An optimal design strategy of decentralized storage tank locations for multi-objective control of initial rainwater quality

Huifeng Li, Lijun Lu, Xiangfeng Huang, Haidong Shangguan and Zhongqing Wei

ABSTRACT

In recent years, frequent non-point source pollution has raised serious challenges for urban water environmental management. The efficiency and cost of water quality storage tanks, which can prevent and control urban pollution effectively, are significantly affected by their locations. However, few studies have determined the location of decentralized storage tanks with consideration of the characteristics of initial rainwater quality, which has led to unsatisfactory or extravagant design. Therefore, a new design strategy is proposed to optimize the locations of water quality storage tanks using the InfoWorks ICM model in this study. It includes two basic steps. Firstly, the pollution severity of each node in the corresponding subcatchment is evaluated and ranked through the matter element analysis method and analytic hierarchy process. Secondly, all the nodes are precisely sorted by their excessive multiples using the single factor index method. Its application in the design of the decentralized storage tank locations in Fuzhou, China, proved that the proposed strategy can reduce the total volume of decentralized storage tanks to 0.38 times that of a terminal tank. The strategy presented in this study may also be useful in other research on storage tank design in urban pollution prevention and control systems.

Key words | analytic hierarchy process (AHP), decentralized storage tank locations, InfoWorks ICM, initial rainwater, water quality control

Huifeng Li
Lijun Lu
Xiangfeng Huang
Zhongqing Wei (corresponding author)
College of Environmental Science and Engineering, State Key Laboratory of Pollution Control and Resource Reuse,
Tongji University,
Shanghai 200092,
China
E-mail: *654606536@qq.com*

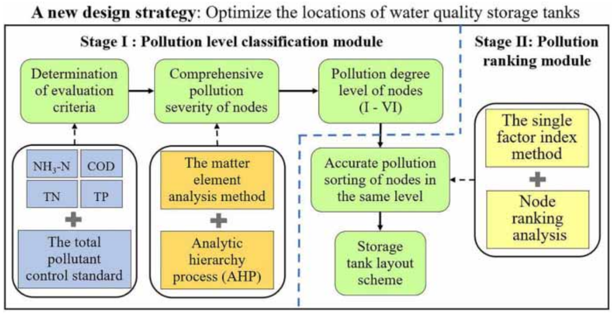
Haidong Shangguan
Zhongqing Wei
Fuzhou City Construction Design & Research Institute Co., Ltd,
Fuzhou, Fujian 350000,
China

HIGHLIGHTS

- The location of a water quality storage tank affects its cost and efficiency of pollution control.
- A quantitative evaluation framework was designed to optimize storage tank locations.
- The matter element analysis method and analytic hierarchy process were used for optimization.
- The single factor index method was employed for accurate pollution sorting of candidate nodes.
- The strategy established can optimize the storage tank design in urban pollution control systems.

doi: 10.2166/ws.2020.097

GRAPHICAL ABSTRACT



INTRODUCTION

Due to rapid urbanization, natural surfaces are increasingly being replaced by impermeable surface. The corresponding increase in rainfall runoff has led to urban waterlogging and water quality deterioration due to the washoff of urban underlying surfaces. Excessive rainwater runoff carrying large amounts of pollutants eventually drains into the receiving water through the urban pipe network system, which results in different levels of pollution in urban water bodies (Kong *et al.* 2017; Peng *et al.* 2017). Since 2010, rainwater runoff pollution in Beijing and Shanghai has accounted for approximately 12% and 20% of total water pollution, respectively (Peng *et al.* 2016). In the United States, approximately 60% of river pollution and 50% of lake pollution are linked to runoff pollution (Jeon *et al.* 2015). In Lake Ontario, North America, rainwater runoff also has a substantial impact on water quality, with 93% of total suspended solids (TSS), 78% of the biological oxygen demand (BOD), 66% of total nitrogen (TN), and 45% of total phosphorus (TP) originating from storm water runoff (Peng *et al.* 2016). Furthermore, due to the first-flush effect, the initial rainwater carries the majority of pollutants and has a high pollution load (Fai & Yusop 2017; Zhang *et al.* 2018a). Hence, initial rainwater treatment is crucial in the control of runoff pollution and improvement of the urban water environment (Andrés-Doménech *et al.* 2018).

Best Management Practices (BMPs), mainly including storage tanks, water storage ponds, and constructed wetlands, are effective methods to control rainwater runoff pollution. Due to the need for much space and complex construction of water storage ponds and constructed wetlands, they have often been used in places where land resource is not a restricting factor. They certainly become unusable in highly urbanized areas where the land resource is limited. Thus, decentralized storage becomes an ideal choice to reduce floods and control water pollution in highly urbanized areas (Bellu *et al.* 2016). It has been advocated by many researchers to adopt in order to achieve effective management of rainwater (Wang *et al.* 2017; Lu *et al.* 2019). Relevant studies also show that decentralized storage is superior to the traditional methods (such as increasing the pipe diameter), and it is easy to integrate with the pipe network. In the upper-middle reaches of highly urbanized areas, using the decentralized storage method can effectively reduce floods and control water pollution (Ngamalieu-Nengoue *et al.* 2019; Wang *et al.* 2019a). Rainwater storage tanks can be divided into hydraulic storage tanks and water quality storage tanks according to their different treatment objectives. The former mainly aim to reduce runoff and control flooding, whereas the latter consider pollution control and water quality improvement as their main purpose. Most current research pays attention to the runoff reduction effect, with water quality improvement as an additional benefit (Wang *et al.* 2017). Rarely research focuses on the design of water quality storage tanks, which has a significant influence on their control effect on initial rainwater pollution.

Regardless of the type of storage tanks, the efficiency and cost of them are directly related to many factors, such as their location, number and volume. Among them, the location is the first factor which needs to be considered during the design of decentralized storage tanks. For hydraulic storage tanks, there are usually two approaches to determining their locations. One is to place the storage tanks directly next to the nodes which are identified as the risky flooding nodes via the designers' experience. Those places are usually critical infrastructure, such as power stations, schools, and train stations (Li *et al.* 2015). The other assumes that all nodes are potential risky nodes and uses mathematical methods or algorithms to find out the real flooding nodes (Iglesias-Rey *et al.* 2017; Wang *et al.* 2017; Li *et al.* 2019). Despite those related studies on the location of hydraulic storage tanks, research on the location of decentralized storage tanks for initial rainwater control is still rare. Thus, it is really necessary to set up a feasible storage tank design strategy to recognize polluted nodes and achieve effective pollution control.

