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REVIEW ARTICLE

China's Sponge City construction: A discussion on technical approaches

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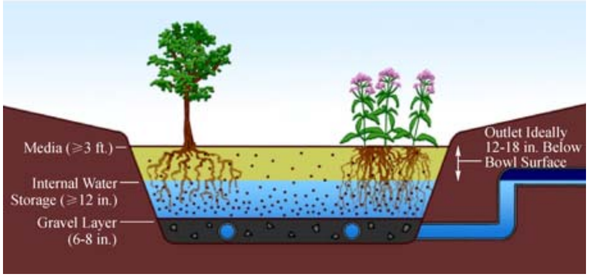
HIGHLIGHTS

- Barriers and challenges of Sponge City construction were presented.
- Several key technical points on Sponge City implementation were discussed.
- Recommendations on Sponge City implementation strategy are proposed.

GRAPHIC ABSTRACT



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ABSTRACT

Since 2014, China has been implementing the Sponge City Construction initiative, which represents an enormous and unprecedented effort by any government in the world for achieving urban sustainability. According to preliminary estimates, the total investment on the Sponge City Plan is roughly 100 to 150 million Yuan (RMB) ($15 to $22.5 million) average per square kilometer or 10 Trillion Yuan (RMB) ($1.5 Trillion) for the 657 cities nationwide. The Sponge City Plan (SCP) calls for the use of natural processes such as soil and vegetation as part of the urban runoff control strategy, which is similar to that of low impact development (LID) and green infrastructure (GI) practices being promoted in many parts of the world. The SCP includes as its goals not only effective urban flood control, but also rainwater harvest, water quality improvement and ecological restoration. So far, the SCP implementation has encountered some barriers and challenges due to many factors. The present paper presents a review of those barriers and challenges, offers discussions and recommendations on several technical aspects such as control goals and objectives; planning/design and construction of LID/GI practices; performance evaluation. Several key recommendations are proposed on Sponge City implementation strategy, Site-specific regulatory framework and technical guidance, Product innovation and certification, LID/GI Project financing, LID/GI professional training and certification, public outreach and education. It is expected that the successful implementation of the SCP not only will bring about a sustainable, eco-friendly urbanization process in China, but also contribute enormously to the LID/GI research and development with the vast amount of relevant data and experiences generated from the Sponge City construction projects.

1 Introduction

Over the past decade China's urban population has grown to 52.4% in 2015 from 42.5% in 2005, and the build-up areas have increased by 17,252 km^2. This roughly equates to an addition of 165 million people dwelling in urban areas in a decade! This rapid urbanization process has led to a worsening "city syndrome" situation such as urban flooding, water pollution, heat-island effects and ecologic deterioration, etc. [1].

To promote a sustainable urbanization strategy, the Chinese government announced in late 2013 a "Sponge

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*Hot Column—Low Impact Development and Sponge City (Responsible Editors: Haifeng Jia & Shaw L.Yu)

City" initiative in building urban infrastructures. Deviating from the traditional "rapid-draining" approach, the new paradigm calls for the use of natural processes such as soil and vegetation as part of the urban runoff control strategy. The "six-word" principle, which includes infiltrate, detain, store, cleanse, use and drain, forms the guidelines for urban storm water management. These principles are similar to those under the Low Impact Development (LID) paradigm that has been promoted and implemented in many parts of the world [2]. LID technology employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treat storm water as a resource rather than a waste product [3].

In October 2014 the China Ministry of Housing and Urban-Rural Construction (MHURC) issued a draft technical manual on Sponge City construction. In October 2015 the State Council of China announced a major expansion of the Sponge City Initiative, which is being implemented nationwide. Recognizing the limitation of Low Impact Development (LID) / Green Infrastructure (GI) facilities in controlling large or less frequent storm events, the government mandates the integration of green and gray infrastructure. The expanded Sponge City Plan (SCP) includes as its goals not only effective urban flood control, but also rainwater harvest, water quality improvement and ecological restoration. The use of LID/GI practices will be required for all new development and retrofit sites, science and commercial parks, green spaces, non-mechanical vehicle roads, pedestrian walkways, etc.

During 2015 and 2016, the China Ministry of Finance (MOF), with support from MHURC and the Ministry of Water Resources (MWR), selected 30 cities (Fig. 1), among more than five hundred applicants, as pilot sites under the SCP. Each city is to receive 400 to 600 million Yuan (RMB) (60 to 90 million US$) annually from the central government for three years, with the total investment estimated to be about 42.3 billion Yuan (RMB) or 6.35 billion US$. Local matching is required and public-private partnerships (PPP) are encouraged. Cities will receive a 10% bonus from the central government if the PPP contribution exceeds a certain percentage of the overall budget. According to preliminary estimates, the total investment on the SCP is roughly 100 to 150 million Yuan (RMB) ($15 to $22.5 million) average per square kilometer or 10 trillion Yuan (RMB) ($1.5 Trillion) for the 657 cities nationwide [4–6].

