Retracted: Evaluating the stormwater management model to improve urban water allocation system in drought conditions

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ABSTRACT

Improving the urban water allocation system has depended on different technical and management components. One of the main solutions for increasing the available capacity is the predetermined plan for constructing a water circulation system to restore the existing water resources. For this objective, a combination model was conducted based on a stormwater management technique and environment landscape system (ELS) under drought conditions. A hydrological framework was established using the long-term meteorological information in central China to estimate the extreme values of surface water in each stress period. A data analysis system was generated at three meteorological points of the study area and the developed model was incorporated to simulate the behavior of the subsurface flow. Consequently, a growth simulation model was developed according to the soil structure and vegetation canopy cover to formulate a real-time plan for the restoration of ELS. Results showed that the proposed model could improve the water process in urban and environment consumptions. Furthermore, technical analysis confirmed the suitability and applicability of the developed plan in cities with water shortages.

Key words | landscape system, surface and subsurface flows, water planning, water scarcity

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HIGHLIGHTS

- The implementation of the SWMM-based sponge city plan encountered some obstacles and challenges.
- Water reuse was considered as an important decision strategy.
- Data analysis was carried out based on real-time information.
- A physical model was implemented for many experiments.
- The results illustrated the acceptable achievement of the expected objectives.

INTRODUCTION

According to the United Nations, more than half of the world's population lives urban areas, which are affected by urban development. The volume and maximum discharge of urban floods are increased when considering the reduction of permeable urban area (Chunlin *et al.* 2014; Bellos & Tsakiris 2015; Wang *et al.* 2018). Many studies have been conducted around the world in relation to runoff estimation in urban basins and flow simulation, as well as evaluation of surface water collection and disposal networks in urban basins, which shows the importance of this issue (Jia *et al.* 2017; Imaizumi *et al.* 2018; Yang *et al.* 2018).

doi: 10.2166/ws.2021.027

Modeling in urban watersheds has become important due to problems related to water resources management such as floods and pollution control. Hence, the approach of engineers in recent years is towards computer models for estimating and simulating runoff. Therefore, many rainfall–runoff models with different capabilities and complexities have been developed and used to predict floods. These models include Storm Water Management Model (SWMM), URBAN, MIDUSS, STORM, RISURSIM, ILLUDASS, etc. The SWMM is a powerful tool for urban drainage calculations and runoff management. Simplicity of work and its power in quantitative and qualitative analysis and management of floods in urban areas are the features of this model (Gironas *et al.* 2010; Fei *et al.* 2017).

Jang *et al.* (2007) investigated the effectiveness of the SWMM in a number of natural watersheds in South Korea. Park *et al.* (2008) simulated the flow hydrograph and the volume of pollutant loads in the South Korean sewer drainage network using the SWMM. The results showed that the SWMM gave a good estimate of peak discharge and runoff volume. Yu *et al.* (2014) used the SWMM to estimate the runoff of Jinan city in China. They used 14 events to validate and evaluate the model's performance, and eventually found that the model could be used in large cities.

Jia *et al.* (2012) conducted a study using the SWMM to simulate a drainage network in a Chinese Olympic village. Sun *et al.* (2013) estimated the parameters and uncertainties in the SWMM in Syracuse. Kourtis *et al.* (2017) evaluated the SWMM for two Greek urban basins. In addition to these studies, other researchers have used this model for different regions of the world (Huang *et al.* 2015; Del-Guidice & Padulano 2016; Wu 2019).

According to the previous studies, water shortage is a reason to implement an environment landscape system (ELS) in urban management frameworks to achieve sustainability of water resources. Developing a combination system for landscape restoration and the SWMM could be a new urban rainwater management concept. For this object, it is necessary to determine hydrologic characteristics to establish a sustainable system using the urban landscape and the storm management model. The development of a restoration system that can integrate stormwater management functions is a necessary step to truly realize the sustainable development of green cities.

The Chinese government has begun implementing the ELS plan to resolve the drought in urban water supplement. The construction of the proposed plan is a complex systematic project that requires a large amount of data to support the city's physical geography, socioeconomics, water resources, and ecological environment. Moreover, EPA's SWMM has been incorporated to the decision system, which was used in previous studies for planning, analysis, and design related to stormwater runoff and drainage systems in urban areas. However, the implementation of the landscape plan based on the SWMM encountered some obstacles and challenges. The meteorological situation of a city with water shortage was incorporated to establish the surface water hydrological model of Teaneck Creek in central China.

