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Sponge-city-based urban water system planning: a case study of water quality sensitive new area development in China

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ABSTRACT

In recent years, sponge city has been booming in China aiming to alleviate urban flooding and improve water quality of natural water bodies. LID/green infrastructure has been gradually introduced to urban planning and urban water system planning. Efficient deployment of LID facilities is critical, which requires modeling and evaluation to develop rational planning. A case study of Guian New Area was presented to show the application of SWMM and the planning methods in sponge-city-based urban water system planning for water quality sensitive new areas development. Based on SWMM, two river network water quality models, the Dongmenqiao River and the Chetian River, were established through a systematic analysis of the case study area. Baseline scenarios were simulated and analyzed, and assimilation capacities of the two river basins were calculated by a trial-and-error method. Finally, two LID scenarios were carefully designed, simulated, and analyzed to support the planning. The simulations showed that in order to meet the strict water quality requirements in Guian New Area, large scales of LID facilities are required to cut down the rainfall-runoff pollution. Moreover, measures such as more frequent cleaning to reduce pollutants accumulation on the ground should also be taken to mitigate the maximum buildups of pollutants.

Key words: LID, nature-based solution, sponge city, SWMM, urban planning, urban water system

HIGHLIGHTS

- A sponge-city-based urban water system planning method is demonstrated for water quality sensitive new areas.
- The methodology integrates system analysis of the case study area, water quality modeling, baseline scenario analysis, assimilation capacity calculation, and LID scenario analysis.
- SWMM is an effective tool for modeling urban water system and LID measures, as well as evaluating the system performance and LID effectiveness.

INTRODUCTION

China has experienced a high speed of urbanization over the past decades, while many new areas of different tiers have been built. However, due to the unreasonable development model and insufficient stormwater management, the urbanization of new areas has significantly changed the characteristic of local hydrology and water quality and caused urban flooding and water quality deterioration (Shen *et al.* 2014; Xu *et al.* 2017). Thus, developing a new nature-based ecological development model is in urgent demand in China. It is critical to make a rational planning of urban water system, which incorporates a new ecological development model, at the beginning of new area development, since it is more efficient to protect and control at source than to treat and restore at the end of pipe. In China, master plan is the fundamental plan for a city or a new area. It depicts the general future map, constructs the overall spatial development framework, and causes significant impacts on the ecosystem, including water environment. The urban water system plan is suggested to be compiled with the master plan, especially for new areas, and provides key information including area and location, water system layout, main water infrastructures, and land use suggestions of the aimed area as supplementary of master plan to protect or restore natural water system (Kong *et al.* 2013).

Low impact development (LID), best management practice (BMP), water-sensitive urban design (WSUD), sustainable urban drainage systems (SUDS), green infrastructure (GI), nature-based solutions (NBS), and some other similar concepts have been proposed in recent decades in developed countries to tackle stormwater management (Fletcher *et al.* 2014). LID focuses on achieving a natural hydrology through site layout and integrated control measures, discouraging large end-of-catchment detention facilities, which is widely used in North America and New Zealand (Coffman 2000; Shaver 2000; Dietz 2007). The emphasis of LID is avoiding pollution and a similar term named low impact urban design and development (LIUDD) is also used in New Zealand (Shaver 2003; Eason *et al.* 2006). BMP focuses on pollution prevention, using non-structural methods (such as good housekeeping and preventive maintenance) and structural facilities (such as bioretention systems or green infrastructures), which is widely used in North America (Environmental Protection Agency 2011a, 2011b). WSUD originated from Australia, and it is increasingly used worldwide now, especially in the UK and New Zealand (Ashley *et al.* 2013). WSUD is described as a conceptual approach to urban planning and design, aiming at the whole urban water system, including flood control, flow management, water quality improvement, and stormwater harvest (Whelans *et al.* 1994; Lloyd *et al.* 2002; Wong 2007), although the early application mainly focused on stormwater management. SUDS is mainly used in the UK, whose principle is similar with LID, providing a more sustainable way, based on the concept of replicating the natural, pre-development hydrological characteristic on site wherever possible (CIRIA 2001; Woods-Ballard *et al.* 2007). GI, widely used in the United States, has become almost synonymous with LID since the US EPA and other agencies realized the potential use of green infrastructure in helping with stormwater management (Struck *et al.* 2010), although it goes well beyond stormwater management.

These concepts present a holistic approach of stormwater management from the perspective of the entire natural and social water cycles, mimicking the natural hydrological characteristics, emphasizing the importance of distributed small-scale on-site measures and facilities and represent a new paradigm of land development/re-development requiring multidisciplinary cooperation among water system, environment, urban planning and design, landscape, ecology, sociology, etc. In recent years, sponge city, which draws on concepts from the developed countries and combines with traditional Chinese wisdom, has been widely applied in China, especially since the Chinese government launched an initiative to facilitate sponge city construction. Thus, LID/green infrastructure has been gradually introduced to urban planning and urban water system planning in China with the purpose to alleviate urban flooding, prompt water reuse, and improve water quality.

Models are useful to quantify planning measures and support the development of scientific plannings. There is a need to model water quantity and quality throughout the entire urban water system planning processes ranging from surface rainfall-runoff, to urban drainage system, to receiving water body, i.e. rivers and lakes, as well as LID measures. Storm Water Management Model (SWMM), developed by the US EPA (Huber & Dickenson 1998; Rossman 2015), is a widely used open-source model for stormwater management that is suitable for the above-mentioned tasks. Traditionally, SWMM has been mainly applied to simulate urban drainage networks, which can also be used to model water quantity and quality in channels and rivers.

El-Sharif & Hansen (2001) applied SWMM to the flooding problem in Truro, Nova Scotia, and recommended SWMM to be the best model for a flood warning system since it can handle both natural and engineered systems on the same platform. Gatling *et al.* (2004) applied a single storm event from the NOAA rainfall database to SWMM to model the TSS source from each subcatchment and the spatiotemporal river water quality. Tsai *et al.* (2017) modeled water quantity and water quality in the 50 km long river, with non-point source pollution from agriculture being the main pollution source in the watershed Peishi Creek in a high pervious Taipei forest area by SWMM. Some other researchers also used SWMM to model open channels and rivers (Delfs *et al.* 2012; Gamache *et al.* 2013; Wu *et al.* 2016; Zhu *et al.* 2019; Althouse *et al.* 2018; Gulbaz *et al.* 2019). However, the LID module of SWMM for simulation in open channels and rivers has not been used in the above-mentioned studies.

A case study of Guian New Area, where water quality requirements are extremely strict, was presented in this paper to show the application of planning method and SWMM in sponge-city-based urban water system planning for water quality sensitive new area development. During the planning, water quality models of two river networks were developed through SWMM for two main river basins in the research field, followed by baseline scenario simulation and analysis. After which, assimilation capacities were calculated to determine the priorities for the planning. Consequentially, two LID scenarios were designed, simulated, and evaluated to provide solutions to meet the strict water quality requirements and recommended effective measures for the planning.

MATERIAL AND METHODS

System analysis for the case study area

Basic information and the natural water system

The case study area is the core area of Guian New Area, a national-level new area in Southwest China, with an area of 235 km^2. Guian is a portmanteau of Guiyang and Anshun city, formed by several adjacent parts of these two cities. The current land use types are mainly farmlands, grasslands, and woods, which will be turned into urban areas in the following years. We hope that a new model of LID will be applied here to avoid the traditional problems of urban flooding and water quality deterioration caused by the traditional development model.

The core area of Guian New Area owns an abundant natural water system including four rivers, six small reservoirs, and multiple wetlands. The four rivers are the Chetian River, the Dongmenqiao River, the Machang River, and the Gan River, in which the Chetian River basin and the Dongmenqiao River basin covering three quarters of the core area. Six reservoirs are the Wangguan Reservoir, the Liujiazhuang Reservoir, the Sizhaihe Reservoir, the Kechou Reservoir, the Dasongshan Reservoir, and the Kaizhang Reservoir. The Chetian River and the Dongmenqiao River run into Huaxi Lake and Baihua Lake, respectively, which are located out of the core area of Guian New Area.