To assess the implementation effectiveness of storage tanks, appropriate evaluation indicators are required. In the study of hydraulic storage tanks, several hydraulic indicators, such as the flooding coverage area, flood depth, flood duration, and number of flood nodes, have been used to evaluate the extent and improvement of waterlogging (Li *et al.* 2015; Duan *et al.* 2016; Wang *et al.* 2017). For these indicators are closely related, and only slight differences in simulation results are yielded whether one or several indexes are used. In other words, it is still reliable to determine the location of storage tanks even only using one indicator. On the other hand, TSS or chemical oxygen demand is often used to determine approximate changes in water quality (St-Hilaire *et al.* 2016; Cheng *et al.* 2017; Raei *et al.* 2019). However, whichever of the indicators is used, it cannot comprehensively reflect the improvement of water quality. Thus, it is necessary to design a reasonable and comprehensive evaluation index as the design criterion of the location of storage tanks for the purpose of water quality improvement.

In order to avoid the limitation in the determination of location of water quality storage tanks mentioned above, a new strategy is proposed in this study, which is divided into the following two steps. (1) The matter element analysis method and analytic hierarchy process (AHP) are employed to analyze the comprehensive pollution severity of rainwater collected by each node in the corresponding subcatchment area and determine the pollution level of each node. (2) The single factor index method is adopted to obtain comprehensive excessive multiples of node pollutants. It subsequently obtains the precise sorting of nodes at the same level and gets the storage tank layout scheme for pollution reduction. Finally, this optimal design strategy was applied to a practical case study to verify its feasibility and effectiveness.

SOFTWARE AND METHOD

Simulation model

InfoWorks ICM (InfoWorks Integrated Catchment) model was used as the simulation software, which is the first model of urban drainage networks and river channel hydraulic water quality in the world.

Pollution-level classification module

Evaluation indicators and criteria for determination

Based on the *Environmental Quality Standards for Surface Waters* (GB3838-2002) (SEPA 2002) (Table 1), four water quality indicators NH_3-N, chemical oxygen demand (COD), TP, and TN were selected as the analytical indexes of water quality pollution. The total pollutant control standard of the four indexes is calculated by Equation (1), which is used as the criterion for the degree of water quality pollution:

$$W = \frac{CV}{10^6} \tag{1}$$

where W is the total standard value of the water quality index (kg); C is the standard concentration value (mg/L) of the five levels in the *Environmental Quality Standards*

Table 1 | Standard limits for surface water environmental quality

Index	I (mg/L)	II (mg/L)	III (mg/L)	IV (mg/L)	V (mg/L)
NH_3-N	(0, 0.15]	(0.15, 0.5]	(0.5, 1.0]	(1.0, 1.5]	(1.5, 2.0]
COD	(0, 15]	(0, 15]	(15, 20]	(20, 30]	(30, 40]
TN	(0, 0.2]	(0.2, 0.5]	(0.5, 1.0]	(1.0, 1.5]	(1.5, 2.0]
TP	(0, 0.02]	(0.02, 0.1]	(0.1, 0.2]	(0.2, 0.3]	(0.3, 0.4]

for Surface Waters (SEPA 2002); and V is the average runoff volume (L) of the corresponding subcatchment area collected per node during the simulation.

Pollution-level classification of nodes

Due to the existence of several evaluation indicators, it is impossible to simply determine the pollution level of each node. Hence, the matter element analysis method and AHP are introduced to conduct a comprehensive division of the pollution degree level under multiple indexes.

According to the principle of the matter element analysis method, the correlation function value between the indicator vector and the evaluation matrix is obtained by establishing the index evaluation matrix and normalizing the indicator vectors (Li *et al.* 2017; Wang *et al.* 2019b). In this study, the evaluation matrix describes the five levels of control standard for the total amounts of four types of pollutant, and the index vector describes the total amount of four types of pollutant sent to each node from the subcatchment area. Thus, the correlation function values between the four water quality evaluation indexes and five control standards can be calculated. The correlation function value indicates the degree of conformity of the matter-element to be evaluated according to the standard level. The greater its value, the higher the degree of conformity. Correlation values $T(X_j)$ can be calculated by Equations (2) and (3):

$$T(X_j) = \begin{cases} \dfrac{-\theta(X, X_0)}{|X_0|} & X \subset X_0 \\ \dfrac{-\theta(X, X_0)}{\theta(X, X_j) - \theta(X, X_0)} & X \not\subset X_0 \end{cases} \tag{2}$$

$$\theta(X, X_0) = \left| X - \frac{A+B}{2} \right| - \frac{1}{2}(B - A) \tag{3}$$

where X is the matter-element value of the water pollution degree in the subcatchment area to be evaluated; X_0 is the value range for classic domain matter elements; X_j is the value range for section domain matter elements; $\theta(X, X_0)$ represents the distance between X to a control standard interval X_0 ($X_0 = [A,B]$, where A and B respectively indicate the minimum and maximum value of the finite element interval); and θ is the distance between X and the control standard interval X_p ($X_p = [A_j,B_j]$).

AHP is widely used in decision analysis systems as it is convenient and practical for determining the index weight (Miguez & Veról 2017). In this study, it is used to determine the weight value of four types of water quality index. The process is as follows: obtain the relative importance, r_{ij}, of four types of evaluation index using the nine scale judgment matrix (when r_i is equally important as r_j, $r_{ij} = r_{ji} = 1$; when r_i is slightly more important than r_j, $r_{ij} = 3$, $r_{ji} = 1/3$; when r_i is obviously more important than r_j, $r_{ij} = 5$, $r_{ji} = 1/5$; when r_i is intensively more important than r_j, $r_{ij} = 7$, $r_{ji} = 1/7$; when r_i is extremely more important than r_j, $r_{ij} = 9$, $r_{ji} = 1/9$), then form the comparison matrix, F (Equation (4)), of evaluation indicators. Simultaneously, employ the normalization method to conduct hierarchical single ranking, then obtain the weight vector $W=(v_1, v_2, v_3, v_4)^\mathrm{T}$, and finally perform consistency checks. When the consistency ratio $CR=CI/RI \leq 0.1$, the available feature vector can be considered as the weight value of each indicator if its degree of inconsistency is within the allowable range and it passes the consistency test. The operation process of AHP is relatively cumbersome, so the MATLAB running program of AHP is written to reduce repetitive operations.

