Ecological Engineering 71 (2014) 448–457

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

A closed urban scenic river system using stormwater treated with LID-BMP technology in a revitalized historical district in China

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ARTICLE INFO

Article history:
Received 15 February 2014
Received in revised form 7 May 2014
Accepted 11 July 2014
Available online 14 August 2014

Keywords:
Closed water system
LID-BMPs
Urban stormwater control
Urban river restoration

ABSTRACT

Urban river restoration is becoming a concern as a result of economic development. One scientific focus is how to restore urban river systems by integrating principles and practices of land use planning, landscaping, aquatic environmental protection, and flood control. A river revitalization project in a historical district in Suzhou City, Jiangsu Province, China is used here as a case study. The study demonstrates the development of a systematic solution that integrated knowledge of urban planning, landscape ecology, environmental science, and hydrology. In accordance with a low impact development (LID) strategy, the planning objectives were designed to give the district the ability to maintain the quantity and quality of the closed scenic water system and to reduce risks of flooding. Low impact development best management practice (LID-BMP) facilities were selected, placed and designed based on landscape planning and the other factors listed above. A model based on the storm water management model (SWMM) was developed to assess the water quantity and quality benefits to be expected by implementing the LID-BMPs under different storm scenarios. Based on an investigation of the pollution sources and the design of the water system, water quantity requirements were then estimated. Deployment of sources for the water system and a water quality maintenance scheme were proposed. In addition, according to the SWMM modeling analysis, although the stormwater pipe system in the district met only the standard required for 2-year recurrence-interval storms, there would be no local flooding in a 5-year recurrence-interval storm, and the local flooding situation would not be serious even when a 20-year recurrence-interval storm occurred.

1. Introduction

The Taihu Lake Basin in Southeastern China has one of the highest degrees of industrialization and urbanization in China. However, along with the rapid urbanization and extreme land use changes over the past 30 years, many cities in the Taihu Lake basin such as Suzhou have faced serious urban water system problems. River corridors have been encroached upon, rivers have been truncated, and the numbers of blocked-off rivers and enclosed water systems have increased, all because of urban expansion and retrofit needs (Zhang et al., 2013). Similar situations have occurred in many other cities in China and other countries that have experienced rapid urbanization. Such hydro-modification activities have often resulted in a reduction of streams' self-purification capacity and ecosystem degradation (Ballo et al., 2009; Du et al., 2012; Moore et al., 2012), which have seriously affected the quality of life and the sustainable development of cities. Urban river restoration to improve the water quality and ecological functions is becoming a concern for the government and the general public all over the world (Mitsch, 2012; Palmer et al., 2014; Hao, 2005). However, urban river restoration is a complex task for local governments, particularly in old historical cities, as it involves interactions among administrative agencies with regard to land use, landscape, aquatic environment protection, flood control, etc. (Sun et al., 2011; Loucks and Jia, 2012). An integrated systematic solution that combines knowledge of urban planning, landscape ecology, environmental science, and hydrology is needed. Low impact development best management practices (LID-BMPs) are an innovative, integrated set of methodologies and engineering systems for urban runoff control (Davis, 2005). In addition to their benefits in flood control,

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http://dx.doi.org/10.1016/j.ecoleng.2014.07.049
0925-8574/

LID-BMPs enhance water quality purification, rainwater harvesting, esthetics, and ecology (Dietz, 2007; Jia et al., 2013b). In this context, incorporating an LID strategy in urban river restoration during new urban development or old urban revitalization has become a focus for urban planners, researchers, and managers (Wong, 2002; USEPA, 2004; Jia et al., 2012). Using the opportunity of performing a revitalization project in the Taohuawu Cultural District in Suzhou, Jiangsu Province, we conducted a case study of LID-BMP technology for stormwater harvesting, treatment, and water quality maintenance for closed urban scenic river systems. The main goal of the case study, which is the focus of the present paper, was to develop a plan that would maintain a sound habitat for aquatic life by providing the required water quantity and quality. The ecosystem restoration plan of the closed urban river systems will be considered for implementation by the local government in the ultimate development and management of the historic site restoration project.

2. Methods

2.1. The study site

Suzhou is an important, highly developed historical city in Jiangsu Province in eastern China. After a decade of fast economic development, the local government has begun to work rigorously on water pollution control and urban river rehabilitation projects. In this context, a revitalization project for the Taohuawu Cultural District in the Suzhou historical area was proposed by the local government. The Taohuawu Cultural District is the former residence site of Tang Yin, a very famous Chinese scholar, painter, calligrapher, and poet during the Ming Dynasty period, whose life story has become legendary. The location of the Taohuawu Cultural District is shown in Fig. 1. According to historical records, there were once rivers and lotus ponds in the Taohuawu Cultural District. However, these water bodies were buried along with urban construction over time. Recently, the Suzhou municipal government launched a revitalization project to restore the historical landscape, including restoration of the lost river system. Currently, densely-spread private houses surround the Taohuawu Cultural District. It would be very difficult to remove these old private houses in the near future. Consequently, the Taohuawu Cultural District revitalization project is only the Phase I construction of the overall revitalization effort, which includes the restoration of only the part of urban river and lakes located within the project area. Due to these limitations, the restored water system had to be closed, without any connection to a nearby river or other external water supplies in the near future. The master plan for the revitalization project is shown in Fig. 1.

2.2. Research roadmap

The aim of the revitalization project was to create a healthy water system with guaranteed high water quantity and quality before its connection to an outer urban river in the future. It involved how to harvest and treat the local runoff by LID-BMPs to provide a water source for the Taohuawu closed water system and how to give the system the ability to maintain water quality.