Rainfall and runoff characteristics

The rainfall data from 1951 to 2012 collected from the Guiyang weather station, which is the nearest weather station around Guian New Area, was applied for analysis. The annual rainfall for 62 years is shown in Figure 1. The average annual rainfall over 62 years was 1,116.7 mm within which the maximum annual rainfall of 1,759.2 mm was observed in 1954 and the minimum of 718.6 mm in 1981, with the maximum to minimum ratio of 2.4. The monthly average rainfall over 62 years is shown in Figure 2. The rainfall from May to August accounts for 60% of annual rainfall, while that from December to March only accounts for 10%.

The daily rainfall statistics, shown in Table 1 and Figure 3, indicated that 46.8% of the observed 22,646 days over 62 years were rainy days, among which light rains (<10 mm), moderate rains (10–25 mm), heavy rains

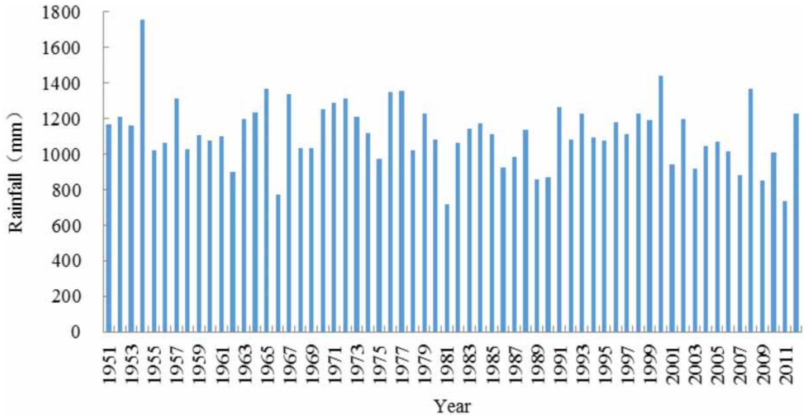

Figure 1 | Guiyang annual rainfall (1951–2012).

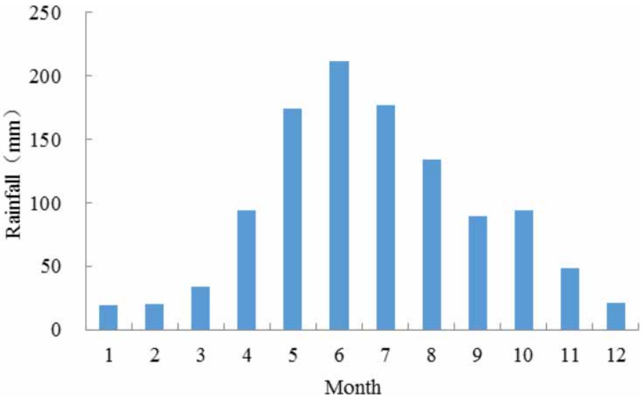

Figure 2 | Guiyang monthly average rainfall 1951–2012.

Table 1 | Daily rainfall statistics of Guiyang (1951–2012)

Rainfall (mm)	Days	Percentage
0–1	4,281	39.9
1–3	2,231	20.8
3–5	965	9.0
5–10	1,271	11.9
10–25	1,255	11.7
25–50	552	5.1
50–100	153	1.4
100–150	16	0.1
150–200	1	0.01

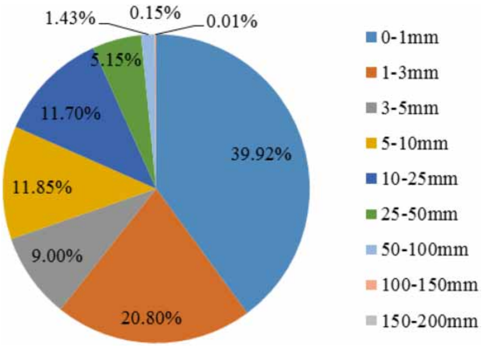

Figure 3 | Rainfall intensity percentages of Guiyang (1951–2012).

(25–50 mm), and torrential rains (>50 mm) accounted for 81.6, 11.7, 5.1, and 1.5%, respectively (characterized according to the national standard of Grade of Precipitation (GB/T 28592-2012)). Most rainfalls are light rains in Guiyang, with even three fifths were less than 3 mm.

In the core area of Guian New Area, all the rivers rise in the mountains, whose runoffs are derived from rainfalls, without any runoff flows in across boundaries. According to the historical rainfall data and related planning, the annual runoff and waste water generation of core area of Guian New Area were estimated to be 70–180 million m^3 and 100 million m^3, respectively, leading to an annual runoff to waste water ratio of only 0.7–1.8, while the ratio in the dry season is much less. Under these circumstances, the river assimilation capacity is quite limited. The waste water must be treated to meet a highly strict standard, while the rainfall-runoff pollution should also be strictly controlled.

Water quality protection requirements

Guaranteeing the water quality in Guian New Area is of great importance, because it locates at the upstream of drinking water sources of Guiyang city, the capital of Guizhou Province. The two main rivers in the core area of Guian New Area, namely the Dongmenqiao River and the Chetian River, flow across the region before running into the drinking water sources of Guiyang city, the Huaxi Reservoir and Baihua Lake, respectively. According to the national standard, the downstream water quality of those two rivers shall meet all water quality requirements of Grade III in the Environmental Quality Standards for Surface Water (GB3838-2002) in China, which will present a great challenge to the development of Guian New Area.

River network water quality model

Due to the high requirements of water quality protection standard, the local authority of Guian New Area required to build a separate drainage system in the new area, where all wastewater will be discharged to the receiving water body outside the new area after treated by the wastewater treatment plants, leaving stormwater-induced non-point source pollution as the main source of pollution in the region. Therefore, only non-point source pollution needed to be considered and modeled in water quality modeling. Additionally, since the stormwater system has not yet been planned at the initial stage, the simulation of rainfall-runoff and its pollution would be carried out without pipe network in SWMM.

In this study, water quality models of two river networks, namely the Dongmenqiao River basin and the Chetian River basin, were developed through SWMM to support the urban water system planning, compiled with the master planning of the core area of Guian New Area. Simulations were conducted at the beginning of the planning to determine key considerations for the planning.

The schematic of the two river networks is shown in Figure 4. The Dongmenqiao River network model is comprised of 32 reaches, 33 computational sections, and 70 subcatchments to simulate a total length of 28.4 km covering 53.66 km^2 in the Dongmenqiao River network, whereas the Chetian River network model consisted of 71 reaches, 72 computational sections, and 172 subcatchments covering a total length of 63.8 km, with a basin area of 108.4 km^2. The river length, basin area, and modeling scale of the Chetian River network are twice as large as those of the Dongmenqiao River network.

According to the water quality protection requirements in Guian New Area and the relevant Chinese surface water quality standards, chemical oxygen demand (COD), ammonia nitrogen (Amm-N), and total phosphorus (TP) were selected as water quality indicators for simulation.

The land use data of the master plan for the core area of Guian New Area, and the current river conditions including length, section shape, etc., were applied to water quality models for baseline scenario analysis, assimilation capacity calculation, and LID scenario analysis. Simulations for pollution buildup and wash off module in SWMM models were conducted separately for two land use types, permeable and impermeable areas.

Since the land use will be greatly modified from farmland, grassland, and woods to urban areas, value of planned hydrological and water quality parameters was supposed to be considerably distinct from the current situation. Therefore, parameters' value of the planning scenarios shall be adopted in simulation rather than the current.

Rainfall data

The 1-year return rainfall in Guiyang is 33.4 mm, which is classified as heavy rain, according to the national standard of Grade of Precipitation (GB/T 28592-2012). In order to provide comprehensive analysis of non-point source pollution, it is reasonable to apply rainfall intensities rather than rainfall return period for baseline scenario analysis, which will take the contributions of both light and heavy rainfall into account.

1, 5, 10, 25, 50, 100, and 150 mm were selected for baseline scenario analysis, among which 10, 25, 50, and 100 mm were the upper limit values of light rain, moderate rain, heavy rain, and torrential rain in the standard, respectively. In addition, since 1 and 5 mm rainfalls accounted for a large percentage of historical rainfall events, they were also chosen for analysis. 150 mm occurred several times in historical record, and was, therefore, chosen to represent extremely heavy rainfall events for simulation.

