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Benefits of coupled green and grey infrastructure systems: Evidence based on analytic hierarchy process and life cycle costing

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ABSTRACT

Green infrastructure complements grey infrastructure to provide effective urban stormwater management. Design of coupled green and grey infrastructure systems need a systems-based analysis considering multiple criterion. This study used analytic hierarchy process (AHP) and life cycle costing (LCC) to evaluate environmental and economic benefits of various types of coupled green and grey infrastructure systems. AHP results showed that, based on the local conditions and characteristics, the coupled green and grey scenario with green space, permeable pavement, green roof, and stormwater detention cell performed better than other scenarios in urban residential drainage and flood control. Also for the coupled green and grey scenario, the simulation results showed that no flooding was occurred during the ten-year return period rainfall. Coupled green and grey infrastructure scenarios can save the life cycle cost up to 94% compared to the traditional grey infrastructure scenario considering the design, construction, operation, and maintenance stages. Approximately 13% of commercial loan interest (1.03 million USD) can be saved for homebuyers. In future, urban designers and developers should consider the optimization of coupled green and gray infrastructures system under multiple criterion for the environment, economy, and safety benefits.

1. Introduction

Rapid urbanization has led to increasing impervious areas and thus changing natural hydrological processes (Baek et al., 2015). As urban area expands, urban floods happen more frequently, causing great economic losses and adverse impacts on urban ecosystems. Urban infrastructure of drainage and flooding control in urban residential area which occupies approximately 25%–40% of urban construction cost (MOHURD, 2010) has become increasingly important to improve a city's resilience against urban floods. Traditionally, grey infrastructure, which are mainly composed of concrete and steel (thus the grey part of the term) and installed as part of the urban drainage system (Dong et al., 2017), played an important role in urban flood control. However, rapid urbanization and more frequent extreme storm events instigated by climate change make traditional grey infrastructure become less effective and efficient. At the same time, water scarcity has become increasingly severe in many cities around the world. Urban rainwater,

as a useful water resource, has not been properly collected and utilized in many cities. Innovative urban stormwater management strategies have been developed to better address urban floods and water resource reuse in urban residential areas.

New strategies for urban runoff control can be summarized as best management practices (BMPs) (Schueler, 1987; Clar et al., 2004), low impact development (LID) (Prince George's County, 1999a and 1999b), sustainable urban drainage systems (SuDS) (Martin et al., 2000; Martin, 2001), and water sensitive urban design (WSUD) (Whelans et al., 1994; Wong, 2007). These new strategies emphasize the use of green infrastructure to protect, restore, or mimic the natural water cycle to effectively and efficiently improve community resilience and quality of life (Allen, 2013). Despite their benefits, green infrastructure cannot replace grey infrastructures completely considering the safety during extreme storm events (Xu et al., 2019). In practice, green infrastructure should be used together with grey infrastructure. However, many studies just made economic cost comparisons rather than the multi-

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criterion comparisons in life cycle perspective. In addition, most research papers on the coupling of green infrastructure and grey infrastructure are qualitative descriptions (Casal-Campos et al., 2015; De Sousa et al., 2012; O'Sullivan et al., 2015). The evaluation of coupled green and grey infrastructure system is a multi-objective and multi-criterion problem. Accordingly, a systems-based evaluation is needed to understand the cost and benefit of coupled green and grey infrastructure systems. Moreover, the configuration of the coupled green and grey infrastructure needs to be optimized under multiple criterion of the environment, economy, and safety.

At present, there are several models (e.g., Principal component analysis (PCA), linear weighting model, analytic hierarchy process (AHP)) that can be used to conduct multi criterion problems analysis. PCA is a multiobjective approach that aims to provide useful decision support (Petroni and Braglia, 2000; Geng et al., 2017a). However, it needs the knowledge of advanced statistical technique. Linear weighting model can rate the problem based on several criterion and finally combine these ratings into a single score (Nydyck and Hill, 1992). But this method can not consider qualitative evaluation criterion very effectively. AHP is a theory of measurement by using pairwise comparison to derive priority scales based on the judgements of experts (Saaty, 1987, 2000; Saaty, 2008). The application of AHP is worldwide, such as government, business, industry, and healthcare (Saaty and Peniwati, 2013; Han et al., 2014 and 2017; Geng et al., 2017b; and 2018). AHP results can represent the decision preference of the stakeholders (e.g., experts, decision-makers, local residence) for the current situation of the studied residential area. Accordingly, this study used AHP to conduct the best scenario selection considering multiple criterion and then used life cycle costing (LCC) to evaluate and optimize the coupled green and grey infrastructure system.

2. Methods and materials

2.1. Methods

2.1.1. Methodological framework

As shown in Fig. 1, a set of scenarios representing different configuration of the coupled grey and green infrastructure in an urban setting are first developed. Analytic hierarchy process (AHP) is then used to evaluate these scenarios to identify the best suitable scenario for urban flood control in the study area. There are four scenarios presented. C1 is the baseline grey-only scenario, C2, C3 and C4 are coupled green and grey scenario. C2 is the combination of optimized pipelines, green space, permeable pavement, green roof, and stormwater detention cell. C3 is the combination of optimized pipelines, permeable pavement, grassed swale, bioretention, and buffer strip, C4 is the balanced scenario, which is the combination of optimized pipelines and many types of green infrastructures. The SWMM model is used next to simulate the flood control effect of the selected scenario (Rossman, 2010; Jia et al., 2012) to compare with the baseline grey infrastructure-only scenario. If the selected scenario performs the same or better in flood control compared to the baseline scenario, economic cost and benefit are then evaluated using life-cycle costing (Xu et al., 2017).

2.1.2. Analytic hierarchy process (AHP)

As mentioned before, AHP method was used to select the most suitable scenario for the studied residential area because it can solve complex multi-objective and multi-criterion issues and has worldwide applications (Saaty, 2000, 2008). The objective of the decision is at the top level of the hierarchy. The criterion that contribute to the decision is showed at the intermediate level. The solutions or decision alternatives are at the last level of the hierarchy (Haq and Kannan, 2006).