The research plan is shown in Fig. 2. First, based on the investigation and analysis of the study area, and considering the regional situations and developmental requirements, planning objectives for the LID-BMP facilities in the Taohuawu Cultural District were determined. Second, suitable LID-BMP facilities were selected based on the regional characteristics of the Taohuawu Cultural District. A specific LID-BMP engineering planning scheme was then established. To assess stormwater control effects, a runoff simulation model based on the SWMM model was developed and used. Finally, the amounts of water needed for the closed water system were calculated. The deployment of water sources for the closed water system and its water quality maintenance scheme were then proposed.

2.3. LID-BMP planning in Taohuawu Cultural District

2.3.1. Planning objectives

The primary objective of the LID-BMP planning was to select a number of suitable LID-BMPs according to the local conditions, and then to devise an integrated LID-BMP scheme to harvest and treat the local runoff to provide a water source for the Taohuawu closed water system.

In addition, to utilize the multiple functions of LID-BMPs fully in promoting urban sustainability and safety, a secondary objective of reducing flood events in Taohuawu was included. This was borne out of recent concerns over an increased risk of storm flooding disasters resulting from rapid urbanization (Jia et al., 2013b).

2.3.2. LID-BMP selection

There are many types of LID-BMPs. Each type has intrinsic technical and economical characteristics and installation limitations. Jia et al. (2013a) developed a multi-criteria selection index system for LID-BMP planning to assist in the selection of the most appropriate LID-BMP type(s) for a specific installation site. The selection indices include regional suitability, runoff control, and economics. The regional suitability index incorporates the location of the planned development, the soil conditions, the groundwater level and variation, terrain and drainage areas, and the LID-BMP space requirements. The runoff control index incorporates the quantity, quality, and other effects. The economics index includes factors such as the construction and maintenance costs and the cost uncertainty associated with LID-BMPs. Based on the local conditions in the Taohuawu Cultural District (Fig. 3), bioretention cells, permeable pavements, and infiltration pits were considered appropriate in the vicinity of the Boutique Hotel, Intangible Cultural Heritage Exhibitions Hall, Comprehensive Cultural Industry Areas, and the Tang Yin Temple. The stormwater treated with the bioretention cells, permeable pavements, and infiltration pits would then be harvested through a permeable pipe system linked to the closed water system. In the Tang Yin Formal Residence Area, there are large green landscaped areas, so some natural landscape LID-BMP measures were selected, including grassed swales, buffer strips, and constructed wetlands. The conceptual integrated LID-BMP framework design in Taohuawu is illustrated in Fig. 4.

2.3.3. LID-BMP facilities planning

As described above, the selected LID-BMP facilities included bioretention cells, permeable pavements, infiltration pits, grassed swales, constructed wetlands, and buffer strips.

In the Taohuawu cultural area, stormwater runoff from most areas will be collected and treated by the planned LID-BMP facilities. These are the main water sources for the local closed water system. To avoid flooding, a separate conventional stormwater drainage system is also planned to drain excess stormwater runoff which could not be captured by LID-BMPs.

The LID-BMP facilities planning scheme is illustrated in Fig. 5. The total area of the footprint of the LID-BMP installations in Taohuawu is 3303 m^2, accounting for 4.8% of the entire constructed area, in which the area of the constructed wetlands is 1718 m^2, bioretention cells is 337 m^2, permeable pavements is 300 m^2, grassed swales is 445 m^2, infiltration pits is 288 m^2, and buffer strips is 215 m^2.

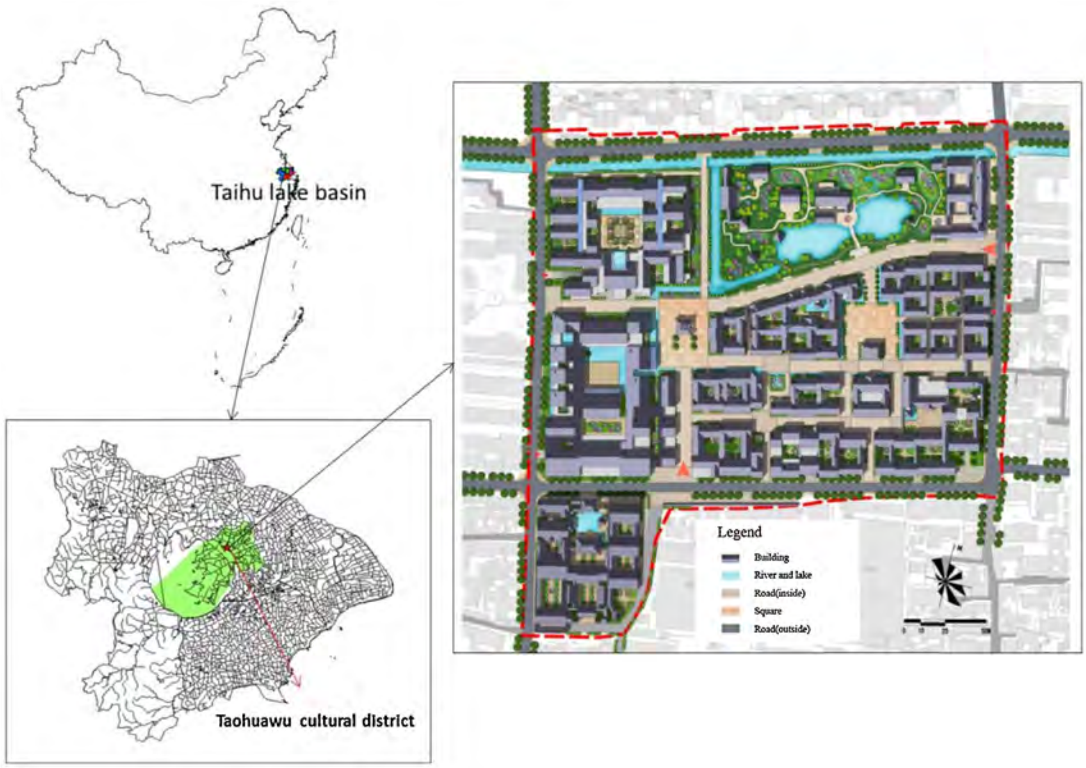

Fig. 1. Location of the case study.

