Journal of Cleaner Production 213 (2019) 1103–1114

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Review

Progress on environmental and economic evaluation of low-impact development type of best management practices through a life cycle perspective

Changqing Xu [a], Mingyi Jia [b], Ming Xu [c, d], Ying Long [e], Haifeng Jia [a, *]

[a] School of Environment, Tsinghua University, Beijing, 100084, China
[b] Department of Environmental Sciences, Wagniengen University, 6708GA, Netherlands
[c] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, 48109-1041, United States
[d] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, 48109-2125, United States
[e] School of Architecture, Tsinghua University, Beijing, China

ARTICLE INFO

Article history:
Received 9 November 2018
Received in revised form
19 December 2018
Accepted 26 December 2018

Keywords:
Sponge city
Low-impact development type of best management practices
Life-cycle assessment
Life-cycle costing
Environmental benefit
Economic benefit

ABSTRACT

A rapid progress of low-impact development type of best management practices for urban storm water runoff quantity and quality control at a global scale has occurred in the past decade. In-depth research on low-impact development type of best management practices as useful technologies and measures to control stormwater runoff is being conducted worldwide. This paper presents a literature review of the environmental and economic evaluation of low-impact development type of best management practices through life cycle perspective. Research gap and future agenda are also proposed. Results show that life cycle assessment or life cycle cost analysis for low-impact development type of best management practices are widely documented. However, certain challenges still exist. Most works involved only on-site or facility scale or just considered certain environmental effect aspect. In addition, the lack of onsite monitoring data of water quality and quantity affects further research on low-impact development type of best management practices evaluation. In most emerging and developing countries, low-impact development type of best management practices implementation is still in the start-up stage. Quantitative life cycle assessment or life cycle cost analysis studies of low-impact development type of best management practices can provide necessary and useful information for decision-makers in regional scale low-impact development type of best management practices arrangement. Low-impact development type of best management practices database based on specific regions should also be established to support further in-depth research. Finally, low-impact development type of best management practices can offer various benefits to urban eco-systems. Researchers should provide a combination of environmental, economic, and social benefits of low-impact development type of best management practices to fulfill sustainability.

Contents

---

* Corresponding author.
E-mail address: jhf@tsinghua.edu.cn (H. Jia).

https://doi.org/10.1016/j.jclepro.2018.12.272
0959-6526/

1. Introduction

The increasing urbanization can lead to social and economic progress, but also puts pressure on cities to provide infrastructure and social services. As we know, excessive urban runoff caused by dramatic increases of urbanization is causing flooding in urban areas and urban water quality deterioration in receiving water bodies and even economic losses (Baek et al., 2015). It thus brings negative impacts including urban flooding, water shortage, water pollution, and other water related ecological environment problems.

The urban runoff control has been the worldwide focus and different countries have their own solutions and approaches to deal with it. At present, some commonly used practices such as low impact development (LID) (Prince George's County, 1999a and 1999b) and best management practices (BMPs) (Schueler, 1987; Clar et al., 2004) in the U.S., sustainable urban drainage systems (SuDS) (Martin et al., 2000; Martin, 2001) in the U.K., and water sensitive urban design (WSUD) (Whelans et al., 1994; Wong, 2007) in Australia gained much attention in the world. All of them are aimed to protect and utilize natural resources to control stormwater and urban runoff. But different practices have different priorities, application scopes, and management styles (Fletcher et al., 2014). These practices can be divided into different types according to their functions, such as infiltration (e.g., bioretention, permeable pavement, green roof, seepage well, and concave-down greenbelt), storage (e.g., constructed wetland, wet pond, and cistern), regulation (e.g., regulation pond and regulation pool), transmission (e.g., wet and dry grassed swale), and purification (e.g., buffer strip and first flush devices) (Eckart et al., 2017). Decision- or policy-makers should choose suitable practices based on the actual condition. In 2013, the Chinese government announced a “Sponge City” initiative. In 2015, 2016, the China Ministry of Finance, with support from Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD) and the Ministry of Water Resources, selected 30 cities among more than 500 applicants, as pilot cities under the Sponge City plan (MOHURD, 2014). The total investment was approximately $6.4 billion (Jia et al., 2017). The low-impact development type of best management practices (LID-BMPs) are essential for Sponge Cities.

LID-BMPs, a sustainable, innovative, and effective stormwater runoff control method (Jia et al., 2015), has gained considerable attention for controlling stormwater and non-point source pollution (Dietz, 2007; Pyke et al., 2011). As reported, LID-BMPs can achieve good runoff quantity (e.g., peak flow rate and total runoff volume) (Brown and Hunt, 2011; Chapman and Horner, 2010; Chen et al., 2013; Houng Li, 2008) and quality reduction performance compared with gray infrastructures (Jia et al., 2015; Mangangka et al., 2015; Spatari et al., 2011; Trowsdale and Simcock, 2011). However, the implementation (including production and transportation of raw materials, installation, operation, maintenance, labor, and decommissioning) of LID-BMPs can generate environmental and economic burdens (Santos et al., 2017; Xu et al., 2017). Accordingly, the comprehensive evaluation of environmental and economic benefits or impacts of LID-BMPs should be conducted. Many researchers began to realize the importance of comprehensive benefits of LID-BMPs to appropriately implement especially in developed countries.

Life cycle assessment (LCA) is a scientific and systematic tool used to assess environmental effects throughout the whole lifecycle of a product, process, or practice (ISO 14040, 2006). Similarly, life cycle costing (LCC) (Woodward, 1997; Standards Australia/StandardsNew Zealand, 1999) is defined as a process of determining the sum of all expenses associated with a complete life-cycle of a product system. Material acquisition, installation, operation, maintenance, and disposal cost are all included. Studies using LCA (Flynn and Traver, 2013; Kosareo and Ries, 2007; Lopsik, 2013; O'Sullivan et al., 2015; Spatari et al., 2011; Xu et al., 2017) or LCC (Carter and Keeler, 2008; Dabbaghian, 2014; Hadjimichael et al., 2016; Hasik et al., 2017; Wang et al., 2016; Zhan and Chui, 2016) to evaluate the environmental and economic effects of LID-BMPs are widely investigated. For further in-depth research on LID-BMPs evaluation, both LCA and LCC should be used. This combination is important for decision- and policy-makers when assessing the sustainability of individual LID-BMPs projects (Zuo et al., 2017).

LCA studies of LID-BMPs are now widely acceptable, However, in order to further prompt the research and application, the current research results of these evaluation need to be summarized and future research agenda need to be discussed.