MATERIALS AND METHODS

Urban landscape system

To create a stable structure in urban water consumption, it is necessary to pay attention to the flow circulation mechanism, the use of unconventional water sources with acceptable quality such as rain and floods. Investigations showed that currently the development and use of unplanned water resources to solve the problem of water scarcity is a strategic policy. Desalination, groundwater balancing and the effective use of rainfall are examples of these policies. In addition, reuse of water such as rainwater and flood control and its application for urban use after treatment is essential based on regional conditions. The schematic of the considered structure to combine the water environment restoration system and the SWMM is shown in Figure 1.

Stormwater management model (SWMM)

SWMM is a dynamic hydraulic–hydrologic simulation model that is used for a single event or long-term data sets of runoff quantity and quality from primarily urban areas. The runoff component operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion transports this

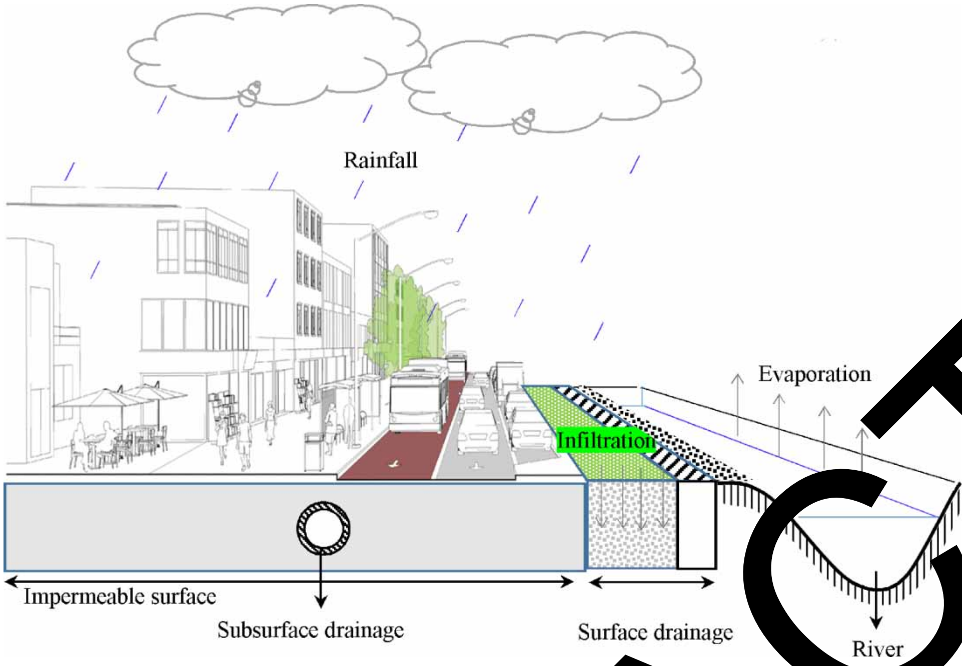

Figure 1 | Schematic system of water circulation.

runoff through a system of channels, subsurface pipes, storage/treatment pools, regulators and pumps. SWMM tracks the flow depth, flow rate, and quality of water during a simulation period made up of multiple time steps in each sub-catchment (Tobio *et al.* 20[illegible]; Xu *et al.* 201[illegible]).

The basic equations used in the SWMM have been updated in several stages. These changes have occurred due to modules that must be changed for different conditions. However, the main process of the model and its assumptions are based on basic principles. The environmental components required to simulate a project are hydrological information, surface and groundwater resources, water delivery and storage systems, pollutant accumulation and treatment, and quantitative impact control (Kumar *et al.* 2017; Johannessen *et al.* 201[illegible]). SWMM has recently been extended to model the hydrologic performance of specific types of low-impact development (LID) controls. The LID controls that the user can choose include the following seven green infrastructure practices: permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration trenches, and vegetative swales (Leandro & Martins 2016).

In the main framework of the landscape plan, a block paving system could be applied with impervious pavement blocks laid on a sand or pea gravel layer supported by a gravel storage layer below. Rainwater is collected in the open space between the blocks and transported to the storage area and native soil below. Other equipment is a rainwater reservoir (bucket) for collecting rainwater, which will be released or reused during a drought period. The reservoir can be located on the surface or subsurface with the storage capacity larger than the common bucket.