2.4. LID-BMP facilities effectiveness assessments

2.4.1. Runoff simulation model

To assess the implementation of the LID-BMP facilities, a SWMM-based urban runoff simulation model was developed for Taohuawu. SWMM is a dynamic rainfall-runoff simulation model for single-event or long-term (continuous) runoff quantity and quality, primarily from urban areas (Rossman, 2010; Jia et al., 2012; Ma et al., 2012).

The Taohuawu Cultural District has a total land area of 70,618 m^2 and is divided into sub-watersheds. The drainage system includes 29 nodes, 29 conduits, and 3 outlets. The required data include the area, slope, width (width = area/flow length), percent imperviousness of the subcatchment, and pipe diameters and lengths. All of these data can be obtained by measurements or from available information. The depression storage of the impervious and pervious areas; the Manning coefficients of the impervious surfaces, pervious surfaces, and pipelines; and infiltration rates were determined according to Liu et al. (2007), Zhao et al. (2009), Che et al. (2010), Hou et al. (2012), Huang and Nie (2012), and Wang et al. (2012).

Two scenarios were proposed. Scenario 1 was a conventional drainage system without LID-BMPs, and Scenario 2 was a drainage system using the LID-BMP facilities planning scheme described above. Annual rainfall data for a typical year and synthesized storm data were used to perform the simulations, and the results of the two scenarios were analyzed and compared. The rainwater collection and runoff control by the LID-BMP facilities were assessed by analysis and comparison of the simulations.

2.4.2. Synthetic design rainfall on flooding control assessment

The developed runoff simulation model can be used for either an annual simulation or a singular rainfall event simulation. In the annual timeframe simulation, the objective was to assess the annual rainfall harvest, the step of the input rainfall series was 1 h, which was not suitable for analysis of short-term flooding situations. Therefore, a 2-h design storm rainfall with a 5-min time step was used to assess the effects of the LID-BMP facilities on flood control.

Since there has been little research on rainfall patterns in Suzhou, the well-known Chicago-storms (Keifer and Chu, 1957) synthetic rainfall pattern was chosen to simulate a rainfall event in Suzhou using a local storm intensity formula.

The storm intensity formula for Suzhou was

$$i = \frac{a}{(t+b)^c} = \frac{A(1+C\ \log P)}{(t+b)^c} = \frac{19.83 \times (1+0.8201 \times \log P)}{(t+18.99)^{0.7735}}, \quad (1)$$

where i is the storm intensity in mm/min, P is the storm recurrence interval, t is the convergence time in min and a, b, and c are the parameters in Suzhou: $a = 19.83 \times (1 + 0.8201 \times \log P)$, $b = 18.99$, and $c = 0.7735$. The formulae for synthetic Chicago storms are

$$i_b = \frac{a\left[\frac{(1-c)t_b}{r} + b\right]}{((t_b/r)+b)^{c+1}} \quad (2)$$

and

$$i_a = \frac{a\left[\frac{(1-c)t_a}{1-r} + b\right]}{\left(\frac{t_a}{1-r}+b\right)^{c+1}} \quad (3)$$

where i_a (i_b) is the storm intensity before (after) the peak time point in mm/min, r is the peak time point in the storm period 0–1, 0 represents the peak occurrence at the beginning of the storm, 0.5 represents the peak occurrence in the middle of the storm, and 1 represents the peak occurrence at the end of the storm. For this research, 0.5 was chosen. Here a, b, and c are parameters that can be obtained from the local storm intensity formula.

