large number of facilities, such as green roof, ground infiltration pavement, infiltration gallery or concave green space, have been built in Xiamen, Wuhan, Shanghai and other places with the concept of low-impact development (LID). The effect of sponge facilities on reducing urban flood disasters can be distinguished intuitively (Yang *et al.* 2019). However, in recent years, more and more researchers have begun to pay attention to the control effect of LID facilities on pollutants. Baek *et al.* (2020) improved the SWMM water quality model and conducted LID water quality simulations under various climate change scenarios. Rosa *et al.* (2015) comparatively analyzed the hydrological and water quality benefits of traditional development and LID under 10-, 25-, 50- and 100-year rainfall return periods and analyzed the impact of parameter calibration on the simulation results. Fan *et al.* (2019) studied the migration and transformation of nitrogen in the bioretention system during rainfall. The mechanism of the denitrification process of biological interception system with different flow patterns and planting methods was clarified. On the other hand, with the massive construction of LID facilities, many scholars have begun to study how to scientifically and objectively evaluate the benefits of these LID facilities. Zhang *et al.* (2015) used the reduction rate of runoff and pollutant concentration as the standard for evaluating green roofs. Mao *et al.* (2017) used SUSTAIN as a model tool to evaluate the ecological benefits of aggregate LID-BMPs in controlling rainwater runoff and pollution, and found the optimal layout of aggregate LID-BMPs. Li

et al. (2018) used the SWMM model and analytic hierarchy process to establish a comprehensive evaluation system and obtained the optimal layout of LID facilities.

The urban water system is a valuable resource. It has multiple functions such as drinking, watering, viewing and shipping. Once the water system is polluted, these functions will be affected and the value of water resources will also be impaired. Chen *et al.* (2019) analyzed the econometric models of three pollutants: the concentration loss curve model, the empirical model and the analytical model. Guan *et al.* (2019) established a set of ecological compensation models using the emergy analysis and pollution loss rate theories to calculate the value of water resources and pollution loss rates. Based on the mechanism model of environmental pollution loss of pollutants, logistic equation, Sha (2018) established an economic loss estimation model of environmental pollution and used this model to calculate the economic loss caused by industrial water pollution.

Existing research mainly evaluates LID facilities from two aspects: the effectiveness and cost-effectiveness of LID facilities. The decision-making process requires a sufficient understanding of the types and limits of pollutants, which is unfavorable for decision-making. The construction of LID facilities can reduce the discharge of pollutants in the water system, reduce the impact of pollutants on the function of water resources and enhance the value of water resources. Based on the SWMM software, this work established a water resource value model to show the value of water resources in the form of monetary value and calculates the impact of LID facilities on the value of urban water resources under different rainfall conditions from a quantitative economic perspective.

2. METHODS

Maluan Bay is the first batch pilot area of sponge city construction in China, with an average annual temperature of about 21°C, 122 days of annual average rainfall and an annual rainfall of 1,236 mm. Maluan Bay has a short main channel, with a total confluence area of about 124 km^2, a water area of about 745 hm^2 and a construction land of about 863 hm^2, dominated by villages in the city and industrial land. In the area where LID facilities have been built, the construction area of green roof, infiltration pavement and infiltration gallery are about 110, 80, and 50 hm^2. These three types of LID facilities account for 60% of the Maluan Bay sponge city area, they are widely used and highly representative.

Multiple parameters related to three devices in the SWMM software, such as simulation parameters, basic parameters of underlying surface, LID facility parameters, were obtained by surveying the green roof of the building on the west side of Xinjia Road in this area, the infiltration pavement of Changgeng Hospital Square and the infiltration gallery constructed by 462 county roads (shown in Supplementary Material, Tables S1–S3). The other parameters of SWMM water quality model and rainfall intensity simulation data were put into the SWMM software to calculate the concentration of rainfall–runoff pollutants at the end discharge port of three LID facilities. Meanwhile, the simulation results were tested by the measured data of runoff pollutant concentration of LID facilities during rainfall, and then the reliability of the evaluation model was determined.

3. MODELS

In the process of rainfall converging into runoff, rainfall will wash off the road surface and carry a large number of pollutants into the river, and they will gradually spread with the flow of the river. As the pollutant concentration in river increases, the water resource value is decreasing. The construction of LID facilities can effectively slow down the wash-off effect of rain water on pollutants, reduce the concentration of water pollutants and enhance the water resource value. In this work, the SWMM water quality model was selected to simulate the process of runoff washing off pollutants and calculate the runoff pollution concentration data. The zero-dimensional steady-state model was used to simulate the diffusion and dilution of pollutants in the river, and the pollution loss model was used to calculate the water resource value of the river.

