Front. Earth Sci. 2016, 10(2): 366–377
DOI 10.1007/s11707-015-0516-5

RESEARCH ARTICLE

Green stormwater infrastructure eco-planning and development on the regional scale: a case study of Shanghai Lingang New City, East China

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Abstract Urban underlying surface has been greatly changed with rapid urbanization, considered to be one of the major causes for the destruction of urban natural hydrological processes. This has imposed a huge challenge for stormwater management in cities. There has been a shift from gray water management to green stormwater management thinking. The green stormwater infrastructure (GSI) is regarded as an effective and cost-efficient stormwater management eco-landscape approach. China's GSI practice and the development of its theoretical framework are still in the initial stage. This paper presents an innovative framework for stormwater management, integrating green stormwater infrastructure and landscape security patterns on a regional scale based on an urban master plan. The core concept of green stormwater infrastructure eco-planning is to form an interconnected GSI network (i.e., stormwater management landscape security pattern) which consists of the location, portion, size, layout, and structure of GSI so as to efficiently safeguard natural hydrological processes. Shanghai Lingang New City, a satellite new town of Shanghai, China was selected as a case study for GSI studies. Simulation analyses of hydrological processes were carried out to identify the critical significant landscape nodes in the high-priority watersheds for stormwater management. GSI should be planned and implemented in these identified landscape nodes. The comprehensive stormwater management landscape security pattern of Shanghai Lingang New City is designed with consideration of flood control, stormwater control, runoff reduction, water quality protection, and rainwater utilization objectives which could provide guidelines for smart growth and sustainable development of this city.

Keywords stormwater management, green stormwater infrastructure, urban master plan, landscape security pattern, Shanghai Lingang New City

1 Introduction

Rapid urbanization has greatly changed the urban underlying surface. Numerous research studies have documented that land use/land cover change caused by urban expansion, and resulting from an increase of impervious surface, is considered as the main cause for the change of urban natural hydrological cycling (Sanders, 1986; Marsalek et al., 2008). Rapid urbanization will lead to a series of stormwater problems, such as an increase in flash floods (Leopold, 1968; Jennings and Taylor Jarnagin, 2002), increased pollution generated by urban nonpoint sources (Makepeace and Schreier, 1995; Line and White, 2007), shortage of water resource, degradation of ecological value of rivers (Ballo et al., 2009), and larger climatic variability (IPCC, 2007), to name but a few.

Conventional gray stormwater management methods remove runoff with piped conveyance systems, and route runoff directly to streams to prevent ponding, exacerbating pollutant inputs and hydrologic disturbances that result in the degradation of ecosystem structures and functions (Yang and Cui, 2012). Further, these methods are no longer adequate to deal with larger and more intense storm events and the associated pollution coming from the combined effect of rapid land use/land cover changes and increased climatic variability. In contrast, the urban landscape green space system plays a significant role in stormwater management, and there has been a shift from gray water

Received October 18, 2014; accepted January 26, 2015

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management to green stormwater management thinking in urban watershed management (Novotny and Brown, 2007). Many countries have integrated stormwater treatment into landscape eco-planning and stormwater management (SWM) in order to maintain urban natural hydrological cycling and enhance the urban eco-process safety, and some noticeable practices include Best Management Practice (BMPs), Low Impact Development (LID), Smart Growth (SG), Sustainable Urban Drainage Systems (SUDS), and Water Sensitive Urban Design (WSUD) (U.S. EPA, 1993; Davis and McCuen, 2005; Melbourne Water, 2005; Malmqvist, 2006; Van Room et al., 2009).

Green stormwater infrastructure (GSI) is an important eco-landscape stormwater management (SWM) approach. Compared to conventional gray forms of water infrastructure that rely on concrete gutters, sewers, and end-of-pipe treatment, green stormwater infrastructure is the interconnected network of urban open spaces, natural areas, permeable pavement, and other landscape-based drainage features that naturally manages stormwater, reduces the risk of floods, captures pollution, improves water and air quality, increases groundwater recharge, eases water resource shortage, provides recreational opportunities and wildlife habitat, saves money and energy, reduces and sequestrates carbon, and supports urban sustainability (Mark and McMahon, 2006; Tackett, 2008; Wise, 2008). The ability of these practices to deliver multiple ecological, economic, and social benefits or services has made GSI an increasingly popular strategy for urban sustainable development. GSI has different meanings for different scales (Wise, 2008). A combination of proposed GSI systems ranging from small-scale drainage facilities on the property or neighborhood level, to large-scale drainage facilities on the regional scale, and transfer GSI linked to an interconnected network is presented in Fig. 1. On a regional scale, GSI refers to large-scale and sink-treatment facilities known as BMPs-GSI. BMPs-GSI, such as greenways, wetlands, stormwater ponds, and forest preserves, are usually planned in open spaces and natural areas, constructed and maintained by specialized governmental agencies. On the municipal or neighborhood scale, GSI refers to small-scale, on-site source-treatment facilities, such as rain gardens, vegetated swales, permeable pavements, rain barrels, and green roofs (Marsalek et al., 2008), preferably termed as LID-GSI. LID-GSI are usually constructed and maintained by government-legislated proprietors or residents.

The core concept of GSI eco-planning is an interconnected network system which consists of the location, portion, size, layout, and structure of GSI. On a regional scale, the theories and spatial analysis methods of landscape security pattern (SP) can provide theoretical and technical support for BMPs-GSI eco-planning and implementation. In a comparative and spatial sense, landscape security pattern emphasizes the relationship between pattern and process, identified around the ecological processes. Earlier studies reported that all points (locations) or portions of the landscape are not equally important in terms of their influences on certain ecological