In this study, three levels hierarchy are constructed (Fig. 2). The top level is urban residential drainage and flood control. The intermediate level includes six criterion based on the Sponge City Construction Performance Evaluation and Assessment Indicators (Ministry of

Housing and Urban-Rural Development of the People's Republic of China (MOHURD), 2015), which are used as general principles for developing green infrastructure in China. These six criterion can be classified into two categories, one for effectiveness evaluation (i.e., volume capture ratio of annual rainfall (B_1), urban heat island effect (B_2), non-point source pollution control (B_3), utilization ratio of rain-water resource (B_4), and urban flood prevention and control (B_5)) and the other for cost evaluation (i.e., economic benefit of the whole process (B_6)). There are four scenarios at the last level including one baseline grey-only scenario (C1) and three coupled green and grey scenarios (C2, C3, and C4).

After the hierarchy is established, comparative judgements are made to determine element priorities at each level. The comparison matrices are constructed to prioritize comparative judgements into ratio scale measurements. A nine-point scale is used to compare two elements (Table 1). The pairwise comparison is used to compare the importance of two elements. Information of these elements and weights are collected from interviews with decision-makers, experts, stakeholders, and local residents.

The matrix of relative rankings for the intermediate and last levels of the hierarchy is generated in the pair-wise comparison. After developing matrices, the consistency ratio can be calculated by using Eq. (1) and Eq. (2).

$$CI = (\lambda_{max} - n) / (n - 1) \quad (1)$$

$$CR = CI / RI \quad (2)$$

where CI is consistency index; λ_{max} is the maximum eigenvalue for each matrix; n is the order of matrix; CR is the consistency ratio; and RI is average random index.

The acceptable CR for 3 by 3, 4 by 4, and all large matrix is 0.05, 0.08, and 0.1, respectively (Cheng and Li, 2001; Haq and Kannan, 2006). If the calculated CR is equal to, or less than the acceptable value, it indicated that the comparative judgements showed in that matrix had a good consistency level. If the calculated value of CR is larger than the acceptable value, inconsistency of judgements of the matrix have occurred and the evaluation should be reconsidered (Haq and Kannan, 2006).

2.1.3. Storm water management model (SWMM)

SWMM is used to simulate the flood control effect of different scenarios. SWMM can effectively simulate the actual situation in the drainage network. It is extensively used for water quality and quantity simulation, worldwide researchers have proved its functions and effects (Jia et al., 2012; Rossman, 2010). Details of the SWMM model configuration are presented in the case study description section below.

2.1.4. Life cycle costing (LCC)

The economic cost and benefit of the selected scenario is evaluated using the LCC method (Xu et al., 2017). LCC is based on life cycle assessment but considered cost rather than the environmental impacts (Fig. 3). The economic cost and benefit analysis can be conducted from two perspectives, namely, for real estate developer and purchaser. The design, construction, operation, and maintenance stages of coupled green and grey systems are all included in the economic cost and benefit analysis. The LCC in this study is calculated by using Eq. (3):

$$TB = B_1 + B_2 + B_3 + B_4 = A_1 \times W' \times (S_1 - S_2) + (C_1 + C_2 - C_3) + (U_1 - C_4) + U_2 \times 30 \quad (3)$$

Where, TB is the total benefit, RMB; B_1 is the design benefit, RMB; B_2 is the construction benefit, RMB; B_3 is the operation benefit, RMB; B_4 is the maintenance benefit, RMB; A_1 is the construction area, m^2 ; W' is the total weight coefficient of green infrastructure; S_1 is the financial subsidy for three-star level green building per square meter, RMB; S_2 is the design fee for three-star level green building per square meter, RMB; C_1 is the construction cost of green infrastructure, RMB; C_2 is the

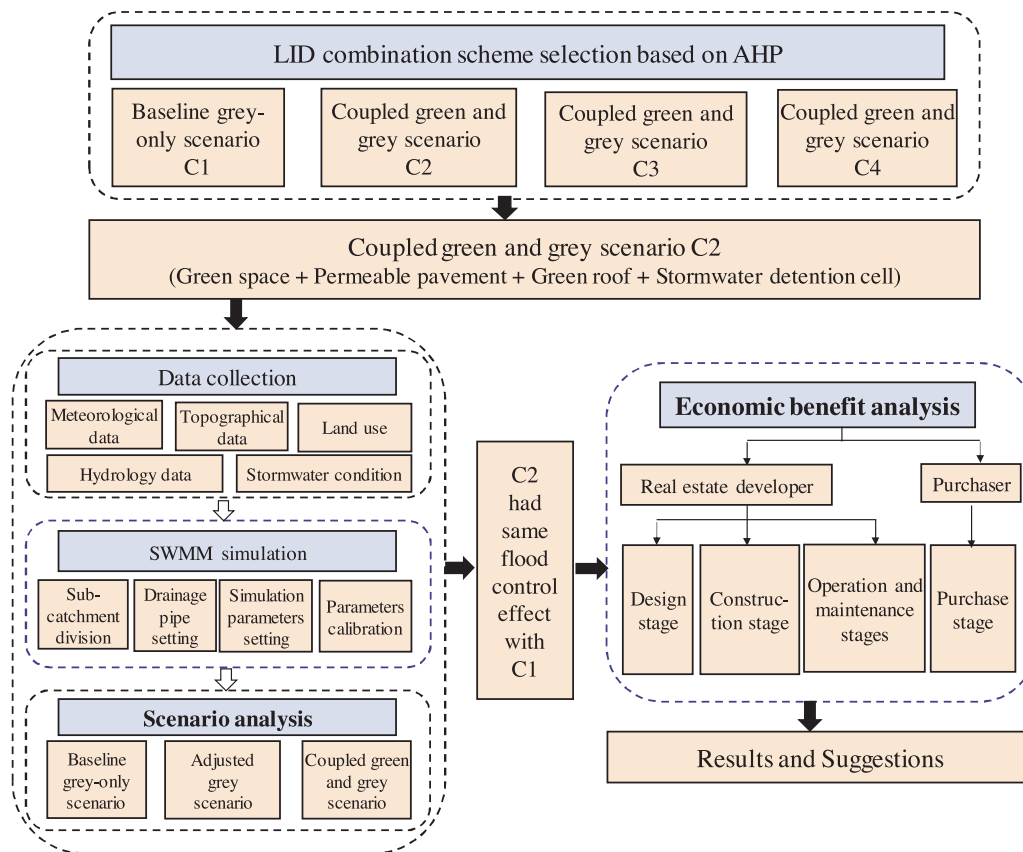


Fig. 1. Methodological framework.

construction cost of adjusted grey infrastructure, RMB; C_3 is the construction cost of original grey infrastructure, RMB; U_1 is the saved water utilization fee annually, RMB; C_4 is the construction cost of stormwater detention cell, RMB; U_2 is the annual saved maintenance fee, RMB.