A rain garden is a hydraulic structure that could be constructed in a landscape to collect the rainwater from a roof, road or street and helps it to penetrate into the ground. Grass and flower plantating can be a cost-effective and beautiful way to reduce runoff from the proposed landscape. Moreover, rain gardens provide shelter and food for song birds, butterflies, and other wildlife and help to filter out pollutants in runoff. More advanced rain gardens with drainage systems are often applied as bioretention to amend soils. Vegetation sunken landforms include dips, ditches or slopes covered with grass and other vegetation. Vegetation depressions slow down the speed of collected runoff and give it more time to penetrate the underlying native soil.

Infiltration ditches are shallow trenches with stone or rubble that construct temporary subsurface storage of stormwater runoff, thereby enhancing the natural capacity of the ground to store and drain water. They allow water to infiltrate into the surrounding soils from the bottom and sides of the trench. Usually, Infiltration ditches should receive inflow from an adjacent impermeable surface, but point source inflows may be acceptable. Additionally, a continuous permeable pavement system should be designed to achieve the artificial porous media through the road immediately, where the rainwater will penetrate into the site at a natural speed.

A green roof system is an extension for the common roof which involves a root repellent system, water-proofing, drainage system, filter, and vegetation cover. It contains vegetation that allows rainfall to penetrate and store water for evapotranspiration. Green roofs are particularly cost effective in dense urban areas with high land values and in large industrial or office buildings where stormwater management costs may be high. Downpipe treatment is a beneficial system for cities with combined sewerage structures to cut off downpipes and which are used to store rainfall or help seepage into the soil. Moreover, this system allows the rainwater to drain into permea[illegible]scape areas and lawns instead of direct flow into gu[illegible]rs.

Model calibration

Calibration and verification of hyd[illegible]nami[illegible] that has been considered [illegible] many re[illegible]hers and users of these models. Point of [illegible]w research pa[illegible]s confirmed the need for a calibrat[illegible] pr[illegible]s but the cali[illegible]tion methods were different (Kleidorfer *et a*[illegible]09; Jain *et al.* 2015; Formiga *et al.* 2016; [illegible]es *et al.* 2016). The [illegible]ter cycle balance in the hydrologi[illegible] range has the parame[illegible]s of rainfall, surface water [illegible]filtration, [illegible]apotranspiration, groundwater flow and deep in[illegible]atio[illegible] These para[illegible]eters are calculated based on [illegible]raulic, [illegible]rological [illegible]d hydrogeological information (Ma[illegible] & Alam[illegible]d 20[illegible]). Therefore, it is necessary to estimate the [illegible]ntioned val[illegible] in calibration processes and specified in th[illegible] [illegible]ce equations using the following equation:

$$[illegible]V = P + S_i + G_i - ETa - I - S_0 - G_0 \pm T \tag{1}$$

where ΔV = storage capacity variation; P = precipitation; S_i = surface water infiltration; G_i = surface water infiltration; ETa = actual evapotranspiration; I = infiltration; S_0 = surface water seepage; G_0 = surface water seepage; T = tidal current.

The surface flow rate will be obtained using the Manning equation:

$$Q = \frac{1}{n} A R^{2/3} S^{1/3} \tag{2}$$

where Q = discharge, n = [illegible]nning ro[illegible]ghness [illegible]effi[illegible]ent A = cross-section area o[illegible]e discha[illegible]; R = the h[illegible]raulic radius, and S = the h[illegible]rauli[illegible]rad[illegible]nt (Chow *e[illegible]l.* 1988).

Infiltration ra[illegible](I_r) is one o[illegible]e main c[illegible]ponent of the decision syste[illegible]t is formulated [illegible] fol[illegible]s:

$$I_r = I_s(1 + C_p(SM_m - S[illegible])/SM_m) \tag{3}$$

[illegible]ere I_s = infiltration rate under the saturated condition; [illegible] = the permeab[illegible]y coefficient; SM_m = soil water capacity; [illegible]M = soil water c[illegible]tent.