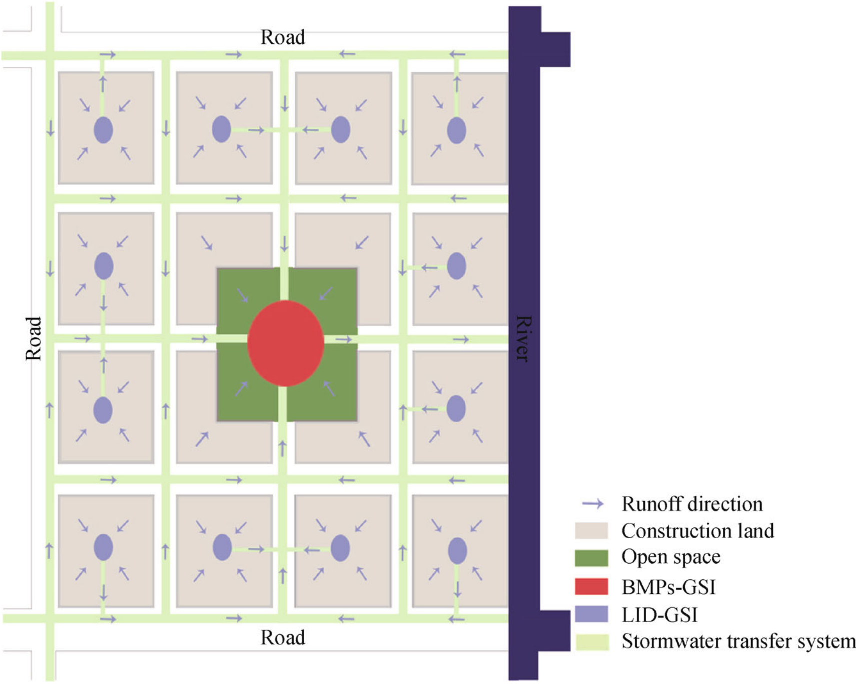


Fig. 1 A schematic diagram of GSI network system. (Abbreviations: BMPs-GSI = large-scale and sink-treatment green stormwater infrastructure; LID-GSI = small-scale, on site and source-treatment green stormwater infrastructure).

processes and the features of spatial heterogeneity (Forman and Godron, 1986). Each landscape has a potential spatial pattern composed of certain strategic portions, locations, and their spatial relationships, namely the landscape security pattern (SP), which have, or potentially have, critical significance in safeguarding ecological processes (Yu, 1995, 1996). SP was first applied to biological conservation (Noss and Harris, 1986; WRI, IUCN and UNEP, 1992), and has been widely considered in urban or rural eco-planning, especially in China (Ma et al., 2004; Li and Tang, 2006; Gong et al., 2008; Yu et al., 2009a; Li et al., 2010). Through the analysis and simulation of urban hydrological processes, BMPs-GSI can be identified in certain critical landscape strategic nodes to form an integrated stormwater management landscape security pattern (SWMSP), which can contribute to the flood control, stormwater control, runoff reduction, water quality, and rainwater utilization of the urban ecosystem.

Being one of the most rapidly urbanizing countries in the world, China is suffering a great deal from the environmental and ecological problems induced by urban stormwater. Meanwhile, China's GSI practice and the development of its theoretical framework are still at the initial stage (Mo and Yu, 2012). In China's current master plan system, the two special planning schemes related to urban stormwater management are urban flood proofing planning and municipal drainage planning, which are both determined by conventional gray stormwater management methods. The problem of such a system on an administration level is that these two schemes belong to different government sectors (i.e., the water sector and the municipal engineering sector), and the planning of these schemes are done independently, which often leads to conflicting objectives (Ma, 2010). In such a case, there is an urgent need to integrate multi-objective GSI eco-planning into the urban master plan. The objective of this paper is to propose such a framework for regional-level urban stormwater management eco-planning that integrates BMPs-GSI development and SP eco-planning. The proposed framework will provide strategies for integrating BMPs-GSI in the maintenance of healthy water recycling in cities, and is also expected to provide an important contribution to urban water security and water resources sustainable utilization. Shanghai Lingang New City (SHLNC), a satellite new town of Shanghai, China was selected as a case study in the present work.

2 Framework of BMPs-GSI eco-planning on a regional scale

This section provides a brief introduction to the proposed framework for BMPs-GSI eco-planning on a regional scale, based on the urban master plan. The division of BMPs-GSI eco-planning is a stormwater management landscape security pattern (SWMSP). An illustration of the framework has been shown in Fig. 2 depicting six steps of a project.

Step 1: Establishing regional stormwater management (SWM) objectives

The first step is setting the comprehensive goals of regional SWM that cover flood and stormwater control, runoff reduction, water quality, and rainwater utilization, with considerations of related laws and legislations, stakeholders' perspectives, and rainwater resource protection incentives.

Step 2: Construction of SWM database

The regional SWM database is built on the Geographic Information System (GIS) platform. The database contains natural environment data such as climate, rainfall, soil, groundwater, terrain, elevation, vegetation, and social environment data including urban planning related variables, population, industry, stakeholders' perspectives, etc.

Step 3: Analysis and simulations of stormwater hydrological processes

The theories of landscape security pattern (SP) and its spatial analysis methods are intensively applied in the analysis and simulations of urban hydrological processes,

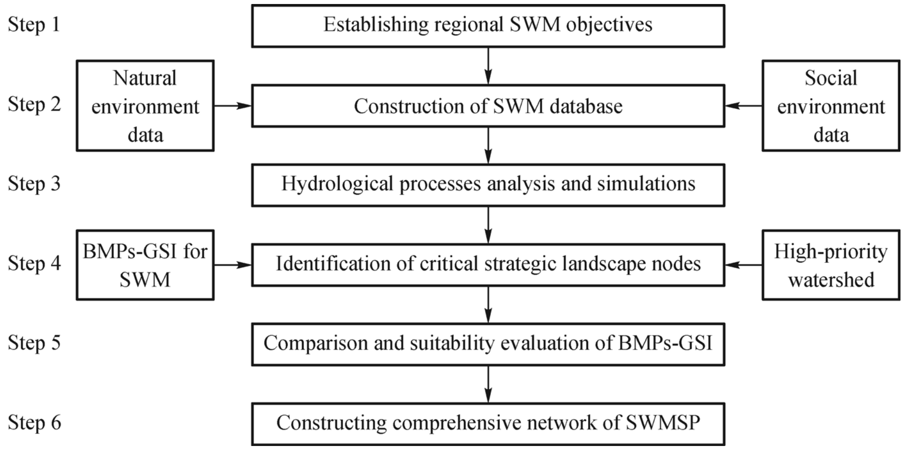


Fig. 2 Framework of BMPs-GSI eco-planning on regional scale.

which consist of runoff production, flood, water logging, runoff pollution, groundwater recharge, and rainwater reuse. Based on the simulations of stormwater hydrological processes, the high-priority watersheds for SWM can be analyzed.

Step 4: Identification of critical strategic landscape nodes for SWM

The fourth step is representing and identifying the critical significant landscape nodes in the high-priority watersheds that may efficiently safeguard the hydrological processes. BMPs-GSI for SWM should be planned and implemented in these identified landscape nodes.