China's SCP represents an enormous and unprecedented

Fig. 1 Locations of pilot Sponge Cities

undertaking by the government for achieving urban sustainability. MHURC officials recognize that the success of the Sponge City construction will require a combined and coordinated effort by many government agencies in areas such as landscape/architectural planning, construction, municipal, water, transportation, finance, environmental protection and input from other stakeholders. In addition, to finance all the Sponge City projects is a real challenge. The government has listed some innovative strategies for fund-raising, which includes, in addition to government grants and subsidies, local matching and public-private partnerships. The government is also encouraging participation by financial institutions, and will allow qualified entities to issue construction bonds to finance the Sponge City projects.

2 Barriers and challenges for the Sponge City construction

Since the initial implementation of LID practices in the United States during the early 2000s, significant barriers and challenges have existed and hindered its progress. The China Sponge City projects are now encountering similar situations. The following is a list that is compiled from experiences in both countries [1,7]:

(1) Resistance to change. Inertia of traditional approaches

It is human nature to resist change, especially regarding something that is unproven for its suitability and cost-effectiveness. LID technology is relatively new and has not be widely understood, especially at the local level. Many misconceptions still exist, e.g. LID can solve all urban flooding problems. Gradually people begin to realize LID targets only smaller storm events and must be integrated with traditional gray infrastructure approach for managing larger runoff events. In China, e.g., the age-old notion of man can conquer nature, yet the basic concept of the Sponge City approach is living with nature and making use of nature's abilities. Although the Central Government has mandated the Sponge City construction and has issued technical guidelines, some provincial and local government officials are slow to act due to inertia of traditions.

(2) Limited technical guidance on planning, design and assessment of LID facilities

Even though LID practices have been widely used beginning in early 2000s, revised or new technical manuals and guidance books still are been issued in the United States. Urban runoff characteristics are very site-specific [8] and local environmental and social-economic conditions vary from location to location. Therefore, local, or at least regional, guides would be most helpful. A case in point is the need for a list of native plants suitable for use in bioretention cells. Currently, localized technical guidance is still not available for many designated sponge cities in China.

(3) Lack of close coordination among agencies at the local level

For example, design of the LID practice, bioretention cell, needs input from both storm water and landscape architect professionals. Such a coordinated effort has not been the norm because storm water management and road side vegetation management are responsibilities belonging to different agencies. Currently, there is close coordination among the key agencies responsible for implementing the Sponge City Plan at the ministry level, i.e., MHURC, MOF and MWR. However, at the local, or Sponge City level, often many agencies are involved, such as the urban planning, construction, water conservancy, and environment protection bureaus, etc. A smooth and efficient Sponge City implementation requires a great effort and time for inter-agency coordination. To facilitate such efforts, some Sponge City pilot cities have created the "Sponge City Offices," which include representation from all bureaus related to urban water.

(4) Quantification of LID cost effectiveness

Currently, performance of an LID practice is usually measured as "percentage of runoff volume" or "fraction of pollutant load" removed by the practice. However, how this "percentage of fraction" is calculated is still been discussed. Should this be based on a subjectively selected "design storm"? Or it should be calculated on a continuous basis for all storms occurred during a specific period of time, say, a year? The other important factor is how the success (or failure) of the LID/GI implementation be incorporated into the performance evaluation of local officials. If the promotional evaluation process could be modified to include results of Sponge City implementation, local officials would be much more committed to its success.

(5) Finance Sponge City project

Sponge City construction is a public endeavor and would require public financing. A number of financing schemes have been used in the US, e.g., storm water utilities, federal government grants, state government cost-sharing, etc. However, if the use of LID is a mandated activity, a strong financing plan should be provided to local governments.

Public-private partnerships (PPP) are encouraged in financing Sponge City project. However, there are several factors which influence the invest interest of social capital, such as the perceived high costs of design, construction and maintenance; inadequate investment and return estimates; no clear economic incentive for using LID.

(6) Education and training do not provide skills to design and implement LID

To implement successfully an LID/GI practice construction project, knowledge from many disciplines is required. Subjects of expertise needed are many. For example, planning/design of LID facilities would need skills in storm water management, urban hydrology and hydraulics (scales from site to region to watershed), water quality modeling, optimization techniques, etc. However, the specific system education and training programs are still lack in University and College.

The present paper is aimed at providing a discussion of and recommendations for addressing a number of challenges listed above, with emphasis on the technical aspects of implementing LID/GI practices.

3 Discussions on some technical approaches for Sponge City Plan implementation

3.1 Set clear management goals and objectives

(1) LID/GI practices are designed for controlling smaller storm events.