1.1. Fundamentals of existing LCA method

LCA can be traced back to 1960s in the study area of packaging field (Zuo et al., 2017). At present, with the rapid development and further research, LCA has been recognized as a motivation mechanism in government policies to promote sustainable development. Nowadays, the applications of LCA are extensive, including product design, strategic planning, and marketing, process improvements. LCA provides an opportunity to address a product or a system in a

Table 1
Introduction of eight commonly used LCA models.

LCA Models	Owner	Website	Description
eBalance	China. IKE company	http://www.ike-global.com/archives/738.html	The first Chinese LCA software with independent intellectual property rights.
LCAiT	Swedish Chalmers Industriteknik.	https://lcait.com/	Providing energy, fuel production and logistics, chemicals, plastics, pulp and paper products database.
GaBi	Germany, Thinkstep Global Headquaters.	http://www.gabi-software.com	Including 800 different energy and material processes. Providing 400 kinds of industrial processes.
PEMS	British Pira International Company.	http://tbt.testrust.com/zt/co2/8-react-202.html	Parameters mainly adopts the European data, and not be modified or edited by oneself.
SimaPro	Netherlands.	http://www.pre-sustainability.com/simapro	Incorporating a number of LCIs including ecoInvent and a number of impact assessment methods. It has the most detailed database in the manufacturing stage.
TALLY	United States.	http://choosetally.com	The first LCA app that calculate the environmental impacts of your building material selections directly in an Autodesk® Revit® model.
IMPACT	England.	http://www.impactwba.com/	Measuring the embodied environmental impact and life cycle cost performance of buildings. Integrated into 3D CAD/BIM (Building Information Modeling) software tools.
eTool LCA	Perth, Australia.	http://etool.net.au/	Life Cycle Design software for the built form. It only can calculate GWP.

holistic approach and to understand the resulting impacts and their causes. So far, approaximately nine models are available worldwide to assist LCA. Table 1 presents the eight commonly used LCA softwares worldwide. Most models are developed by developed countries, but many of them are location-specific and may not occupy an international market. Users should choose suitable model according to their database, products, and processes.

1.2. *Fundamentals of existing LCC method*

The conventional costs of all LID-BMPs were assessed through the LCC method. The history of LCC originated from procurement techniques in the 1930s. Subsequently, LCC was widely used into different industries, and many standards that cover LCC were conducted (Zuo et al., 2017). LCC is a framework for the life cycle evaluation of costs that may be used along with or independently from LCA (Swarr et al., 2011). The steps involved in LCC are similar to those in LCA but do not include an environmental impact assessment phase (Xu et al., 2014, 2017). The flowchart of the LCC methodology is presented in Fig. 1. In the LCC flowchart, the cost of raw materials, labor, additional equipment and mainenance of the construction, operation, and maintenance stages are considered. All the inputs and outputs are listed based on functional unit. Several commonly used modeling tools for LID-BMPs economic assessment are shown in Table 2.

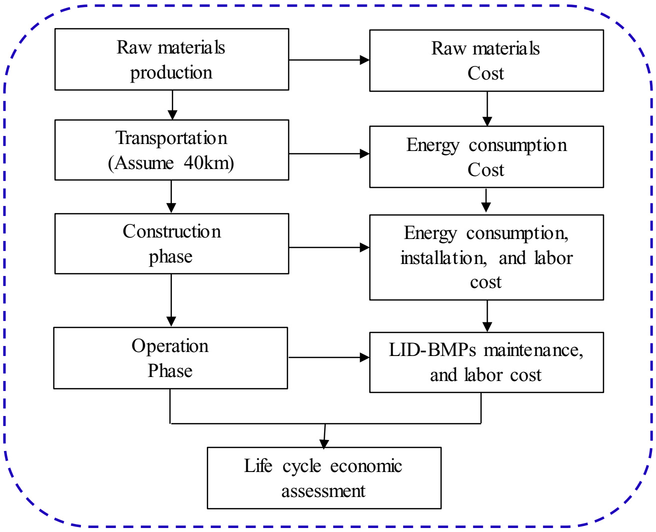

Fig. 1. The flowchart of LCC for LID-BMPs methodology.

In numerous developing countries, LCA or LCC research on LID-BMPs is scarce. This is mainly because the national implementation of LID-BMPs is later than developed countries (Güneralp et al., 2017). China is considered as an example to introduce certain difficulties encountered in LID-BMP implementation given its regional scale construction of LID-BMPs in recent years. In China, studies on the evaluation of LID-BMPs through LCA and LCC have yet to be published in international journals. Xu et al. (2017) attempted to use LCA specific to LID-BMPs in China. LCA of LID-BMPs is a relatively new area of research and is a powerful tool toward sustainable and restorative planning and design. The experience of worldwide studies on LCA and LCC of LID-BMPs should be summarized for the practical application of LID-BMPs.

This research presents a review of LID-BMPs evaluation through a life cycle perspective. In particular, the use of LCA and LCC of LID-BMPs worldwide is reviewed. In addition, knowledge gap and future research agenda are proposed.

2. Methodology

This study conducted a comprehensive review by using the content analysis method (Elo and Kyngäs, 2008) to achieve research objectives and provide academics an in-depth understanding of the research areas and structure in environmental and economic evaluation of LID-BMPs through a life cycle perspective. The main steps of content analysis are shown in Fig. 2. First of all, defining the concept to analysis, such as searching for the relevant literature based on the specific words or phases in the title and abstracts. Then, distinguishing these concepts by investigating the selected studies to remove the duplicates. What's more, coding the texts to confirm suitable papers for reviewing by eliminating “irrelevant” information. The out of focus knowledge areas and LID-BMPs evaluation that do not through a life cycle view were used as the exclusion criteria. Finally, analysing the selected articles in full-text to recognize the types and stages (e.g., construction, operration, and maintenance) of LID-BMPs and LCA methods (Zuo et al., 2017). In this study, the Web of Science database was choosen for content analysis. This was mainly because it has a large coverage of the most relevant and influential journals. Also, it is regarded as the most comprehensive database due to its record combined with scientific robustness (Timothy and Daniel, 2018; Thome et al., 2016).

Table 2
Introduction of five commonly used LCC models.