3.1. SWMM water quality model

As one of the basic models of SWMM software, the SWMM water quality model can simulate the concentration change of various pollutants in rainfall–runoff after rainfall events (Temprano *et al.* 2006). The SWMM water quality model consists of two parts, the first part is the pollutant accumulation model which can simulate the accumulation of pollutants on the underlying surface with the change of time. The second part is the pollutant washing model which can simulate the process of rainfall washing off the ground and carrying pollutants into the river. When LID facilities were built on the underlying surface, the closure and infiltration of vegetation and soil in the facilities can effectively reduce the content of runoff pollutants.

In water quality simulation, SWMM provides three kinds of pollutant accumulation models, such as power function, exponential function and saturation function. In this work, the exponential function pollutant accumulation model was selected to simulate and calculate the process of pollutant growth, with the formula as follows:

$$B = C_1(1 - e^{-C_2 M}) \tag{1}$$

where B represents the mass of pollutants accumulated per unit area in the study area (kg). C_1 represents the maximum pollutant accumulation per unit area (kg/hm^2). C_2 represents the cumulative rate constant. M represents the number of drought days before rainfall events (d).

In the water quality simulation, SWMM provides three kinds of pollutant wash-off models: exponential wash-off, performance curve wash-off and event average concentration wash-off. In this work, the performance curve wash-off model was selected to simulate and calculate the pollutant wash-off process, with the formula as follows:

$$W_t = D_1 Q_t^{D_2} \tag{2}$$

where W_t represents the concentration of rain water wash-off pollutants at t in rainfall events (kg/s). D_1 represents wash-off coefficient. D_2 represents wash-off index. Q_t represents the volume of runoff at t in rainfall events (L/s).

3.2. Water resource value loss model

According to the 'loss-concentration curve' put forward by James (James & Lee 1971; Hu et al. 2014; Changqing & Meijun 2019), the loss caused by a pollutant to water can be expressed as follows:

$$S_i = K \cdot R_i \tag{3}$$

where S_i represents the loss of water resource value caused by the i pollutant (RMB) (COD, TN and TP were selected as calculated pollutants, thus $i = 1,2,3$, the same below). K represents the original value of water resources (RMB). R_i represents the value loss rate of water resources under the action of the i pollutant, which can be calculated by formula (4):

$$R_i = 1/[1 + a_i \cdot \exp(-b_i \cdot C_i)] \tag{4}$$

where a_i and b_i represent the value loss parameters of pollutants, which can be estimated by using water quality standards and toxicity data of pollutants and can be applied to the calculation of any water area once determined. C_i represents the concentration of the i pollutant in water (mg/L). It is worth noting that when there is more than one kind of pollutant in the water, the comprehensive loss rate is not the simple sum of all loss rates. When there are several independent pollutants, the recurrence formula of the comprehensive loss rate is as follows:

$$R^{(n)} = R^{(n-1)} + (1 - R^{(n-1)}) \cdot R_n \tag{5}$$

where $R^{(n)}$ represents the loss rate of water resource value under the synergistic action of the n pollutant. $R^{(n-1)}$ represents the loss rate of water resource value under the synergistic action of the $n-1$ pollutant. R_n represents the loss rate of water resource value under the action of the n pollutant, with $n = 3$ in this paper.

In summary, after the river is polluted, the formula for calculating the loss of water resource value caused by pollutants is as follows:

$$S = R^{(n)} \cdot Q \cdot P_{H_2O} \tag{6}$$

where S represents the loss of water resource value caused by water pollution (RMB). Q represents the volume of polluted water resources (m^3), P_{H_2O} represents the basic value of water resources (RMB/m^3).

3.3. Zero-dimensional steady-state model

In the above loss model, the parameters, such as pollutant concentration C_i and polluted water volume Q, are affected by many factors, which are related not only to the concentration of pollutants in rainfall–runoff, but also to the hydrological condition and water quality of the river. When rainfall–runoff flows into the river, the degradation of pollutants in the river is not taken into account because the main channel in the study area is narrow and close to the estuary and the pollutants stay shortly in the river. Based on this, the zero-dimensional steady-state model (completely mixed model) was selected as the diffusion model of pollutant concentration to calculate the influence range and concentration of all kinds of pollutants in rainfall–runoff after entering the river, with the formula as follows (Formica *et al.* 2016):

$$C = \frac{C_P Q_P + C_h Q_h}{Q_P + Q_h} \tag{7}$$

where C represents the concentration of pollutants after diffusion and dilution (mg/L). C_p represents the concentration of pollutants in rainfall–runoff (mg/L). Q_p represents sewage flow (m³/s). C_h represents the concentration of pollutants in the upstream river (mg/L). Q_h represents the upstream river flow (m³/s).