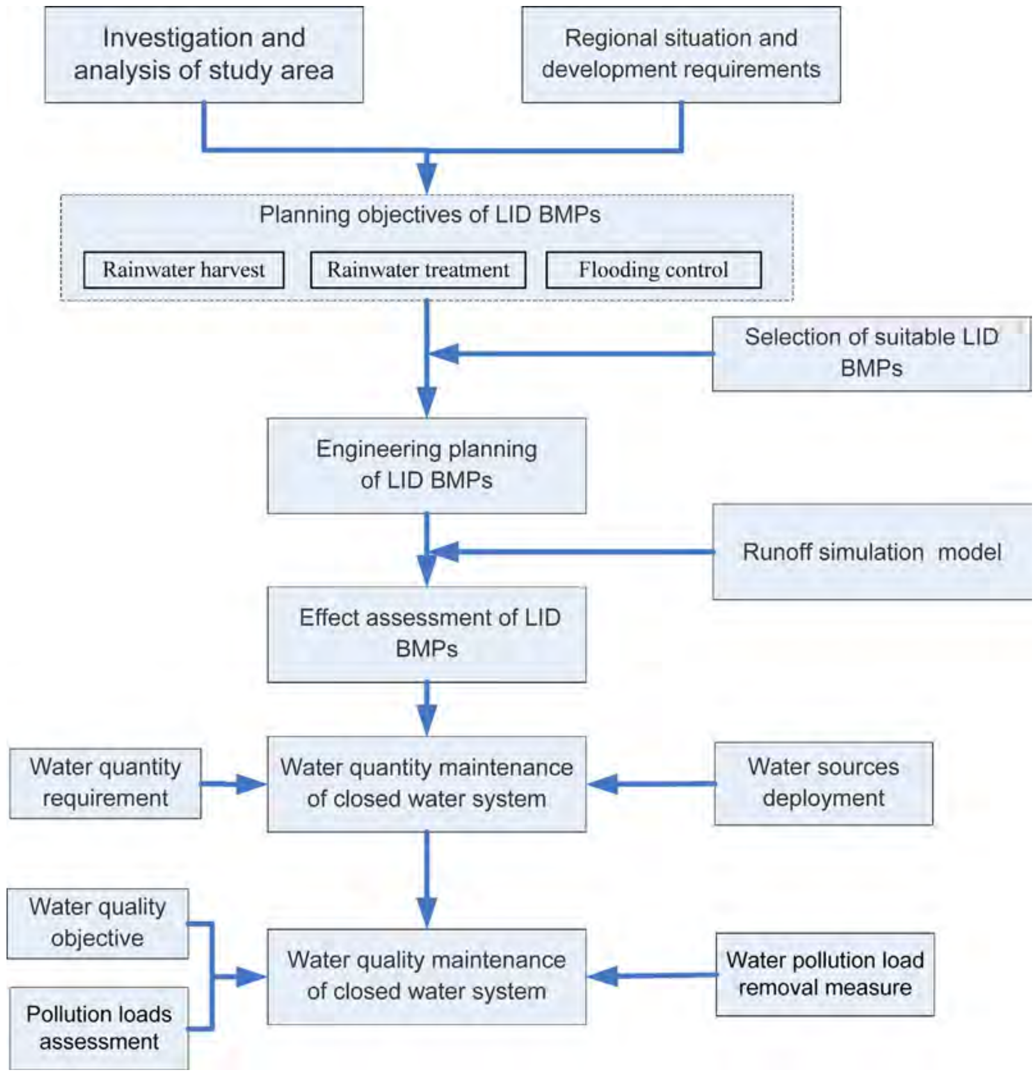

Fig. 2. Research plan.

Using the above equations, 2-h synthetic storms with recurrence intervals of 2, 5, and 20 years were calculated (Fig. 6).

3. Results and discussion

3.1. Assessment of effects on rainwater harvest

According to the long-term monthly average rainfall data, the storms usually occur during April to October, which account for 75% annual rainfall amount. The rainfalls in other month are relatively few, and most important, these are usually light rains which are difficult to harvest. In the study, hourly rainfall data during April to October from 2001 to 2007 were collected and analyzed. The data from a representative year for Suzhou, i.e., 2005, was used for the runoff model simulation and assessment. For 2005, the total rainfall during April to October was 647.8 mm, which is close to the long-term average rainfall amount during April to October. The monthly rainfall data during that period are illustrated in Fig. 7. The total rainfall volume in that period for the study region was 45,346 m^3.

Under Scenario 1, the impervious area was calculated from the planning map, based on areas of buildings, roads, and open squares. Under Scenario 2, the impervious area was decreased by the presence of the LID-BMP facilities. Water surfaces (river and ponds) were considered as yielding no runoff into the conventional stormwater drainage systems under either scenario. Analyses of the scenarios were conducted using the runoff simulation model. The results showed that with the LID-BMP facilities in place under Scenario 2, the benefits brought about in terms of rainwater harvesting and stormwater control were quite evident. The runoff volume entering into the conventional stormwater drainage system decreased by 39.8% and the infiltration amount increased by 42.7% compared with that under Scenario 1. The amount of harvested rainwater during April to October was 7598 m^3. Detailed data are shown in Tables 1 and 2.

Table 1
Water quantity assessment for the two scenarios during April to October.

	Scenario 1 (m^3)	Scenario 2 (m^3)	Change ratio (%)
Harvested rainwater	0	7598	–
Runoff amount	29,700	17,877	−39.8
Infiltration amount	10,021	14,316	42.7
Evaporation from water system	5555	5555	0
Total	45,346	45,346	0

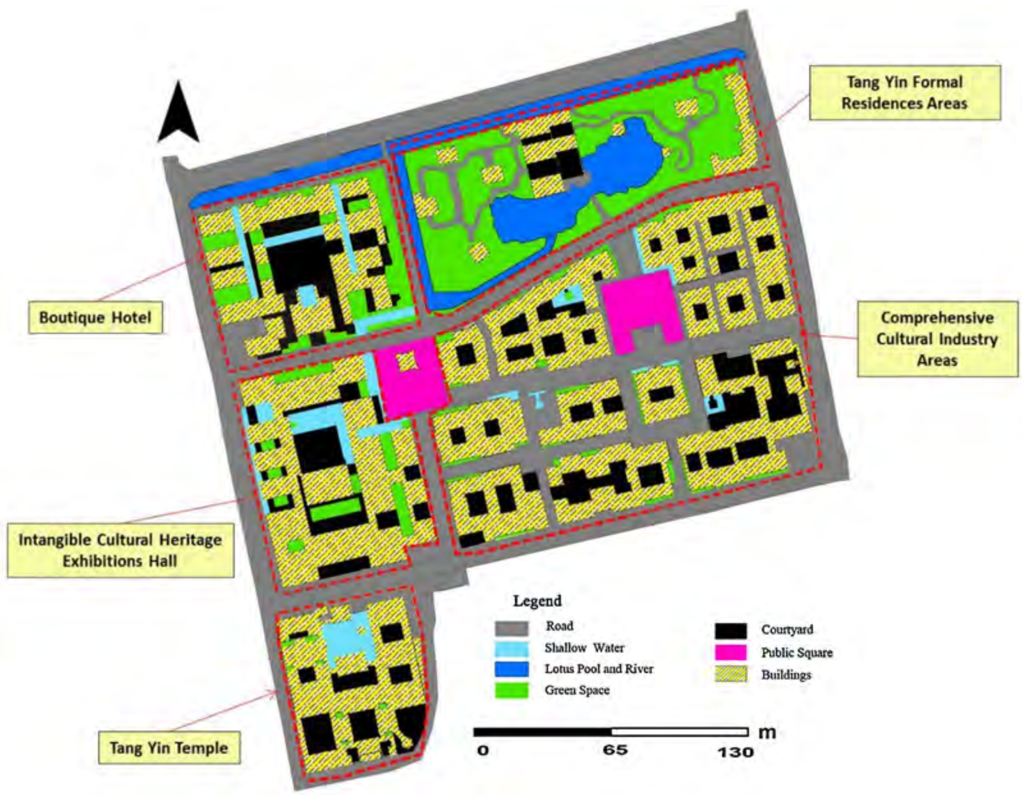

Fig. 3. Land use map of the Taohuawu Cultural District.