LCC Tools	Owner	Website	Description
GI-Val	The Mersey Forest.	http://www.merseyforest.org.uk/services/gi-val/	Identifying the marginal benefit, the additional value of the LID-BMPs and trying to ensure that there is no 'double counting' of value.
BMP and LID whole life cycle cost modeling tools	Water Environment Research Foundation (WERF), Alexandria.	http://www.werf.org/i/a/Ka/Search/ResearchProfile.aspx?ReportId=SW2R08	Providing a framework for calculating life-cycle costs (capital, land, and operation/maintenance costs) of LID-BMPs.
The National GVC	Center for Neighborhood Technology, Chicago.	http://greenvalues.cnt.org/national/calculator.php	Comparing the performance, costs, and benefits of Green Infrastructure, or LID-BMPs quickly.
SUSTAIN	United States Environmental Protection Agency.	https://www.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain	Evaluating cost effectiveness of GI and selecting the most cost-effective solution in stormwater quality. The cost database in SUSTAIN is expressed in terms of unit costs of individual construction components of a LID-BMP.
LIDRA	eDesign Dynamics, New York Open SourceWeb-Based tool.	http://www.lidratool.org/database/database.aspx	Comparing the cost effectiveness of reducing runoff with different LID technologies. Users can run LIDRA simulations for free

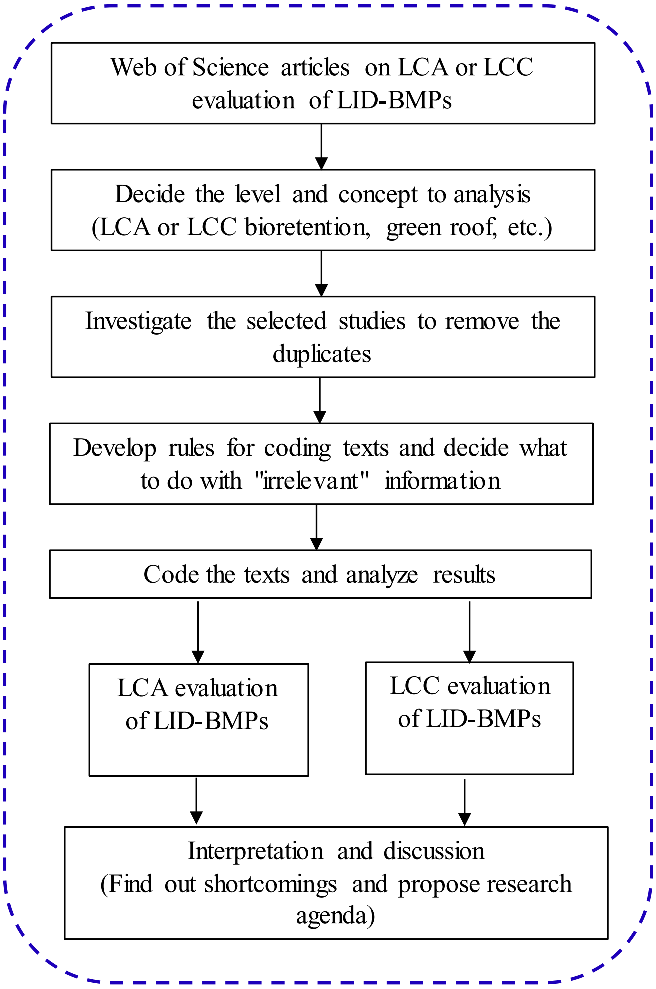

Fig. 2. Main steps of content analysis method.

3. Review results and discussion

3.1. Literature search results

The review results are shown in Fig. 3 after searching the keywords, removing the duplicates, and analysisng the content from the Web of Science, the results are shown in Fig. 3. Fig. 3a depicts that the initial study related to the LCA/LCC evaluation of LID-BMPs can date back to 2006, before 2006, no study on this field was found. Besides, the number of papers increased from 2006 to 2017, but the total number was not that much. This phenomenon revealed that LCA/LCC evaluation of LID-BMPs is a relatively undeveloped area of study. Fig. 3b presents keywords search results but we find that studies are mainly confined to green roof (i.e., 45), constructed wetland (i.e., 15), and bioretention (i.e., 6). Other LID-BMPs study were relatively few. Fig. 3c shows the publications by the top fifteen journals in number of papers. Results depicts publications of LCA/LCC evaluation of LID-BMPs derived from a variety of journals which is mainly because this research field is interdisciplinary. Noteworthy, many studies are come from international conferences. This phenomenon reveals that face-to-face exchanges is an favor option for many researchers in some extent.

Thome et al. (2016) presented a systematic review of the extant literature in sustainable infrastructure and found that the fields of LID-BMPs and green infrastructures are relatively new, lively, and ever growing. According to the literature search results in section 3.1, LCA/LCC evaluation of green roof, constructed wetland, and bioretention are much more than other LID-BMPs. Sections 3.2 have shown detailed LCA/LCC evaluation on them. Table 3 presents a brief summary of worldwide LCA/LCC studies on LID-BMPs. Results show that all LCA studies have been conducted in developed countries, such as America, Canada, Austrilia, and European countries. In Asia, especially in China, no studies on the evaluation of LID-BMPs by using LCA have been published in English-language peer-reviewed journals except that of Xu et al. (2017). This can be mainly attributed to the large scale construction of LID-BMPs was in the early stage compared with developed countries. Researchers worldwide began to focus on the LCC since the 1930s (Zuo et al., 2017), but the application on LID-BMPs started to appear only in the last decade. Studies on the LCC of LID-BMPs are less than that of LCA. As presented in Table 3, most of LCC studies were conducted in developed countries.

Above all, no matter for the number of papers or conducted types of LID-BMPs, conclusions can be drawn that LCA/LCC evaluation of LID-BMPs is a new research field. Different practices have their own advantage based on their function. Therefore, in order to provide more useful information for decision- or policy-makers, in-depth evaluation of different types of LID-BMPs should be conducted in the future research.