Considering that the minimum time step that SWMM can simulate is 1 min, the final pollutant concentration data are discrete sample data with 1 min as span and the parameters in the zero-dimensional steady-state and pollution loss models are continuous parameters. To put the discrete pollutant concentration data into the above two models for calculation, the model is modified to some extent with the results as follows:

$$C_t = \frac{C_{Pt} Q_{Pt} + C_{ht} Q_{ht}}{Q_{Pt} + Q_{ht}} \tag{8}$$

where C_t represents the concentration of pollutants after rainfall–runoff is completely mixed in t minutes (mg/L). C_{pt} represents the concentration of pollutants in rainfall–runoff in t minutes (mg/L). Q_{Pt} represents rainfall–runoff in t minutes (m³/s). C_{ht} represents the concentration of pollutants in the upstream river within t minutes (mg/L). Q_{ht} represents the upstream river flow in t minutes (m³/s). t represents the t minute after the start of the rainfall event ($t = 0, 1, 2,…$).

$$S = \sum_{t=0}^{T'} R_t^{(3)} A v P_{H_2O} \tag{9}$$

where S represents the loss of water resource value caused by water pollution (RMB). $R_t^{(3)}$ represents the loss rate of water resource value under the synergistic action of three pollutants (COD, TN and TP) within t minutes (the calculation results after C_t is put into formulas (4) and (5). A represents the average area of river section (m²). v represents the average velocity of river section (m/s). T' is the time from the beginning of rainfall event to the end of runoff. P_{H_2O} represents the basic value of water resources (RMB/m³).

Based on the above models, the rainfall–runoff and pollutant concentration were simulated and calculated after the LID facilities were installed, meaning that the data were put into the zero-dimensional steady-state model and the pollution loss model to calculate the loss of the water resource value (RMB) under the condition of setting up an LID facility, which is recorded as S'_{LID}. The value loss of this part is caused by rainfall–runoff pollutants and pollutants carried by the upstream river, and thus it is also necessary to out the hydrological and water quality data of the river into formulas (4)–(6) to calculate the loss of water resource value caused by pollutants carried by the upstream river, which is recorded as S_{river}. From this, the loss of water value per unit area caused by LID facilities can be calculated as follows:

$$S_{LID} = \frac{S'_{LID} - S_{river}}{A_{LID}} \tag{10}$$

where S_{LID} represents the loss of water resource value per unit area of LID facilities (RMB/hm²). A_{LID} represents the area of LID facilities (hm²).

After the LID facilities are removed, the loss of water resource value (RMB/hm^2) caused by rainfall–runoff was calculated again according to the above model under the condition that the LID facilities were not installed, which is recorded as $S_{\overline{LID}}$. The reduced loss of water value per hectare of LID facilities is defined as the water resource value brought about by LID facilities and the formula is as follows:

$$X_{LID} = S_{\overline{LID}} - S_{LID} \tag{11}$$

where X_{LID} represents the water resource value brought about by LID facilities per unit area (RMB/hm^2).

4. PARAMETERS

4.1. SWMM water quality model parameters

According to the 'SWMM User Manual' and the studies of Zeng *et al.* (2019) and Kreb *et al.* (2013), as well as the concentration data of rainwater pollutants, the model parameters in the SWMM software are shown in Table 1.

Before SWMM simulation calculation, it is necessary to input the intensity data of rainfall events changed with the time series of rainfall duration. At present, the widely used rainfall pattern in the world is the Chicago rainfall pattern. Mei *et al.* (2018) and Tang *et al.* (2019) used the Chicago rainfall pattern as the design rainfall pattern and carried out research on LID facilities in Xiamen. The rainfall process of this rainfall pattern is easy to simulate, and the simulated rainfall process is highly consistent with the real rainfall process. Therefore, the Chicago rainfall pattern was chosen to simulate the rainfall process in the study area and uses the Xiamen rainfall intensity formula to calculate the rainfall intensity of the rainfall pattern (the parameters of rainfall intensity formula are shown in Supplementary Material, Formula (S1)). The rainfall duration was set to 120 min, the simulation step size is 1 min and the peak ratio is 0.4. Five kinds of rainfall patterns with recurrence intervals (T) of 1*a*, 2*a*, 5*a* and 10*a* were simulated, with the simulation results shown in Figure 1, and the rainwater quality data of Xiamen Haicang District is shown in Supplementary Material, Table S4.