Step 5: Comparison analysis and suitability evaluation of BMPs-GSI

Different BMPs-GSI approaches are compared and suitability evaluation is carried out to determine the most appropriate types of BMPs-GSI in the study area considering local guidelines, stakeholders' concerns, and other related environmental and economical factors.

Step 6: Constructing comprehensive network of SWMSP

The sixth step is developing planning guidelines for BMPs-GSI on the regional scale for a single SWM objective, and integrate them into a comprehensive BMPs-GSI network (i.e., stormwater management landscape security pattern (SWMSP)), for maintaining water recycling systems, regulating hydrological processes, and protecting water resources.

3 Case study: Shanghai Lingang New City, China

3.1 Study area

Shanghai Lingang New City (SHLNC) is one of the major satellite towns of Shanghai, and an important sector of Shanghai as an international shipping center. It is located southeast of Shanghai, East China (Fig. 3(a)). It is an pre-planned new city, with an area of about 69.11 square km, and is planned for over 800 thousand residents. 65.85% of the city has been reclaimed from the East China Sea since 2002. With Dishui Lake at its center, planners followed the "garden city" model. The water area, construction land, and unutilized land occupy 12.51%, 36.41%, and 51.09% of the total area, respectively. Dishui Lake, round in shape, around 2.50 km in diameter, with an average depth of 3.70 m, and about 5.60 km^2 in area, is the biggest man-made freshwater lake in China. Dishui Lake and the artificial stream constitute the regional water system (Fig. 3(b)).

SHLNC is facing a series of hydrological and environmental challenges. As the study area is located in the seaside zone, the dominant land use is tidal flats covering approximately 56% of the area, and an average elevation of only about 4.10 m leads to high risks for flooding and the shortage of freshwater. Also, being an artificial ecosystem, Dishui Lake serves as the terminal of regional non-point source pollution which makes the function and security of the lake more fragile, and sometimes can result in a series of environmental problems. For example, according to the report of the Shanghai Environmental Monitoring Center (SHEMC), the landscape and ecological epicenter of Dishui Lake was weakly eutrophicated, and the pollution is becoming increasingly severe due to continuous urban construction projects. In such cases, SWM and maintenance of water quality in this area is in urgent need.

3.2 Comprehensive regional SWM objectives

Legislation and regulations for rainwater flow control and water quality protection are still at their initial stages in China. To help in forming the stormwater management landscape security pattern (SWMSP), we aim to set the integrated objectives of regional SWM by consulting related laws and SWM design guidelines of the U.S., and also take local stakeholders' perspectives into consideration. The following section presents a brief introduction to the goal setting process.

3.2.1 Flood and stormwater control

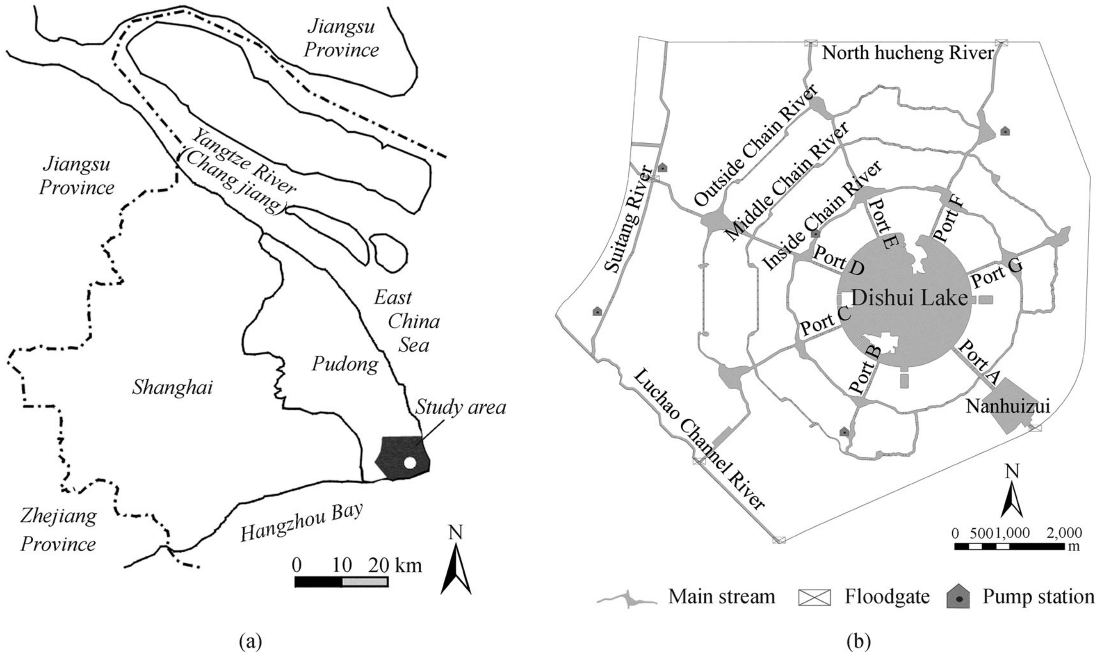
Based on the Urban Flood Control Engineering Design Disciplines, China (GB/T50805-2012), we proposed a set of criteria to ensure that the stormwater induced by a once-in-a-twenty-years rainfall event can be discharged in 24 hours through a series of water conservation facilities and structures, and the regional water level can be reduced to less than 3.30 meters, which was the highest flood water level of the study area based on the SHLNC master plan.

3.2.2 Runoff reduction

As per the Leadership in Energy and Environmental Design (LEED) standards developed by the U.S. Green Building Council (USGBC), an initial planning principle is proposed. If the existing impervious surface ratio is less than 50%, there should not be a net increase in the rate or quantity of stormwater runoff from existing to developed conditions in one year. Thus, 24-hour rainfall event (80 mm/(24 hours) in the study area) should occur.

3.2.3 Water quality protection

The Water Quality Volume (WQ_V) criteria of BMPs developed by the U.S. Environmental Protection Agency (USEPA) should be adopted in water quality protection in the study area. By definition, WQ_V is the storage required to capture and treat the runoff generated from the 90th percentile of storm events — i.e., the storm event is greater than 90% of the storms that occur within an average year (42 mm/(24 hours) in the study area).



(a) (b)

Fig. 3 Location (a) and water system (b) of the study area.