LID practices are “on-site” and “distributed” facilities and therefore are basically used to control smaller runoff events. Also, a major consideration for targeting smaller, more frequent runoff events is the “first-flash” phenomenon observed in many urban areas [8]. For example, by controlling the first 0.5 inches (13 mm) of runoff, a significant amount (~80%) of pollutants carried by the runoff can be removed. The first LID design manual [9] clearly identified the control target of LID facilities, as shown in Fig. 2.

In Fig. 2, the amount of rainfall volumes (vertical axis) are roughly divided into four control categories using rainfall data for Prince George’s County, Maryland, USA. At high frequencies, e.g. less than one year, the rainfall volumes are small and control goal is to enhance infiltration for groundwater recharge and to remove pollutants in the first-flush of runoff for water quality protection. For storms with 2-year frequency or less, the goal is to control channel erosion and also water quality. A 10-year frequency is commonly used for peak flow reduction for erosion and flood control. The regulations usually require the use of a 100-year frequency for detention facility emergency spillway design.

A more recent version of the control target illustration is given in Fig. 3 [10]. It illustrates the overall strategy for urban storm water runoff control. In the figure, Curve ① represents the flows across all frequencies expected after development (increase in imperviousness). The ultimate goal of runoff control is to restore the site hydrology (runoff peak and volume, time of concentration, etc.) to the original regime or pre-development conditions exited at the site, as depicted by Curve Ⓖ. The traditional storm water management approach relies mainly on detention processes (design frequency 10-100 years) that moves Curve ① to Curve ②. With some modifications (e. g. extended detention) Curve ③ could be achieved for additional water quality benefits. The current LID/GI strategy is to optimize the control of smaller storms (frequency 2 years or less) so that Curve ④ can be reached and water quality protection is further enhanced.

The final selection of control targets should be made considering local environmental, social and economic situations. Of special interest, however, it should be noted that if the control target is a frequency (e.g., 95%), it will mean different design volumes for different locations. On the other hand, if the target is a volume for control (e.g., 13 mm runoff), then it means different frequencies for different locations, as shown in Fig. 4 for several typical cities in United State [11].

An example of control targets and goals set by a locality is given below [12]. In Town of Chapel Hill in North