$$F = (r_{ij}) = \begin{bmatrix} & c_1 & c_2 & \cdots & c_n \\ c_1 & r_{11} & r_{12} & \cdots & r_{1n} \\ c_2 & r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ c_n & r_{n1} & r_{n2} & \cdots & r_{n3} \end{bmatrix} \tag{4}$$

Eventually, to apply the two types of value to Equation (5), the correlation function value determined by the matter element analysis method and the weight value determined by AHP are calculated. Then, in the related subcatchment area, the comprehensive correlation function value, T, between the water quality index and the total pollution control standard is calculated:

$$T = T(X_1)v_1 + T(X_2)v_2 + T(X_3)v_3 + T(X_4)v_4 \tag{5}$$

where $T(X_1)$, $T(X_2)$, $T(X_3)$, and $T(X_4)$ are the respective correlation function values between four types of water quality index and total quantity control standards; and v_1, v_2, v_3, and v_4 are the weight values of the four water quality indexes.

The matter element analysis method and AHP comprehensively consider the pollution degree of the four water quality assessment indicators and divide the subcatchment area into corresponding pollution levels according to the pollution total control standard. Therefore, this approach provides a more accurate selection basis for the control object of the storage tanks.

Approach to pollution ranking

As the matter element analysis method and AHP cannot rank the pollution severity of the nodes at the same level, this study uses the single factor index method to calculate the comprehensive excessive multiple N of the pollution degree in the subcatchment area (Equation (6)). Then, the subcatchment area at the same level is sorted according to the water quality pollution degree. The larger the N value, the more serious the contamination:

$$N = \frac{W_1'}{W_1}v_1 + \frac{W_2'}{W_2}v_2 + \frac{W_3'}{W_3}v_3 + \frac{W_4'}{W_4}v_4 \quad (6)$$

where W_1', W_2', W_3', and W_4' indicate the total amounts of the four water quality indexes (kg) in the subcatchment area; W_1, W_2, W_3, and W_4 are the total control standard values (kg) of the four water quality indexes; and v_1, v_2, v_3, and v_4 are the weight values of the four water quality indexes.

Through the pollution ranking module, the nodes under the same pollution level are sorted precisely. When the control target is set to outfall rainwater to meet the established water quality standards, the object to be controlled is the node determined by the quantitative evaluation framework and where the water pollution level is above the standard.

Design and simulation of the scheme

In order to verify how the runoff at different nodes affects regional pollution, two schemes for determining the location of storage tanks are adopted. One is setting decentralized storage tanks in necessary subcatchment areas which can directly collect the runoff of each subcatchment area according to the pollution ranking of the corresponding nodes. Thus, improvements of the water quality of the outfall can be assessed with the increase of the quantity of storage tanks until it meets the treatment aim. The other scheme is setting terminal storage to collect the incoming water, which is the traditional approach for intercepting terminal rainwater. The volumes of storage tanks of both schemes are determined as follows.

There are three procedures for determining the volume of the storage tank. Firstly, object selection: selecting the nodes and outfalls of which the pollution level exceeds the water quality control criterion (*Surface Water Environmental Quality Standard* (SEPA 2002)). Secondly, time period setting: choosing the longest period of time among the four time periods from the start of the rainfall to when it accomplishes the target standard value for the four indicators. Lastly, volume determination: determining the certain volume of the storage tank as the volume of rainwater flowing in within the longest time period.

Meanwhile, in order to compare the pollution control effect between the terminal and decentralized storage tank with the same volume, another terminal storage tank is set whose volume is equal to the smallest total volume of the decentralized tank.

CASE STUDY AND ANALYSIS

Overview of the study area

In this study, a region of Fuzhou in China was used as the research area, and the model was established by using InfoWorks ICM. The regional model consists of 301 subcatchments, 313 conduits, and 313 inspection nodes, with a total subcatchment area of 890,000 m^2. In addition, Ditch Meiting at the end of the area drains rainfall into Ming River.

Model construction

The underlying surface in the area was divided into four types: roofs, pavements, green spaces, and mountains. A fixed percentage runoff model was used to analyze the roads and roofs whereas the Horton model was employed for the green spaces and mountains. As the confluence model, the Storm Water Management Model (SWMM) was used for all underlying surfaces. The local rainfall intensity formula (Equation (7)) of Fuzhou was adopted to conduct the simulation analysis on water quality. The peak rainfall position was 0.398, the rainfall duration was 120 min, the simulation time was 3 h, and the recurrence period was one year. In this study, two actual rainfall events were used for calibration of the model, and the relevant parameter values were regulated until the simulation results agreed with the actual results. The result of hydraulic model calibration showed that the NSE efficiency coefficient of terminal outfall flow is 0.89; the result of water quality model calibration suggested the NSE efficiency coefficient of TN, TP and NH_3-N were all higher than 0.86, except that of terminal outfall COD equaling 0.63.

$$i = \frac{14.715(1 + 0.633 \lg P)}{(t + 11.951)^{0.724}} \quad (7)$$

In Equation (7), i represents the rainfall intensity (mm/min); P is the designed recurrence interval (a); and t is the rainfall duration (min).

Pollution-level classification and sorting results

When the rainfall was under the condition $P = 1$, the concentration of the four water quality indexes of the rainwater discharged from the outlet first increased then decreased. Particularly in the early stages of rainfall, it greatly exceeded the standard value and showed a clear initial effect (Figure 1). The total amount of the four pollutants collected in each node within 3 h was obtained by multiplying the corresponding concentration of the four pollutants every 5 min, which is the minimum step of the simulation in InfoWorks ICM, with the amount of rainwater in the model, respectively. In order to avoid repeated calculation, only the rainwater collected from the corresponding subcatchment area for each node was counted regardless of the upstream water. Table 2 lists the top ten nodes based on the amounts of NH_3-N, COD, TN, and TP.