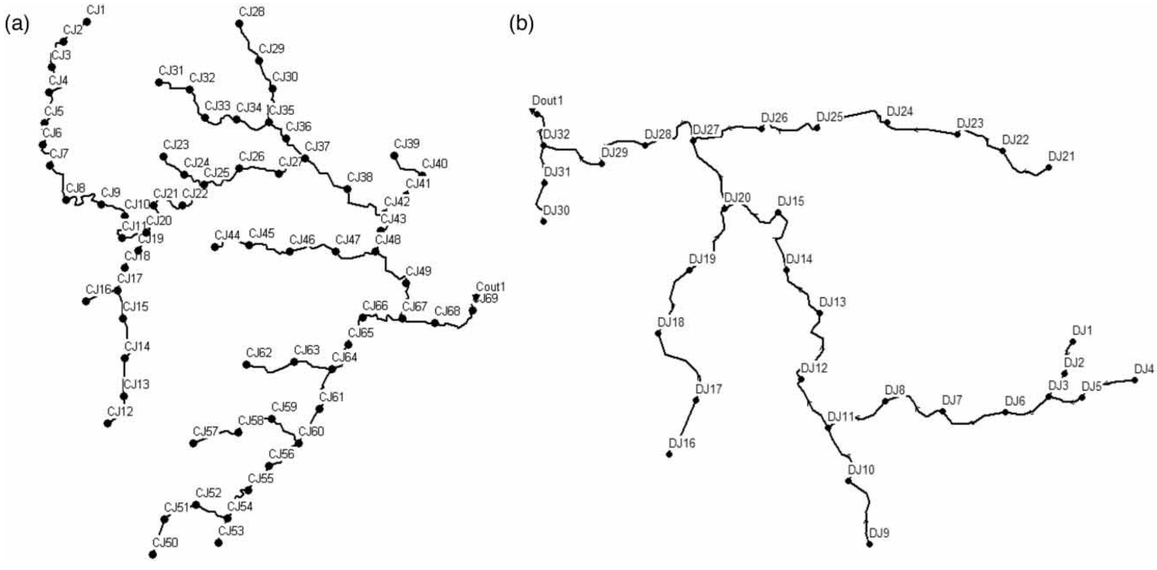

Figure 4 | Schematic of the two river networks in the core area of Guian New Area: (a) the Chetian River and (b) the Dongmenqiao River.

Since there was only few research for the local rainfall patterns in Guian New Area, the widely used Chicago-storms synthetic rainfall pattern (Keifer & Chu 1957) was applied to synthesize the rainfall events of different intensities for the core area of Guian New Area, using the storm intensity formula of Guiyang.

For the assimilation capacity calculation and two LID scenarios analysis, the year of 1997 was chosen as a typical year, whose annual rainfall is 1,115.1 mm close to 1,116.7 mm, the average annual rainfall over 62 years.

Baseline scenario

The baseline scenario was initially simulated without non-point source pollution control measures in the plan, in which all urban rainfall-runoff pollutants were discharged directly into the rivers.

Dynamic changes of water depth and discharge of the two rivers under different rainfall intensities were first simulated to provide fundamental information for further water quality simulation in the baseline scenario. After which, river water quality changes were simulated in terms of COD, Amm-N, and TP under different rainfall events. The total pollutant loads, event mean concentrations (EMC), and peak pollutant concentrations of COD, Amm-N, and TP under different rainfall intensities in the two river basins were calculated respectively for further analysis.

The values of hydrological parameters were initially determined according to the local soil types, SWMM manual (Rossman 2010) and other relevant researches (Zhao *et al.* 2009; Ma *et al.* 2012; Wang *et al.* 2012), and then adjusted by the calculated runoff coefficients, according to the national standard of urban drainage design (MOHURD 2014a). The values of water quality parameters were determined by referring to empirical values from previous researches within similar regions (Xu *et al.* 2005; Yang 2007; Huang & Nie 2012). The maximum buildup values of each water quality indicator of the two land use types in the two river basins are listed in Table 2. These values were also used in subsequent assimilation capacity calculation and LID scenario analysis, except the maximum buildup values were different in LID Scenario 2.

Assimilation capacity

After the baseline scenario analysis, the assimilation capacities for non-point source pollution throughout a year were calculated in the two river basins to provide support for the urban water system planning. Because the downstream of the two rivers transported rainfall-runoff pollutants to the Huaxi Reservoir and Baihua Lake, respectively, they were regarded as the control points of river basins and each of the downstream outflows was applied to calculate the assimilation capacities.

Due to high pollution loads brought by runoff under rainfall intensities, it is not possible for both rivers to consistently meet the national surface water quality standards for Grade III. Therefore, the criteria for assimilation capacity of the two river basins were proposed as follows:

1. Exceedance days in a whole typical year are less than 5%.
2. Exceedance day: the time of river water quality worse than Grade III in a day is more than 10%.

The initial water quality of the two rivers for assimilation capacity calculation was proposed as the Grade III surface water quality in national standard, listed in Table 3.

Table 2 | Maximum buildup values of the two land use types of the two rivers

		Maximum buildup		
River basin	**Land use type**	**COD (kg/hm^2)**	**Amm-N (kg/hm^2)**	**TP (kg/hm^2)**
Dongmenqiao	Impervious Area	100	8	1.5
	Pervious Area	40	3	1
Chetian	Impervious Area	100	8	1.5
	Pervious Area	40	3	1

Table 3 | The initial river water quality for assimilation capacity calculation

COD (mg/L)	**Amm-N (mg/L)**	**TP (mg/L)**
20	1.5	0.3

A trial-and-error method was used to calculate the assimilation capacity. The calculation steps are listed as follows:

1. Using the SWMM-based river network water quality models to calculate the water quality variation for the two rivers throughout a typical year based on the initial water quality value. The calculated pollutant concentrations in downstream outflows were regarded as the baseline pollutant loads.
2. Applying removal rates of pollutants to simulate the yearly variation of water quality based on the obtained baseline pollutant loads in each river and checking whether the new scenario meet the above-mentioned assimilation capacity criteria.
3. Repeating step 2 until the criteria was satisfied. The pollutant loads in the outflow of each control point in the satisfied scenario were the assimilation capacities of the two rivers, respectively.

LID scenarios

According to the calculated assimilation capacities, LID facilities, such as sunken green belts, permeable pavements, green roofs, and rainwater storage modules, were planned to be widely deployed in most subcatchments in Guian New Area to support sponge city construction and reduce non-point source pollution. As a support for developing the rational urban water system planning, two LID scenarios were simulated by the above-mentioned SWMM-based river network water quality models for LID facilities deployment and effectiveness evaluation over a typical year.

LID Scenario 1

Due to the limited assimilation capacities, the removal rates of non-point source pollution were required to be high, indicating a large demand of green infrastructure deployment. After considering the conditions set by the master plan, which included land use, building density, greenbelt ratio, and construction conditions, the possible maximum scales of green infrastructure in the core area of Guian New Area were determined, as shown in Table 4. Furthermore, almost all of the rainfall-runoff generated from impervious area was set to be treated by the LID facilities. It was also required to maximize the reuse of the harvest rainwater, or treat the harvest rainwater properly before being discharged into pipes or rivers. During the simulation, the parameters of LID facilities were determined as typical LID facilities as recommended in the SWMM manual (Rossman 2016; Rossman & Huber 2016) and the Technical Guide for the Construction of the Sponge City in China (MOHURD 2014b).

In LID Scenario 1, if the discharged non-point source pollutants are lower than the assimilation capacities of the two rivers, it means that the possible maximum scales of LID facilities installed in this scenario is sufficient and can be appropriately reduced in the planning. Conversely, if the discharged non-point source pollutants are higher than the assimilation capacities of the two rivers, additional actions shall be taken to further decrease the discharged pollutants to meet the assimilation capacity requirements.