4.2. Parameters of pollution loss and zero-dimensional steady-state models

The value loss parameters *a* and *b* of pollutants in the pollution loss model can be estimated from water quality standards and pollutant toxicity data. Once determined, they can be used for calculation in similar waters (Zhen *et al.* 2011). The values of parameters *a* and *b* are shown in Table 2.

Table 1 | Parameters of pollutant accumulation and wash-off model on the underlying surface

| Type of land use on the underlying surface	Model type	Parameters	COD	TN	TP
Roof	Index model	Maximum accumulation (kg/hm^2)	90	4	0.6
		Cumulative rate constant	1	1	1
	Performance curve model	Wash-off coefficient	20	1.5	0.2
		Wash-off index	1.4	1.4	1.4
		Land cleaning efficiency (%)	0	0	0
Square	Index model	Maximum accumulation (kg/hm^2)	180	6	0.6
		Cumulative rate constant	1	1	1
	Performance curve model	Wash-off coefficient	60.4	1.5	0.07
		Wash-off index	1.2	1.2	1.4
		Land cleaning efficiency (%)	70	70	70
Green space	Index model	Maximum accumulation (kg/hm^2)	45	3	0.4
		Cumulative rate constant	1	1	1
	Performance curve model	Wash-off coefficient	30.45	1	0.07
		Wash-off index	1.2	1.2	1.2
		Land cleaning efficiency (%)	0	0	0
Road	Index model	Maximum accumulation (kg/hm^2)	180	6	0.6
		Cumulative rate constant	1	1	1
	Performance curve model	Wash-off coefficient	30	0.8	0.17
		Wash-off index	1.2	1.2	1.2
		Land cleaning efficiency (%)	70	70	70
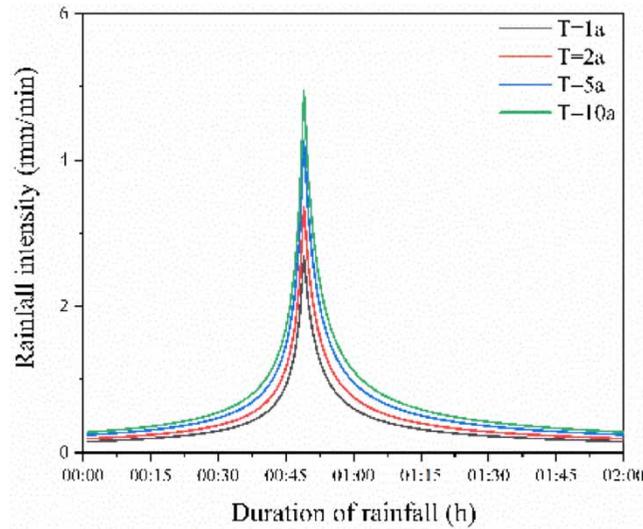
Figure 1 | Simulation results of Chicago rainfall pattern.

Table 2 | Values of pollutant value loss parameters *a* and *b*

	COD	TN	TP
a	5,118.6	160.6	160.6
b	0.4	0.48	0.48

The hydrological and water quality parameters of the Maluan Bay main canal involved in the zero-dimensional steady-state model were confirmed through field investigations and sampling tests, as shown in Table 3.

5. RESULTS AND DISCUSSION

5.1. Pollutant concentration of rainfall–runoff

The parameters of LID facilities investigated surveyed on site, selected SWMM model parameters and intensity data changed with time series of rainfall duration were put into SWMM for calculation, the pollutant concentration curves and the average concentration reduction rate of rainfall–runoff in three LID facilities under rainfall conditions in different recurrence intervals are obtained.

According to Figure 2, the concentration of pollutants appeared to be the maximum near 50 min after rainfall, decreased significantly after the rain stops and finally tended to be stable. When the green roof was set up, the concentration of pollutants in rainfall–runoff decreased significantly, especially in the short rainfall recurrence interval. However, the variation curves of pollutant concentration become steeper. Due to the low intensity of the rainstorm at the beginning and end of the rain, the closure and infiltration effect of plants and soil in green roof are obvious, which have good effect in removing pollutants. With the increase of rainfall, the runoff also increased gradually, and the influence of closure and infiltration become smaller, which led to the sharp increase of pollutant concentration. In addition, 1 h after the beginning of the rainfall

Table 3 | Hydrological and water quality parameters of main channel in Maluan Bay