3.2. Assessment of flooding control

The aim of the drainage system in Taohuawu is to control stormwater runoff for a 2-year recurrence-interval design storm. Using the developed Taohuawu urban runoff simulation model, the LID-BMP effects on flood control were evaluated under storm conditions with 5- and 20-year recurrence intervals. The flooding situations of the two scenarios under storm conditions with 5- and 20-year recurrence intervals are shown in Fig. 8. The different colors represent 5-min maximum floodwater volumes from each manhole during the synthetic storm period. As can be seen, the 5-min maximum floodwater volumes from each manhole are much less under Scenario 2 than those obtained under Scenario 1.

Based on the floodwater volumes from each manhole and the site topography, the standing water depths were calculated. Using a standing water depth of 0.15 m as the criteria for flooding, the time series of the flooded areas was obtained. Considering storm conditions with 20-year recurrence intervals, the time series of the flooded areas for the two scenarios are illustrated in Fig. 9. In addition, taking the lowest elevation site as an example, the variations in standing water depth in the synthetic storm period under the two scenarios are illustrated in Fig. 10. The duration of

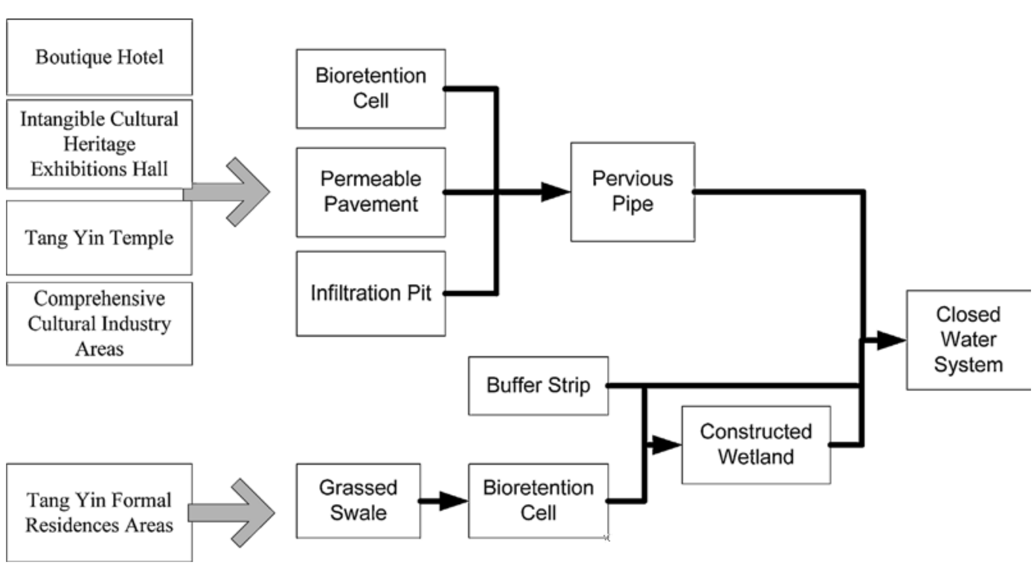

Fig. 4. Conceptual integrated LID-BMP framework for the Taohuawu Cultural District.