3.2. LCA/LCC evaluation on three most studied practices

3.2.1. Green roof

3.2.1.1. Life cycle environmental performance. Green roof is partially or completely covered with vegetation and a growing medium and

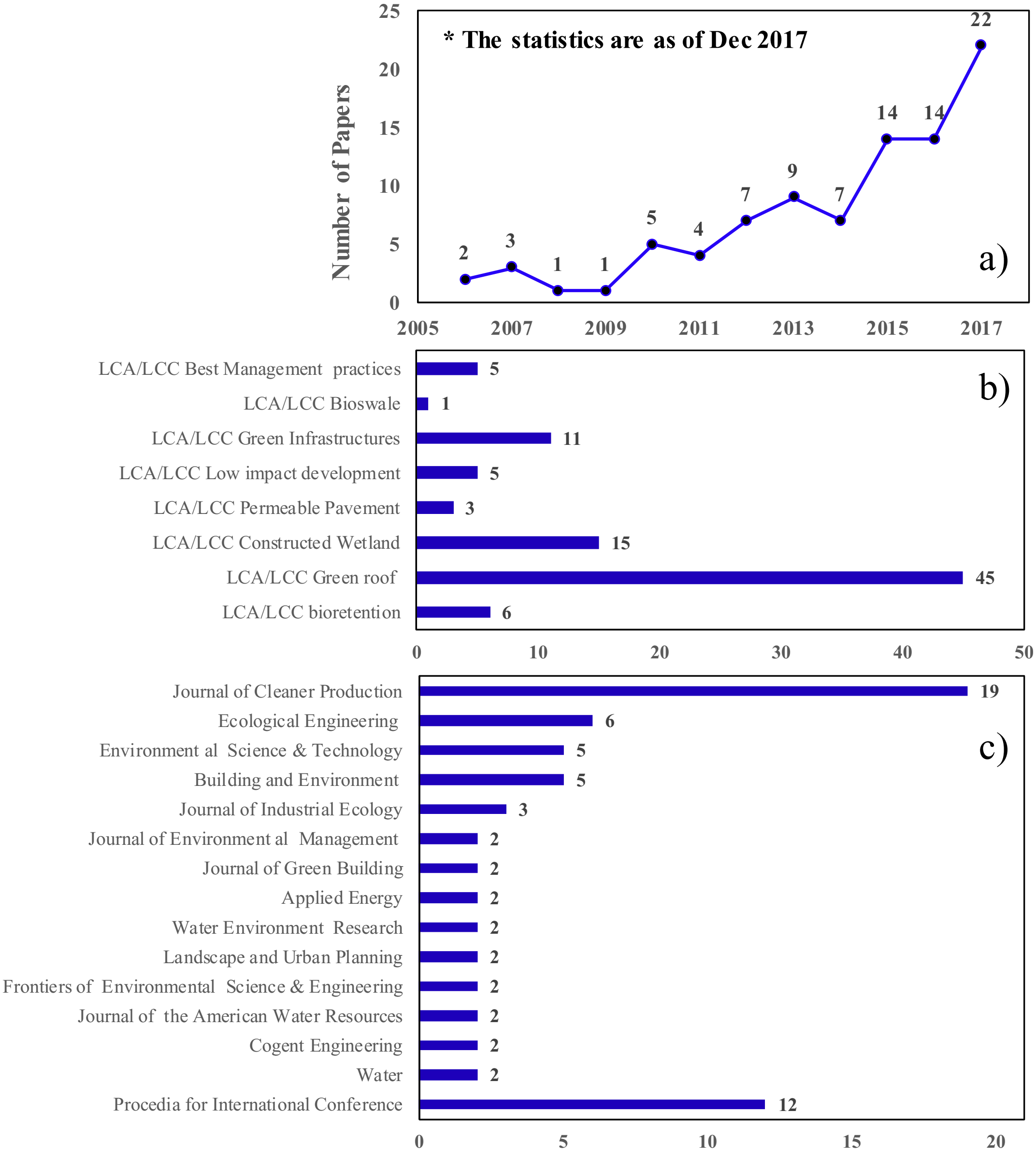

Fig. 3. Literature search results.

planted over a waterproofing membrane (Demuzere et al., 2014; Vandermeulen et al., 2011). Green roof is mainly classified into two types, namely, intensive green roof and extensive green roof (Vacek et al., 2017). Based on the statistics from Web of Science, green roof has gained the most attention with the papers number is 45. This can be mainly attributed to the multiple environmental and economic benefits. The commonly recognized environmental benefits of green roof are water pollutants mitigation (Jia et al., 2015; Jia et al., 2015), air pollution mitigation (Currie and Bass., 2008; Gwak et al., 2017; Yang et al., 2008), energy savings (Cubi et al., 2016; Pan and Chu, 2016; Gargari et al., 2016; Julia et al., 2016), runoff control (Jia et al., 2015; Liu et al., 2015; Law et al., 2017) and peak flow reduction (Jia et al., 2015; Vijayaraghavan, 2016).

Green roofs have gained global acceptance with their considerable potential in mitigating the environmental problems of urban centers compared with conventional roofs (Corrie Clark et al., 2008) and mitigate extremely climates. Jaffal et al. (2012) conducted a comprehensive study on the impact of a green roof on building energy performance, this study showed that green roofs are thermally beneficial for hot, temperate, and cold European climates. Fabricio Bianchini and Kasun Hewage (2012a) evaluated the environmental benefits of green roof by comparing the emissions of NO_2, SO_2, O_3, and PM_{10} in the production of green roof material. Results showed that green roof can balance air pollution generated from polymer production in 13–32 years. However, polymer production can cause negative environmental impacts other than air pollution. Therefore, environmentally friendly and sustainable materials should replace polymers. This suggestion was also recommended by researchers Flynn and Traver (2011) and Xu et al. (2017). Alternatives should also be evaluated using LCA. Kosareo and Ries (2007) compared the LCC and environmental effects of intensive green roofs and extensive green roofs and conventional roofs in the USA. The LCA was performed based on the different life stages of all three roofing systems (i.e., fabrication, transportation, installation, operation, maintenance, and end of life). The results

Table 3
Examples of LCA studies on LID-BMPs worldwide.