LID Scenario 2

If the possible maximum scales of LID facilities can meet the assimilation capacity requirements, reduce both the LID scales and maximum buildups of pollutants properly in LID Scenario 2 as appropriate. If not, maintain the same scales as in LID Scenario 1 and reduce the maximum buildups of pollutants. On the basis of LID Scenario 1, additional actions that will be conducted to cut down the maximum buildups of pollutants, such as frequent cleaning to reduce pollutants accumulation on the ground, was simulated in LID Scenario 2.

The trial-and-error method was used to calculate the required maximum buildups of pollutants under the restriction of assimilation capacity. The calculation steps were included as follows:

1. Setting appropriate LID scales and maximum buildups of pollutants as the initial searching condition.
2. Calculating the yearly water quality variation of the two rivers based on the initial water quality condition listed in Table 3.

Table 4 | Possible maximum LID scales in LID Scenario 1

Sunken Green Belt	Permeable Pavement	Green Roof	Rainwater Storage Module
40%	50%	10%	150 m^3/ha

3. Checking whether the calculated downstream outflows meet the assimilation capacity requirements of the two rivers. If not, adjusting the maximum buildups of the three pollutants in both two rivers.
4. Repeating steps 2 and 3 until the downstream outflows of the two rivers meet the assimilation capacity requirements. Under the satisfied scenario, the maximum buildups of the three pollutants in the two rivers were the recommended values for making the urban water system planning for the core area of Guian New Area.

RESULTS AND DISCUSSION

Baseline scenario results

Water quantity

Water quantity calculation provides not only fundamental for water quality calculation but also suggestions for water quantity balance, urban flood control, and natural water system layout.

The runoff characteristic values of the two rivers are shown in Table 5. The runoff coefficients of both rivers were similar and increased along with rainfall intensity rise. Under extremely heavy rainfall events of 150 mm, the runoff coefficients were approaching 0.9.

Simulation results showed that the maximum water depth and discharge occurred at the downstream points of the two rivers. Figures 5 and 6 demonstrate the temporal variation of water depth and discharge along with rain time under different rainfall intensities at downstreams for each river, respectively. Generally, with the increase of rainfall intensity, the water depth and discharge of both rivers increased rapidly. Under the 150 mm extremely heavy rainfall condition, the maximum downstream water depth of the Dongmenqiao River was 4.18 m and the maximum downstream discharge was 458.8 m^3/s, whereas the maximum downstream water depth of the Chetian River was 3.67 m and the maximum downstream discharge was 598.0 m^3/s.

Simulation results indicated that the Dongmenqiao River and the Chetian River were under great flooding pressure, especially for extremely heavy rainfall conditions, where high water levels and even overtopping were found in some reaches. It was recommended that these weak points should be strengthened by widening or deepening the river sections, combined with proper landscape design and ecological river construction measures. Moreover, wetlands and other storage facilities should be planned in proper places with appropriate scales.

Water quality

The dynamic changes of river water quality, represented by the indicators of COD, Amm-N, and TP under different rainfall intensities were simulated for both river basins and the results of total pollutant loads, EMC, and peak pollutant concentrations for each indicator under different rainfall intensities are demonstrated in Tables 6–8, respectively. The downstream COD curves of the Dongmenqiao River and the Chetian River under different rainfall intensities are shown in Figures 7 and 8, respectively.

The simulation results showed that both the two rivers were heavily polluted by the rainfall-runoff pollution in the baseline scenario. The pollution characteristics of the two rivers were similar, with some little difference. The Chetian River was more heavily polluted than the Dongmenqiao River when the rainfall was less than 50 mm, whereas the Dongmenqiao River was more heavily polluted when the rainfall was greater than 50 mm.

Table 5 | Runoff characteristic values of the two rivers

	Dongmenqiao River basin		Chetian River basin	
Rainfall (mm)	Surface runoff (10^3 m^3)	Runoff coefficient	Surface runoff (10^3 m^3)	Runoff coefficient
1	4.9	0.092	8.2	0.076
5	105.1	0.392	205.4	0.379
10	254.5	0.474	506.3	0.467
25	833.4	0.621	1,727.2	0.637
50	2,025.6	0.755	4,180.0	0.771
100	4,546.7	0.847	9,299.6	0.858
150	7,098.0	0.882	14,464.1	0.890

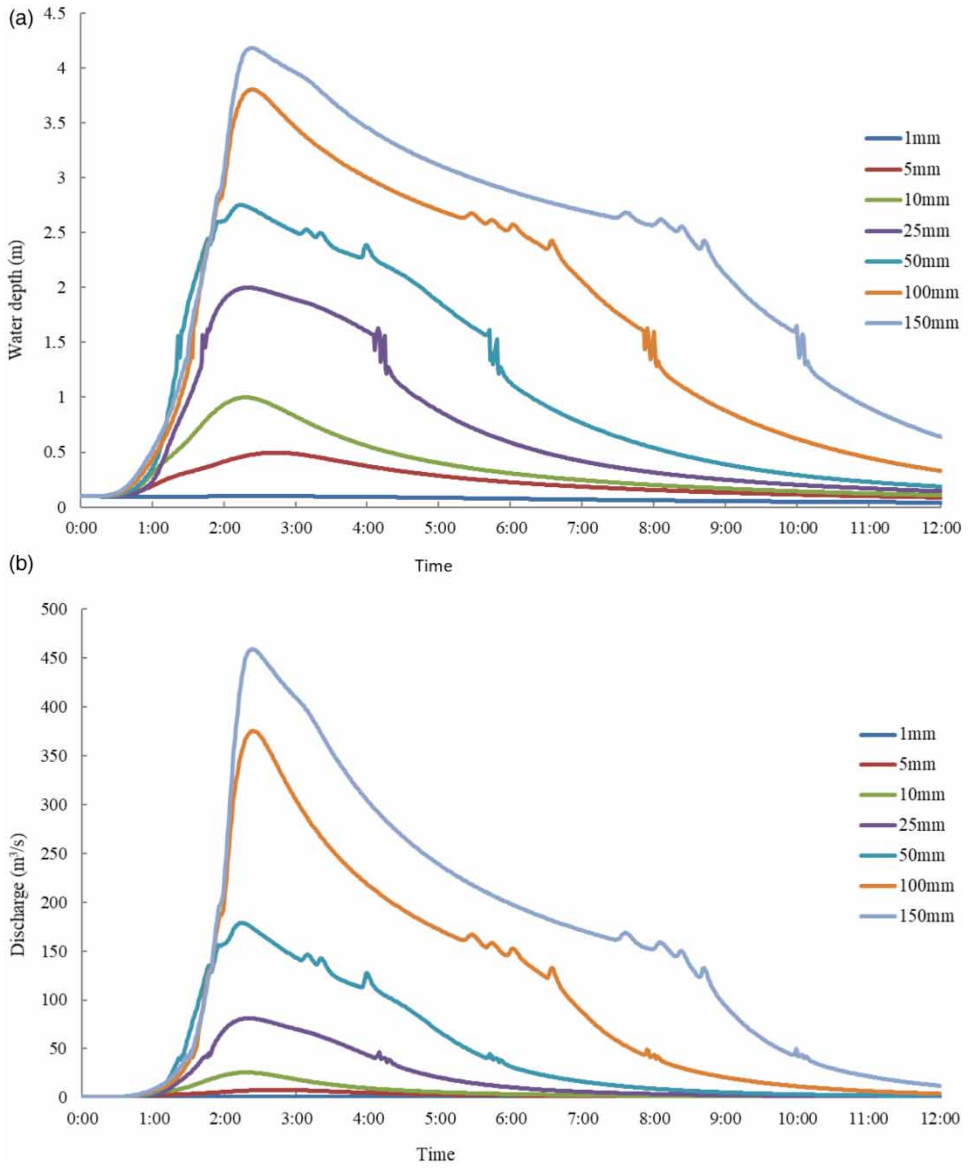

Figure 5 | Downstream hydraulic curves of the Dongmenqiao River under different rainfall intensities. (a) Water depth and (b) discharge.