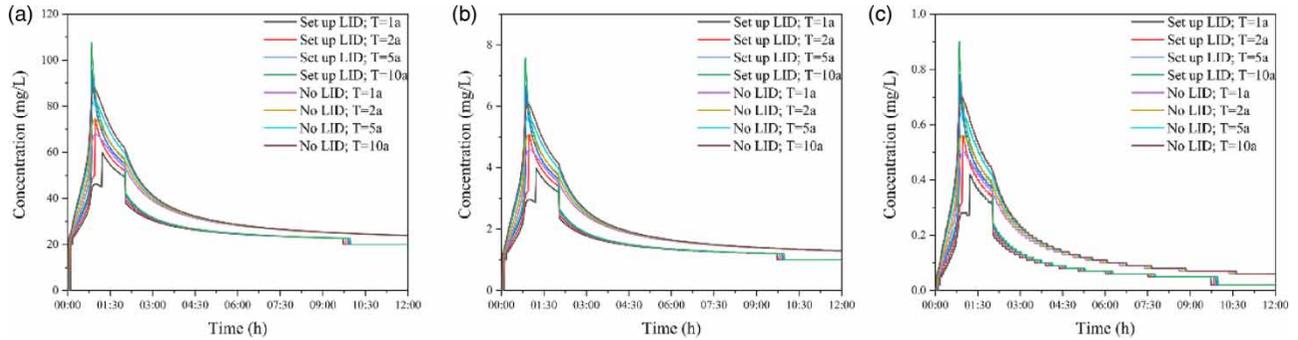| Width (m)	Depth (m)	Velocity (m/s)	Gradient (‰)	COD concentration (mg/L)	TN concentration (mg/L)	TP concentration (mg/L)	Water resource value (RMB)
20	10	0.1	0.0067	20	1	0.1	1.1

Figure 2 | Simulation results of green roof concentration: (a) simulation results of COD, (b) simulation results of TN and (c) simulation results of TP.

process, the concentration of runoff pollutants suddenly increased, and the longer the return period, the earlier the time corresponding to the rainfall pattern jump point. The reason for this phenomenon is that the green roof has only surface vegetation and soil layer, with no infiltration at the bottom. When the gaps in the soil layer are filled with pollutants, the runoff produced by the subsequent rainfall will no longer have infiltration, the rainfall will all be transformed into runoff and a large number of pollutants will be carried, resulting in a sharp increase in the concentration. The longer the recurrence interval of rainfall, the faster the gap of soil layer is filled, which leads to the advance of jump point.

According to Figures 3 and 4, the concentration curves of runoff pollutants in infiltration pavement are basically similar to those in infiltration gallery, but the difference is that there is a sudden drop in concentration curves of pollutants in infiltration pavement in the range of 6–10 h because the installation point of infiltration pavement is located in a square containing a
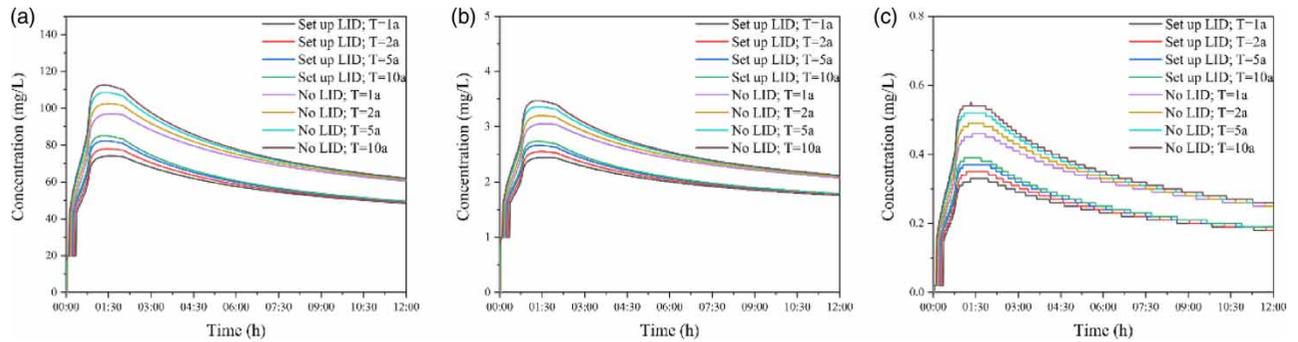