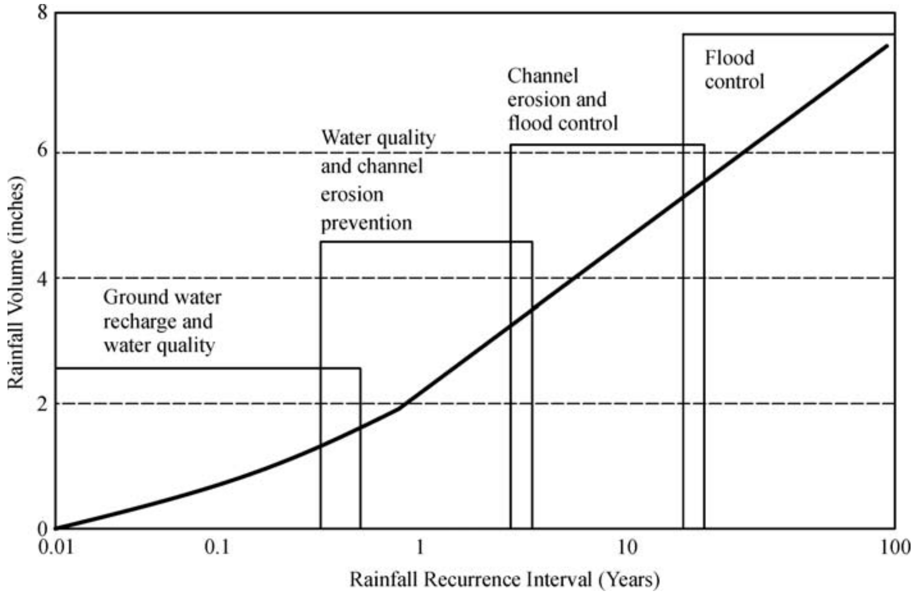

Fig. 2 Storm water management basic control targets

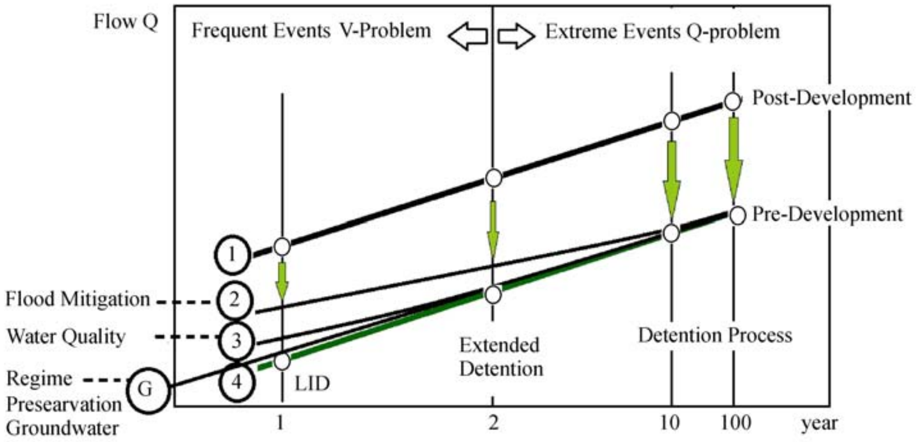

Fig. 3 Urban runoff control strategies

Carolina, USA, the control target of TSS is 85% removal for first 1 inch of precipitation; Volume leaving site post-development shall not exceed volume pre-development for the 2 year 24 h storm event (3.60 inches); Rate leaving site post-development shall not exceed rate pre-development for the 1, 2, 25 and 50 year storm are set as 3.00, 3.60, 6.41 and 7.21 inches respectively.

In China, the Guiding Opinions on Advancing the Construction of Sponge Cities issued by the China State Council sets a control goal of 70% annual runoff volume for 20% of the built-up areas by 2020. To achieve such goals, cities in different climate regions will need different design criteria for their control practices, as in United State illustrated in Fig. 4.

(2) Hydrograph generation and temporal distribution of rainfall

Hydrograph generation is needed for facility design and detailed analysis of performance. The within storm rainfall distribution, or temporal distribution of rainfall, enables the determination of a hyetograph, which is needed for hydrograph generation [13].

The most commonly used method in US for determining the temporal distribution of a design storm is the SCS rainfall distribution curves as shown in Figs. 5 [14].

Using rainfall charts shown in Figs. 5, one can generate the appropriate design rainfall hyetograph and then the design runoff hydrograph. An example of hydrograph generation application is shown in Fig. 6 below [9].

In Fig. 6, Q is discharge flow; T is Time. Curve ① represents the existing hydrograph at the site from a design storm. Curve ② is the hydrograph from the same storm under post-development conditions. Curve ③ shows the