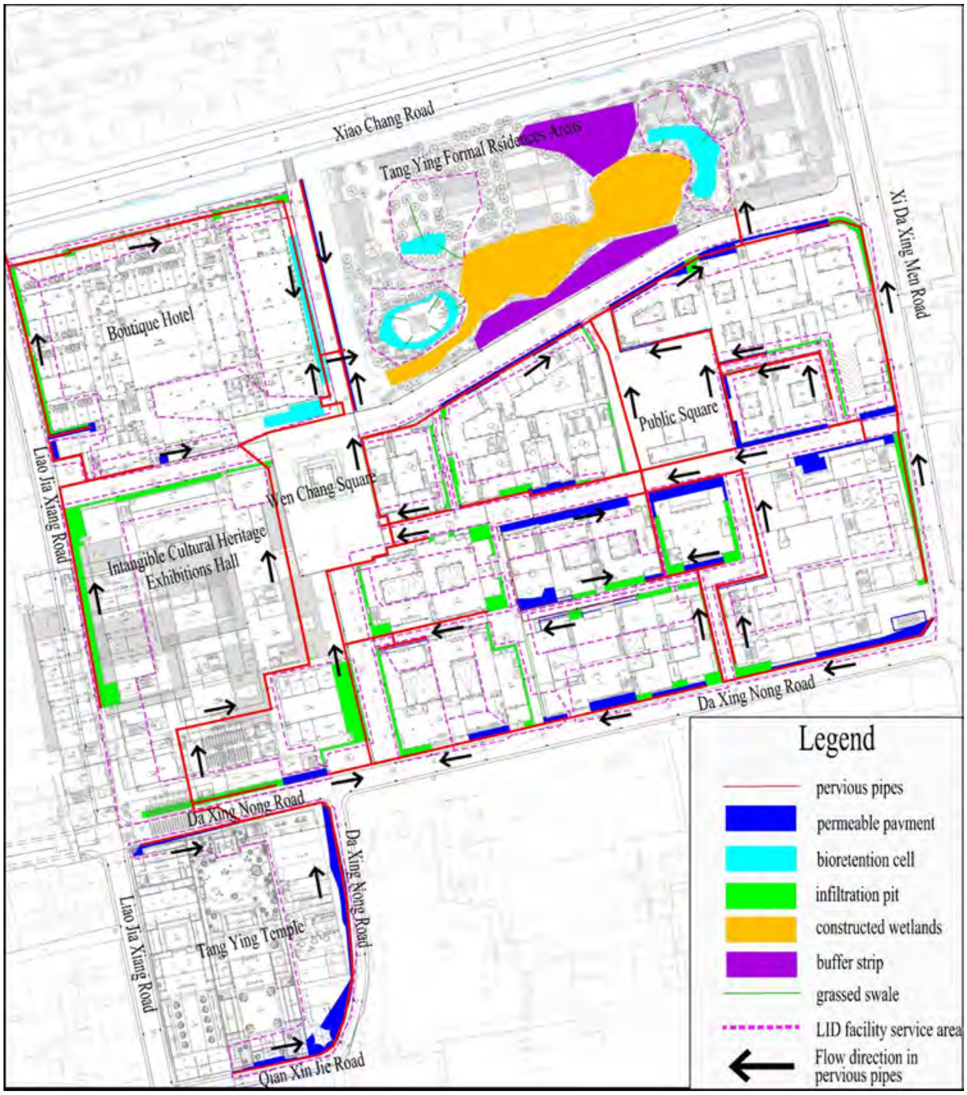

Fig. 5. LID-BMP facilities planning scheme for the Taohuawu Cultural District.

standing water depths greater than 0.15 m was 20 min under Scenario 2, but was 60 min under Scenario 1, clearly demonstrating the flood-control benefit of the LID BMP facilities.

3.3. Water quantity requirement estimation and water sources deployment

3.3.1. Water quantity requirement estimation

The water quantity requirement of the Taohuawu closed water system to retain ecological function is mainly the water needed for replenishment (Jia et al., 2011). This includes water replenishment for evaporation, evapotranspiration, leakage, and water consumption by on-site river-water filtration equipment. Based on the monthly evaporation/evapotranspiration and leakage data for Suzhou, together with the water surface area of the

Table 2
Monthly rainwater quantities harvested by the LID-BMP facilities during April to October.

Month	Harvested rainwater (m^3)
April	893
May	1339
June	1292
July	1382
August	1402
September	1290
Total	7598

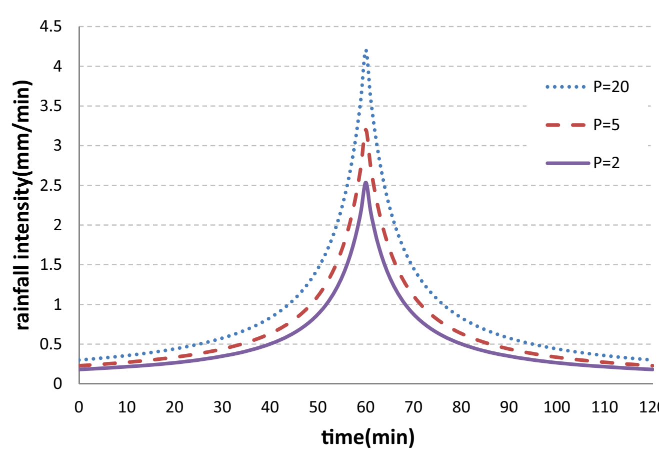

Fig. 6. Two-hour synthetic rainfall events with 2-, 5-, and 20-year recurrence intervals for Suzhou.

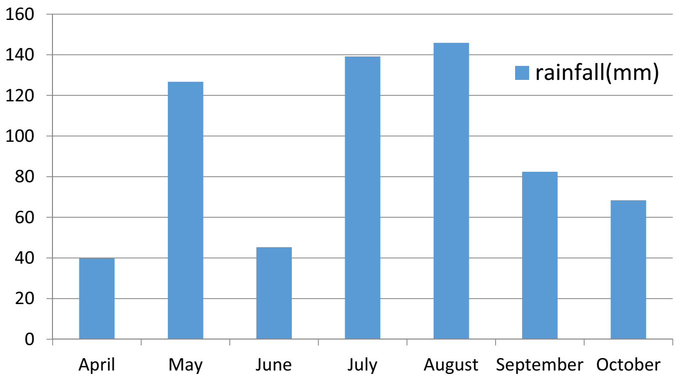

Fig. 7. Monthly rainfall for Suzhou during April to October in 2005.

closed water system (including river and wetlands), the ecological water quantity required to replenish the losses from evaporation/evapotranspiration and leakage was calculated. The monthly water loss by on-site river-water filtration was also estimated. The scale of the continuous on-site river-water filtration facility was 1000 m^3/d. According to the technical data of the continuous on-site river-water filtration facility, 5% of the treated water would be used for backwashing. Therefore, about 50 m^3/d backwash water need to be discharged to the municipal wastewater system. The results are shown in Table 3. The annual total water quantity requirement would be expected to be about 21,802 m^3, and the monthly water demand to be between 1540 and 2038 m^3.

3.3.2. Water source deployment

Based on the local situation, three types of water resources could be used for water replenishment in Taohuawu: harvested rainwater, groundwater, and tap water. Based on the requirements for ecological conservation (saving energy and water), rainwater harvested by the LID-BMP facilities should be a priority. However, due to the seasonal variation in rainfall and the uneven annual rainfall, other water resources would need to be used to guarantee the ecological water quantity required. Local groundwater and tap water must be considered here if the closed river system cannot be connected with the outer river system. Suzhou is located in the Taihu Lake basin plain with inter-connected river networks. In this region, groundwater usage is relatively low due to the abundance of surface water resources and government regulations. The groundwater level is shallow and water exchange between groundwater and river water is rapid. After discussion with local authorities and developers, groundwater was chosen based on the local hydrogeological conditions. The water deployment for the closed water system is shown in Table 3.

Based on the water resource analysis described above, we found that in order to maintain a normal water level in the closed water system, groundwater would be needed throughout the year. Because winter is the dry season, groundwater is the only water source available from January to March and from October to December. The maximum monthly water requirement from groundwater would be 1855 m^3. In the wet season, rainwater could be the main source, and the maximum monthly groundwater water requirement would be 914 m^3. The total annual water requirement would be 21,802 m^3, of which harvested rainwater could supply 7598 m^3. The remaining 14,204 m^3 would be supplied by groundwater. From the assessment results shown in Table 1, we found that with the LID-BMP facilities, the amount of infiltration would be 14,316 m^3 in Taohuawu. This means that the groundwater recharge would be greater than the groundwater requirement. Hence, sufficient local water would be available to meet the requirements of the closed water system in Taohuawu.