With regards to runoff pollution, TSS was shown to be closely correlated with other pollutants in many previous studies. The other main contaminants were also removed a lot when most of the TSS had been removed (Cheng *et al.* 2017). However, there were still different results presented in other studies. For example, TSS was poorly correlated with TP and TN in the runoff of Sydney, Australia (Ekanayake *et al.* 2019), whereas it was better correlated with total Kjeldahl nitrogen (TKN) but poorly correlated with TP in the runoff of Doha, Qatar (Mamoon *et al.* 2019). Zhang *et al.* (2018b) found that the COD of the runoff of Handan, China, was strongly correlated with other pollutants. As shown in Table 2, the difference between the node ranking for NH_3-N and COD in the top ten is small and the correlation is good, but they are poorly correlated with TN and TP (such as YS1307, YS122). Therefore, the removal rate of NH_3-N or COD cannot be directly used to reflect the removal of TN and TP. Therefore, any one of the indicators cannot indicate the overall water quality changes. Thus, the four water quality indicators should all be concerned in order to achieve the target standard simultaneously. Among these nodes, the four water quality indicators of YS1313 rank first or second, indicating that the corresponding subcatchment area has the highest degree of pollution. Nodes YS1333 and YS1340 also rank highly, which should be of concern in the subsequent layout scheme.

For the matter element analysis method, the criteria of discrimination should be determined. According to the standard concentration values of the five levels in the *Surface Water Environmental Quality Standard* (SEPA 2002) and the average runoff of the subcatchment area collected from each node in the InfoWorks ICM simulation, the total pollutant control standards of the four indicators, calculated using Equation (1), should be used as the criteria for determining the severity of water pollution (Table 3).

For the AHP, the significance of the four water quality indicators should be determined. According to the *Statistical Yearbook* (Fuzhou Statistics Bureau 2016) and the *Water Resources Bulletin* (Fujian Provincial Department of Water Resources 2016) of Fuzhou City from 2011 to 2015, the environmental capacities of the four water quality indicators of Ming River exhibit the following order: TP > TN > COD > NH_3-N; thus, the importance of the four water quality indicators follows the opposite order. To obtain the comparison matrix F, the nine scale judgment matrix was adopted. Hierarchical single ranking was performed to obtain $CR = 0.0806 < 0.1$, which was consistent with the consistency test. The weights of the four water

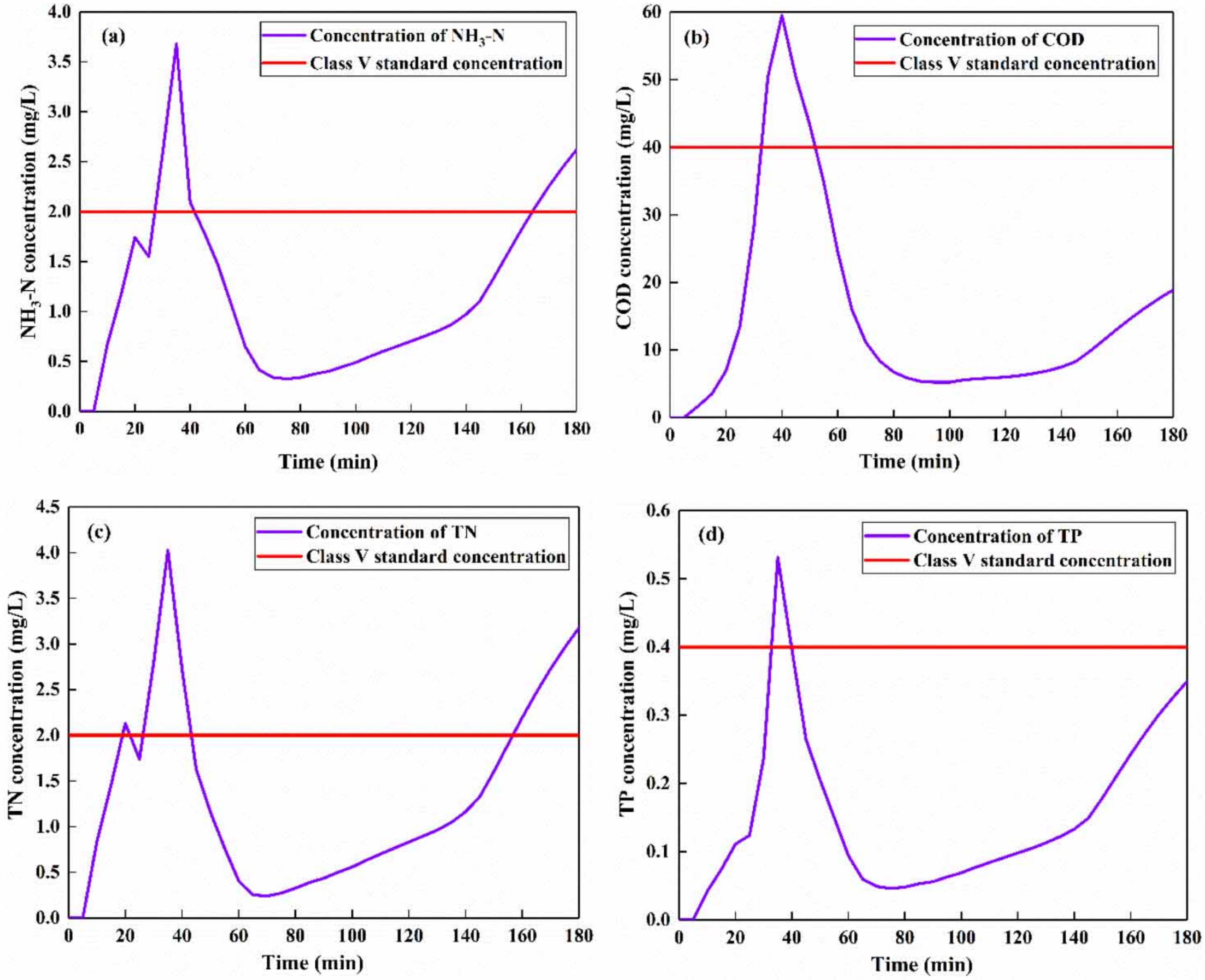


Figure 1 | Time-concentration curves of the water quality index in rainwater from Ditch Meiting: (a) NH_3-N, (b) COD, (c) TN, and (d) TP.

quality indicators are NH_3-N: 0.3835, COD: 0.2732, TN: 0.2185, and TP: 0.1248.

$$F = \begin{bmatrix} 1 & \frac{1}{2} & 2 & 2 \\ 2 & 1 & 2 & 2 \\ \frac{1}{2} & \frac{1}{2} & 1 & \frac{1}{3} \\ \frac{1}{2} & \frac{1}{2} & 3 & 1 \end{bmatrix}$$