3.2.4 Rainwater utilization

Rainwater utilization includes two parts: one is groundwater recharge, and the other is rainwater reuse. This criterion is based on the Building and Community Utilization Project Disciplines, China (GB 50400-2006). The daily water consumption index is the basis for measuring the capacity of rainwater storage facilities, and the size of rainwater storage facilities should be greater than 40% of the daily water consumption.

3.3 Data sources and construction of database

The regional SWM database was built on the GIS platform. A topography map with a scale of 1:100,000 in the format of the Digital Elevation Model (DEM) is used as the basic data layer. Satellite images (i.e., Landsat TM5 images retrieved in 2006) were also used to generate land-use and land cover maps. Natural environment data, such as climatic data, rainfall, and soil data were extracted from statistical materials, which were further combined with on-site survey data, such as a meteorological station, the soil and water sampling analysis to provide a complete natural environment dataset. Meanwhile, the urban master plan of SHLNC (2003−2020) released by the Shanghai Planning and Land Resources Bureau provided the vision for city development, such as the city’s nature and functions, population projection, land use, road network, public facilities, water system, etc.

3.4 Simulation and analysis of stormwater hydrological processes

3.4.1 Watershed division

The study area was mostly flat terrain and independent of surrounding catchment, isolated from other river networks by the constructed hydraulic structures. The watershed zoning system is formed by two layers: the upper-level watershed layer and the lower-level sub-watershed layer. The upper-level watershed is related to the total quantity control of stormwater, and the most important factors affecting this layer were the major road and stream systems. The low-level sub-watershed layer is related to the mechanism exposition and the critical elements of stormwater hydrological processes, which were identified within the upper-level watershed using the D8 method on a GIS platform. Based on the DEM dataset, 84 upper-level watersheds and 5,805 lower-level sub-watersheds were divided in the study area. The upper-level watersheds were in accordance with the first-class land development plan so as to guarantee the stakeholders’ benefits and the implementation of SWMSP strategies.

3.4.2 Runoff path

The modeling of the original terrain runoff flow path was conducted based on DEM using GIS tools for hydrological simulation. It has great significance in identifying the critical important landscape nodes and the locations of BMPs-GSI in the view of the "source-process-sink" control principle. A schematic diagram identifying critical significant landscape nodes based on the runoff path, is shown in Fig. 4.

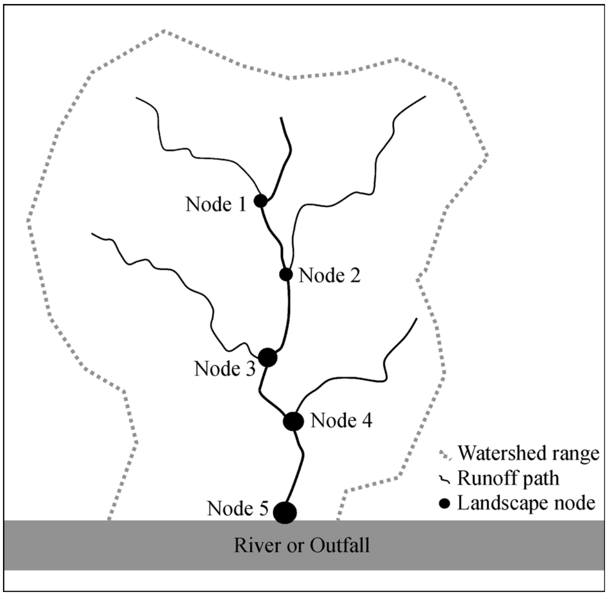


Fig. 4 Schematic diagram of critical significant landscape nodes identification for stormwater management in a watershed.

3.4.3 Runoff production

The SCS (Soil Conservation Service) model, proposed by the U.S. Department of Agriculture (USDA), has the advantages of clear mechanism, simple principle, limited parameter, and easy implementation (Soil Conservation Service, 1972; Mishra and Singh, 2002; Singh et al., 2008). It is well suited for simulating the surface runoff production for study terrains with various land use patterns, soil types, water contents, and pre-precipitation conditions, especially in an urban master plan on a regional scale.

Since SCS has been mostly applied in the U.S., which has different climate, soil types, and land use compared to China, we reclassified the hydrologic soil group and adjusted the model parameters, such as different land use types, to make it applicable in China. Parameter settings were further calibrated based on settings proposed by earlier studies in Shanghai (Jiang, 2005).

The simulation results showed that there was a significant difference in runoff production of the study area before and after urban construction. The total runoff production of a once-in-a-twenty-years rainfall event (80 mm/(24 hours)) before urban construction is $2.72\times10^6\,m^3$, while it will rise to $3.36\times10^6\,m^3$ by 2020, under the planning scenario. There are great varieties among different watersheds, due to different types of hydrologic soil groups and land use. The differences in runoff per unit area between the highest rate and the lowest rate were about 5 times and 7 times, respectively, for the two watershed layers.

3.4.4 Flood and stormwater inundation

The simulation of flood inundation is based on the DEM and 3D model of the stream channel. In the example of highest flood water level (3.30 m), there is a considerable amount of submerged area — i.e., 7.34 km^2, which equals 10.61% of the total area, including 2.30 square km as 9.11% of the planned construction area.

The annual water depth of submerging of stormwater is derived using DEM data based on the "non-source submerge" method (Bao, 2009). The results show that the study area is under high risk of stormwater inundation, with the most impacted being the planned construction area. The submerged areas account for 18.67 square km, which equals 26.98% of the total area, including 7.61 square km as 30.14% of the planned construction area.

3.4.5 Runoff pollution

PLOAD, a model of BASINS (Better Assessment Science Integrating Point and Nonpoint Source) proposed by USEPA, is one of the most commonly used models for the simulation of runoff pollution. It has the character of a simple principle, limited parameter, and easy implementation, and is especially suitable for regions with poor long-term monitoring data. EMC (event mean concentration) is the most important parameter of the model. The EMC values of different land use types were determined based on the earlier researches in Shanghai (Jiang, 2005; Wang, 2005).