The cost of materials and labor associated with the construction, operation, and maintenance stages are also included. The cost data of design, construction, operation, and maintenance stages are collected from construction contract and local government files.

2.2. Case study description

A typical residential area in Nanjing city in China is selected as the case study (Fig. 4) mainly because residential area is the main type of land use of the urban areas and Nanjing is the Jiangsu provincial pilot sponge city. The related data is easy to collect. The studied residential area is in the axial end of sponge city pilot area and has complete supporting facilities, convenient transportation, and landscape. In order to promote energy conservation and environment protection, the MOHURD issued the Green Building Evaluation Standard in 2014

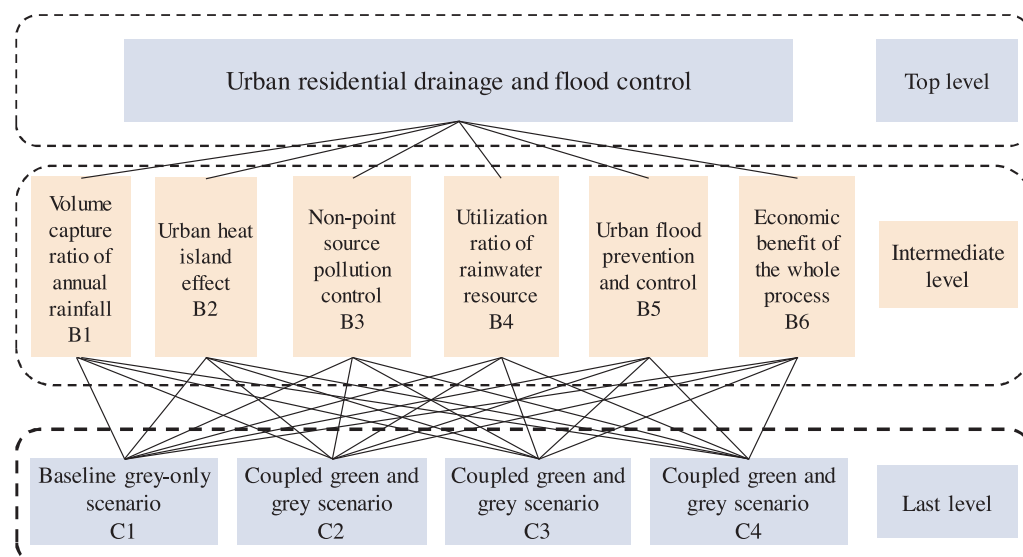


Fig. 2. AHP structural hierarchy.

Table 1
Scale measurement between two elements.

i compare with j	a_{ij}	a_{ji}
Equally important	1	1
Slightly important	3	1/3
Obviously important	5	1/5
Highly important	7	1/7
Absolutely important	9	1/9

Note: 2, 4, 6, and 8 also can be used as indicators, importance among 1, 3, 5, 7, and 9.

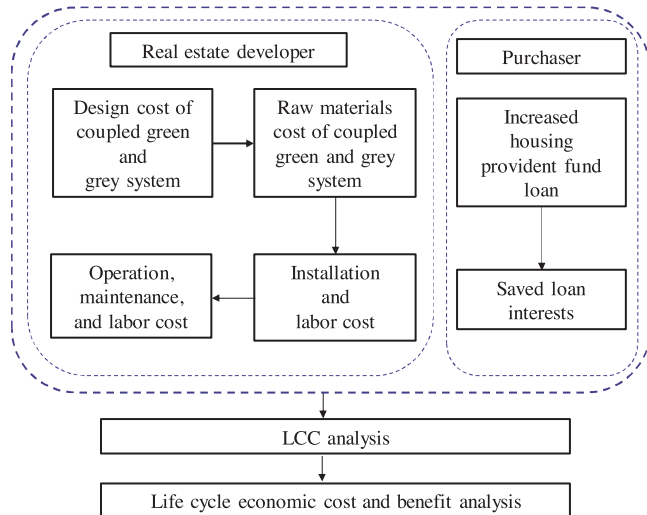


Fig. 3. LCC methodology flow chart.

(MOHURD, 2014b) to classify green buildings into four levels, namely, the basic level, one-star level, two-star level, and three-star level. The selected residential area plans to build a three-star level green building.

In the SWMM model, different return period rain intensity was set based on Nanjing rainfall intensity formula. According to actual situation of drainage network, the studied area is divided into A, B parts, 300 sub-catchments, 465 sub-sink nodes, and 387 pipelines. The largest sub-catchment area is 1300 m² and the average area of sub-catchments is approximately 300~500 m² (Fig. 5). The layout of LID facilities for studied residential area is shown in Fig. 6. The area of green space (i.e., red squares) occupies 100% of the sub-catchment. The area of permeable pavement and green roof (i.e., yellow squares) occupies 50% of the sub-catchment. The volume of stormwater detention cell (i.e., the white area) for A, B part is 250 m³ and 400 m³, respectively. The blue and red slash represents the grey and green infrastructure related drainage area, respectively. The SWMM used in this study has been calibrated and proved by other projects (Xue et al., 2014; Cai et al., 2017).

Hydrologic parameters setting are shown in Table 2. There are 13 parameters needed by SWMM. The first five parameters can be obtained from the geological report and actual measurement of the underlying soil in the early stage of the project. The other nine parameters are according to the established SWMM by previous projects in this area (Xue et al., 2014; Cai et al., 2017).