The characteristics of the three indicators were similar. The total pollutant loads increased along with rainfall intensity in both rivers, but the increase slowed down from 100 to 150 mm comparing to smaller rainfall intensities. EMC initially increased with rainfall intensity in the Dongmenqiao River while after reaching the peak at 50 mm, it decreased with the increasing rainfall intensity. The Chetian River shared the similar EMC changing tendency with the Dongmenqiao River, where EMC increased with increasing rainfall intensity below 25 mm followed by a slight drop at 50 mm, and decreased drastically with rainfall intensity increase thereafter. The peak pollutant concentrations also increased with the increase of rainfall intensity. Specifically, the peak concentrations in the Dongmenqiao River were comparable at 100 and 150 mm, both were slightly higher than that at 50 mm. Whereas in the Chetian River, peak concentrations at 50 and 100 mm were almost identical and both slightly higher than that at 150 mm.

COD spatial distributions for a 6-h simulation period of the Chetian River at different stages under 50 mm rainfall intensity are shown in Figure 9, where COD concentration of each reach was labeled next to the reaches. During the simulation period, water quality of most reaches was below the minimum water quality Grade V in the national standards for most of the time. Specifically, from 1 h 15 min to 4 h 42 min, nearly three and a half hours, water quality of all the reaches was below Grade V. The COD concentration of the most heavily

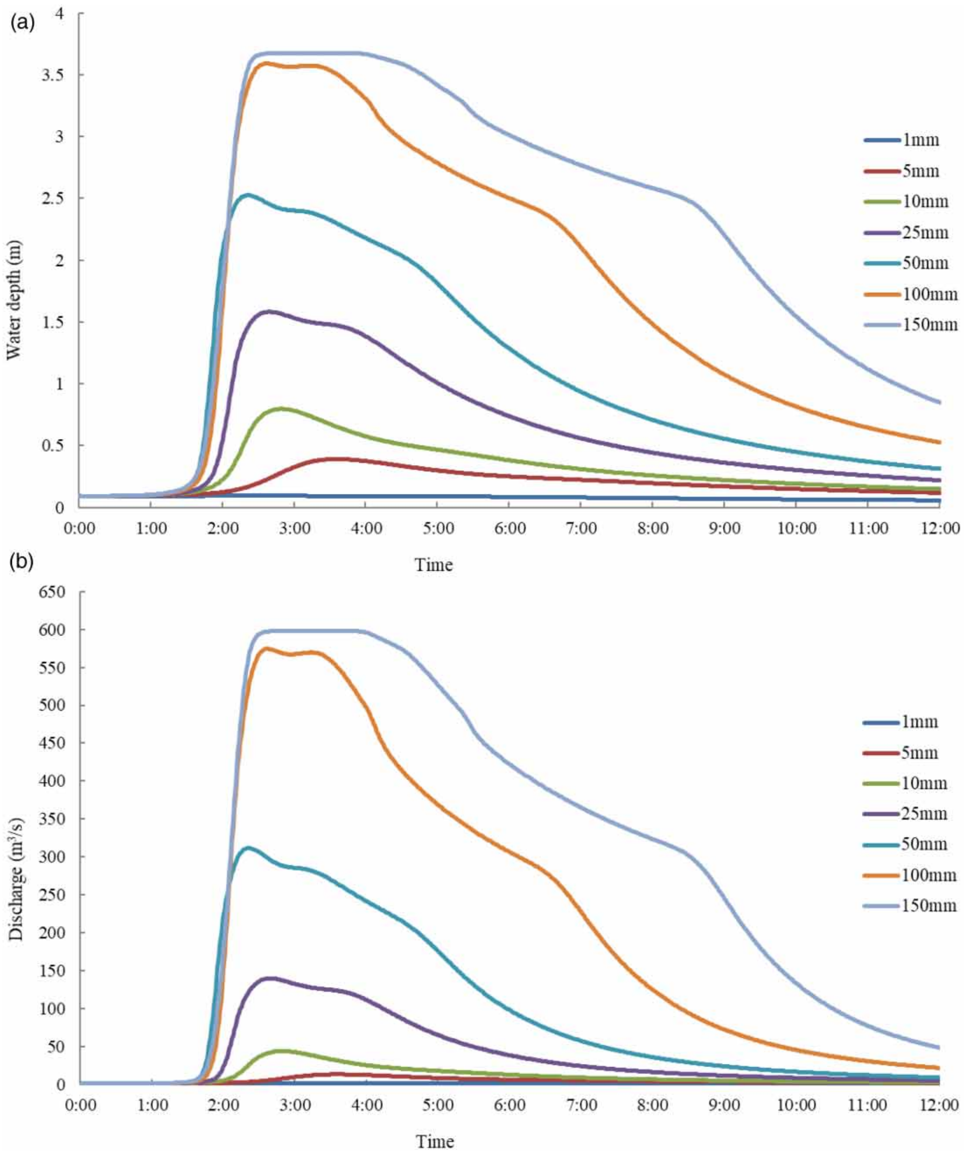

Figure 6 | Downstream hydraulic curves of the Chetian River under different rainfall intensities. (a) Water depth and (b) discharge.

Table 6 | COD characteristic values of the two river basins

	Dongmenqiao River basin			**Chetian River basin**		
Rainfall (mm)	**Total pollutant load (t)**	**EMC (mg/L)**	**Peak pollutant concentration (mg/L)**	**Total pollutant load (t)**	**EMC (mg/L)**	**Peak pollutant concentration (mg/L)**
1	0.08	16.05	20.00	0.10	12.55	20.00
5	4.73	45.01	53.01	10.98	53.44	56.50
10	19.10	75.04	91.47	48.54	95.87	110.68
25	102.73	123.26	160.35	249.16	144.26	188.18
50	294.31	145.30	234.81	593.16	141.91	251.11
100	504.17	110.89	250.25	885.92	95.26	250.88
150	568.16	80.04	250.35	970.68	67.11	239.32

Table 7 | Amm-N characteristic values of the two river basins

	Dongmenqiao River basin			**Chetian River basin**		
Rainfall (mm)	**Total pollutant load (t)**	**EMC (mg/L)**	**Peak pollutant concentration (mg/L)**	**Total pollutant load (t)**	**EMC (mg/L)**	**Peak pollutant concentration (mg/L)**
1	0.004	0.86	1.00	0.006	0.70	1.00
5	0.33	3.17	3.75	0.81	3.95	4.08
10	1.41	5.55	6.82	3.71	7.32	8.39
25	7.83	9.39	12.31	19.26	11.15	14.55
50	22.57	11.14	18.23	45.74	10.94	19.55
100	38.22	8.41	19.45	67.31	7.24	19.53
150	42.25	5.95	19.46	72.48	5.01	18.61

Table 8 | TP characteristic values of the two river basins

	Dongmenqiao River basin			**Chetian River basin**		
Rainfall (mm)	**Total pollutant load (t)**	**EMC (mg/L)**	**Peak pollutant concentration (mg/L)**	**Total pollutant load (t)**	**EMC (mg/L)**	**Peak pollutant concentration (mg/L)**
1	0.001	0.18	0.20	0.001	0.14	0.20
5	0.07	0.64	0.76	0.16	0.80	0.84
10	0.29	1.12	1.38	0.75	1.48	1.71
25	1.57	1.89	2.48	3.96	2.30	2.97
50	4.53	2.24	3.66	9.60	2.30	4.00
100	7.69	1.69	3.91	14.36	1.54	4.03
150	8.52	1.20	3.91	15.49	1.07	3.85