The comprehensive correlation function values between the four water quality indicators of 312 nodes and the six pollution levels are calculated using the matter element analysis method and AHP, respectively, along with Equation (5). The greater correlation function value at a certain level indicates the higher compatibility between the contamination degree and the pollution level, which can be used to classify the pollution grade. The results of the 312 nodes demonstrated that there were 267 nodes at level I, 19 at level II, nine at level III, seven at level IV, one at level V, and nine at level VI (Table 3). As the matter element analysis method and AHP cannot rank the contamination degree for each node at the same level, the single factor index method is introduced and the weight values in the two methods are additionally used to calculate the comprehensive multiple N (Equation (6)). The aim of this process is

Table 2 | Total amount of rainwater contaminants collected from different nodes

	NH_3-N		COD		TN		TP	
Node ID	Amount (kg)	Ranking	Amount (kg)	Ranking	Amount (kg)	Ranking	Amount (kg)	Ranking
YS1313	16.4740	1	91.6788	2	19.6542	1	2.6821	1
YS305	7.8503	2	78.2156	4	0.0476	45	0.1627	6
YS1333	5.9929	3	88.2953	3	2.7894	3	0.4299	3
YS1340	5.1782	4	102.0655	1	4.9300	2	0.6534	2
YS1258	2.2030	5	22.2564	5	0.0202	54	0.0453	13
YS1307	1.9566	6	19.7445	6	0.0174	57	0.0399	15
YS122	1.7346	7	17.1602	7	0.0082	60	0.0344	16
YS348	1.7296	8	14.6004	8	1.3992	5	0.1659	5
YS339	1.6667	9	13.4593	9	1.4056	4	0.1660	4
YS355	1.4744	10	11.3041	10	1.0180	6	0.1123	7
YS281	0.6833	14	5.7861	21	0.4889	7	0.0595	9
YS342	0.7997	12	7.1369	13	0.4875	8	0.0613	8
YS347	0.7291	13	6.4827	17	0.4594	9	0.0572	10
YS178	0.6301	18	5.0698	29	0.4438	10	0.0495	12

Table 3 | Total pollutant control standards of the four indicators

Indicator	Level I (kg)	Level II (kg)	Level III (kg)	Level IV (kg)	Level V (kg)	Level VI (kg)
COD	(0, 5]	(5, 5.5]	(5.5, 6.5]	(6.5, 10]	(10, 13]	>13
NH_3-N	(0, 0.05]	(0.05, 0.2]	(0.2, 0.35]	(0.35, 0.5]	(0.5, 0.7]	>0.7
TP	(0, 0.007]	(0.007, 0.035]	(0.035, 0.065]	(0.065, 0.1]	(0.1, 0.13]	>0.13
TN	(0, 0.07]	(0.07, 0.2]	(0.2, 0.35]	(0.35, 0.5]	(0.5, 0.7]	>0.7

Table 4 | Comprehensive correlation function values and over-standard multiples for the level VI nodes

	Comprehensive correlation function value						Over-standard multiple				
Node ID	Level I	Level II	Level III	Level IV	Level V	Level VI	NH_3-N	COD	TN	TP	Comprehensive over-standard multiple *N*
YS1313	−0.963	−0.963	−0.963	−0.961	−0.960	0.040	23.534	7.052	28.078	20.631	19.662
YS1340	−0.632	−0.627	−0.620	−0.613	−0.605	0.185	7.397	7.851	7.043	5.026	7.148
YS1333	−0.593	−0.586	−0.577	−0.566	−0.553	0.211	8.561	6.792	3.985	3.307	6.422
YS305	−0.387	−0.518	−0.595	−0.609	−0.599	0.047	11.215	6.017	0.068	1.252	6.116
YS348	−0.465	−0.442	−0.409	−0.346	−0.265	0.040	2.471	1.123	1.999	1.276	1.851
YS339	−0.462	−0.438	−0.403	−0.335	−0.245	0.035	2.381	1.035	2.008	1.277	1.794
YS1258	−0.303	−0.479	−0.438	−0.508	−0.514	−0.229	3.147	1.712	0.029	0.349	1.725
YS1307	−0.308	−0.474	−0.458	−0.510	−0.505	−0.249	2.795	1.519	0.025	0.307	1.531
YS122	−0.332	−0.481	−0.485	−0.512	−0.493	−0.270	2.478	1.320	0.012	0.264	1.347

to accurately rank the severity of water pollution at the same pollution level (Table 4).

This research aims to control the rainwater discharged from the outfall to meet the class V standard for water quality by installing rainwater storage tanks to collect the initial rainwater in the subcatchment area. According to the ranking results obtained by the matter element analysis method and AHP, the level VI nodes are selected as the control objects for the collecting and processing of the initial rainwater.

Node ranking analysis

To verify the correctness of the ranking of level VI nodes, an equal volume (1,400 m^3) storage tank was installed on the nine level VI nodes to collect rainwater in the corresponding subcatchment area. The ratios of peak concentration value of the outfall to the class V standard concentration value for the four water quality indicators were used to examine the impact of the storage tank locations on pollution reduction (Figure 2).

When the ratio is less than 1, it means the water quality of the water from Ditch Meiting reaches the class V standard. As shown in Figure 2, all the ratios were significantly decreased when the storage tank was installed at a node with a higher pollution degree, which indicated that the location of the storage tank has a particularly significant impact on the collection of pollutants. When the storage tank was installed at node YS1313, which has the highest pollution level in the subcatchment area, the water quality of the outfall was significantly improved. Moreover, when only one storage tank was installed, no matter where it was located, the four water quality indicators of the regional outfall could not reach the class V standard of surface water. The results indicated that the quantitative evaluation framework can obtain a valid and reasonable ranking of the pollution degree of nodes and can provide the basis for the location selection and design of decentralized storage tanks.

Discussion of simulation results

According to the volumetric design method in the section above on 'Design and simulation of the scheme', the time period for collecting water and the design volume of the storage tank are obtained for each level VI node and Ditch Meiting (Table 5). The simulation results performed by InfoWorks ICM were statistically analyzed (Table 6).