3.4. Water quality maintenance

3.4.1. Water quality objectives

Based on a comprehensive analysis of the beneficial use and the ecological functions of the closed water system in the Taohuawu Cultural District, a Class V water quality designation, based on the Chinese Surface Water Environmental Quality Standards (GB3838-2002) was chosen for the water quality objective for the Taohuawu water system.

Taohuawu Cultural District is designed to be a recreational site without any industrial land use. In addition, a new separate wastewater system will be constructed and all the domestic wastewater would be collected and transported to a wastewater treatment plant nearby. It is expected that fecal bacteria and heavy metals pollution should not be the potential causes of closed water system degradation. However, algae bloom might be the main concern here, as in the case for urban water bodies (Jia et al., 2011; Zhang et al., 2013). Therefore, NH_3-N, TN and TP were selected as the water quality indicators for evaluation based on relevant experience of water quality status in Suzhou and similar cities (Ballo et al., 2009; Hu et al., 2012). The water quality objectives values of NH_3-N, TN and TP were listed in Table 4.

3.4.2. Pollution loads assessment and required removal rate

Based on above analysis, the closed water system would not receive any domestic and industrial wastewater. The sediment

Table 3
Water quantity requirements and water resources deployment (units: m^3).

Month	Water quantity loss				Water resources deployment	
	Evaporation from river	Evapotranspiration from wetlands	Water loss by water-filtration equipment	Total water quantity requirements	Harvested rainwater	Groundwater
1	71	49	1550	1670	0	1670
2	83	57	1400	1540	0	1540
3	134	92	1550	1776	0	1776
4	182	125	1500	1807	893	914
5	234	162	1550	1946	1339	607
6	224	154	1500	1878	1292	586
7	272	187	1550	2009	1382	627
8	289	199	1550	2038	1402	636
9	222	153	1500	1875	1290	585
10	180	124	1550	1855	0	1855
11	125	86	1500	1712	0	1712
12	86	60	1550	1696	0	1696
Total	2102	1448	18,250	21,802	7598	14,204

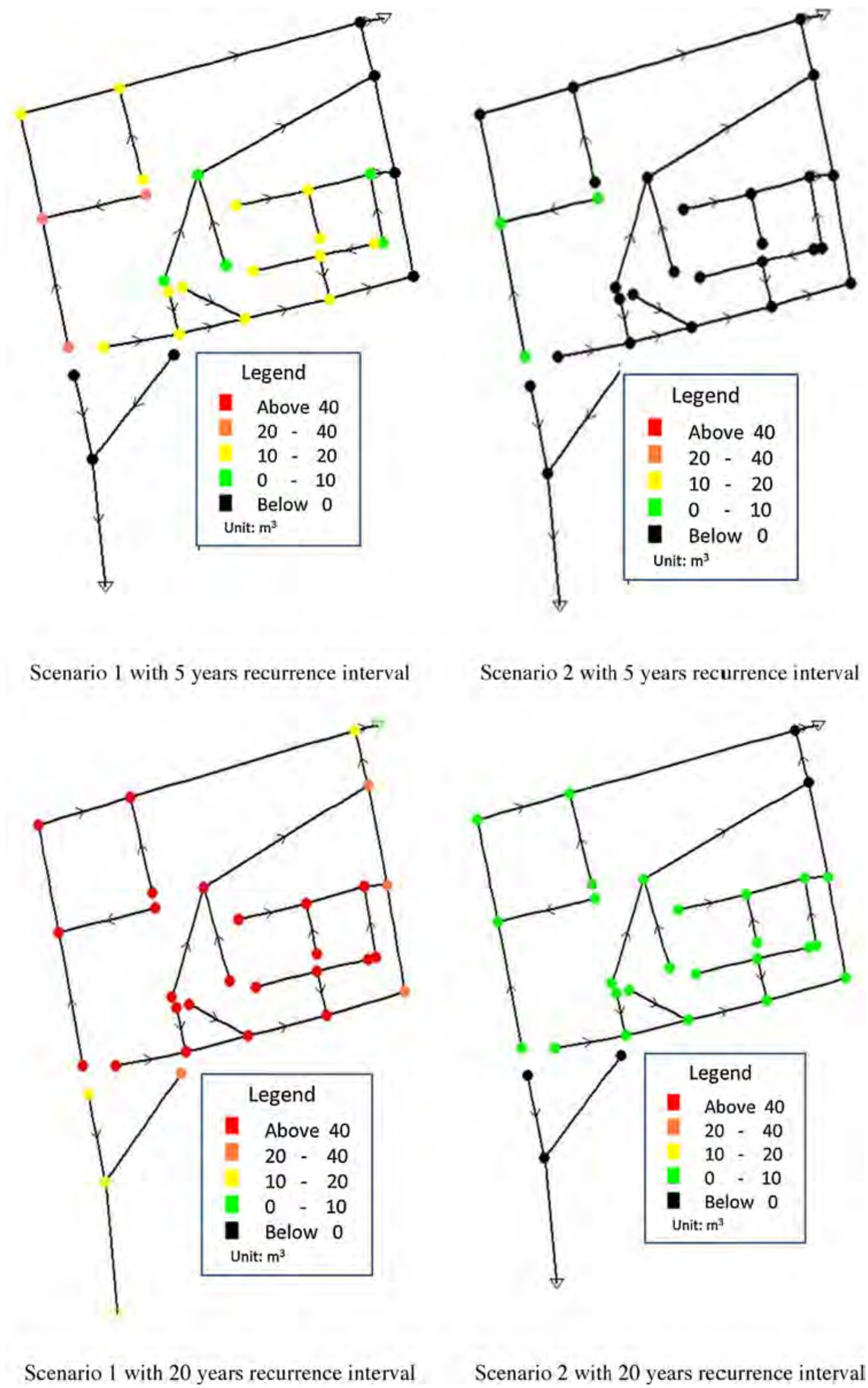

Fig. 8. Flood situation for the two scenarios under storm conditions with 5- and 20-year recurrence intervals.