Figure 3 | Simulation results of infiltration pavement concentration: (a) simulation results of COD, (b) simulation results of TN and (c) simulation results of TP.
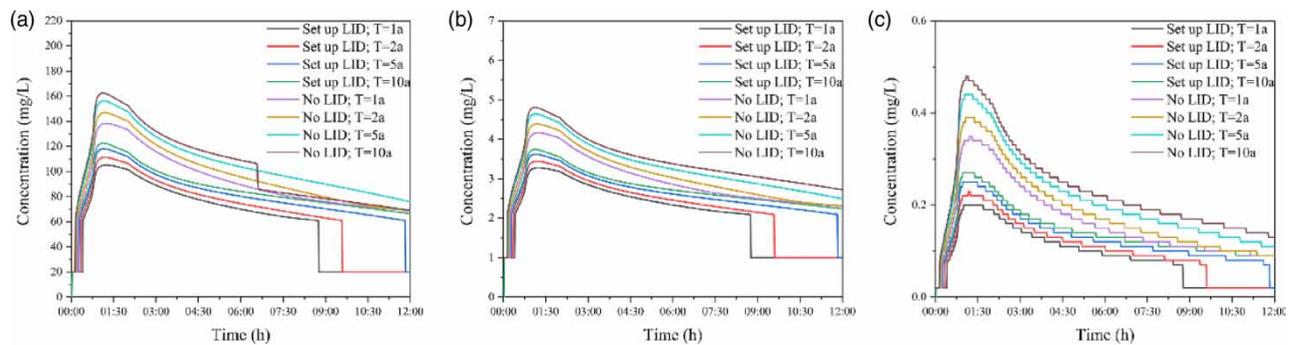

Figure 4 | Simulation results of infiltration gallery concentration: (a) simulation results of COD, (b) simulation results of TN and (c) simulation results of TP.

large number of green spaces with less pollutant content. When the pollutants were washed off, there would be a sudden drop in the concentration curves. However, the infiltration gallery was set up next to the road. Because of the passage of vehicle on the road, there is a high concentration of pollutants. The pollutants were not washed off completely in the simulation time period, with no sudden drop point.

It can be seen from Table 4 that after the green roof was installed, the average concentration of COD decreased by 18.04–20.38%, the average concentration of TN decreased by 23.11–26.75% and the average concentration of TP decreased by 34.30–37.78%. With the extension of the recurrence interval, the green roof's ability to intercept pollutants was declined, with the decrease of reduction rate of average pollutant concentration. The reduction rate of average pollutant concentration of infiltration pavement and infiltration gallery is similar to that of the green roof decreasing as the return period increases. The reduction rate of the three types of pollutant concentrations is 30–40%.

Supplementary Material, Table S5 shows the calculation conclusions of other studies on the ability of LID facilities to reduce the concentration of pollutants. The pollutant concentration reduction calculated in this work is close to the data range of the conclusions of these studies. To further verify the reliability of the model, the measured values of runoff pollutant concentration of three LID facilities under the condition of rainfall recurrence intervals of 1a and 2a and SWMM simulated data were subject to matched sample t-test. According to the results, the significant value of correlation between them is lower than 0.05. This indicates that at the 95% confidence level, there is a significant correlation between the simulated data and the measured data. Therefore, based on SWMM simulation, the concentration of runoff pollutants under different recurrence intervals and the impact assessment model of water resource value of LID facilities are reliable.

5.2. Impact of LID facilities on the water resource value

The pollutant concentration data obtained from SWMM were put into the pollution loss and zero-dimensional steady-state models to solve the problem.

According to Table 5, with the increase of rainfall recurrence interval, the loss of water resource value caused by rainfall–runoff pollutants is also gradually increasing, but after the installation of LID facilities, the loss of water resource value is greatly reduced.

In Table 6, X_{LID} represents the water resource value per hectare of LID facilities for a single rainfall event. It can be seen that the infiltration gallery brought the largest water resource value, followed by green roof, and the infiltration pavement is

Table 4 | Reduction rate of average pollutant concentration after LID facility construction

Pollutants Recurrence interval	COD reduction rate (%)				TN reduction rate (%)				TP reduction rate (%)			
	$T = 1a$	$T = 2a$	$T = 5a$	$T = 10a$	$T = 1a$	$T = 2a$	$T = 5a$	$T = 10a$	$T = 1a$	$T = 2a$	$T = 5a$	$T = 10a$
Green roof	20.38	19.13	18.41	18.04	26.75	24.86	23.67	23.11	37.78	31.02	36.46	34.30
Infiltration pavement	31.92	31.65	31.38	29.74	26.85	26.85	26.83	27.08	42.48	41.75	41.35	40.88
Infiltration gallery	29.61	30.20	30.79	31.15	23.46	24.14	24.87	25.31	39.17	39.39	39.69	39.54
Total	27.30	26.99	26.86	26.31	25.69	25.28	25.12	25.17	39.81	37.39	39.17	38.24