[illegible]he actual [illegible]nsplantation (ETa) value is obtained by applyin[illegible]rection factor to the potential evapotranspira[illegible]n which is calculated by the following equations:

$$ETp_i = 1.6\left(\frac{10\tau_i}{\theta}\right)^a \tag{4}$$

$$\theta = \sum\left(\frac{\tau_i}{5}\right)^{1.514} \tag{5}$$

$$E = 0.675\theta^3 - 77.1\theta^2 + 17920\theta + 0.49 \tag{6}$$

where ETp = the monthly potential evapotranspiration (ETp); τ_i = the average monthly temperature, θ = the local thermal index, E = is the actual evaporation. In the developed simulation, it is assumed that the groundwater inflow (G_i) is negligible and not included in the water budget calculation (Tan *et al.* 2017). Although there is some evidence of groundwater movement in some places, there is a highly impermeable clay layer under most parts of the system, minimizing the impact of groundwater. In this study, 10 measured precipitation events were used to calibrate the model and three events were considered for model validation (Table 1).

Infiltration coefficients, the amount of permeable and impermeable lands were the components that need to uncertainty analysis. The initial values of these parameters should be adjusted in the calibration stage. Then analyze the curve of observed flow and measured flow of each calibration

Table 1 | Rainfall–runoff characteristics (11, 12, and 13 were used for verification)

	Rainfall			
Storm number	**Depth (mm)**	**Peak (mm/hr)**	**Duration (min)**	**Peak flow (m^3/s)**
1	13.1	4.6	247	31
2	7.6	3.8	322	36
3	9.7	4.1	365	42
4	3.2	2.7	473	28
5	7.5	3.2	418	35
6	21.5	5.2	243	43
7	11.8	4.1	267	33
8	5.7	2.3	353	27
9	32.4	6.3	264	54
10	14.9	4.7	297	46
11	8.2	3.9	334	37
12	22.1	5.9	326	39
13	4.6	3.4	430	31

simulation to verify the model. However, the parameters affecting the concentration time of the basin have been used for calibration, which are equivalent width, basin slope, percentage of permeable and impermeable areas, weighting coefficient of permeable and impermeable areas and depression storage. The range of changes of the initial parameters to calibrate the important parameters of the SWMM are presented in Table 2.

The calibration of the model continues until it is determined by statistical indicators that the results of the calibrated model are in good agreement with the measured data. To evaluate the models from the statistical indicators of eff model efficiency, the mean of the second root of the

Table 2 | Initial range of calibrated parameters

Parameter	**Index**	**Value**	**Reference**
Permeable area	PA	0–2.8	Huber & Dickinson (1992)
Impervious area	IA	0–11.033	Huber & Dickinson (1992)
Depression storage of permeable area	DSP	2.7–5	Tsihrintzis & Hamid (1998)
Depression storage of impervious area	DSI	0.2–3.5	Huber & Dickinson (1992)
The percentage of permeability	PPer	−30%–+30%	Temprano *et al.* (2006)

error is RMSE, the normalized RMSE (NRMSE), the residual mass coefficient of CRM:

$$EFF = \left(1 - \frac{\sum_{i=1}^{n}(O_m - O_c)^2}{\sum_{i=1}^{n}(O_m - \overline{O_m})^2}\right) \times 100 \quad (7)$$

$$RMSE = \left(1 - \frac{\sum_{i=1}^{n}(O_m - O_c)^2}{n}\right) \quad (8)$$

$$CRM = \left(1 - \frac{\sum_{i=1}^{n} O_m - \sum_{i=1}^{n} O_c}{\sum_{i=1}^{n} O_m}\right) \times 100 \quad (9)$$

where O_m is the measured value, O_c is the calibrated value, n is the number of samples used and $\bar{O}$ is the average value of the observed parameter.

Landscape simulation based on SWMM

SWMM hydraulically simulates runoff and concentration time and its relationship to rainfall intensity in an urban environment. Furthermore, it is able to calculate the runoff flow in open canals, pipelines and other waterways using the dynamic wave equation. SWMM can also include water pollution load changes in calculations to consider water quality parameters. It also uses several modules to determine the amount of runoff drainage and provides an acceptable estimates. Therefore, SWMM calculates runoff generation and variation curves by calculating water distribution between different modules with the occurrence of precipitation. In SWMM, the rain gauge is used to estimate the amount, duration and intensity of rainfall over time. In this study, rainfall was recorded in the atmospheric module and the volume of water and pollutants affected by rainfall was transferred directly to the surface module.