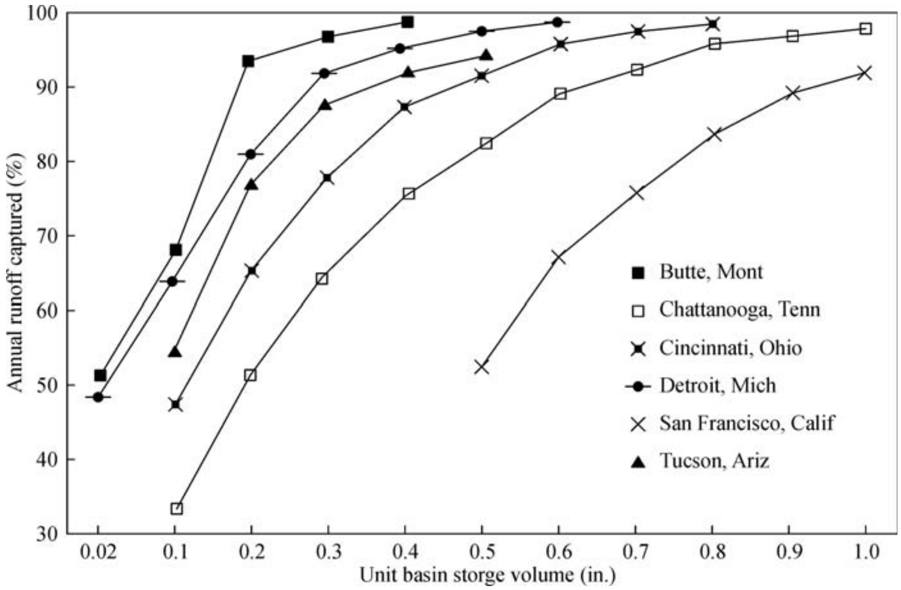

Fig. 4 Percentage runoff capture rate *vs.* Storage volume required

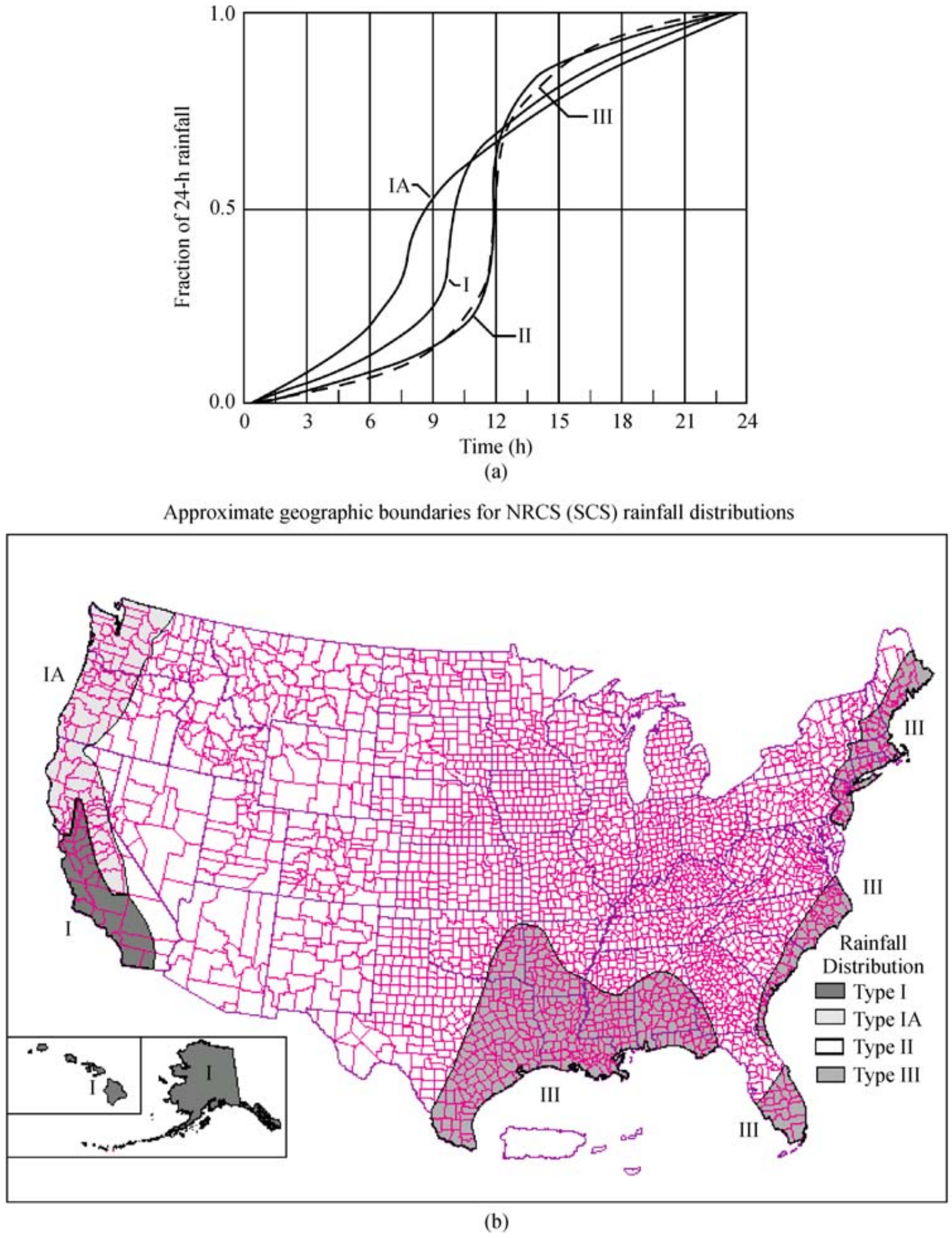

Fig. 5 SCS Temporal Rainfall Charts

(a) Different type of SCS temporal rainfall; (b) Spatial distribution of different type of rainfall distribution

effect of LID plus additional detention facilities. The post-development peak discharge is reduced to the pre-development level and also significantly, the flows during the early time steps are removed or lowered, which helps the removal of pollutants during the first-flash time period.

3.2 Planning and design of LID/GI practices

The planning and design of LID/GI practices normally include the following steps [15,16]:

(1) Site data, information collection and analysis;

(2) Low Impact Development Best Management Practice (LID-BMPs) screening and selection; and

(3) LID-BMPs design and optimization

Local site (could be from block size to region and watershed scale) data are important because runoff characteristics are very site-specific. In the US, storm water management guidelines and manuals have been issued at the national [3], state (e.g. Maryland [17]) and local (e.g. Chapel Hill, North Carolina [12]) levels. Some of the local manuals provide very detailed information such as a list of local plants suitable for use in green roofs, bioretention cells, etc. In China, some LID-BMPs screening and optimization methodologies have been proposed (e.g. [18,19].).