The runoff pollution loads of a 42 mm/(24 hours) rainfall event (i.e., the 90th percentile of storms that occur within an average year), which is the typical control threshold for runoff pollution of Shanghai, were calculated according to WQ_V criteria (Pan et al., 2008a). Results showed that the runoff nutrient pollutant loads of NH_3-N, total phosphorus (TP), and total suspended solids (TSS) could be up to 2.27 t, 1.03 t and 797.33 t, respectively in the whole catchment. The maximum NH_3-N pollution amounts per unit area were $97.99\,mg\cdot m^{-2}$ and $121.91\,mg\cdot m^{-2}$, and TN were $43.66\,mg\cdot m^{-2}$ and $50.15\,mg\cdot m^{-2}$, with TSS of $2.63\times10^4\,mg\cdot m^{-2}$ and $5.41\times10^4\,mg\cdot m^{-2}$, respectively for the two watershed layers.

3.4.6 Rainwater utilization

Due to the high soil salinity, poor infiltration coefficient, and high water table, the precipitation recharge in the study area is impractical. The maximum soil salinity is about 8.10 g/kg, and 40% of the soil in the study area is alkalinized. In such cases, the primary mode of rainwater utilization of the area is to harvest the runoff and reuse natural stormwater to sustain local habitats instead of using freshwater provided by municipal and domestic artificial facilities.

The daily water consumption index is the basis for measuring the capacity of rainwater storage facilities (Pan et al., 2008b). The daily water consumption index of green land, transportation land, residential land, and public facilities land are $0.10\times10^5\,m^3\cdot km^2\cdot d^{-1}$, $0.20\times10^5\,m^3\cdot km^2\cdot d^{-1}$, $0.80\times10^5\,m^3\cdot km^2\cdot d^{-1}$, $1.20\times10^5\,m^3\cdot km^2\cdot d^{-1}$, respectively. Under the guidance of Code for Urban Water Supply Engineering Planning, China (GB50282-1998), and Building and Community Utilization Project Disciplines, China (GB 50400-2006), we determined the capacity of rainwater storage facilities for different land use types. High-density residential area, public facilities, and commercial land have higher requirements for rainwater resource than others due to more intense human activities. The proposed sizes of artificial facilities in these two areas were $3.00\times10^5\,m^3\cdot km^{-2}$ and $2.00\times10^5\,m^3\cdot km^{-2}$.

3.5 Identification of the high-priority watersheds for SWM

Based on the stormwater simulation and analysis, the high-priority watersheds for SWM were identified, as shown in Fig. 5. We suggested that regional BMPs-GSI should be designed in these priority watersheds based on the runoff path analysis, while on-site LID-GSI should be designed in the other watersheds.

As can be seen from Fig. 5(a), the flood submerged areas that cannot meet the requirements of urban construction were mainly located in the south of the catchment close to Hangzhou Bay. These low-lying areas should be reserved for peak storage. As shown in Fig. 5(b), over 30% of the planned construction areas are at high-risk of potential stormwater inundation, and actions are urgently required to minimize the risk of stormwater disasters.

A priority check was carried out by comparing the runoff production and non-point source pollution loads from watersheds. The high-priority areas of runoff and non-point source pollution reduction occupy 43.10%, 39.24%, and 55.05%, 18.52% of the total in two watershed layers, which areas correspond to 29.08 km^2, 26.47 km^2, and 37.16 km^2, 12.49 km^2, respectively. The main parts of these high-priority areas are traffic land, high-density residential land, public facilities, and commercial land. The distribution characteristics are closely related to soil, land use, and imperviousness. The priority watersheds surrounding Dishui Lake areas require more attention in terms of protection of an ecological buffer zone.

3.6 Comparison and suitability evaluation of BMPs-GSI

The multi-objective evaluation system of BMPs-GSI was established including ecological, economic, social, and construction requirements indices (as listed in Table 1). For the particular geographical and ecological characteristics of the study area, the efficiency of improving local habitats is an additional factor to consider. Through the comparison and suitability evaluation analysis of normal regional-scale BMPs-GSI, we proposed recommendations for application guidelines (see Table 2), based on previous studies (USEPA, 2004; SSC, 2007; Wood-Ballard et al., 2007) and on-site survey. For coastal areas where most of the lands are reclaimed from the sea, wet pond and constructed stormwater wetland are considered to be the most effective storage and detention systems for adaptation to the increasing storm events and the increasing pollution from increased traffic and urban activities on the regional scale.

3.7 BMPs-GSI identification and SWMSP eco-planning

A schematic diagram of critical significant landscape nodes identification, based on runoff path and the high-priority watersheds analysis is shown in Fig. 4. BMPs-GSI for SWM should be planned and implemented in these identified landscape nodes for efficient safeguard of hydrological processes. The design strategies for BMPs-GSI are summarized in Table 3, including the portion, location, size, and so on. The appropriate BMPs-GSI measurement mainly consists of green roadside corridor, riparian buffer, wet pond and wetland in the study area. Wet pond and constructed stormwater wetland are considered to be two major components of BMPs-GSI. The scale of BMPs-GSI should contain a treatment volume (T_V) that is capable of capturing the runoff generated by 90% of the runoff-producing storms in the region on an annual basis, and/or zero growth in the rate or quantity of stormwater runoff from existing to developed conditions based on different SWM objectives.

No single measure was sufficient to fully control stormwater risks, therefore individual BMPs-GSI designed for a single SWM objective needed to be integrated into a comprehensive stormwater regulation system and form a network connected by greenway or drainage. A computational GIS mapping approach was used to combine multiple layers of BMPs-GSI designed for a single SWM objective, and then build up an integrated SWMSP in the regional scale, as shown in Fig. 6, following the principle of “ecological threshold” (Yu et al., 2009b). The areas of BMPs-GSI for flood control, stormwater control, runoff reduction, and water quality protection are 3.94 km^2, 1.77 km^2, 1.81 km^2, and 4.49 km^2, respectively. The comprehensive BMPs-GSI network (SWMSP) composes 12.97% of the total area, with a size of 8.75 km^2. Most of BMPs-