	Authors Year	LID-BMPs Type	Country	Methods	Phase Included
1	Saiz et al., 2006	Green roof	Spain	LCA	Construction, operation, and maintenance
2	Kosareo and Ries.2007	Green roof	USA	LCA and LCC	Construction, operation, maintenance, and disposal
3	Carter and Keeler.2008	Green roof	USA	Life cycle cost-benefit analysis	Construction, operation, and maintenance
4	Clark et al., 2008	Green roof	USA	Life cycle cost-benefit analysis	Construction and operation
5	Bianchini and Hewage.2012	Green roof	Canada	Eco-Indicator (H)	Construction
6	Bianchini and Hewage.2012	Green roof	Canada	Life cycle cost-benefit analysis	Construction, operation, and decommissioning
7	Dabbaghian.2014	Green roof	Canada	IMPACT 2002+	Construction and operation
8	El Bachawati et al., 2016	Green roof	Lebanon	IMPACT 2002+	Construction
9	Vacek et al., 2017	Green roof	Czech Republic	CML2001	Production, construction, use, and end of life
10	Flynn and Traver.2013	Bioretention/Rain garden	USA	LCA and i-Tree Eco	Construction, operation, and decommissioning
11	Vineyard et al., 2015	Bioretention/Rain garden	USA	LCA and LCC	Manufacturing, use, and disposal
12	Mangangka et al., 2015	Bioretention/Rain garden	Australia	–	Operation
13	Petit-Boix et al., 2015	Bioretention/Rain garden	Brazil	ReCiPe	Construction and operation
14	Wang et al., 2016	Bioretention/Rain garden	Singapore,	LCA and LCC	Construction and operation
15	Seib.2009	Constructed wetland	USA	LCA	Construction, operation, and disposal
16	Lopsik.2013	Constructed wetland	Estonia	LCA-IMPACT 2002 + and ReCiPe	Construction and operation
17	DiMuro et al., 2014	Constructed wetland	USA	LCA-TRACI and LCC	Construction and operation
18	Flynn.2011	Bioretention/Rain garden and green roof	USA	LCA-TRACI, i-Tree Eco	Construction, operation, and decommissioning
19	Spatari et al., 2011	Permeable pavement	USA	LCA	Construction and operation
20	Xu et al., 2017	LID-BMP train system	China	LCA and LCC	Construction and operation

presented that green roofs can significantly reduce the life cycle environmental impacts of a building by decreasing the energy use. Dabbaghian (2014) investigated the environmental benefits of the three types (i.e., intensive green roofs, extensive green roofs, and conventional roofs) of roofing systems. The LCA results also showed that the extensive green roof system is a more desirable option in terms of long-term sustainability performance criteria. Similarly, El Bachawati et al. (2016) compared the environmental impacts of green roofs and conventional roofs by using LCA. The results clearly indicated the extensive green roof was the best option for all environmental impact categories. Above all, green roofs are more environmetnally friendly than other types of roofs (such as PVC or bituminous layer, ceramic and cement mortar tiles) in most cases (Carretero-Ayuso and García-Sanz-Calcedo, 2018).

3.2.1.2. Life cycle economic performance. Life-cycle costing of green roofs is also an important key factor of its application. There are some factors that can influence the cost of green roof, such as the plant's types, the waterproofing layers, and the life span (Shafique et al., 2018). Fabricio Bianchini and Kasun Hewage (2012b) conducted a life cycle net cost–benefit analysis of extensive green roof and intensive green roofs that considered manufacturing, construction, operation, and decommissioning phases. Results demonstrated that the potential profit of green roofs is considerably higher than its potential losses. In addition, they suggested that future research should reuse the waste materials in green roof construction to increase economic and environmental benefit. Peng and Jim (2015) also conducted an economic evaluation of extensive and intensive green roofs. The results presented that the extensive green roof is more economical than intensive green roof in terms of benefit–cost ratio and payback time. The assumed 40-year life cycle benefit–cost ratio of extensive green roof is 3.84 with a payback period of 6.8 years, whereas the equivalent values for intensive green roof are 1.63 and 19.5 years, respectively. Kosareo and Ries (2007), Clark et al. (2008), Carter and Keeler (2008), and Bianchini and Hewage (2012b) also have presented the economic benefits of green roof. However, these studies showed that the cost of construction and mainenance are some challenges faced with the application of green roofs.

3.2.2. Bioretention

3.2.2.1. Life cycle environmental performance. Bioretention, also called rain garden, is a novel stormwater treatment practice that uses a mixture of soil/sand/mulch as adsorptive filtration media that can capture pollutants generated by urban runoff (Houng Li, 2008). This approach is one of the most commonly used LID-BMP facilities to gather and absorb rainwater. Bioretention emissions may be offset by the sequestration of carbon dioxide and the filtration of air pollutants by its plant life (Flynn and Traver, 2011). Flynn and Traver (2013) conducted a complete LCA analysis of bioinfiltration in the USA through construction, operation, and decommissioning stages. The results showed that the construction phase is the main contributor to the overall environmental effects. However, carbon emissions can be offset by the operation phase in approximately 4 years. Vineyard et al. (2015) used LCA to used LCA to compare environmental impacts of bioretention and traditional wastewater utilities, including material extraction, manufacturing, use, and disposal stages. Results showed that bioretention was more environmentally than traditional wastewater utilities because it has a 62%–98% reduction of environmental impact. Wang et al. (2016) conducted an LCA analysis for a bioretention through construction, operation, and maintenance stages. They found that maintenance contributed most (35.6%) of the climate change and transport was the second greatest contributor (30.2%).

3.2.2.2. Life cycle economic performance. Wang et al. (2016) assessed the capital costs and operation and maintenance (O&M) costs for bioretention systems through LCC analysis over an assumed life cycle of 35 years. Their findings indicated that maintenance and transportation are the most critical elements of LCC and LCA and that rigorous management of maintenance and transportation is crucial to improve the cost–benefit of bioretention. An LCC analysis of bioretention was conducted by Flynn and Traver (2013). Their results showed that the total cost of the construction phase of bioretention is approximately 1.55 × 10^5 USD/per hectare of impervious drainage area (ha-IDA). Xu et al. (2017) also conducted an economic analysis of LID-BMPs, which includes bioretention, grassed swale, infiltration pit, constructed wetland, and buffer strip. Moreover, these factors were quantitatively assessed. The total cost of the construction phase of LID-BMPs is approximately 1.31 × 10^5 USD/ha-IDA. The two results are consistent under the same functional unit (/ha-IDA). Chui et al. (2016) assessed the cost-effectiveness of specific LID practice (such as GR, bioretention, and porous pavement) designs in response to large storm events by using LCC, including land cost, construction cost, and O&M costs. The results indicated that porous pavement is the most cost-effective practice for peak flow reduction.