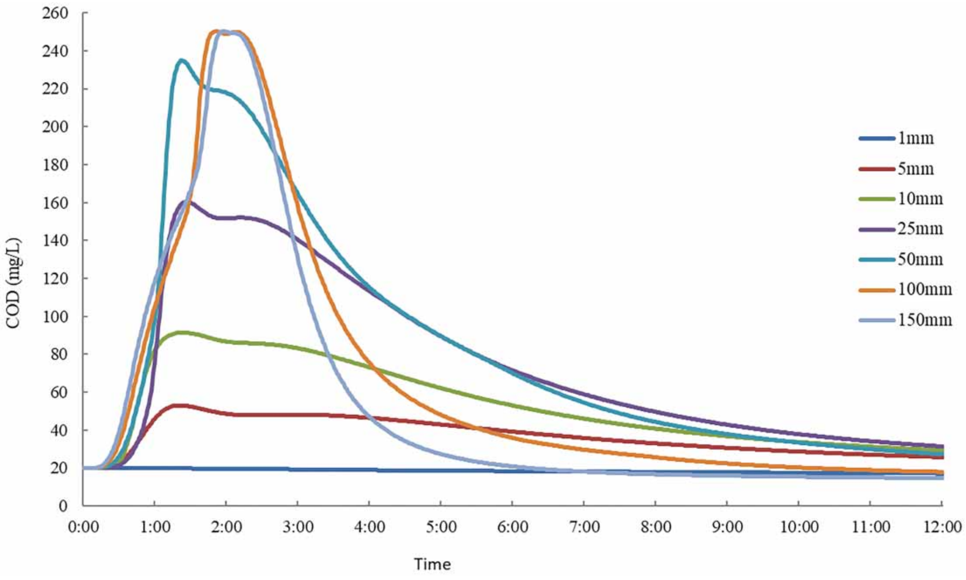

Figure 7 | Downstream COD curve of the Dongmenqiao River under different rainfall intensities.

polluted reach was even 9.7 times higher than that defined as Grade V. Only a few upstream reaches recovered to Grade III several hours after rainfall while water quality at the downstream control point of the Chetian River was still well below Grade V, suggesting severe non-point source pollution from heavy rainfall.

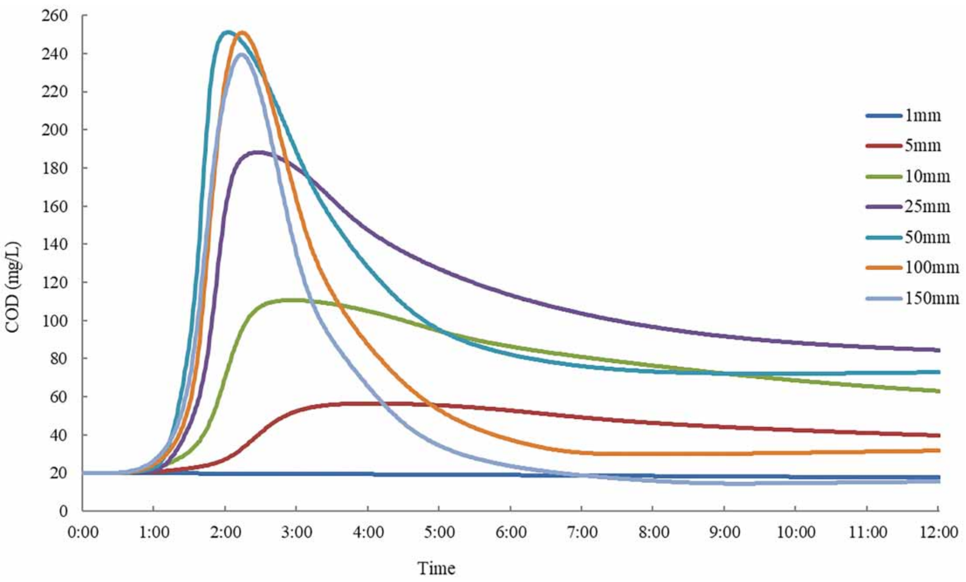

Figure 8 | Downstream COD curves of the Chetian River under different rainfall intensities.

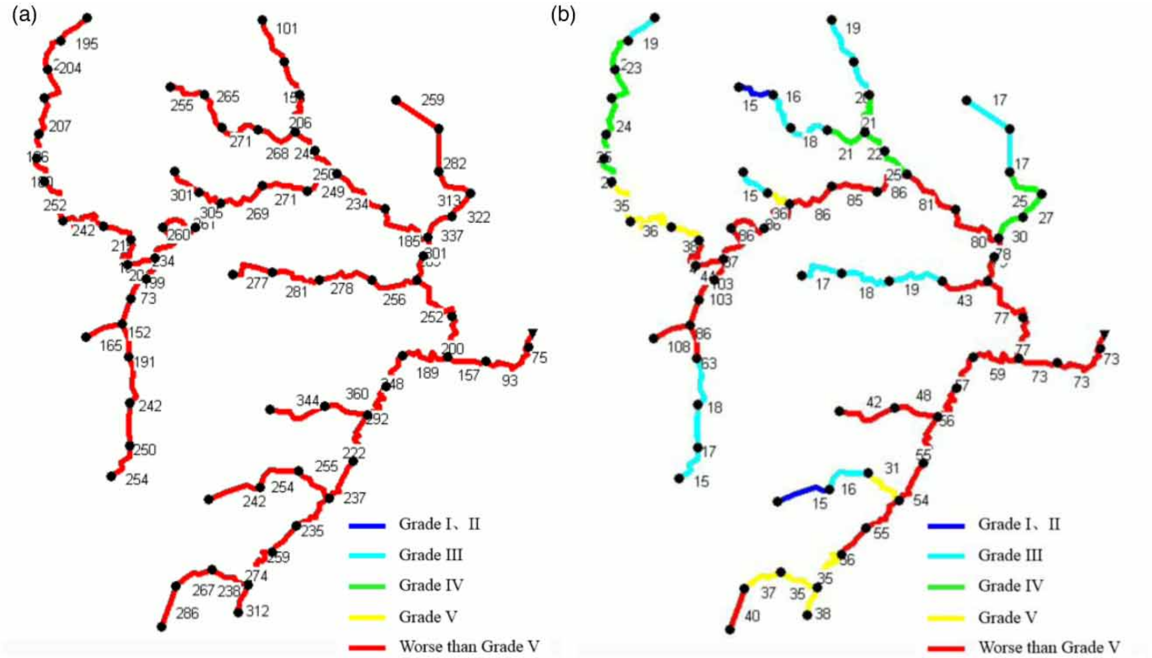

Figure 9 | The COD (mg/L) spatial distributions of the Chetian River at different stages under 50 mm rainfall. (a) The most heavily polluted time and (b) The end of the simulation period.

The simulation results of non-point source pollution and water quality of the two rivers mentioned above showed that the continuation of the traditional development pattern would lead to serious pollution of the two rivers. Therefore, additional efforts were in great need to achieve the goal of maintaining high water quality in order to avoid negative impacts on the downstream drinking water source of Guiyang city.

If a strict requirement of meeting the water quality of Grade III was applied, the required removal rates of COD, Amm-N, and TP of rainfall-runoff pollution under different rainfalls in the Dongmenqiao River basin were 56–86%, 68–91%, and 69–91%, respectively. While those of the Chetian River basin were 62–86%, 75–91%, and 75–91%, respectively (Table 9). The required high pollution removal rates in both rivers indicated that great efforts were required to achieve satisfactory river water quality in the core area of Guian New Area.

Table 9 | Required removal rates of rainfall-runoff pollution of the two river basins

	Dongmenqiao River basin			Chetian River basin		
Rainfall (mm)	**COD**	**Amm-N**	**TP**	**COD**	**Amm-N**	**TP**
5	55.6%	68.4%	68.9%	62.6%	74.7%	75.0%
10	73.3%	82.0%	82.2%	79.1%	86.3%	86.5%
25	83.8%	89.3%	89.4%	86.1%	91.0%	91.3%
50	86.2%	91.0%	91.1%	85.9%	90.9%	91.3%
100	82.0%	88.1%	88.2%	79.0%	86.2%	87.0%
150	75.0%	83.2%	83.3%	70.2%	80.0%	81.3%

Assimilation capacity results

Baseline pollutant loads were initially derived from temporal simulation over a 1-year period for both river basins. The curves of downstream water depth and COD variation in the Dongmenqiao River and the Chetian River throughout a typical year are shown in Figures 10 and 11, respectively.

The baseline pollutant loads for COD, Amm-N, and TP assimilation capacity calculation of the two rivers are shown in Table 10. The COD, Amm-N, and TP loads were 2,994.09, 226.86, and 45.84 t/a in the Dongmenqiao River, and 7,093.95, 534.62, and 112.81 t/a in the Chetian River, respectively.