The surface module receives runoff and pollution load from the atmospheric module and transfers it to the groundwater module based on the characteristics of each sub-basin that is a subset of the surface module. The groundwater module operates as an aquifer layer and receives precipitation and infiltrating contaminants from the surface module. A percentage of water received is transferred to the transport module. In the next step, the transport module composed of a set of units with transfer and processing features including pipes, channels, etc., is embodied in the combination of nodes and connections. The user-defined hydrological process can also be set to receive input from the surface module and groundwater module.

Runoff flow rate in urban environments due to the impermeability of land cover increases the speed and volume of outflow. Hydrological planning in urban conditions is complex with more design and evaluation components and is significantly affected by the urbanization process. In these regions, slope, surface coverage, permeability and social and economic constraints have a greater and more multifaceted impact than the natural environment. Therefore, simulating and monitoring the flow path from rainfall to storage or consumption is a complex process with different sources of uncertainty (Muleta *et al.* 2012).

In this study, SWMM was simulated using the meteorological data recorded in central China. There are some equipment including 1. Catchment sub-basin, 2. Node, 3. Connecting passage and 4. Rain gauge that have been implemented in different modules to generate the simulation system.

Catchment sub-basin can be divided into water area and water-free area, while the water area can be divided into flow area and water storage area. The subwatershed is the smallest hydrological unit, only the one outlet is set, and the setting parameters include the rain gauge, outlet, impervious rate, etc. Node is the confluence or inflection point of the water passage path. There are many types of visualization objects of nodes, including intersections, outfalls, diverters and reservoirs. The intersection is the connection point of the drainage system pipeline, and the main input parameters include the elevation of the inner bottom, the height from the surface, and the external inflow data. The outfall is the final node of the drainage system, and the main input parameters include invert elevation, boundary condition type, etc. The connecting passage is usually composed of a transportation conduit in the drainage system. The connected visualization equipment mainly includes a conduit, water pump, flow regulator, etc. The rain gauge provides rainfall data for sub-basins. The rainfall data can be the precipitation data measured in a user-defined time period or imported from outside. The main input parameters include data type, time step, precipitation data source, etc.

RESULTS AND DISCUSSION

Model evaluation

The results of evaluation criteria for model calibration and validation processes are summarized in Table 3. According to the table, the accuracy of the model is acceptable for predicting and evaluating runoff flow. To illustrate the trend of precipitation and hydrograph changes created by different precipitation patterns, Figure 2 is presented for the three events with the highest rainfall depth. The hydrograph obtained for each rainfall event is estimated by fitting to the calibrated runoff flow. The figure shows that the presence of a storage source can reduce the peak flow and height of the hydrograph.

Different values of runoff flow in different scenarios of the study period using the calibrated model are shown in Figure 3. The maximum flow rate for the river is estimated to be between 60 and 64%. After the river, road, underground drainage and permeable surfaces had the highest runoff capacity, respectively. Figure 2 shows the comparison between the measured and calibrated flow rate of rainwater at different times (early (T1), mid-term (T2), and late (T3)).

Comparing the different outflow ratios shows the relationship between the outflow and rainfall in estimated methods. As shown in Figure 4, as the rainfall time increases, the total outflow of the three roads is increasing.

Table 3 | Error indicators for evaluating the calibration and verification results

Storm number	EFF (%)	RMSE (m^3/s)	CRM (m^3/s)
1	78	7.6	−0.045
2	81	6.9	0.031
3	92	4.3	−0.004
4	83	6.3	0.015
5	94	3.6	0.0045
6	77	7.2	−0.048
7	82	6.7	−0.035
8	89	5.1	0.0087
9	90	5.1	0.017
10	86	5.8	0.012
11	91	3.7	−0.067
12	79	7.4	−0.054
13	88	5.6	0.0091