3.2.3. Constructed wetland

3.2.3.1. Life cycle environmental performance. Constructed wetland is another popular LID-BMP practice because of its acceptable performance in water and air quality purification. At present, most LCA studies of constructed wetland were conducted by analysing different environmental impact categories. Matt Seib (2009) conducted LCA analysis of a treatment wetland through assembly, operation, and disposal stages. Results showed that respiratory inorganics and fossil fuel categories are the most significant categories because of their materials for construction and transportation. These results allow future designers to consider alternative materials, configurations, and management options for wetland design to minimize impact. DiMuro et al. (2014) also conducted an LCA analysis of constructed wetland and demonstrated that lower energy and material inputs to the constructed wetland results in low potential impacts for fossil fuel use, acidification, smog formation, and ozone depletion. Lopsik (2013) presented an LCA analysis of a small-scale constructed wetland in Estonia. The system boundary included construction and operation phases. They concluded that the construction phase and the use of lightweight expanded clay aggregate in constructed wetlands mainly contribute environmental impacts. Wang et al. (2018) evaluated a field tidal flow constructed wetland and traditional constructed wetland for wastewater treatment through environmental impacts. Results indicated that electricity consumption of water pump, which is used for creating tidal flow, was the most contributor to almost all impact categories. The vegetation mitigation CO_2 effect of tidal flow constructed wetland was marginal compared with traditional constructed wetland. The environmental performance of constructed wetland should be evaluated through different factors (e.g., life cycle stage, energy consumption, emissions mitigation).

3.2.3.2. Life cycle economic performance. DiMuro et al. (2014) compared the cost of constructed wetland and gray infrastructures. The financial break-even point of gray infrastructures is approximately two years. After two years, the total cost of gray infrastructures is higher than that of constructed wetland year by year. The low energy and resource requirement and the low O&M support are the main contributors. Tupper (2012) evaluated the LCC of LID-BMPs and traditional gray infrastructures and found that the construction cost of LID infrastructures was 34% higher than the traditional development. However, from the operation perspective, the LID-BMPs provide competitive environmental and economic potential compared with gray infrastructures. Demuzere et al. (2014) estimated the benefits of LID-BMPs through climate change mitigation and adaptation. Maria Raquel et al. (2016) evaluated the potential climate change impacts of LID-BMPs vegatations. Kumari and Kumar Sharma (2016) reviewed the research literature on infrastructure and related issues and presented the results in a systematic manner. These studies revealed that infrastructure is the backbone of all economic and social activities; it helps reduce barriers to national development such as unemployment, poverty, regional imbalances, and low productivity.

3.3. Limitations of current research

3.3.1. Green and gray infrastructure comparison

In addition to the evaluation of single LID-BMP practice, the comparison of green and gray infrastructures is important to scientifically assess the performance of LID-BMPs. A complete LCA analysis of the construction, operation, and maintenance phases of green (such as porous pavements, bioretention, and infiltration pit) and gray combined sewer overflow (CSO) control strategies was conducted by De Sousa et al. (2012). GHG emissions (t CO_2-eq) were considered as the evaluation objective. Evidently, green strategies exhibit considerable potential to reduce CSOs and carbon emissions. Comparisons of green (such as bioretention) and gray (such as pre-fabricated concrete vortex unit and sub-surface sandfilter) infrastructures were conducted by O'Sullivan et al. (2015) through LCA analysis. The environmental effects associated with materials, construction, transport, operation, and maintenance were quantified, and the results indicated that bioretention exerted the lowest environmental impact because of the low maintenance and no concrete construction. An integrated environmental assessment of green (such as permeable pavement and bioretention) and gray (such as existing combined sewer systems) infrastructures has been conducted by Casal-Campos et al. (2015), and green infrastructure alternatives were found to be more environmentally beneficial than their gray infrastructure counterparts. In addition, they suggested that a combination of green and gray infrastructures may exert a mutually beneficial effect. Tiwary and Kumar (2014) provided an emerging perspective to urban ecosystem service of impact evaluation of green–gray infrastructure interaction. A comparison of hypothetical green (such as bioretention, green roof, and permeable pavement) and gray infrastructures was conducted by Wang et al. (2013). They pointed out that green infrastructures can achieve better water quality improvement goals than gray infrastructures.

Most studies only made comparisons of green and gray infrastructures, few made a combination of them. Results presented that green infrastructures can achieve better water quality and quantity control performance, however, green infrastructures can't replace the gray infrastructures completely considering the safety during extreme storm events, the economic cost and benefit also should be considered. In future research, it would be very important to optimize the proportion of green infrastructures and gray infrastructures system under the multi-criteria of environment, economy and safety benefits.

3.3.2. Regional scale evaluation

Studies mentioned above only considered specific LID-BMP case research, regional scale evaluation is rare. However, it is important for policy- and decision-makers to implement LID-BMPs. Few studies made regional scale research. Zhan and Chui (2016) attempted to calculate the life cycle net benefit of LID practices (such as green roof, bioretention, and porous pavements) in a city scale (i.e., Hong Kong). In addition, they quantitatively presented 30-year economic benefits of LID-BMPs are 5.3 billion USD. The research provided a framework to quantify and evaluate the LCC and benefits of LID-BMPs to modify these assumptions based on local condition for application to numerous other cities worldwide.

Chen (2015) presented a nationwide study on how urban LID-BMPs can contribute to the carbon balance through the entire life cycle in 35 major Chinese cities. The estimated carbon storage amounts is approximately 18.7 million tons, with an average carbon density of 21.34 t/ha. These experiences should be applied to improve China's LID-BMP implementation.

3.4. *Research of LID-BMPs performance in China*

As previously mentioned, emerging and developing countries lack the LCA studies of LID-BMPs. However, the researches on the LID-BMPs performance on water quality and quantity control are extensively reported. This study takes China as an example to show the current research of LID-BMPs because of the Sponge City construction project.

Fig. 4 shows the LID-BMPs construction situation of the 16 first pilot sponge cities in China in 2017. Results indicated that bioretention, porous pavement, and grassed swale are the most popular practices, while rain barrels, sunken green belt, and seepage well are seldom built. This phenomenon can be mainly attributed to the good performance in controlling runoff of bioretention, porous pavement, and grassed swale. Selecting the proper LID-BMPs are rather significant for urban runoff control because of the complicated climate, geography, population, and economic growth in China. Future studies should make more accurate assessment of the LID-BMPs performance (e.g., environmental, economic, and social) to provide useful and credible information for decision and policymakers in appropriate implementing LID-BMPs.