loads would not be of concern for the newly constructed closed water system. Also, sediment dredging will be conducted if the sediment loads increase significantly for some reason in the future. Hence, all the potential pollutant loads entering the closed water system will mainly be from urban runoff. The Export Coefficient Model is frequently used to estimate the pollution loads of non-point sources (Liu et al., 2008). Here, the export coefficients, shown in Table 4, were determined based on monitored runoff water quality pollution data for different underlying surfaces in Suzhou and similar cities (Ballo et al., 2009; Hou et al., 2012; Huang and Nie,

Table 4
Pollution loads for different underlying surfaces and required removal rates.

Underlying surface	Area proportion	TP (mg/L)	TN (mg/L)	NH_3-N (mg/L)
Road	31.1%	0.28	5.10	3.00
Green space	12.7%	0.20	4.00	1.80
Yard	9.9%	0.28	4.90	2.70
Piazza	6.8%	0.28	4.90	2.70
Building	39.5%	0.22	4.50	2.10
Aggregate water quality of runoff		0.25	4.69	2.44
Water quality objectives (Class V in GB3838-2002)		0.40	2.00	2.00
Required removal rates		0.00	57.4%	18.1%

2012; Liu et al., 2005). The calculated results are shown in Table 4. According to the pollution load and water quality objectives, the required pollution removal rate would be around 60%.

3.4.3. Water pollution load removal measures and water quality maintenance

To meet the pollutant removal objectives, LID-BMP facilities would be used as the first step in reducing pollution loads from the urban runoff at the various sources. This could reduce pollutants by 35–50%, according to the model assessment. To guarantee the compliance of water quality objectives, a 1000 m^3/d continuous on-site river-water filtration facility would be installed (Li et al., 2011). Integrated with the continuous on-site river-water filtration facilities, a circulating flow regime in the closed water system was formed. In addition, in order to maintain a healthy ecological status of the closed water system, ecologically sound banks (ESBs) have been adopted in the river system construction (Everaert et al., 2013). Also, floating treatment wetlands have been proposed to install in the closed water body (Winston et al., 2013) to ensure quality standards are maintained.

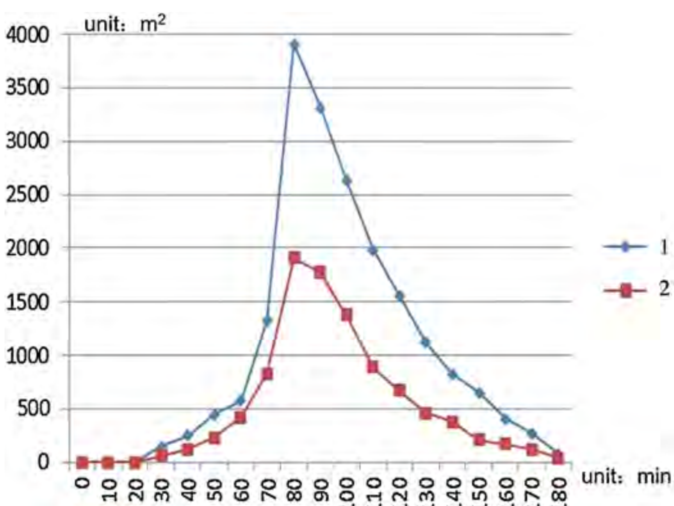

Fig. 9. Flooded area comparison of the two scenarios for a 20-year recurrence-interval storm.

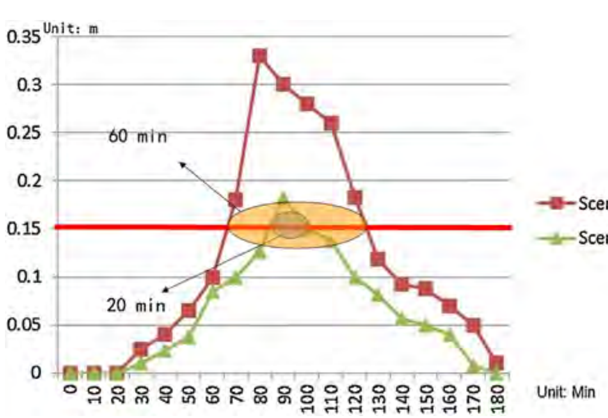

Fig. 10. Standing water depth comparison of the two scenarios for a 20-year recurrence-interval storm.

4. Conclusions

Urban river ecosystem conservation is a major concern for projects involving new urban development and the retrofitting of old cities. LID-BMPs are considered an innovative, integrated method to decrease the negative impacts of urbanization on water systems. A case study was conducted in Suzhou City to create a closed scenic water system using LID-BMP technology in a project to revitalize the Taohuawu Cultural District. It was shown that a closed water system would have the ability to maintain water quantity and quality. In addition, although the conventional stormwater pipe system in the district met only the standard required for 2-year recurrence-interval storms, there would be no local flooding in a 5-year recurrence-interval storm by using the LID-BMPs. The flooding risks are thus reduced with the implementation of LID-BMPs. The proposed scheme has been recently approved by local related government agencies, and the closed water system is under construction now.

Acknowledgments

This work was jointly supported by the National Water Pollution Control Special Project (2011ZX07301-003), the Natural Science Foundation Project (51278267), and the Programme of Introducing Talents of Discipline to Universities (B07002). The authors thank Mr. Zeng Shentao, Vice President of Suzhou Taohuawu Development and Construction, for his extensive support and assistance in data collection.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.07.049.

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