3. Results and discussion

3.1. Scenario comparison based on AHP

As mentioned earlier, the AHP has three levels. Among the six criterion at the intermediate level, the first five (i.e., B₁ to B₅) are quantitative control indicators and B₆ is set as a qualitative control index. Among the five quantitative control criterion, B₁ and B₅ are binding quantitative indexes, which must be strictly implemented in the

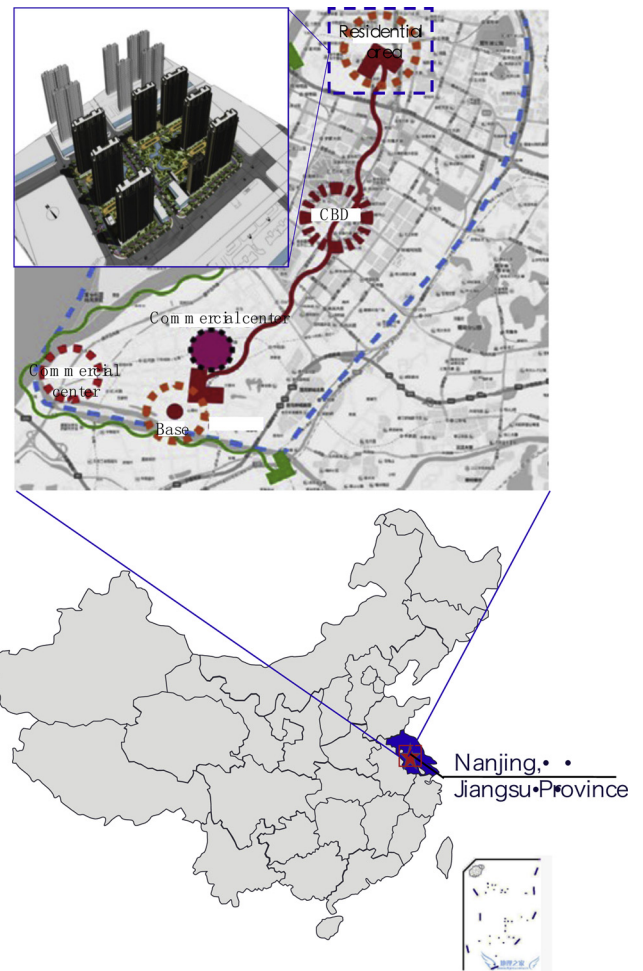


Fig. 4. The location of studied residential area in China.

construction of green building during sponge city construction program. B₄ is also a binding quantitative index, but it should base on the actual hydrological situation, water resource utilization rate and groundwater loss in different regions to set the water resource utilization rate standard, which has certain flexibility in actual implementation. B₃ belongs to the quantitative index of water environment, which is set as a combination of constraint and encouragement in the requirements of the index. It is the recommended standard in the drainage and flood prevention of green buildings. B₂ is only an encouraging quantitative standard for green building of Sponge City construction program. The economic benefit of the whole process (B₆) should be considered during the urban residential drainage and flood control process. The economic benefit of the whole process of the project is a binding qualitative index with a high degree of importance.

Finally, based on the analysis above, the weighting setting of various green building evaluation in the Green Building Evaluation Index and Scheme (MOHURD, 2014b) and the discussion results from interviews with decision-makers, experts, stakeholders, and local residents, the pair-wise comparison results of six criteria are shown in Table 3. Results showed that the importance order of different criterion is: B₅ > B₁ > B₆ > B₄ > B₃ > B₂. This result is then used to select suitable scenario based on each criterion (Table 4).

The overall rating of comprehensive evaluation results was presented in Table 4 according to the weighting importance of four scenarios for six criterion in the criterion layer (Table A.1 to Table A.6). Results showed that the importance order of four scenarios is: C₂ > C₄ > C₃ > C₁. Accordingly, the scenario that including green space, permeable pavement, green roof, and stormwater detention cell

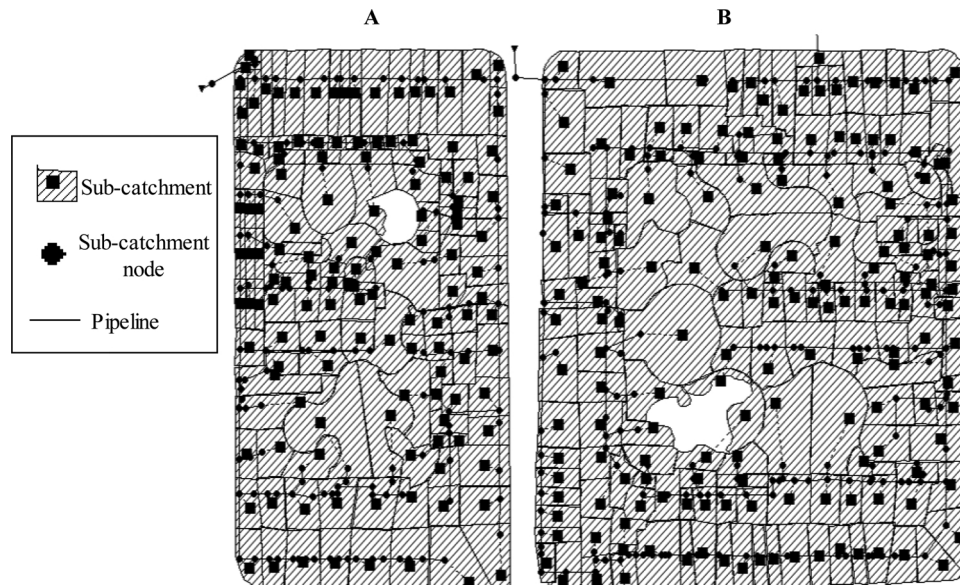


Fig. 5. Sub-catchment and pipeline layout of the studied residential area.

can achieve good performance in urban residential drainage and flood control.