Table 5 | Loss value of water resources under different conditions

LID facilities	Set or not	Loss S of water resource value caused by runoff pollution (RMB/hm²)			
		$T = 1a$	$T = 2a$	$T = 5a$	$T = 10a$
Green roof	Yes	709.55	987.98	1,142.40	1,204.41
	No	1,497.04	1,667.13	1,828.54	1,923.98
Infiltration pavement	Yes	470.20	549.49	704.94	790.15
	No	808.56	824.94	864.88	869.22
Infiltration gallery	Yes	1,749.74	1,857.36	1,955.51	2,010.14
	No	2,771.52	2,799.93	2,823.48	2,835.59

Table 6 | Water resource value from LID facilities

| | Water resource value X_{LID} from LID facilities (RMB/hm^2) | | | |
LID facilities	$T = 1a$	$T = 2a$	$T = 5a$	$T = 10a$
Green roof	787.49	679.14	686.14	719.58
Infiltration pavement	338.37	275.44	159.94	79.07
Infiltration gallery	1,021.79	942.57	867.97	825.45

the lowest. With the increase of rainfall recurrence interval, the water resource value brought by the three types of LID facilities gradually decreases. The main reason is that the urban road surface contains a large content of pollutants, with a large total amount of runoff pollutants intercepted and infiltrated by infiltration gallery. However, most of the infiltration pavement was set up in a large number of green squares, with a less cumulative amount of pollutants and the limited effect of pollutant reduction. With the increase of rainfall recurrence interval, the rainfall intensity and the runoff increase, the closure and infiltration of pollutants weaken, and the water resource value of the three types of LID facilities decreases.

5.3. Water resource value under different rainfall patterns

In Section 5.2, this study used the Chicago rainfall pattern as the rainfall pattern and substituted it into the evaluation model to calculate the water resource value from LID facilities. To make the impact of this study more significant, we calculated and analyzed the changes in the water resource value from LID facilities under different rainfall patterns.

In this section, we select Pilgrim & Cordery rainfall and triangle rainfall patterns as the rainfall pattern for comparative study. The Pilgrim & Cordery rainfall pattern relies on the analysis of past rainfall event data to makes rainfall peaks appear at the most likely position. This rainfall pattern is closer to the real rainfall process (Pilgrim & Cordery 1975). The triangle rainfall pattern is a rainfall pattern for the drainage area of a small watershed, and its rainfall peak position is determined based on the triangle dimensionless first-order moment equal to the average dimensionless first-order moment of the rainstorm process (Yen & Chow 1980). In this study, the measured rainfall data and rainfall intensity formula parameters in Xiamen were used to calculate the rainfall process data of Pilgrim & Cordery rainfall and triangle rainfall patterns under the conditions of recurrence interval $T = 1a$, 2a, 5a and 10a, which are shown in Figure 5.

Substitute the rainfall data of Pilgrim & Cordery rainfall and triangle rainfall patterns into the evaluation model to calculate the water resource value from LID facilities under these two rainfall patterns. Figure 6 compares and shows the water resource value calculated by the Chicago rainfall, Pilgrim & Cordery rainfall and triangle rainfall patterns.

It can be seen from Figure 6 that similar to the calculation results of the Chicago rainfall pattern, the highest water resource value calculated by Pilgrim & Cordery rainfall and triangle rainfall patterns is still the infiltration gallery, followed by green roof and infiltration pavement. With the increase of rainfall recurrence interval, the water resource value from three types of
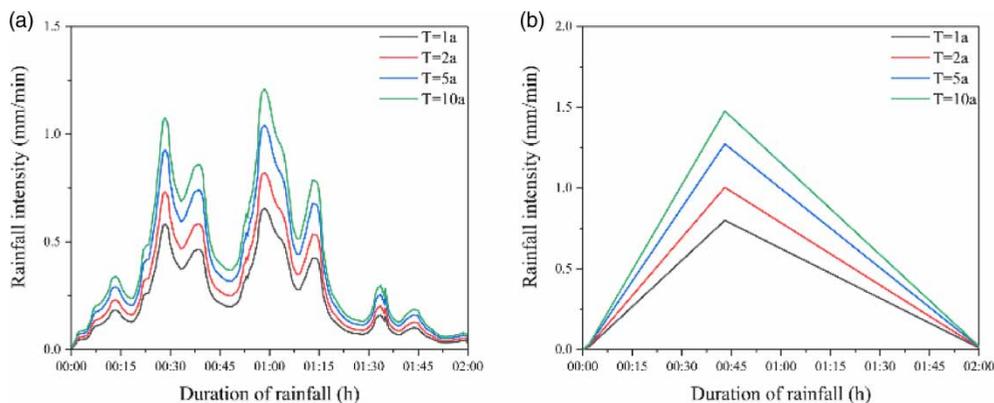