The decentralized storage tanks are sequentially arranged by their volumes from the highest to lowest

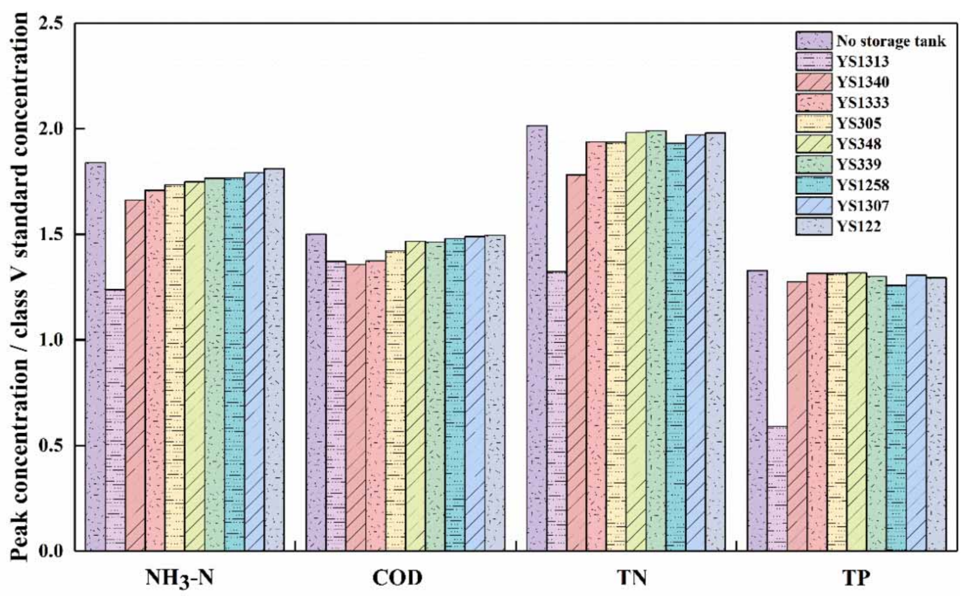


Figure 2 | Verification of the validity of the level VI node ranking, showing the peak concentration value/class V standard concentration value according to storage tank location. An equal volume (1,400 m^3) storage tank is installed at the level VI nodes and the water quality change of Ditch Meiting is simulated.

Table 5 | Set volume of storage tanks

Node ID	YS1313	YS1340	YS1333	YS305	YS348	YS339	YS1258	YS1307	YS122	Ditch Meiting
Collection time (min)	300	55	60	60	60	60	50	45	50	60
Volume (m^3)	531.66	661.18	1,341.66	1,151.29	144.00	102.89	259.69	197.52	211.77	11,080.75

Table 6 | Simulation plan results for storage tanks

			Peak concentration of Ditch Meiting (mg/L)				Peak concentration/class V standard value of Ditch Meiting			
Scheme	Quantity of storage tank	Total volume (m^3)	NH_3-N	COD	TN	TP	NH_3-N	COD	TN	TP
Initial	0	0	3.679	60.000	4.026	0.531	1.840	1.500	2.013	1.328
Decentralized storage	1	531.66	2.474	54.800	2.647	0.236	1.237	1.370	1.324	0.590
	2	1,192.84	2.063	44.114	2.186	0.216	1.032	1.103	1.093	0.540
	3	2,534.50	2.090	42.821	2.286	0.223	1.045	1.071	1.143	0.558
	4	3,685.79	2.164	42.229	2.414	0.234	1.082	1.056	1.207	0.585
	5	3,829.79	2.075	41.059	2.211	0.163	1.038	1.026	1.106	0.408
	6	3,932.68	1.957	41.367	2.094	0.171	0.979	1.034	1.047	0.428
	7	4,192.37	1.861	39.200	1.975	0.172	0.931	0.980	0.988	0.430
	8	4,389.89	1.840	36.19	1.966	0.173	0.920	0.905	0.983	0.433
	9	4,601.66	1.840	36.058	1.962	0.175	0.920	0.901	0.981	0.438
Terminal storage	1	4,192.37	1.549	52.419	2.394	0.356	0.775	1.310	1.197	0.890
	1	11,080.75	0.877	32.286	1.264	0.197	0.439	0.807	0.632	0.493

pollution level (Figure 3); as the number of storage tanks increases, the concentration of pollutants in the outfall is continuously reduced. When the number of storage tanks is one, which is placed at the most polluted node (YS1313), the reduction ratios of the four water quality indicators in Ditch Meiting are the largest. Notably, TP reaches the class V standard for water quality, indicating a marked pollution reduction effect. The indicators of NH_3-N, COD, TN, and TP reach the class V standard for water quality when the number of storage tanks is six, seven, seven and one, respectively. Therefore, if seven or more storage tanks are used, the outfall water can reach the class V standard for water quality. Considering no obvious pollution reduction is achieved by using more storage tanks, the project which set up seven tanks near the first seven of the level VI nodes is the optimal solution.

Regarding terminal storage, when the volume of the storage tank is equal to the total volume of the seven decentralized storage tanks in the optimal solution (4,192.37 m^3), only NH_3-N and TP reach the class V standard. When the volume of the terminal storage tank is 11,080.75 m^3

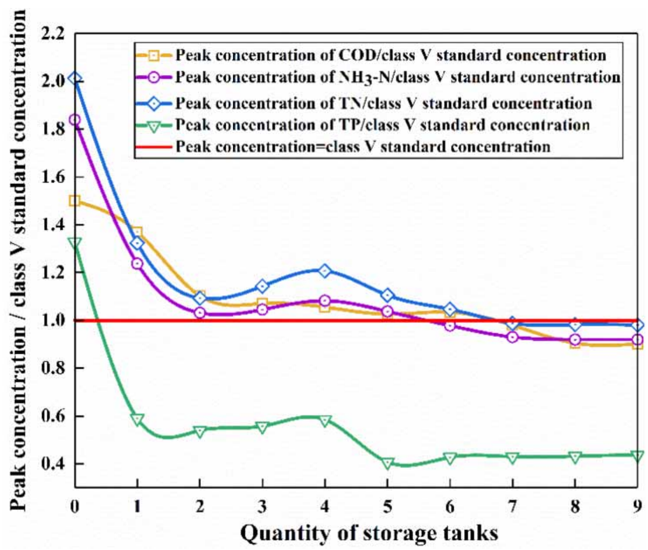


Figure 3 | Peak concentration value/class V standard concentration value according to the number of storage tanks, showing changes in the four water quality indicators of outfall water with an increasing number of storage tanks. In decentralized storage, when the number of storage tanks is seven, eight or nine, the indicators can simultaneously reach the class V standard for water quality. Installing the tank in the first seven of the level VI nodes is the most cost-effective solution.