AHP results represent the decision preference of the stakeholders (e.g., experts, decision-makers, local residence) for the current situation of the studied residential area. The AHP also can be applied to other areas to make complex decisions. But the representation of AHP may vary from different problems and people based on the complexity of the problem.

3.2. Urban flood control performance for different scenarios based on SWMM

As mentioned in section 2.1, there are four scenarios considered in this study. According to the results of section 3.1, the coupled green and grey scenario C2 can achieve better performance than other coupled scenarios. Therefore, we simulated the original grey scenario, the adjusted grey scenario, and the selected coupled green and grey scenario C2 using SWMM. The two-year, ten-year, and fifty-year return period rainfall was simulated for each scenario. The rainfall process and total

rainfall volume used in this study was presented in Fig. 7.

The simulated results for different scenarios were presented in Figure A.1 to A.3. For original grey scenario, simulated results showed that for the two-year and ten-year return period rainfall, no flooding occurred. But for the fifty-year return period rainfall, the waterlogging area is approximately 30%, it can't cope with the fifty-year return period rainfall effectively (Figure A.1). The results indicated that, in some extent, the original pipe size is large and not cost-effective. What's more, the original pipe size doesn't meet the requirement for minimum thickness of 0.7 m of roadway according to the code for design of outdoor wastewater engineering (MOHURD, 2006). Therefore, it is necessary to reduce the original pipe size.

The original and adjusted length of pipe diameters are listed in Table 5. The simulated results for the adjusted grey scenario showed that for the two-year return period rainfall, most pipes can perform well, no flooding was occurred. But for the ten-year return period rainfall, the number of standing water points increased. For the fifty-year return period rainfall, the standing water points and waterlogging area is much larger than original grey scenario (Figure A.2). Besides,

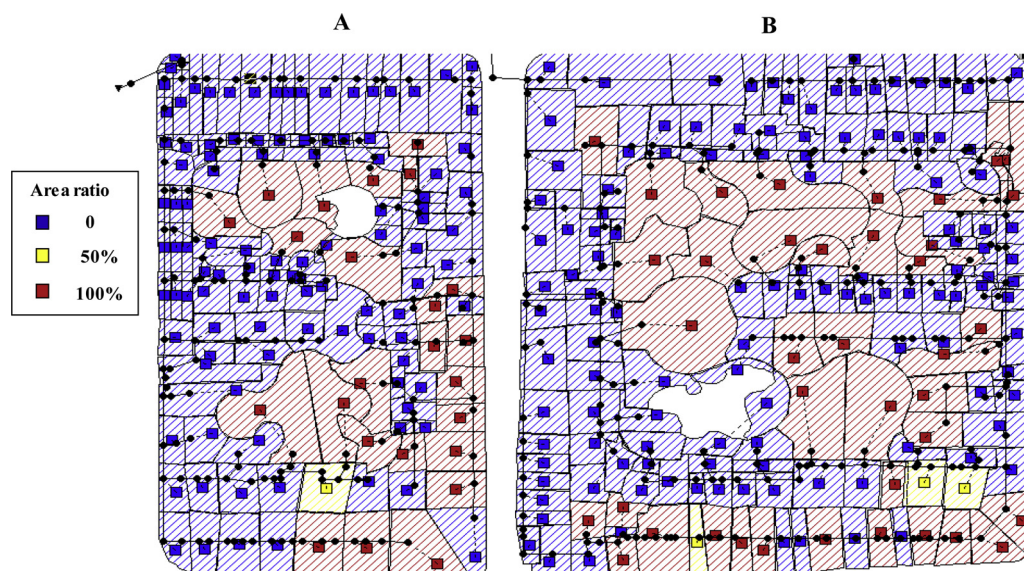


Fig. 6. Layout of the LID facilities for studied residential area.

Table 2
Parameters needed by SWMM.

Number	Parameters	Physical meaning	Parameters setting
1	Area	Catchment area	According to sub-catchment division
2	Width	Width of catchment area diffuse flow	According to sub-catchment division
3	% Slope	Slope of catchment area	0.5
4	% Imperv	Impervious rate of catchment area	90
5	N-Imperv	Manning coefficient of impervious area	0.015
6	N-Perv	Manning coefficient of pervious area	0.4
7	Dstore-Imperv	Water depth of impervious area	0.05
8	Dstore-Perv	Water depth of pervious area	0.05
9	Conduit Length	Length of pipe	According to the distance of each rainwater well
10	Conduit Roughness	Manning coefficient of pipe	0.013
11	MaxRate	Maximum infiltration coefficient	3.0(mm/hr)
12	MinRate	Minimum infiltration coefficient	0.5(mm/hr)
13	Decay	Infiltration decay rate	4(1/hr)

the duration of many standing water points exceeded 30 min, and the depth of standing water points could exceed 40 cm. The requirements of the code for design of outdoor wastewater engineering (MOHURD, 2006) for duration and depth of water is within 30 min and less than 15 cm, respectively. Although the adjusted pipe size can meet the requirement for minimum thickness of 0.7 m of roadway, the simulated results showed that they don't perform well for the ten-year return period rainfall.

The simulated results of the selected coupled green and grey scenario showed that for the two-year and ten-year return period rainfall, no flooding was occurred (Figure A.3). Besides, the duration of standing water points was less than 30 min and the depth of standing water point was less than 15 cm, which can meet the requirement of code for design of outdoor wastewater engineering (MOHURD, 2006). The simulated results for fifty-year return period rainfall are also much better than the other two scenarios. The results also indicate that coupled green and grey scenario can improve stormwater management and have positive effect in restoring ecosystem services.

3.3. Life cycle cost-benefit analysis based on LCC

3.3.1. Economic benefit for real estate developer

There are five indicators for green building's evaluation, namely, land conservation and outdoor environment, energy conservation and utilization, water conservation and utilization, material conservation and utilization, and indoor environment quality. The weight coefficient of these indexes are listed in Table 6.