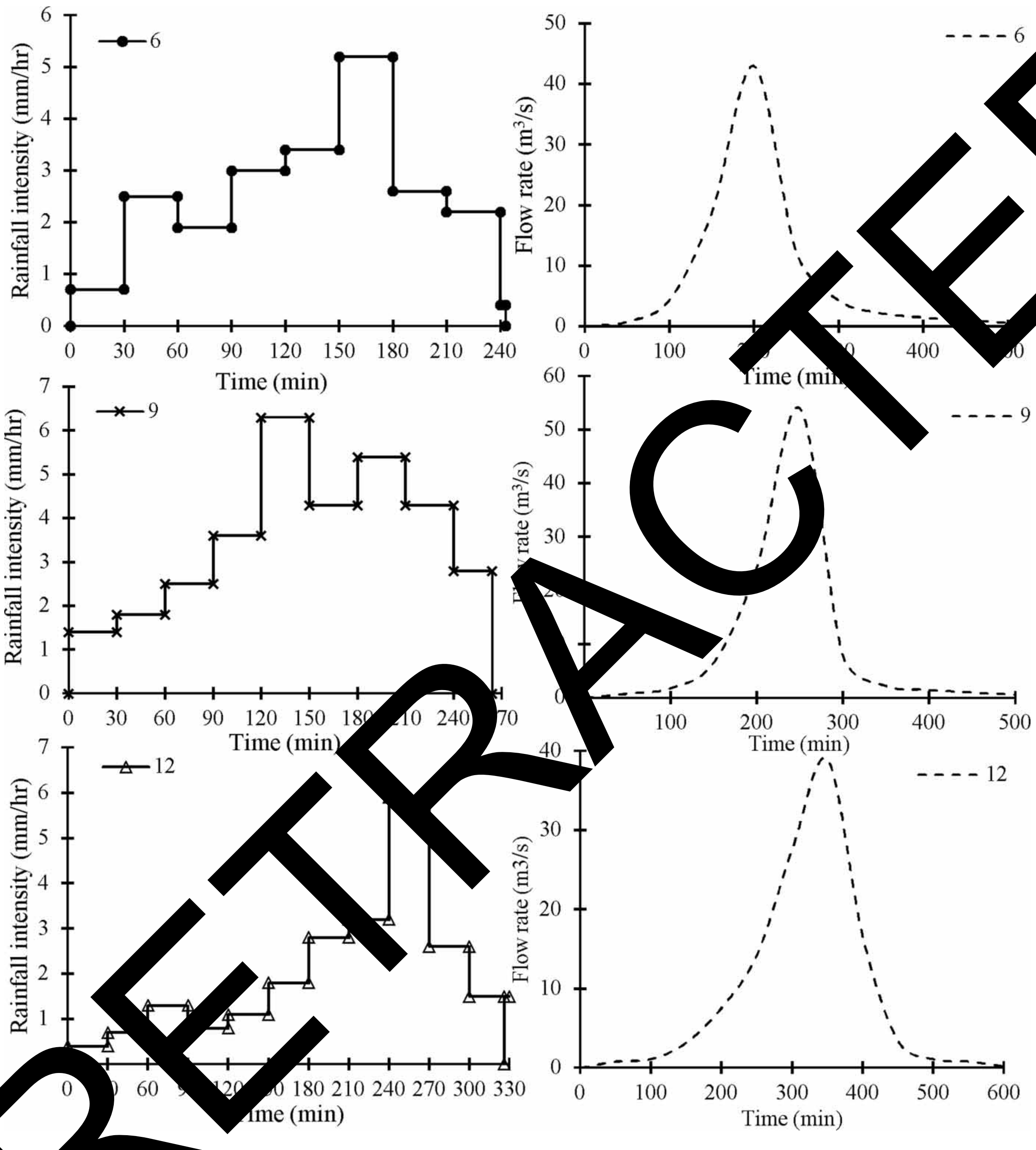

Figure [illegible] outflow hydrograph for three storm events.

Am[illegible] them, the proportion of river outflow increases with rainfal[illegible]e, while the proportion of total outflow of bricks and subsurface drainage system decreases, which indicates that the impact of water flow capacity on roads is greater. After rainfall intensity increases, more water flows out through the river channel. Therefore, it can be seen that the faster the runoff, the more important the river outflow becomes.

Runoff capture rate and storage capacity

The criterion for selecting an appropriate solution is considering the environmental, economic, social and technical