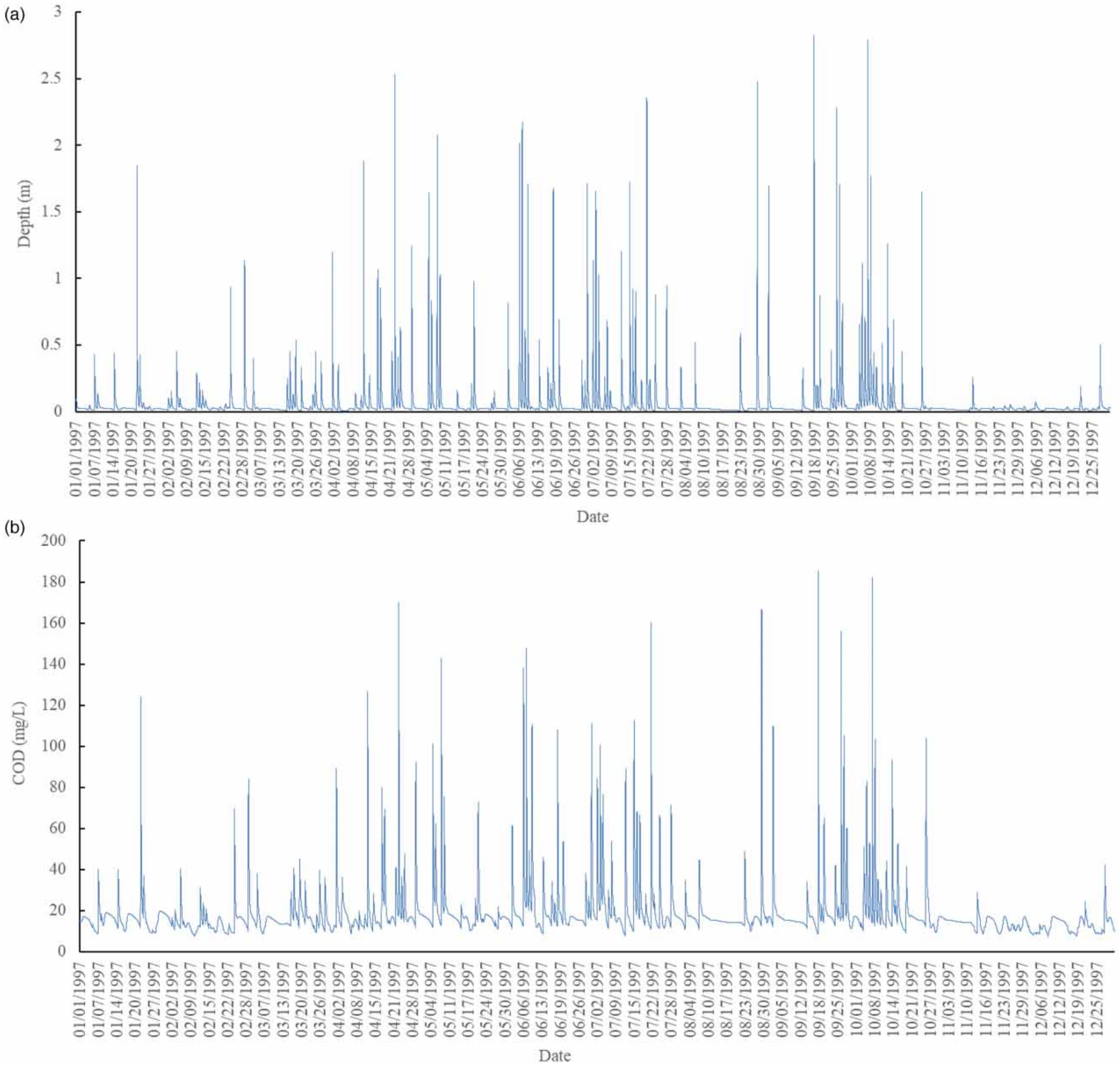

Figure 10 | Downstream curves of the Dongmenqiao River during a whole typical year: (a) Water depth and (b) COD.

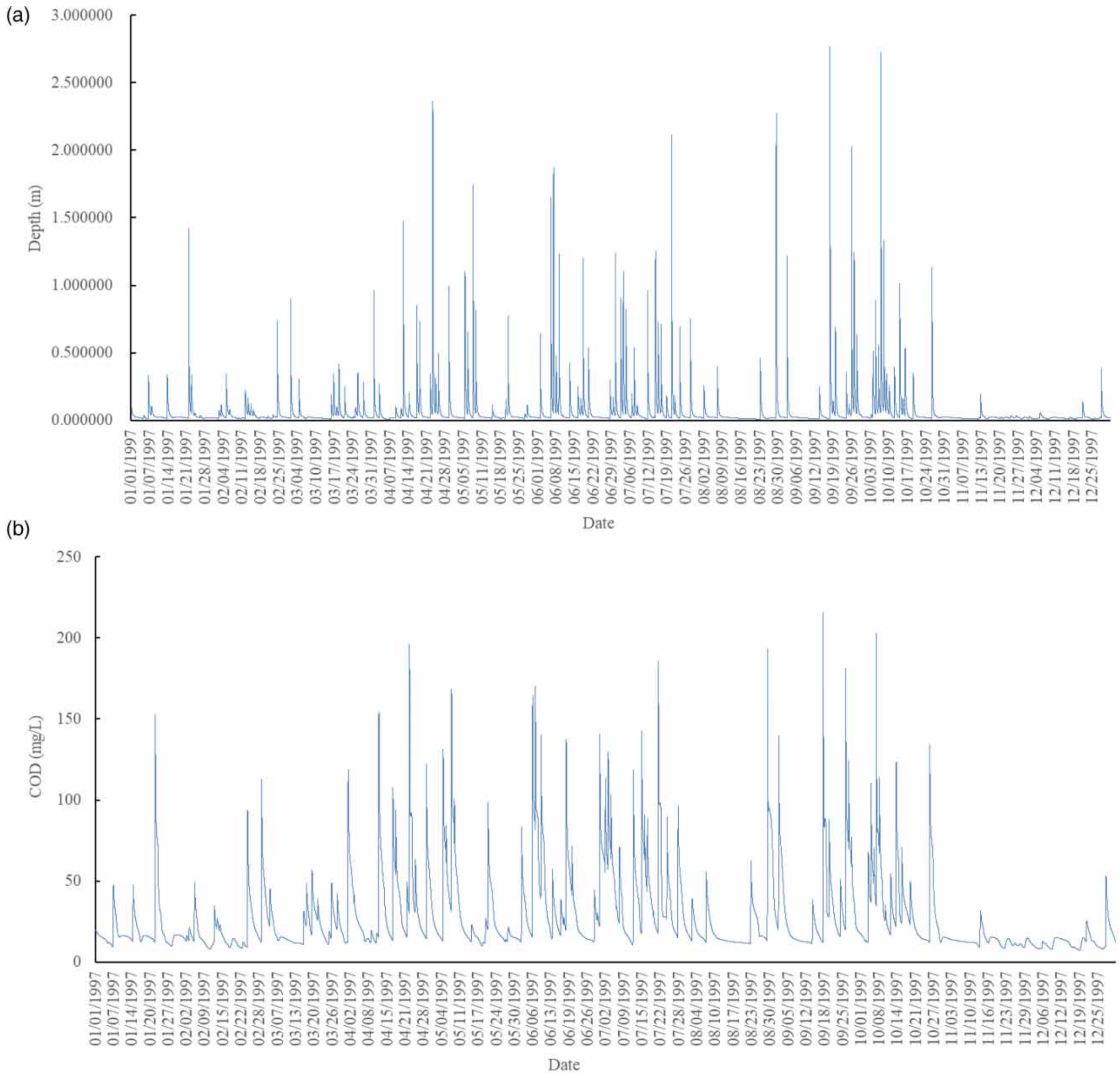

Figure 11 | Downstream curves of the Chetian River during a whole typical year: (a) Water depth and (b) COD.

Table 10 | Baseline pollutant loads for assimilation capacity calculation of the two river basins

River basin	COD (t/a)	Amm-N (t/a)	TP (t/a)
Dongmenqiao	2,994.09	226.86	45.84
Chetian	7,093.95	534.62	112.81

Table 11 shows the assimilation capacities of the two rivers obtained by applying the trial-and-error method. The assimilation capacities of COD, Amm-N, and TP of the Dongmenqiao River were 662.02, 32.60, and 6.50 t/a, respectively, while those of the Chetian River were 1,412.53, 67.46, and 12.75 t/a, respectively.