3.4.1. *Environmental performance*

After the China National Knowledge Internet (CNKI) from 1979 to 2017 was searched with the subject of LID-BMPs, the related literature approximately reached 140. The literature includes engineering measures, planning schemes, and experimental facilities. The results of the runoff control performance (quality and quantity) (Jin et al., 2008; Shi et al., 2007; Wang et al., 2008; Zeng, 2003; Sun et al., 2009; Cheng et al., 2009a,b; Huang et al., 2010) and cost information (Chen et al., 2014; Lu, 2013; Qi, 2013; Wang et al., 2009; Ye et al., 2004; Yan, 2011; Zhou et al., 2011) were collected, but onsite monitoring data, such as runoff volume (Chen et al., 2006; Cheng et al., 2009a,b; Ou and Che, 2001; Shan et al., 2006; Xu et al., 2005) and pollutant removal efficiency (Xiao et al., 2010; Li et al., 2010, 2014; Zhou et al., 2011; Meng et al., 2013; Wei, 2014) were few. The detailed distribution and types of LID-BMPs conducted in China are presented in Fig. 5. Results presented that these researches are mainly from Beijing, Shanghai, Shenzhen, and Wuhan cities which can be attributed to the fast economic and population growth in these cities. The LID-BMPs are mainly targeted on bioretention, constructed wetland, and permeable pavement, this results are similar to Fig. 4.

Most Chinese literature focused on volume analysis, including runoff reduction and peak flow reduction. Few studies focused on water quality. The average removal efficiency of Chinese studies on LID-BMPs is presented in Table 4.

These studies showed that the lack of onsite data of LID-BMPs in China is a considerable challenge for further research because the inlets and outlets, such as permeable pavement, of certain LID-BMPs cannot be defined easily. Inappropriate monitoring method is also another reason. Moreover, some provincial and local government officials lack enthusiasm, which serves an important function. The MOHURD issued a monitoring guide in the late 2017. The guide presented detailed information on how to monitor velocity, volume, and quality. An explicit table for pollutant removal rate and design parameters was also required. This action is useful in developing the Chinese LID-BMP database.

3.4.2. *Economic performance*

Cost analysis can add reliability and veracity to the planning optimization of LID-BMP arrangement. Similar to the LCA studies of LID-BMPs, several LCC studies were conducted by Chinese researchers (Chen et al., 2014; Ma et al., 2013). Chen et al. (2014) performed a cost-benefit analysis of 15 LID practices in China. The results showed that LID practices offer considerble potential in economic benefit (such as reduced costs of stormwater runoff permit, CSO control, rainwater infiltration and purification, flooding control, and heat stroke prevention). The same results were also reported by Ma et al. (2013) that the cost–benefit ratio of LID in China was markedly superior to that of traditional rainwater control strategies. In addition, the social benefit that alleviates the contradiction between water supply and demand was considered. Finally, they pointed out that China lacks economic data and that further research on cost-effectiveness analysis of LID-BMPs is required. Lu et al. (2013) presented a case study and calculated the cost-benefit of bioretention and permeable pavement in Beijing,

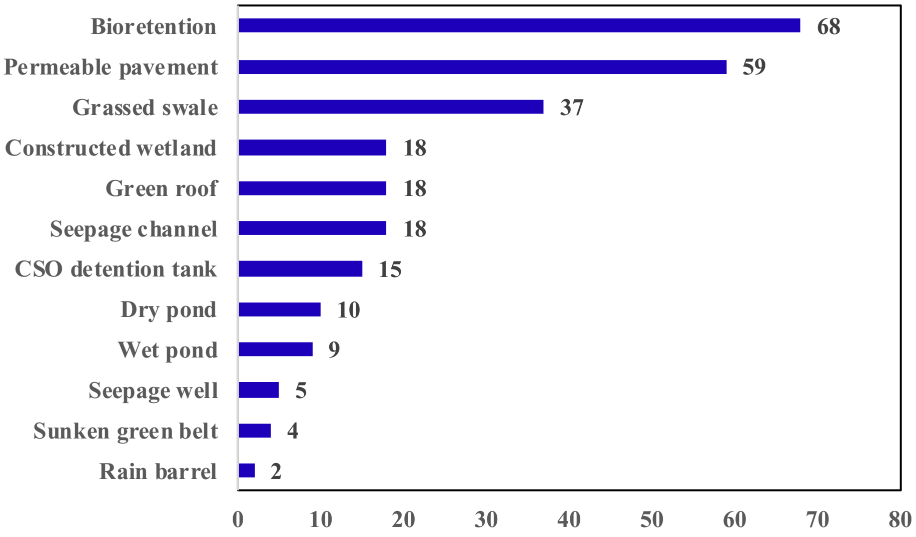

Fig. 4. LID-BMPs construction in China in 2017.

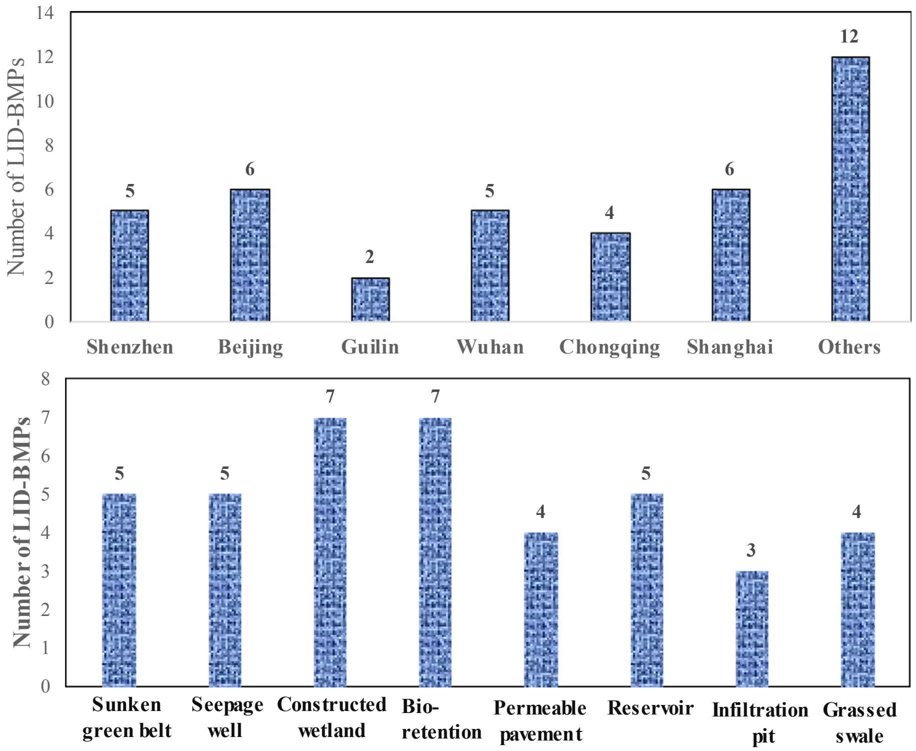

Fig. 5. Distribution and types of LID-BMPs constructed in China.