The design of a LID-BMP facility involvers many

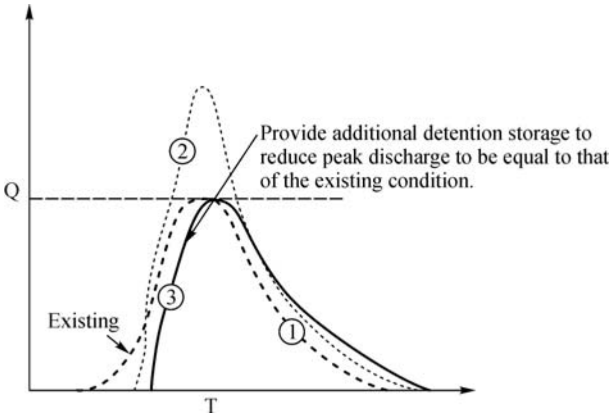

Fig. 6 Hydrograph generation: effect of LID on site hydrology

factors such as the control area, design storm, pollutant characteristics, the regulatory performance requirement, etc. The design of a bioretention cell is used as an example here. Features to be considered for best performance by a bioretention are listed below [12]:

- Siting/Location
- Sizing
- Shape
- Ponding time and Depth
- Velocity
- Planting Soil and In situ Soil
- Underdrain System
- Mulch Layer
- Plant Material
- Edge Protection

For certain purpose, the specific design and innovation is required. For example, Fig. 7 illustrates a cross-section of a bioretention cell, with its features derived from research results. Earlier versions of bioretention cell design guides mostly call for a gravel layer at the bottom with perforated pipes for drainage. Recent research by Brown and Hunt [12] suggested that by using a siphon pipe that creates a water storage layer and thus enhances nitrogen removal. The finding has been incorporated into recent bioretention design guides. Further research is continuing and will lead to better designs and even product innovations.

LID-BMPs optimization is aimed at finding the most cost-effective selection and placement of various LID-BMPs facilities for a specific site. Such an analysis should be carried out before a final decision is made on facility selection, design and placement [20,21]. Many optimization tools are available. Figure 8 shows an example of optimization of the LID-BMPs design scenarios in China using the model SUSTAIN [19]. In the figure, the X axis represents the cost of LID-BMPs implementation, the unit is million YuanYuan (RMB). The Y axis represents the total runoff volume reduction rate of LID-BMPs schemes. We can find the best solution of LID-BMPs design which is the "knee-of-curve" point in the figure.

3.3 Evaluating LID/GI practice performances

Monitoring and assessment of LID/GI practices after their implementation are required, not only for performance evaluation but also for providing quantified proofs of the benefits of using such practices. The USEPA has issued detailed guidelines for monitoring of LID-BMPs and evaluating their performance [22]. The following methods were recommended for assessing LID-BMPs performance:

- Efficiency ratio
- Summation of loads
- Regression of loads
- Mean concentration
- Efficiency of individual storm loads
- Inflow vs outflow probability curves

The most commonly used indicator of storm water runoff pollution is the event mean concentration (EMC). The term event mean concentration (EMC) is a statistical parameter used to represent the flow-proportional average concentration of a given parameter during a storm event. It is defined as the total constituent mass divided by the total runoff volume [22].

Many discussions are still being made regarding the accuracy, reliability and preference of the various methods.