In this study, some green infrastructure was implemented in the residential area, such as green space, permeable pavement, green roof, and stormwater detention cell. Based on the function division of the green building evaluation index system, the implementation of green infrastructure in residential areas can play an important role in land conservation and outdoor environment, water conservation and utilization, and material conservation and utilization. Accordingly, the total weight of green infrastructure can be calculated using Eq. (3) and the value is 0.384.

$$W' = W_1' + W_3' + W_4' \tag{3}$$

Table 3
Pair-wise comparison matrix and relative weights of each criterion.

Urban residential drainage flood control	B ₁	B ₂	B ₃	B ₄	B ₅	B ₆	Relative Weight
Volume capture ratio of annual rainfall (B ₁)	1	9	2	2	1/2	2	0.244
Urban heat island effect(B ₂)	1/9	1	1/4	1/5	1/9	1/7	0.028
Non-point source pollution control(B ₃)	1/2	4	1	1	1/2	1/2	0.120
Utilization ratio of rainwater resource(B ₄)	1/2	5	1	1	1/2	1/2	0.124
Prevention and control of floods in urban rainstorms(B ₅)	2	9	2	2	1	1	0.274
Economic benefit of the whole process(B ₆)	1/2	7	2	2	1	1	0.209

$\lambda_{max} = 6.137$, $CI = 0.027$, $RI = 1.24$, $CR = CI/RI = 0.022 < 0.1$, the evaluation is acceptable.

Table 4
Overall rating of urban residential drainage flood control technology.

Evaluation indicators	B ₁	B ₂	B ₃	B ₄	B ₅	B ₆	Overall rating of comprehensive evaluation
Weight	0.244	0.028	0.120	0.124	0.274	0.209	-
C1	0.047	0.045	0.042	0.043	0.502	0.074	0.176
C2	0.425	0.254	0.246	0.385	0.214	0.297	0.309
C3	0.168	0.386	0.457	0.198	0.121	0.419	0.252
C4	0.360	0.314	0.255	0.374	0.163	0.210	0.263

$CI = 0.017$, $RI = 0.900$, $CR = CI/RI = 0.019 < 0.1$, the evaluation is acceptable.

$$W_1' = 0.8 \times 0.21 = 0.168$$

$$W_3' = 0.8 \times 0.20 = 0.16$$

$$W_4' = 0.8 \times 0.4134 \times 0.17 = 0.056$$

Where, W' is the total weight coefficient of green infrastructure, W_1' is the green infrastructure weight coefficient of land conservation and outdoor environment. W_3' is the green infrastructure weight coefficient of water conservation and utilization. W_4' is the green infrastructure weight coefficient of material conservation and utilization, the saving rate of rain pipe material is 41%.

3.3.1.1. Economic benefit of design stage. According to the notification issued by Ministry of Finance in 2014, the financial subsidy for three-star level green building is 80 RMB per square meter (MOF, 2016). The design fee of Nanjing residential area is 20 RMB per square meter. Based on the above-mentioned total weight coefficient of green infrastructure and the overall floorage of the studied area, the total government financial subsidy can be calculated by Eq. (4).

$$P = A \times W' \times S \tag{4}$$

Where, P is the total government financial subsidy, RMB; A is the overall floorage of the studied area, m^2 ; S is the financial subsidy for three-star level green building per square meter, RMB.

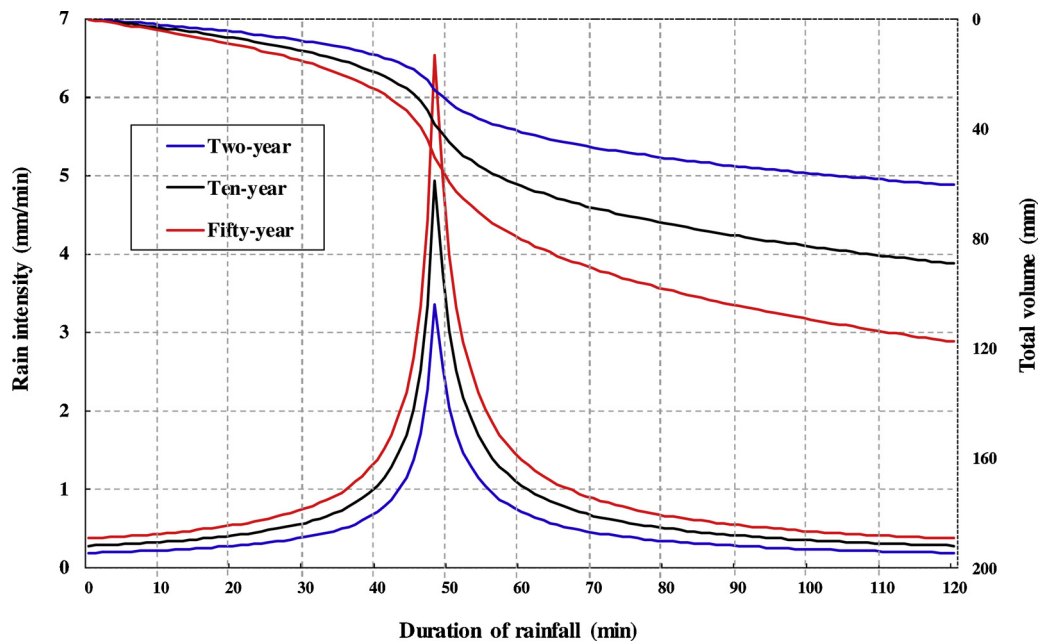


Fig. 7. Rainfall process for the two-year, ten-year, and fifty-year return period rainfall.

After calculation, the total financial subsidy of three-star level residential building is 7.06 million RMB. The total design fee is 4.60 million RMB. So the economic benefit of the design stage is 2.46 million RMB.

To achieve twin-win situation, the real estate developer should make cooperation with design company in successful application of three-star level green building. Real estate developer can use the government financial subsidy to compensate for the design cost of green infrastructure to reasonably guide the design companies to realize the green building design goals.

3.3.1.2. Economic benefit of construction stage. Based on the simulated results of SWMM, the studied residential area can implement green space, permeable pavement, green roof and reduce pipe size to meet the requirement of Code for Design of Outdoor Wastewater Engineering (MOHURD, 2006) for the ten-year return period rainfall. Accordingly, the economic cost-benefit analysis of the construction stage can be mainly calculated from the cost of pipe size reduction and implementation of green infrastructure.