the four water quality indicators reach the class V standard and the optimization effect is rather apparent. However, as shown in Table 6, the total volume of decentralized storage tanks in the optimal solution is only 0.38 times that of the terminal storage, which can significantly cut down the construction cost. As a traditional rainwater treatment method, terminal storage has a certain effect on pollution control and the reduction of the terminal peak; however, there are specific restrictions on the control effect in the upstream and middle river (Mani *et al.* 2019). The design of the storage tank should not only avoid upstream floods, but also comprehensively consider downstream pollution control and the construction costs of the facilities. Therefore, it is difficult for traditional terminal storage to achieve better control effects and meet quality requirements. Storage tank layout should be considered more for the overall area, not just for the terminal discharge area (Wang *et al.* 2019a). Decentralized storage can manage the local peak value and pollution by setting the storage tanks at near positions, achieving overall regional compliance and higher cost-effectiveness under the same construction conditions as terminal storage (Liu *et al.* 2016). As the first step in the design of the scheme, storage tank locations directly affect the subsequent optimization. Therefore, a rational design and optimized layout of decentralized storage is key to current urban water control.

In storage tank design, site selection is typically the first step in optimization, which can be determined through land use, laws and regulations, and capital budgets (Wang *et al.* 2017). Nevertheless, different layouts will result in different control effects (Cunha *et al.* 2016). Flooding nodes are typically considered as locations for hydraulic storage tanks (Mani *et al.* 2019), whereas no studies have attempted to determine polluted nodes for water quality storage tanks. Consequently, NH_3-N, COD, TN, and TP were selected as indicators of water quality and the matter element analysis method and AHP were used to classify the comprehensive pollution degree of the nodes and obtain the candidate nodes requiring control. Additionally, the single factor index method was employed for accurate pollution sorting of candidate nodes of the same level and to obtain the preferred tank layout. According to the results of this study, our approach results in the storage tank being installed at the preferred position that leads to the four water quality indicators of the outfall rainwater reaching the set target. Moreover, the cost-effectiveness of this scheme is better than that of the traditional terminal storage scheme.

To summarize, the storage tank layout scheme determined by the proposed strategy exhibits higher pollutant removal efficiency and can greatly reduce the investment costs of the storage tanks. This approach has been proved suitable for optimizing the location of storage tanks with the purpose of pollution reduction and cost saving.

CONCLUSIONS

Previous research on decentralized storage tank locations has rarely considered the characteristics of initial rainwater quality, which has led to unsatisfactory storage tank locations. This study proposed an optimal design strategy with consideration of multi-objective control. A pollution-level classification module was employed to divide all nodes into different pollution levels and a sorting module was adopted to comprehensively rank the pollution degree of the nodes at the same level. This strategy was then applied to a practical case study in Fuzhou, China. The application results confirmed that storage tanks using this design strategy can effectively reduce pollutants and are more economical than a terminal storage tank. The strategy approached in this paper is applicable to the optimization of storage tank design for the purpose of pollution reduction. Subsequent research will further optimize the control method of the storage tank to make it more efficient.

ACKNOWLEDGEMENTS

This work was supported by the Fujian Construction Science and Technology Research and Development Project under Grant No. 2019Y3003 and the Fuzhou City Construction Design & Research Institute Co., Ltd.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest The authors declare that they have no conflict of interest.

Ethical statement We declare herein that our paper is original and unpublished elsewhere, and that this manuscript complies to the Ethical Rules applicable for this journal.

Huifeng Li, on behalf of all the authors in the paper.

REFERENCES

Andrés-Doménech, I., Hernández-Crespo, C., Martín, M. & Andrés-Valeri, V. C. 2018 Characterization of wash-off from urban impervious surfaces and SuDS design criteria for source control under semi-arid conditions. *Science of The Total Environment* **612**, 1320–1328. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0048969717323537.

Bellu, A., Sanches Fernandes, L. F., Cortes, R. M. V. & Pacheco, F. A. L. 2016 A framework model for the dimensioning and allocation of a detention basin system: the case of a flood-prone mountainous watershed. *Journal of Hydrology* **533**, 567–580. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0022169415009919.

Cheng, J., Yuan, Q. & Youngchul, K. 2017 Evaluation of a first-flush capture and detention tank receiving runoff from an asphalt-paved road. *Water and Environment Journal* **31** (3), 410–417. http://doi.wiley.com/10.1111/wej.12258.

Cunha, M. C., Zeferino, J. A., Simões, N. E. & Saldarriaga, J. G. 2016 Optimal location and sizing of storage units in a drainage system. *Environmental Modelling & Software* **83**, 155–166. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364815216301517.

Duan, H.-F., Li, F. & Tao, T. 2016 Multi-objective optimal design of detention tanks in the urban stormwater drainage system: uncertainty and sensitivity analysis. *Water Resources Management* **30** (7), 2213–2226. Available from: http://link.springer.com/10.1007/s11269-016-1282-1.

Ekanayake, D., Aryal, R., Hasan Johir, M. A., Loganathan, P., Bush, C., Kandasamy, J. & Vigneswaran, S. 2019 Interrelationship among the pollutants in stormwater in an urban catchment and first flush identification using UV spectroscopy. *Chemosphere* **233**, 245–251. Available from: https://linkinghub.elsevier.com/retrieve/pii/S004565351931207X.

Fai, C. M. & Yusop, Z. 2017 Determination of stormwater first flush treatment strategies at tropical urban catchments. *Desalination and Water Treatment* **79**, 196–203. Available from: http://www.deswater.com/DWT_abstracts/vol_79/79_2017_196.pdf.

Fujian Provincial Department of Water Resources 2016 *Water Resources Bulletin 2011–2015*.

Fuzhou Statistics Bureau 2016 *Statistical Yearbook 2011–2015*. China Statistics Press, Beijing, China.

Iglesias-Rey, P. L., Martínez-Solano, F. J., Saldarriaga, J. G. & Navarro-Planas, V. R. 2017 Pseudo-genetic model optimization for rehabilitation of urban storm-water drainage networks. *Procedia Engineering* **186**, 617–625. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1877705817314315.