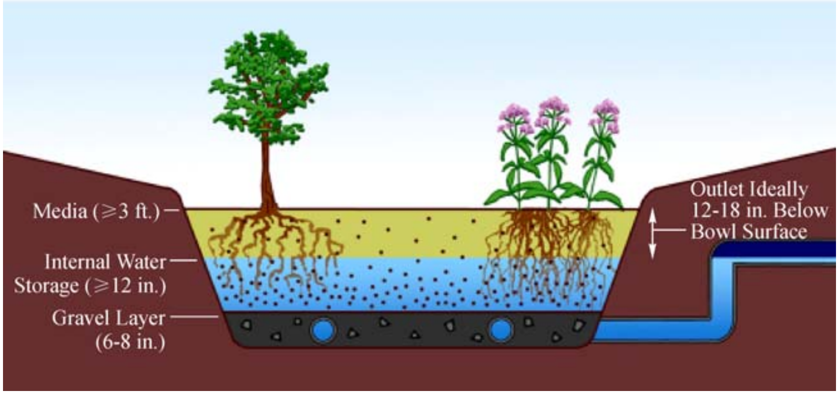

Fig. 7 Bioretention design features example

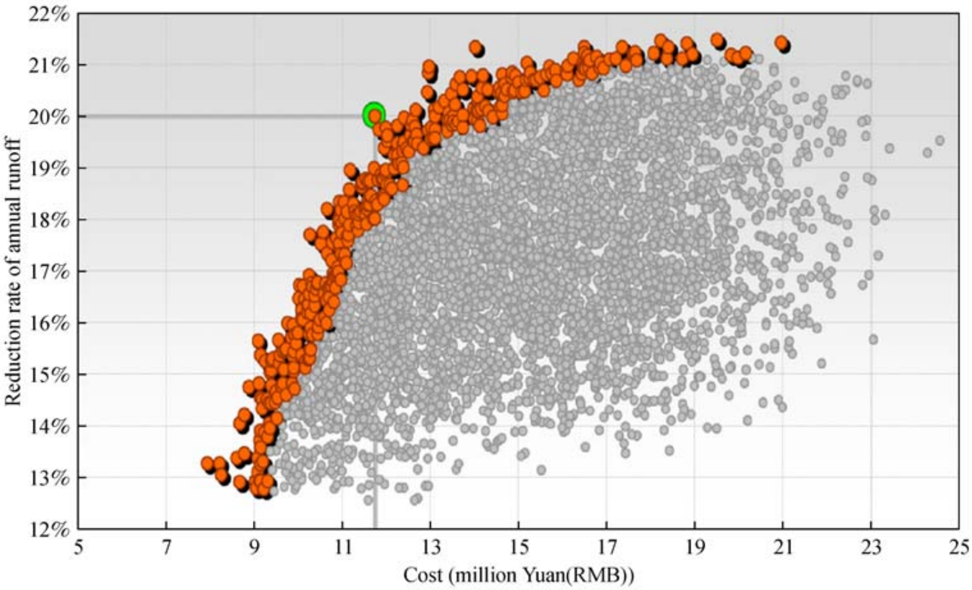

Fig. 8 Optimization of LID-BMPs Design using SUSTAIN

Theoretically, the summation of loads method, which is based on a mass balance computation of pollutant loads going into and out from the facility, is the most reliable if the samples are taken over a wide range of flow conditions [22]. Significant advances have been made in the past decades with respect to traditional BMP and LID-BMP monitoring and evaluation [23–25]. However, data are still relatively scarce, especially in China [7]. It is expected that the Sponge City projects will generate a vast amount of data that would be very valuable to researchers and practitioners in the field.

Currently, most LID-BMP pollutant removal requirements are based on the “performance based” approach, which sets subjectively the percentage of pollutant removed, e.g., 40% removal of total phosphorus. However, it might be more cost-effective to consider a “water quality based” approach, which determines the percentage pollutant removal needed for maintaining a specified water quality for a water body [26–28].

In addition, many methods and tools are used to evaluate the environmental and economic performance of LID-BMPs, such as life cycle assessment [29] and modeling [30].

4 Looking ahead — Recommendations for Sponge City construction strategies

4.1 The Sponge City implementation strategy

The current Sponge City Plan scope has been expanded to include not only dealing with the urban water runoff problem, but also with the broader management of urban water. For example, the integration of green and gray infrastructures is required for flood control, water quality improvement and ecological protection and restoration. Local governments will need to adjust their land use planning and storm water infrastructure construction strategies to satisfy Sponge City requirements [31,32]. To effectively improve water quality, the government could consider establishing regulations similar to the National Pollution Discharge Elimination System (NPDES) and the Total Maximum Daily Load (TMDL) programs used successfully in the United States [33–35]. Also, to provide a strong incentive for local government officials, the success of Sponge City implementations could be used as a performance evaluation factor for promotion consideration for local officials.

4.2 Site-specific regulatory framework and technical guidance

The China Sponge City implementation experience so far has suggested that because the core principles of the expanded version of the initiative are aimed at the integrated management of urban storm water quantity and quality, the legal status for Sponge City construction should be enhanced. In essence, the construction of LID/GI facilities should be planned as part of the urban overall master planning at the beginning. Moreover, since the level and scope of controlling storm water runoff depends largely on local climate, rainfall, ecology and importantly social and economic factors, it is suggested that localized regulations should be considered under the state’s regulatory framework. An example of such an approach is the federal government, state and local stormwater regulations in the United States [27].

The first technical guidance issued by MHURC in 2014 [6] has laid the foundation for the initial phase of Sponge City construction nationwide in China. As the Sponge City projects get underway, it has been recognized that detailed technical guidance, including information such as local climate, hydrologic, soil and even plants should all be included in the guidance documents. Also, an operational and maintenance instruction is needed, plus detailed requirements for monitoring and analysis in order to provide quantitative information on facility performance and cost-effectiveness.

4.3 Product innovation and certification

Some of the control practices, such as an underground storm water treatment system, are manufactured by private companies. An evaluation and certification process would be highly desirable before such products are used for public projects. A sustainable development of Sponge City requires a robust industrial base. The central government should consider assisting related industries and establishing a viable Sponge City industry chain. Under the current economic climate of "over-capacity reduction," the Sponge City projects can offer good business opportunities for manufacturers producing pervious concrete, permeable bricks, infiltration pipes, etc. A stable supply system will help ensure the successes of the Sponge City projects. The certification process in Unite States can be referenced for us [36].