There are four aspects for pipe size adjustment cost, namely, pipe material cost, pipe laying cost, pipe shaping cost, and excavation and backfilling cost. The detailed cost is listed in Table 7. The total cost of original and pipe size adjustment is 1.27 and 0.96 million RMB, respectively. The pipe size adjustment can save 24% of the original total pipe cost.

The pipe size adjustment not only generates economic benefit, but also reduces the construction time. Table 8 shows the construction time analysis of pipe size with and without green infrastructure. Results indicate that after implementing green infrastructure, the reduced fixed construction time is 375.58 man-days (Jiangsu Provincial Department of Housing and Urban Rural Construction, 2014). The total construction area is 229,953 m² and artificial invest is 92 persons. So the final

reduced construction time is 4.08 days and it also can save 4 days of financial cost.

The construction cost of implementing green infrastructure is presented in Table 9. The price of each green infrastructure is based on Sponge City Construction Technical Guide issued by MOHURD in 2014 (MOHURD, 2014a). Total construction area of each green infrastructure is statistics from SWMM. After calculation, the final cost of implementing green infrastructure is 1.7 million RMB.

Combined with these two aspects, the total cost of original pipe is 1.27 million RMB. The total cost of pipe size adjustment and implementation of green infrastructure is 2.66 million RMB. The results showed that implementation of green infrastructure can increase the construction cost. Thus, the cost department of real estate development company will adopt the method of enlarging the diameter of drainage pipe instead of adopting green infrastructure to meet the requirements of drainage and flood control standard. However, through the whole life cycle cost of the project (i.e., design, construction, operation, maintenance and use), the implementation of green infrastructure can bring economic benefit. Accordingly, all stages should be taken into consideration to make comprehensive analysis and evaluation of the whole project.

3.3.1.3. Economic benefit of operation and maintenance stage. The economic benefit of operation and maintenance stages can be evaluated through the comprehensive utilization of rainwater and pipe clean and maintenance. Based on the empirical calculation of housing households, people in the residential area, and the standard for water-saving design of civil buildings (MOHURD, 2010), the stormwater detention cell, 650 m³, was built. According to the unit price provided by Sponge City Construction Technical Guide (MOHURD, 2014a), the total construction cost is 0.65 million RMB.

According to the standard for water-saving design of civil buildings

Table 5
Length of different pipe diameters of original and adjusted scenarios.

Rain pipe size and length (Original grey scenario)	Diameter (mm)	DN300	DN400	DN600	DN1000	Total
	Length (m)	2231.88	408.73	448.59	102.98	3192.18
Rain pipe size and length (Adjusted grey scenario)	Diameter (mm)	DN200	DN300	DN400	DN1000	Total
	Length (m)	2195.39	427.73	511.58	57.48	3192.18

Table 6
Weight of green building evaluation index.

Green building evaluation indicator	Land conservation and outdoor environment (W ₁)	Energy conservation and utilization(W ₂)	Water conservation and utilization (W ₃)	Material conservation and utilization(W ₄)	Indoor environment quality (W ₅)
Residential Building	0.21	0.24	0.20	0.17	0.18

Table 7
The economic cost comparison of reducing pipe size.

Process	Without Green infrastructure (RMB)	With Green infrastructure (RMB)
Pipe material cost	576,505	338,188
Pipe laying cost	49,251	37,254
Pipe shaping cost	296,457	257,948
Excavation and backfilling cost	344,752	326,940
Total	1,266,965	960,330

(MOHURD, 2010) and the climatic, economic, and water utilization habits of Nanjing, three types of water utilization (i.e., grass irrigation, street washing, and landscape filling water) are selected to calculate the total water consumption (Table 10). Based on the green space area, road area, landscape volume, and the daily water consumption, the total annual water consumption is 13,430.68 m³.

The total amount of annual rainwater that be comprehensively utilized needs to be summarized through the hydrology, soil condition, and implementation of green infrastructure. The total amount was calculated by Eq. (5).

$$W = 10 \times \Psi_c \times h_y \times F \tag{5}$$

Where, W is the designed rainwater runoff volume (m³); Ψ_c is the rainwater runoff coefficient, different runoff coefficient underlying surfaces is presented in Table 11; h_y is the designed rainfall thickness (mm), the designed rainfall thickness of Nanjing city is 1116 mm; F is the catchment area (hm²). After calculation, the annual rainfall that be collected in this studied area was 31,056.34 m³.

The reused rainwater volume was calculated by Eq. (6).

$$W' = W \times \alpha \times \beta = 31,056.34 \times 0.85 \times 0.87 = 22,966.16 \text{ m}^3/\text{yr} \tag{6}$$

Where, α is seasonal reduction factor, 0.85; β is initial runoff rejection coefficient, 0.87. The total collected rainwater volume that can be reused is 22,966.16 m³/yr.

Accordingly, combined with the total annual water consumption, the annual saving amounts of water is 13,430.68 m³. The residential water price of Nanjing is laddered water price and the first-step water price is 3.1 RMB/m³. The operation cost of rainwater comprehensive utilization system is 0.37 RMB/m³. This means the cost of reuse of 1 m³ rainwater is 2.73 RMB. So after implementing Green infrastructure, the annual saving water fee is 36,665.76 RMB. The pipe maintenance (e.g., pipe cleaning and flushing) also generates economic benefit after

Table 8
The construction time analysis of pipe size with and without Green infrastructure^a.

Pipe diameter	Pipe length		Unit	Fixed construction time (Man-day)		
	Without Green infrastructure	With Green infrastructure		Pipe shaping	Pipe laying	Excavation and backfilling
DN200	-	21.95	100 m	35.672	8.292	85.1
DN300	22.32	4.28	100 m	-	10.536	89.1
DN400	4.09	5.12	100 m	-	12.389	93.2
DN600	4.49	-	100 m	60.953	20.831	101.3
DN1000	1.03	0.57	100 m	137.489	28.913	117.5
Total (without Green infrastructure)	-	-	-	1357.39	409.15	2944.96
Total (with Green infrastructure)	-	-	-	1196.69	307.02	2832.21

^a Jiangsu Provincial Department of Housing and Urban Rural Construction, 2014.

reducing the pipe size. The annual saved maintenance fee after implementing green infrastructure is 1143.09 RMB/yr.