Jeon, J. C., Kwon, K. H., Jung, Y. J., Kang, M.-J. & Min, K. S. 2015 Characteristics of stormwater runoff from junkyard. *Desalination and Water Treatment* **53** (11), 3039–3047. Available from: http://www.tandfonline.com/doi/abs/10.1080/19443994.2014.922305.

Kong, F., Ban, Y., Yin, H., James, P. & Dronova, I. 2017 Modeling stormwater management at the city district level in response to changes in land use and low impact development. *Environmental Modelling & Software* **95**, 132–142. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364815216310131.

Li, F., Duan, H.-F., Yan, H. & Tao, T. 2015 Multi-objective optimal design of detention tanks in the urban stormwater drainage system: framework development and case study. *Water Resources Management* **29** (7), 2125–2137. Available from: http://link.springer.com/10.1007/s11269-015-0931-0.

Li, B., Yang, G., Wan, R. & Hörmann, G. 2017 Dynamic water quality evaluation based on fuzzy matter–element model and functional data analysis, a case study in Poyang Lake. *Environmental Science and Pollution Research* **24** (23), 19138–19148. Available from: http://link.springer.com/10.1007/s11356-017-9371-0.

Li, F., Yan, X.-F. & Duan, H.-F. 2019 Sustainable design of urban stormwater drainage systems by implementing detention tank and LID measures for flooding risk control and water quality management. *Water Resources Management* **33** (9), 3271–3288. Available from: http://link.springer.com/10.1007/s11269-019-02300-0.

Liu, Y., Cibin, R., Bralts, V. F., Chaubey, I., Bowling, L. C. & Engel, B. A. 2016 Optimal selection and placement of BMPs and LID practices with a rainfall–runoff model. *Environmental Modelling & Software* **80**, 281–296. Available from: https://linkinghub.elsevier.com/retrieve/pii/S136481521630069X.

Lu, W., Qin, X. & Yu, J. 2019 On comparison of two-level and global optimization schemes for layout design of storage ponds. *Journal of Hydrology* **570**, 544–554. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0022169419300150.

Mamoon, A. A., Jahan, S., He, X., Joergensen, N. E. & Rahman, A. 2019 First flush analysis using a rainfall simulator on a micro catchment in an arid climate. *Science of The Total Environment* **693**, 133552. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0048969719334722.

Mani, M., Bozorg-Haddad, O. & Loáiciga, H. A. 2019 A new framework for the optimal management of urban runoff with low-impact development stormwater control measures considering service-performance reduction. *Journal of Hydroinformatics* **21** (5), 727–744. Available from: https://iwaponline.com/jh/article/21/5/727/68968/A-new-framework-for-the-optimal-management-of.

Miguez, M. G. & Veról, A. P. 2017 A catchment scale integrated flood resilience index to support decision making in urban flood control design. *Environment and Planning B: Urban Analytics and City Science* **44** (5), 925–946. Available from: http://journals.sagepub.com/doi/10.1177/0265813516655799.

Ngamalieu-Nengoue, U. A., Martínez-Solano, F. J., Iglesias-Rey, P. L. & Mora-Meliá, D. 2019 Multi-objective optimization for urban drainage or sewer networks rehabilitation through pipes substitution and storage tanks installation. *Water* **11** (5), 935. Available from: https://www.mdpi.com/2073-4441/11/5/935.

Peng, H., Liu, Y., Wang, H., Gao, X., Chen, Y. & Ma, L. 2016 Urban stormwater forecasting model and drainage optimization based on water environmental capacity. *Environmental Earth Sciences* **75** (14), 1094. Available from: http://link.springer.com/10.1007/s12665-016-5824-x.

Peng, H.-Q., Liu, Y., Gao, X.-L., Wang, H.-W., Chen, Y. & Cai, H.-Y. 2017 Calculation of intercepted runoff depth based on stormwater quality and environmental capacity of receiving waters for initial stormwater pollution management. *Environmental Science and Pollution Research* **24** (31), 24681–24689. Available from: http://link.springer.com/10.1007/s11356-017-9800-0.

Raei, E., Reza Alizadeh, M., Reza Nikoo, M. & Adamowski, J. 2019 Multi-objective decision-making for green infrastructure planning (LID-BMPs) in urban storm water management under uncertainty. *Journal of Hydrology* **579**, 124091. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0022169419308261.

State Environmental Protection Administration (SEPA) 2002 *Environmental Quality Standards for Surface Water (GB3838-2002)*. China Environmental Science Press, Beijing, China.

St-Hilaire, A., Duchesne, S. & Rousseau, A. N. 2016 Floods and water quality in Canada: a review of the interactions with urbanization, agriculture and forestry. *Canadian Water Resources Journal/Revue Canadienne des Ressources Hydriques* **41** (1–2), 273–287. Available from: http://www.tandfonline.com/doi/full/10.1080/07011784.2015.1010181.

Wang, M., Sun, Y. & Sweetapple, C. 2017 Optimization of storage tank locations in an urban stormwater drainage system using a two-stage approach. *Journal of Environmental Management* **204** (Pt 1), 31–38. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0301479717308095.

Wang, M., Wang, Y., Gao, X. & Sweetapple, C. 2019a Combination and placement of sustainable drainage system devices based on zero–one integer programming and schemes sampling. *Journal of Environmental Management* **238**, 59–63. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0301479719302889.

Wang, Y., Ran, W., Wu, L. & Wu, Y. 2019b Assessment of river water quality based on an improved fuzzy matter-element model. *International Journal of Environmental Research and Public Health* **16** (15), 2793. Available from: https://www.mdpi.com/1660-4601/16/15/2793.

Zhang, P., Cai, Y. & Wang, J. 2018a A simulation-based real-time control system for reducing urban runoff pollution through a stormwater storage tank. *Journal of Cleaner Production* **183**, 641–652. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652618304426.

Zhang, W., Zhang, X., Fan, J., Shi, Z., Zhao, Y. & Li, S. 2018b Runoff pollution characterization and first flush effect of urban roof catchment. *Desalination and Water Treatment* **119**, 262–266. Available from: http://www.deswater.com/DWT_abstracts/vol_119/119_2018_26.pdf2.

First received 9 January 2020; accepted in revised form 1 May 2020. Available online 20 May 2020