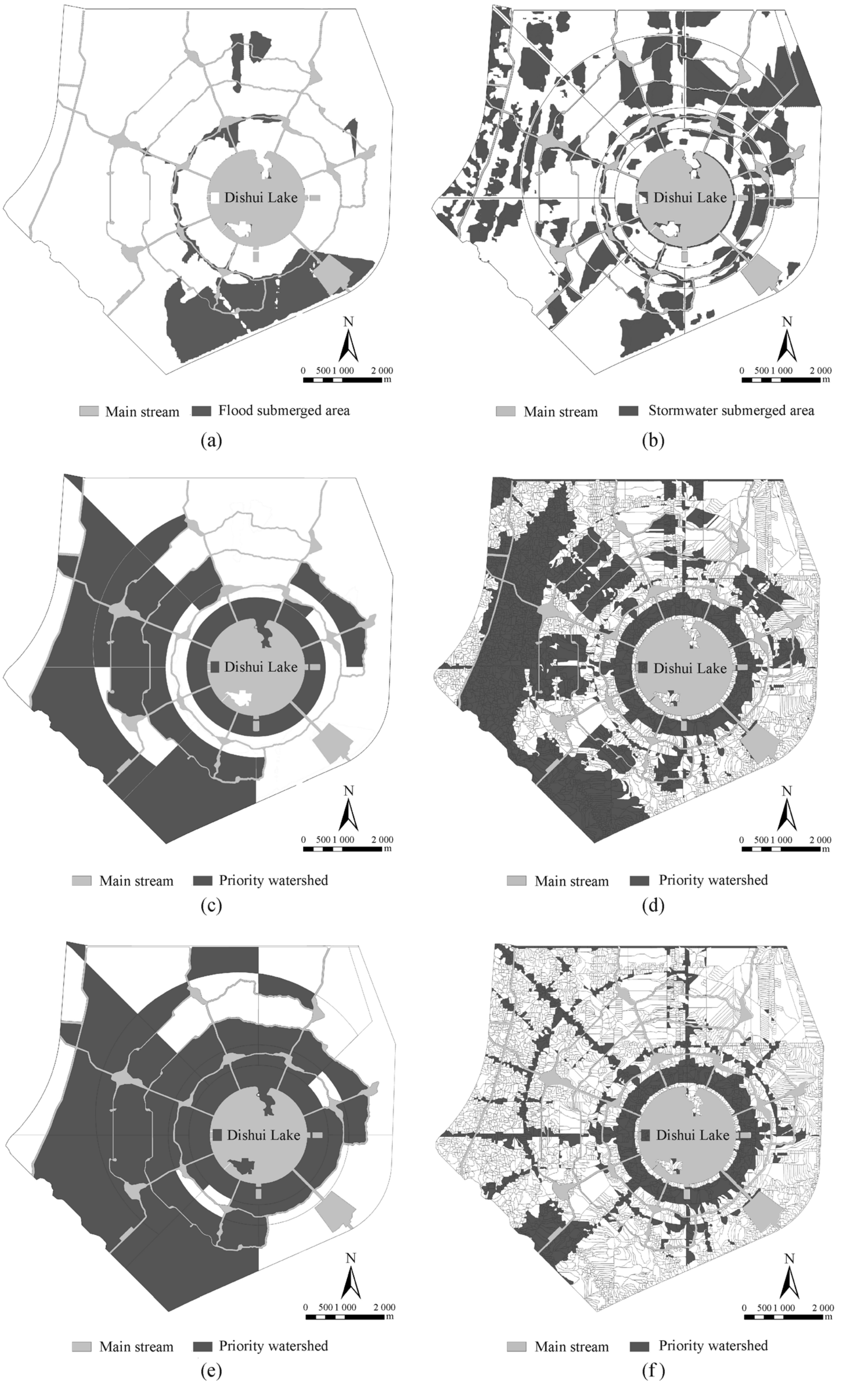


Fig. 5 Analysis and simulation of stormwater management in the study area. (a) Flood submerged area simulation in the scene of highest flood water level; (b) rainstorm submerged area simulation in the once-in-a-twenty-years rainfall event; (c, d) high-priority watersheds simulation of runoff reduction in first-level watershed and second-level watershed layer; (e, f) high-priority watersheds simulation of water quality protection in two watershed layers.

GSIs were designed in the green open space and will not occupy the planned construction lands, which could guarantee the construction lands and ensure their economic value. Moreover, it shows that through proper landscape eco-planning and protection of strategic BMPs-GSI nodes, economic benefit to urban developers could be achieved

Table 1 Comparison of BMPs-GSI in the study area

Index		Vegetated swale	Bio-retention system	Detention ponds		Wetland	Infiltration pond
				Dry pond	Wet pond		
Ecological	Runoff reduction and retention	Poor	Medium	Strong	Strong	Strong	Strong
	Pollutant removal	Poor	Strong	Medium	Strong	Strong	Medium
	Rainwater collection and reuse	Hard	Medium	Easy	Easy	Easy	Hard
	Potentiality of vegetation	Low	Medium	Medium	High	High	Medium
	Promotion of habitats	Poor	Medium	Medium	Strong	Strong	Medium
Economic	Construction cost	Low	High	Low	Medium	Medium	High
	Maintenance cost	Low	High	Low	Medium	Medium	High
Social	Landscape value	Low	High	Low	High	High	Medium
	Security risk	No	No	Yes	Yes	Yes	Yes
	Local public acceptance	High	Low	Low	High	High	Low
Construction requirements	Area ratio of watershed /%	10–20	5	0.5–3	2–3	3–5	0.5–5
	Absolute covering area	Small	Small	Medium	Large	Large	Medium
	Relative covering area	Large	Medium	Small	Small	Small	Small
	Distance to groundwater level	By type	By type	⩾0.6	/	/	⩾1.1–1.8
	Soil condition	By type	Strict	Medium	Lax	Lax	Strict

Table 2 Suitability evaluation of BMPs-GSI in the study area

Application guidelines		Vegetated swale	Bio-retention system	Detention ponds		Wetland	Infiltration pond
				Dry pond	Wet pond		
Treatment phase	Source	√	√				
	Process	√					
	Sink			√	√	√	√
Applicable region	Low density area	√	√	√	√	√	√
	High density area	√	√				
	Heavily polluted area		√		√	√	
Proposed application		As transmission facilities	In high density area	Not recommended	Low-lying areas in green space	In the flood submerged areas	Not recommended

without compromising SWM functionalities. Therefore, SWMSP, which is formed by strategic BMPs-GSI nodes, should be strictly protected and must not be used for construction.

4 Conclusions

Efficient use of green stormwater infrastructure can reduce the public cost of stormwater management infrastructure and flood control, stabilize soil to prevent or reduce erosion, filter water pollutants, reduce energy usage, provide wildlife habitat, improve quality of life, and so on. The benefits of green stormwater infrastructure are numerous, and these have made GSI an effective and cost-efficient tool for urban stormwater management.