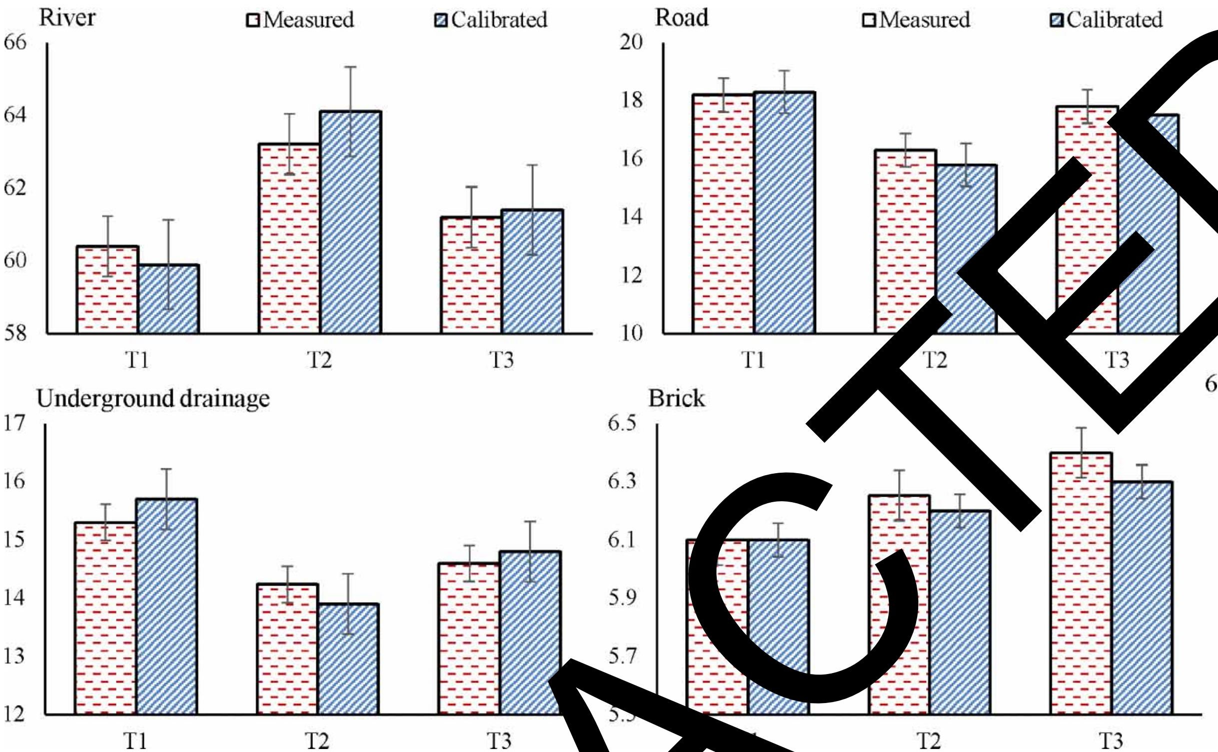

Figure 3 | Percentage of measured and calibrated outflow in different times.

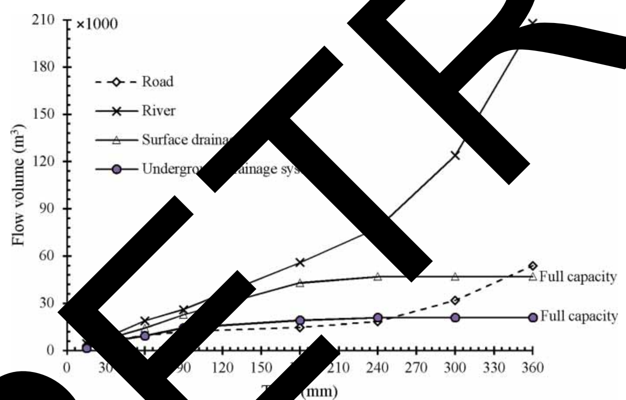

Figure 4 | The relationship between the total amount of outflow and rainfall in four outflow ways.

conditions of the project. According to the mentioned criteria, it is necessary to consider appropriate instructions in the design in different regions that have different climatic conditions. Therefore, according to the geographical coordinates and climate of the study area, the relationship between runoff production and required water storage volume is obtained as Figure 5.

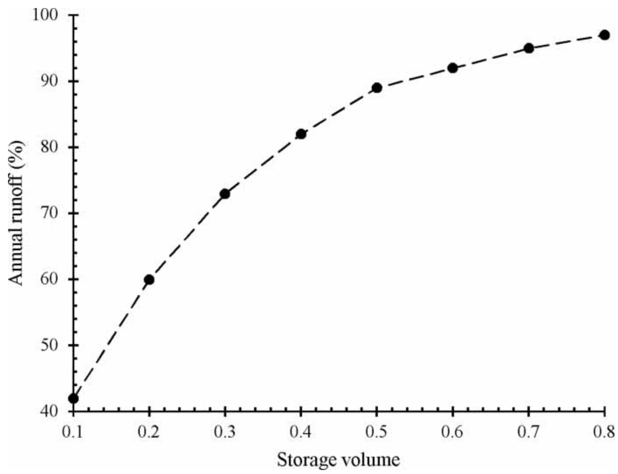

Figure 5 | Runoff capture rate versus required storage volume.