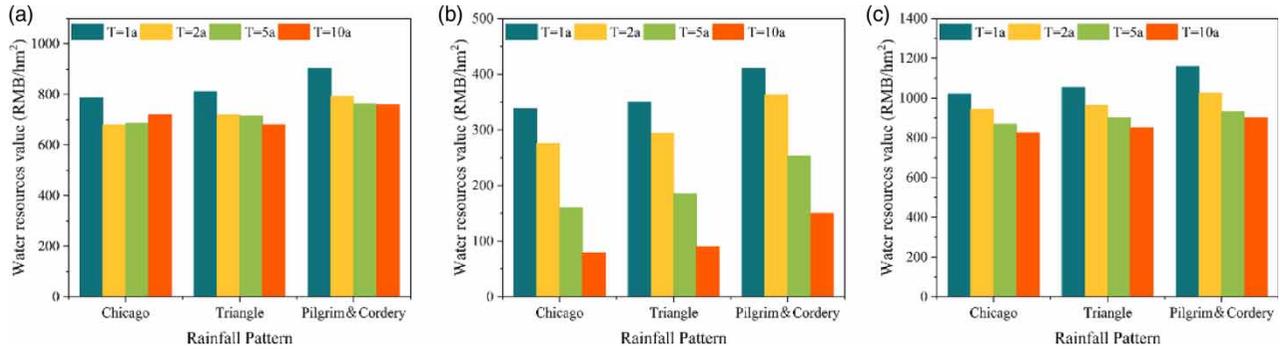**Figure 5** | Simulation results: (a) Pilgrim & Cordery rainfall pattern and (b) triangle rainfall pattern.

Figure 6 | Water resource value from different LID facilities under three rainfall patterns: (a) green roof, (b) infiltration pavement and (c) infiltration gallery.

LID facilities was gradually declining. The water resource value calculated by the triangle rainfall pattern is similar to that of the Chicago rainfall pattern, mainly because the two types of rainfall patterns are single-peak rainfall patterns and have similar structures. The calculation result of Pilgrim & Cordery rainfall pattern is higher than that of the other two rainfall patterns. This is because the Pilgrim & Cordery rainfall pattern is a multi-peak rainfall pattern. During the entire rainfall duration, the rainfall is more uniform, and the rainfall at the peak is less. According to the analysis in Section 5.2, LID facilities have better pollutant removal effects when rainfall is low, so the water resource value calculated by the Pilgrim & Cordery rainfall pattern is higher.

The three rainfall patterns have their own advantages and disadvantages. The simulated results of Pilgrim & Cordery rainfall pattern are close to the real rainfall process. However, the calculation of this pattern requires a large amount of measured rainfall data as the calculation sample. If the sample selection is unreasonable or the sample size is not large enough, the simulation results of Pilgrim & Cordery rainfall pattern and the actual rainfall process would have a huge deviation. The Chicago rainfall and triangle rainfall patterns can be calculated by relying on the various parameters of the rainfall intensity formula determined by the city weather bureau based on the multi-year rainfall data. The parameters are easy to obtain, and the rainfall process data obtained from this calculation are also closer to the real rainfall process data. The triangle rain pattern is simpler than the Chicago rainfall pattern and cannot well reflect the change of rainfall intensity before and after the rainfall peak. Therefore, in China, weather bureau in most cities recommends using the Chicago rainfall pattern as the design rainfall pattern. The *Xiamen Rainfall Pattern Design Technical Report* approved by Xiamen weather bureau in March uses the Chicago rainfall pattern as the design rainfall pattern.

6. CONCLUSIONS

From the perspective of quantitative economy, this work established an evaluation model for the value of water resources which combined multiple mathematical models such as SWMM water quality model, zero-dimensional steady-state model and pollution loss model. Based on the Chicago rainfall pattern, this work simulated the rainfall process in the study area and calculated the effect of LID facilities on the value of water resources by the evaluation model during the rainfall process.

- LID facilities can greatly reduce the loss of water resource value caused by rainfall–runoff, with remarkable effect in case of short rainfall recurrence interval and low intensity.
- In a single rainfall event of 1–10a recurrence interval, the value of water resources brought by green roof is 679.14–787.49 RMB/hm^2, the infiltration pavement brought about 79.07–338.37 RMB/hm^2 and the infiltration gallery brought about 825.45–1,021.79 RMB/hm^2.
- The water resource value calculated from the triangle rainfall pattern from LID facilities is closer to that from the Chicago rainfall pattern, while Pilgrim & Cordery rainfall pattern calculation results are the highest.
- This method is more intuitive and more realistic than the past method of evaluating LID facilities based on pollutant removal effects.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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