An innovative framework of BMPs-GSI eco-planning for the integration of stormwater management functions

Table 3 Design strategies of BMPs-GSI in the study area

BMPs-GSI	Positions	Design scale	References	Remark
Green road-side corridor	On both sides of the trunk road	20%–30% of the traffic land, varied by road red line	Code for Planting Planning and Design on Urban Road, China (CJJ75-97)	Pre-treatment measures, like grass swale and sand filters is designed inside
Riparian buffer	On both sides of the stream and river, beside the water level fluctuation areas	Widths of 10 meters for the protection of water quality	Castelle et al., 1994; Tilley and Brown, 1998	Application of native plants
Wet pond	Strategic points or low-lying land in the green space within the priority watersheds	The storage volume is designed based on LEED and WQ_V criteria, and the average depth of ponds varied from 1 to 2 meters for safety concern	USEPA, 2004	The combined volume of wet pond and wetland equal to T_V of runoff in the priority watersheds
Wetland	Submerged areas of flood and stormwater; stream confluence reaches and surrounding area of Dishui Lake	1%–5% of the watershed, with an average depth of about 1 meter	Mitsch and Gosselink, 2000; Carleton et al., 2001	Topographical reform design and manual drainage measures are pluses in the high-risk of potential inundation watershed

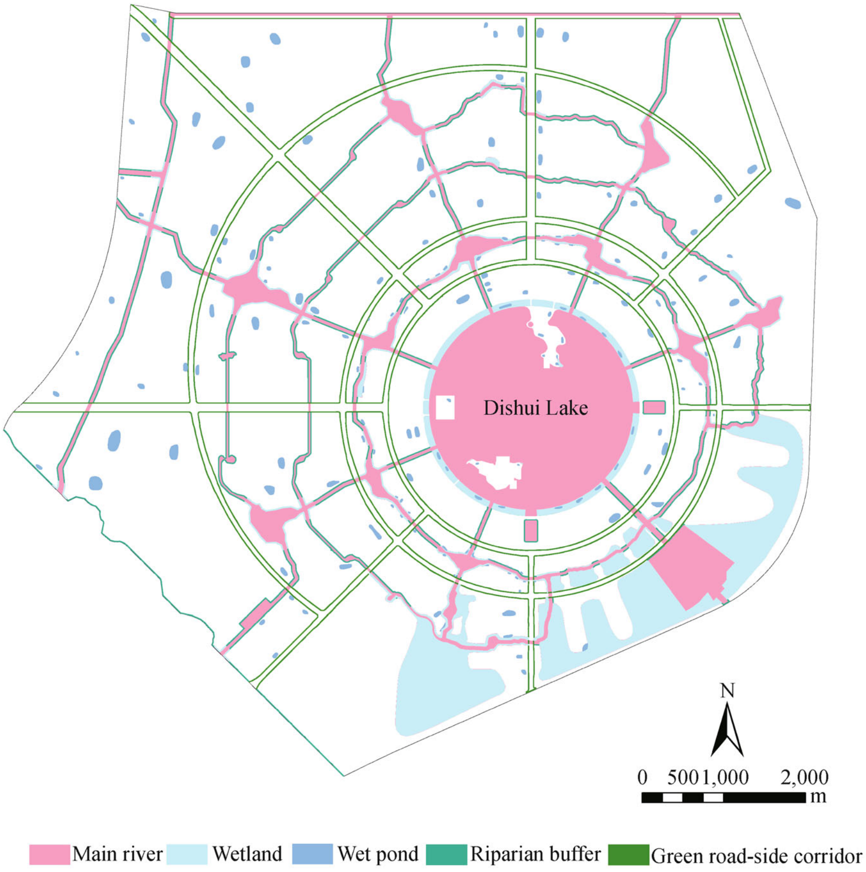


Fig. 6 Stormwater management landscape security pattern for comprehensive stormwater management objectives in the study area.

with contemporary urban master plans was presented on the regional scale. The framework is based on the theories of SPs and GSI, and aims at identifying, maintaining, and consolidating the potential strategic landscape nodes for the healthy water cycle in the urban area by hydrological eco-processes analysis and simulation. It provides guidelines for smart growth and sustainable development through scientific landscape spatial planning and the preservation of BMPs-GSI without sacrificing construction land and its economic value.

However, there are still some problems and challenges which should be solved in future:

1) Although the benefits of GSI have been widely advocated and commonly accepted, China's GSI practice and its theoretical research development are still in an initial stage. The challenge ahead is to promote national or local legislation and regulations for urban stormwater management. Legislation, regulations, and design standards of rainwater flow reduction and detention, and water quality protections are urgently required for strengthening the implementation of this approach. More localized research efforts on GSI are also needed.

2) The eco-planning of BMPs-GSI of SHLNC has not been implemented yet, and long-term hydrological data are lacking in a reclaimed polder area. However, we have constructed two demonstration projects in the study area, and the verification and evaluation of GSI's ecosystem services will be realized in the future. Follow-up research of the eco-planning and implement of small-scale, on site and source-treatment facilities, preferably termed as LID-GSI, are also being planned on municipal or neighborhood scale based on urban detailed planning.

Acknowledgements This research is financially supported by grants from Ministry of Education of People's Republic of China (No. 20120076120019), Shanghai Science and Technology Committee (No. 12ZR1409100 and 12231205300) and Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration. The authors would like to thank MEPRC, STCSMSTC and SHUES for funding this work. The authors are thankful to Dr. Varenyam Achal for improving the language of manuscript.