Compared with initial pollutant loads, the required removal rates for both rivers are shown in Table 11. The extremely high removal rates, ranging from 77.9 to 88.7%, implied that efforts should be made to achieve the water quality protection goals. Moreover, the removal rates of all the three indicators in the Chetian River were higher than the Dongmenqiao River, which means more efforts should be made in the Chetian River. The calculated assimilation capacities and removal rates determined key considerations for the urban water system plan of the core area of Guian New Area.

Table 11 | Assimilation capacities and required removal rates of the two river basins

	Assimilation capacity (t/a)			Required removal rate (%)		
River basin	**COD**	**Amm-N**	**TP**	**COD**	**Amm-N**	**TP**
Dongmenqiao	662.02	32.60	6.50	77.9	85.6	85.8
Chetian	1,412.53	67.46	12.75	80.1	87.4	88.7

LID scenario results

LID Scenario 1

The simulation results of LID Scenario 1 showed that the pollutant loads of rainfall-runoff were significantly reduced, with removal rates ranging from 77.3 to 79.1% (Table 12). Consequently, water quality for rivers would be greatly improved, which demonstrated the significance of applying green infrastructure in the urban planning and urban water system planning.

However, the pollutant loads were still below the requirements of the assimilation capacities of the two rivers under Scenario 1. As shown in Figure 12, although the COD loads were only slightly above the assimilation capacity, Amm-N and TP loads were much higher than the assimilation capacity. Specifically, Amm-N and TP exceeded by 46.8 and 59.2% in the Dongmenqiao River and by 65.4 and 90.0% in the Chetian River, respectively, which suggested that even the application of possible maximum scales of LID structure was not able to limit discharged pollution amounts below the assimilation capacity. Therefore, subsequent actions were supposed to be adopted to meet the requirements.

Table 12 | Pollutant loads and removal rates of the two river basins in LID Scenario 1

	Pollutant load (t/a)			Removal rate (%)		
River basin	**COD**	**Amm-N**	**TP**	**COD**	**Amm-N**	**TP**
Dongmenqiao	679.46	47.85	10.35	77.3	78.9	77.4
Chetian	1,562.74	111.56	24.22	78.0	79.1	78.5

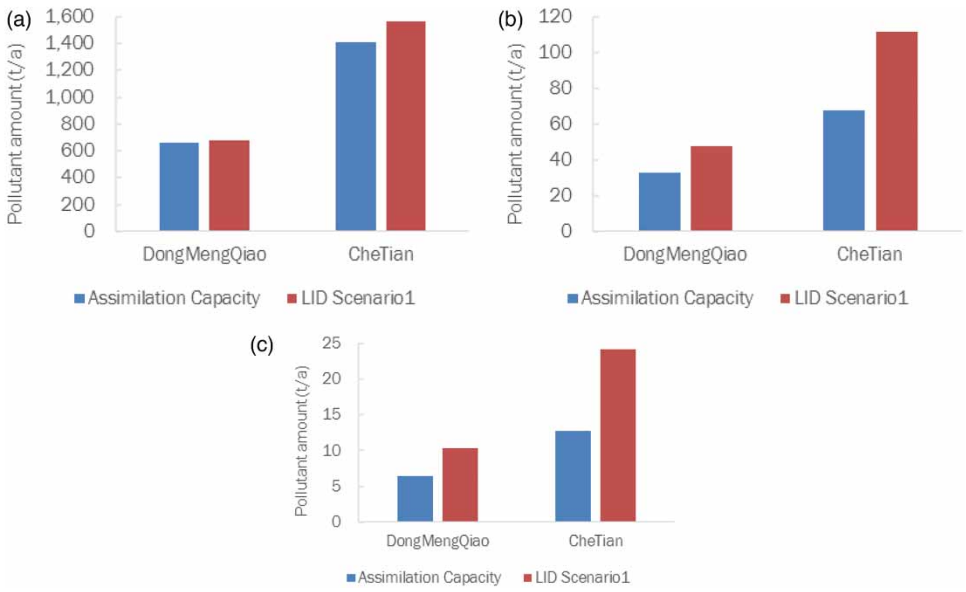

Figure 12 | Comparison between pollutant loads in LID Scenario 1 and assimilation capacities of the two rivers: (a) COD, (b) Amm-N, and (c) TP.

Table 13 | Maximum buildup requirements of the two river basins in Scenario 2

		Maximum buildup		
River basin	**Land use type**	**COD (kg/hm^2)**	**Amm-N (kg/hm^2)**	**TP (kg/hm^2)**
Dongmenqiao	Impervious Area	90	4	0.7
	Pervious Area	40	3	0.7
Chetian	Impervious Area	80	4	0.6
	Pervious Area	40	2.5	0.6

Table 14 | Reduced rates of maximum buildup of the two river basins in Scenario 2 compared with baseline scenario

		Reduced rate of maximum buildup		
River basin	**Land use type**	**COD**	**Amm-N**	**TP**
Dongmenqiao	Impervious Area	10.0%	50.0%	53.3%
	Pervious Area	0.0%	0.0%	30.0%
Chetian	Impervious Area	20.0%	50.0%	60.0%
	Pervious Area	0.0%	16.7%	40.0%

LID Scenario 2

Simulation results of Scenario 2 showed that pollutants and rivers manifested different reducing impacts on the maximum buildups compared to the baseline scenario (Tables 13 and 14). Results also suggested that the maximum buildups of the Chetian River basin should be lower than that of the Dongmenqiao River basin, meaning that more actions should be taken in the Chetian River basin. In addition, the applied solutions should pay more attention to TP and Amm-N control comparing to COD.

This requires additional management measures from a broader perspective to reduce the buildups of pollutants, which included but not subject to more frequent cleaning to reduce pollutants accumulation on the ground and dry deposition reduction through air pollution control measures to make the air cleaner.

The simulation results of the two LID scenarios can provide sound suggestions for determining the scales of green infrastructure and subsequent further control measures to meet the strict requirements of river water quality in the new area and support the application of sponge-city-based urban water system planning in the core area of Guian New Area to make the planning more scientific, reasonable, and feasible.

Due to the uncertainty of the model parameters, there was also some uncertainty of the simulation results, which might affect the planning decisions. Besides, SWMM only incorporated the decrease of runoff mass load led by the reduction in runoff flow volume (Rossman & Huber 2016), which might underestimate the performance of LID and also impact the planning.

CONCLUSION

A case study of the core area of Guian New Area was presented in this paper to show the application of the integrated planning method and SWMM in sponge-city-based urban water system planning for water quality sensitive new area development.

The sponge-city-based integrated planning method is an effective tool to make scientific, reasonable, and feasible urban water system planning for water quality sensitive areas and comprised of five key steps: (1) conducting system analysis for case study areas, (2) establishing water quality models with SWMM (recommended) for rivers in the study area, (3) simulating baseline scenario for rainfall-runoff pollution characteristics analysis, (4) applying a trial-and-error method to assimilation capacities calculation to set boundaries for discharged pollution, and (5) simulating LID scenarios to support the urban water system planning.

Sponge city, which incorporates various well-designed nature-based LID facilities, can effectively protect water environment in water quality sensitive new areas. In such areas, large scales of LID facilities are needed to be deployed to reduce pollution from heavy rainfall-runoff in order to meet strict river water quality requirements. For those new areas with highly strict requirements for surface water quality, additional measures such as more frequent cleaning to reduce pollutants accumulation on the ground and dry deposition reduction through air pollution control measures to make the air cleaner, should also be taken to mitigate the maximum buildups of pollutants.

However, due to the uncertainty of the model parameters and the limited function of LID module in SWMM, the simulation results might also possess uncertainties that can affect the decision-making in planning to some extent.

To better support urban water system planning, recommendations for further researches to obtain more accurate model simulations were proposed: (1) obtaining more local data through monitoring to refine the feasibility of model parameters for local planning and (2) incorporating bio-chemical removal functions for LID module in simulation.

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DATA AVAILABILITY STATEMENT

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

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