4.4 LID/GI project financing

The Sponge City construction represents an urbanization process of an enormous scale that requires a major financial commitment from the government. Innovative financial options, such as appropriate PPP project portfolio, credit support, loan guarantees, special construction funds and bond issuing should be considered and promoted. The government should also simplify the administrative approval process for reducing the upfront costs of PPP projects. Decentralization of administrative authority properly to local governments can help them build a tailored and flexible policy approach appropriate for local social, environmental, economic and cultural situations.

In the era of budgetary constraints and competing needs, how to finance all the Sponge City projects is a real challenge. The government has listed some innovative strategies for fund-raising, which includes, in addition to government grants and subsidies, local matching and public-private partnerships. A major current issue is how to develop a reliable, and tangible, estimate of returns on investments in the Sponge City projects. For example, how to quantify and appraise the benefit of Sponge City implementation is still an important question. Also, after the completion of a Sponge City project, maintenance of the LID/GI facilities will become a crucial factor affecting project sustainability. The lack of information on maintenance requirements and costs would contribute to uncertainties in Sponge City budget estimates.

In the US, with limited budgets, innovative approaches are needed for financing the green infrastructure projects. One of the approaches is the Public-Private-Partnerships, PPP or 3P. The following is an example from the Prince George's County, Maryland [37]:

- The Private Partner is the general contractor and program manager in partnership with the County through a limited liability company (LLC) framework.
- Program transparency is maintained through joint program administration and decision making expressed in the LLC operations.
- The Private Partner will provide all or part of the initial capital costs.
- The County will pay back the Private Partner a monthly fee that would include the debt service and cost for operation and maintenance.
- The Private Partner's revenue is based on a negotiated performance based fee.
- The Private Partner doesn't get paid unless they meet the performance goals.

This performance fee based approach ensures the Private Partner's first priority is to meet the County's program / performance goals; not the optimization of its profits. Figure 9 illustrates the inter-relationships among various partners in the PG County's PPP Program [37]. The County collects water quality (WQ) fees, which provide the basic funding for the LID/GI projects. The County and the selected private partner (LLC) form jointly the LLC Company and implement the projects. Input and collaborations are also solicited from relevant community associations, environmental groups, faith-based non-profit organizations (NPOs), and industrial, commercial entities during planning and design stages. The Private Partner will be responsible for BMP maintenance and will be paid back in accordance with a negotiated scheme as mentioned above.

4.5 LID/GI professional education/training and public outreach

The design, construction and maintenance of LID/GI systems require professionals with appropriate background and training. Therefore, a consorted effort and time is needed for research and development (R/D) in LID/GI technology in order to achieve successes for the Sponge City projects.

In the era of public awareness of the importance of environmental protection, out task is to link the Sponge City initiative to a sustainable urban development strategy

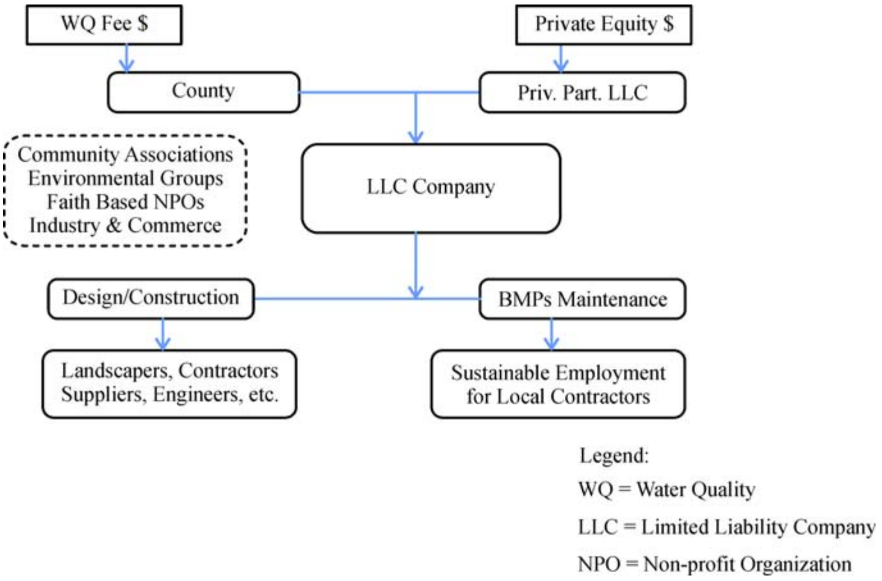

Fig. 9 Partner relationships – Prince George's County PPP program

in a way that the public would clearly understand and fully support. The use of the media, public hearing sessions, comment periods for mandates, training sessions for practitioners, etc. are all viable means of letting people know and gaining their support and even participation. Education at all levels, from kindergarten to college and to adult education, is very important. For example, in the US, some local community colleges offer course to adults on plant selection for bioretention cells or rain gardens. Working with environmental groups (such as the Sierra Club in the US) and relevant non-government organizations (NGOs) would also be an effective way to raise awareness and support.

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