References

Ballo S, Liu M, Hou L, Chang J (2009). Pollutants in stormwater runoff in Shanghai (China): implications for management of urban runoff pollution. Prog Nat Sci, 19(7): 873–880

Bao L J (2009). Vulnerability Assessment of the Rainstorm Floods in Pudong of Shanghai Based on the Scenario. Dissertation for Master degree. Shanghai Normal University, 39–50 (in Chinese)

Carleton J N, Grizzard T J, Godrej A N, Post H E (2001). Factors affecting the performance of stromwater treatment wetlands. Water Resour, 35(6): 1552–1562

Castelle A J, Johnson A W, Conolly C (1994). Wetland and stream buffer size requirements: a review. Journal of Environmental Quality, 23(5): 878–882

Forman R T T, Godron M (1986). Landscape Ecology. New York: John Wiley Press, 1–120

Gong J Z, Xia B C, Chen J F, Lin M Z (2008). Dynamic analysis of the Guangzhou landscape eco-security pattern based on 3S technology. Acta Ecol Sin, 28(9): 4323–4333(in Chinese)

Intergovernmental Panel on Climate Change (IPCC) (2007). Climate Change 2007: the physical science basis. IPCC Secretariat, Switzerland: 2–21

Jennings D B, Taylor Jarnagin S (2002). Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-Atlantic subwatershed. Landscape Ecol, 17(5): 471–489

Jiang W Y (2005). Estimation of Non-point Pollutants Load in Coastal Plain Island and the Relevant Effects on Water Environment. Dissertation for Master degree. East China Normal University, 45–51 (in Chinese)

Leopold L B (1968). Hydrology for urban land planning: a guidebook on the hydrologic effects of urban land use. Geol Surv Circ, 554: 7–17

Li H, Tang C (2006). Establishment of disaster prevention and relief system in the town with mud-rock flow frequently occurring base on landscape ecological security pattern. Urban Stud, 13(1): 18–22, 29

Li Y F, Sun X, Zhu X D, Cao H (2010). An early warning method of landscape ecological security in rapid urbanizing coastal areas and its application in Xiamen, China. Ecol Modell, 221(19): 2251–2260

Line D E, White N M (2007). Effects of development on runoff and pollutant export. Water Environ Res, 79(2): 185–190

Ma K M, Fu B J, Niu S K (2004). The regional pattern for ecological security (RPES): designing principles and method. Acta Ecol Sin, 24 (4): 761–768

Makepeace D K, Smith D W, Stanley S J (1995). Urban stormwater quality: summary of contaminant data. Crit Rev Environ Sci Technol, 25(2): 93–139

Malmqvist P A (2006). Strategic Planning of Sustainable Urban Water Management. London: IWA Publishing, 1–10

Mark B, McMahon E (2006). Green Infrastructure: Linking Landscape and Communities. USA: Island Press, 2–21

Marsalek J, Jimenez-Cisneros B, Karamouz M, Malmquist P A, Goldenfum J, Chocat B (2008). Urban Water Cycle Processes and Interactions. Leiden: Taylor & Francis, 2–5

Melbourne Water (2005). WSUD Engineering Procedures: Stormwater. Melbourne: CSIRO publishing, 1–6

Mishra S K, Singh V P (2002). SCS-CN methodpart-1: derivation of SCS-CN based models. Acta Geophysica Polonica, 50(3): 457–477

Mitsch W J, Gosselink J G (2000). The value of wetlands: importance of scale and landscape setting. Ecol Econ, 35(1): 25–33

Mo L, Yu K J (2012). Structure the urban green sponge: study on planning an ecological stormwater regulation system. Urban Stud, 19 (5): 4–8

Noss R H, Harris L D (1986). Nodes, networks, and MUMS: preserving diversity at all scales. Environ Manage, 10(3): 299–309

Novotny V, Brown P (2007). Cities of the future: Towards Integrated Sustainable Water and Landscape Management. London: IWA Publishing, 267–283

Pan G Q, Che W, Li J Q (2008a). Study on the volume optimization for rainwater collection by storage tank. Water &Wastewater Engineering, 34(12): 42–47 (in Chinese)

Pan G Q, Che W, Li J Q, Li H Y (2008b). Urban runoff pollution control quantity and its design rainfall in China. China Water & Wastewater , 24(22): 25–29 (in Chinese)

Sanders R A (1986). Urban vegetation impacts on the hydrology of Dayton, Ohio. Urban Ecol, 9(3–4): 361–376

Singh P K, Bhunya P K, Mishra S K, Chaube U C (2008). A sediment graph model based on SCS-CN method. J Hydrol (Amst), 349(1–2): 244–255

Soil Conservation Service (1972). National Engineering Handbook, Section 4: Hydrology. USDA, Springfield, VA: 101–103

Stormwater Steering Committee (SSC) (2007). Minnesota Stormwater Manual. Minnesota, USA: 43–57

Tackett T (2008). Seattle's policy and pilots to support green stormwater infrastructure. 2008 International Low Impact Development Conference. Washington: Environmental and Water Resources institute of ASCE, 1–4

Tilley D R, Brown M T (1998). Wetland networks for stormwater management in subtropical urban watersheds. Ecol Eng, 10(2): 131–158

United States Environmental Protection Agency (USEPA) (1993). Guidance Manual for Developing Best Management Practices. Washington, D.C., Document No. EPA-833-B-93-004: 7–11

United States Environmental Protection Agency (USEPA) (2004). The Use of Best Management Practices (BMPs) in Urban Watersheds. Washington: United States Environmental Protection Agency, EPA/600/R-04/18: 21–71

Van Room M, Van Room H T, Trueman S (2009). Low impact urban design and development: the big picture: an introduction to the LIUDD principles and methods framework. Lincoln, New Zealand: Manaaki Whenua Press: 2–8

Wang H Y (2005). Pollution Processes and Management Researches on Urban Rainfall Runoff in Shanghai. Dissertation for Master degree. East China Normal University, China: 26–77 (in Chinese)

Wise S (2008). Green infrastructure rising. Planning, 74(8): 14–19

Wood-Ballard B, Kellagher R, Martin P, Jefferies C, Bray R, Shaffer P (2007). The SUDS Manual. CIRIA, Classic House, 174-180 0ld Street, London ECIV 9BP, UK: 48–55

WRI, IUCN and UNEP (1992). Global biodiversity strategy: guidelines for action to save, study and use Earth’s biotic wealth sustainably and equitably. WRI/IUCN/UNEP: 1–244

Yang R, Cui B (2012). Framework of integrated stormwater management of Jinan City, China. Procedia Environmental Sciences, 13: 2346–2352

Yu K J (1995). Security Patterns in Landscape Planning with a Case Study in South China. Graduate School of Design, Harvard University, MA, USA: 2–14

Yu K J (1996). Security patterns and surface model in landscape ecological planning. Landsc Urban Plan, 36(1): 1–17

Yu K J, Qiao Q, Li D H, Yuan H, Wang S S (2009a). Ecological land use in three towns of eastern Beijing: a case study based on landscape security pattern analysis. Chinese Journal of Applied Ecology, 20(8): 1932–1939 (in Chinese)

Yu K J, Wang S S, Li D H, Li C B (2009b). The function of ecological security patterns as an urban growth framework in Beijing. Acta Ecol Sin, 29(3): 1189–1204