Since the annual comprehensive utilization of rainwater and pipe network clean and maintenance occur in each year of the community's service stage and paid by residents every year, the net present value (NPV) must be used to compare the construction cost of stormwater detention cell. The internal rate of return is 2.75%, which is based on the five-year fixed deposit interest rate of the central bank. The maintenance years of stormwater detention cell should consider the reasonable number of years of drainage pipe network use in residential areas. In this study, based on the current longest mortgage loan years, the maintenance years of stormwater detention cell are set as 30 years.

The total economic benefit generated from utilization of rainwater and pipe network clean and maintenance is 766,300 RMB, the construction cost of stormwater detention cell is 650,000 RMB. After implementing the green infrastructure, the final economic benefit during the operation and maintenance stage is 116,300 RMB.

3.3.2. Economic benefit for purchaser

According to the Nanjing Municipal Housing Provident Fund Management Regulations (The Nanjing government, 2013), the housing provident fund loan quota standard for people who buy three-stat level green building can increase 20%. The original housing provident fund loan quota standard is 600,000 RMB and now it can be reached to 720,000 RMB. The studied area has 1618 households and the average area of each household is 110.63 m². In Nanjing, the average rate of housing provident fund loan is approximately 44%. As mentioned in section 3.3.1.1, LID weight coefficient of green building evaluation indicator is 0.384. Accordingly, the increased amount of housing provident fund loan is 32.8 million RMB.

In China, two types of loan methods were applied, commercial loan and housing provident fund loan. The commercial loan rate is 4.9% and the housing provident fund loan interest is 3.25%. The comparison of commercial loan and housing provident fund loan is presented in Table 12. The increased amount of housing provident fund loan can save loan interests for homebuyers. Assuming the loan period is 20 years, the payment method is equality corpus and interest. The loan interest for commercial loan and housing provident fund loan is 18.72 million RMB and 11.85 million RMB, respectively. The total saving loan interests for homebuyers is about 6.87 million RMB.

The policy of increasing the housing provident fund loan can effectively alleviate the problem of insufficient funds for the advance payment of some newly purchased houses, stimulates the sales of green buildings and improves the economic benefits of the whole project.

Table 9
The construction cost of Green infrastructure.

Green infrastructure	Unit	Quantity	Price (RMB/ m ²) ^a	Cost (RMB)	Total cost (RMB)
Green space	m ²	16,300	45	733,500	1,709,250
Permeable pavement	m ²	4775	130	620,750	
Green roof	m ²	1775	200	355,000	

^a MOHURD, 2014. Sponge City Construction Technical Guide.

Table 10
Annual water consumption of the studied area.

Type of water utilization	Quantity of utilization	Water consumption estimation	Average daily water consumption (m ³ /d)	Annual water consumption (m ³ /yr)	Utilization frequency
Grass irrigation	24051.33 m ²	0.5 m ³ /m ² .a	100.21	12025.67	120 days/yr
Street washing	26707.24 m ²	0.5 l/ m ² .each time	13.35	400.61	30 times/yr
Landscape filling water	74.38 m ³	–	3.72	1004.40	270 days/yr
Total	–	–	117.28	13,430.68	–

Table 11
Rainwater collection of different catchment types of studied area.

Catchment type	Catchment area (m ²)	Underlying surface type	Rainwater runoff coefficient	Rainwater runoff volume (m ³ /yr)
Building roof	13122.87	Rigid roof	0.90	13180.12
Rigid material	12329.76	Rigid road	0.90	12383.55
Permeable pavement	4775.00	Rigid paving	0.37	1971.69
Green space	16,300.00	Green space	0.15	2728.62
Green roof	1775.00	Water surface	0.40	792.36
Annual rainwater runoff volume				31,056.34

Results showed that economic benefit generated from coupled green and grey scenario was noticeable. Therefore, to obtain the win-win situation, cooperation should be made between:

- The local government and real estate developer;
- The real estate developer, construction, and design companies;
- The real estate developer, homebuyers, and property management company.

4. Conclusions and suggestions

This study made a comprehensive analysis of coupled green and grey infrastructure system for urban stormwater runoff control. The coupled green and grey infrastructures can improve stormwater management, restore ecosystem services, and generate economic benefit. The main conclusions can be drawn as follow:

- The scenario that including green space, permeable pavement, green roof, and stormwater detention cell can achieve better performance in urban residential drainage and flood control than other scenarios.
- In the coupled green and grey scenario, no flood was occurred during the ten-year return period rainfall.
- For real estate developers, the economic benefit can generate through the whole life cycle of the project. The total cost of green

infrastructure can save 94% compared with original grey scenario.

- For purchasers, the economic benefit can generate from saving approximately 13% of commercial loan interest (6.87 million RMB).

In future sponge city management, multiple decision factors and conditions should be considered, such as environmental effects, economic effects, social benefit, ecological benefit and so on, to provide comprehensive information. From systematic perspective, road, square, parking lot, and green space are also important composition in the city's land use. In future research, different land use should be taken into consideration. Urban residential drainage and flood control is only part of urban flood control, a holistic analysis from watershed level should be considered to obtain a whole optimization in the future.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from (jhf@tsinghua.edu.cn)

Declaration of Competing Interest

We confirm that there are no known conflicts of interest associated with this publication.

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Table 12
Comparison of commercial loan and housing provident fund loan.

Loan type	Loan Amount (ten thousand yuan)	Length of maturity (Year)	Mode of repayment	Loan rate (%)	Cumulative amount of payment (ten thousand yuan)	Loan interest (ten thousand yuan)
Commercial Loan	3280.53	20	Equality corpus and interest	4.9	5152.62	1872.09
Housing provident fund Loan	3280.53	20		3.25	4465.69	1185.16

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Appendix A. Supplementary data

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