Runoff hydrograph

The traditional development model will cause problems such as the change of land cover type, the advance of peak runoff time, the increase of peak flow and total

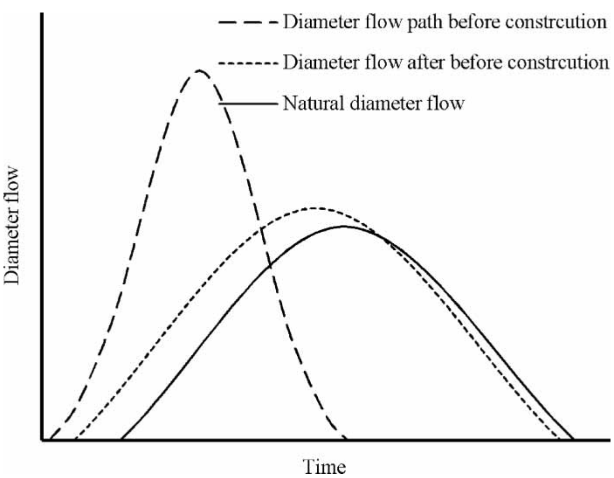

Figure 6 | Effect of construction on-site hydrology.

runoff. As shown in Figure 6, after the comprehensive development of urban water environment landscape stormwater management system proposed in this paper, the peak flow and total runoff will return to the level before the development, or even more slow down the peak rainfall.

The predicted runoff hydrograph is close [illegible] due to the effect of storage sources and outlet reservoir at the beginning of rainfall. In general, various aspects of the evaluation and application of landscape rainwater systems [illegible] natural hydrological background are: optimizing the combination of permeable surfaces (vegetation and porous) and impermeable (road, roof and street) to increase the volume of infiltrated water. Rain infiltration conditions to permeable areas should be provided in terms of slope, porosity and surface cover in such a way that the permeable surfaces are located in the flow path and have a high ability to maintain and percolate. Water storage and release systems reduce the [illegible] and temporary storage of runoff and reduce the peak flow of the hydrograph. This structure, which is a common example of a pool, is an effective measure to control [illegible]water. Runoff storage is based on the comprehensive use of rainwater resources and runoff reduction, whose tasks are to reduce peak flow and control runoff pollution. Through proper design, many landscape rainwater facilities can store, adjust and purify hydrological functions such as rainwater garden, low potential green space, landscape water body, rainwater pond, multi-purpose adjustment and storage, etc.

CONCLUSION

In this paper, the SWMM technology was established based on the correlation between the data of the central water-scarce city, ground elevation data and community drainage official website data. Through the experiment and on-site experimental verification, it was proved that the model could be applied to the central water shortage. The improvement of water resources [illegible] a water [illegible] was conducive to improve the city's water storage capacity and urban anti-pollution ability. Through the established model, it can be found that the application of this model can analyze the water storage capacity and water accumulation status of the community under different rainfall conditions and the velocity of rivers in cities. These can serve the purpose of forecasting the urban [illegible]n period and regulating the urban water storage. The established framework in this study is used for monitoring the speed of the runoff flow and the volume of the flow after the rainfall. In simulation and empirical studies, it was found that the number of urban waterloggings in the reconstructed place was significantly reduced during the rainy period, and the water accumulation status in some places has been improved. Furthermore, the simulation found that the regulation, energy storage capacity of regulation, and energy storage facilities should be dynamic under rainfall conditions because the runoff generation and confluence processes were dynamic. The current source control measures are less rain that may have a negative impact on river ecology. The effect of reducing flood peaks under heavy rainfall conditions is not enough. For the source section, control measures that consider process control were proposed, and new and old measures were adjusted through model simulations. The comparison results show that the new source control measures not only eliminate the negative impact on the river ecology, but also improve the river ecological environment flood peak reduction capacity.

DATA AVAILABILITY STATEMENT

Some or all data or models that support the findings of this study are available from the corresponding author upon reasonable request.

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First received 20 November 2020; accepted in revised form 13 January 2021. Available online 25 January 2021