Table 4
Average removal efficiency of the Chinese studies on LID-BMPs.

LID-BMPs type	Pollutants removal rate (%)								
	BOD	COD	SS	NH_3–N	NO_3–N	TP	TN	Pb	Zn
Concaved down green area	–	51.65	–	60.39	–	54.88	33	–	–
Seepage ditch	70	72.75	75.47	52.5	50	69.48	55.7	–	–
Constructed wetland	44.75	86.23	71.18	67.07	–	70.56	85.33	62.71	–
Bioretention	71.85	59.1	79.15	65.45	–	72	73.9	–	–
Permeable pavement	–	62	34.93	39	75.55	57	53	60	60
Reservoir	19.9	41.88	59.32	21.62		20.05	15		
Infiltration pit	40	77.97	90			85.11	69.93		
Grassed swale	–	26.7	46.25	44.7	−6.8	51.4		98	97

China. Their results indicated that the total costs of bioretention and permeable pavement are 89,895 and 60,458 USD, respectively. The total economic benefit is 5778 USD per year, and the payback times of bioretention and permeable pavement are approximately 14 and 9.5 years, respectively.

At present, several Chinese studies focus on the total cost of runoff control project of a campus and a housing estate, and other studies focus on the separate LID-BMPs. The Sponge City Construction Technology Guide (MOHURD, 2014) showed several reference prices of Beijing LID-BMP projects. However, the cost data were evaluated through the floor space rather than the detailed cost through the entire life cycle, which includes excavation, construction, planning, and operation. A review on Chinese research on the cost of LID-BMPs through CNKI was conducted (Table 5).

Table 5
Chinese research about the cost of LID-BMPs.

LID-BMPs type	Unit	Min	Max
Sunken green belt	RMB/m^2	200	300
Bioretention	RMB/m^2	500	1200
Permeable pavement	RMB/m^2	326	1500
Reservoir	RMB/m^2	30	100
Infiltration pit	RMB/m^2	3500	9000
Grassed swale	RMB/m^2 drainage area	60	450
Green roof	RMB/m^2	576	1600
Wet pond	RMB/m^2	200	1100

RMB: Abbreviation of renminbi, Chinese yuan. (1 RMB is equal to 0.14 USD).

3.5. *Summary of literature results*

3.5.1. *Summary of environmental performance*

Different LID-BMPs perform their own functions to control stormwater runoff quality and quantity. In that way, the water footprint was reduced and the virtual water utilization was increased. But the current research only considered stormwater, so the detailed water footprint and virtual water assessments were not introduced. From the life cycle environmental perspective, each practice offers its own advantage in environmental effect. Therefore, conclusions cannot be simply drawn as to which practice is the most or least environmentally beneficial. For all practices, operation phase can generate better environmental benefit because of the reduced air and water pollutants. On the contrary, construction and maintenance phases generated highest environmental burdens due to the raw materials utilization. Accordingly, the efficiency of raw materials should be improved and optimized. For green and gray infrastructures comparison, most studies showed that green infrastructures are more environmentally friendly than gray ones. But studies also show that in some cases, the combination of green and gray infrastructures can achieve good environmental performance. For further research, especially for Asian countries, the experiences of developed countries should be summarized to promote the implementation of LID-BMPs.

3.5.2. *Summary of economic performance*

From the life cycle economic view, operation stage of LID-BMPs can provide significant economic benefit because of reduced peak flow and total runoff volume. However, construction and maintenance phases can generate high economic burdens. The disposal stage can be treated through two approaches, namely, discarding and recycling. At present, most LID-BMPs are in the operation stage. The disposal stage lacks detailed data for conducting a research, but certain studies developed an idealized model based on the construction phase to calculate the environmental and economic burden and benefit of the disposal stage. Besides, extremely few studies offered the evaluation through a unit area or a certain functional unit, thus, it's hard to compare the economic cost or benefit among different practices. Accordingly, the efficiency of raw materials should be improved and optimized, and evaluations based on certain functional unit should be presented. Future research on economic assessment of LID-BMPs should be holistically analyzed through the entire life cycle, especially in China.

4. Conclusion and future research agenda

This review analyzed studies related to the LCA/LCC evaluation of LID-BMPs from 2006 to 2017. Based on the discussion, the following conclusions can be drawn:

- For life cycle environmental assessment, operation stage generated environmental benefit while construction and maintenance generated highest environmental burdens.
- In most cases, green infrastructures are more environmentally friendly than gray infrastructures.
- The efficiency of raw materials should be improved and optimized to reduce the environmental effects of construction and maintenance stages.
- For life cycle economic assessment, operation stage generated economic benefit while construction and maintenance generated high economic burdens.
- At present, the disposal stage lacks detailed data due to most LID-BMPs are still in the operation stage.
- Most studies only considered on-site or facility scale evaluation, regional scale evaluation is extremely few.
- In China, lack of the onsite data is the biggest challenge in LID-BMPs evaluation. However, along with the national pilot sponge city construction many onsite data would be available in the near future.

Results indicated that LCA and LCC evaluation of LID-BMPs is an expanding research field. LID-BMPs offer various benefits to urban eco-systems, generating environmental benefits by mitigating air pollutants and water pollutants. Also, LID-BMPs provide economic benefits by reducing the cost of water treatment and energy consumption. The social service value is another aspect that LID-BMPs can offer. Therefore, their regional scale application has been widely prospected although the multidisciplinary nature of regional scale application causes considerable challenges. However, as shown before, certain limitations exit. Studies related to the quantitatively evaluation of ecological service value extremely few. At present, most countries, especially developing countries, lack the indigenized LCA and LCC research on LID-BMPs. Besides, very few studies have considered comprehensive benefits (such as economic, environmental, social benefits) or the different types of LID-BMPs at a regional scale. Moreover, onsite monitoring data are significant in guiding the future application of LID-BMPs while few cities have monitored operation data. Finally, the lack of disposal data is another limitation that affects the whole life cycle assessment of LID-BMPs.

Therefore, future research should address numerous scientific and technical challenges to present an increasingly systematic and credible assessment. First, efficient target-oriented LCA and LCC studies on LID-BMPs should be conducted, and a detailed database on LID-BMPs construction and operation phases should be established. Second, modification and optimization of current construction materials and development of novel materials should continue to obtain better environmental and economic benefits. Third, the generality and individuality of different types of LID-BMPs should be proposed to guide further in-depth studies. Finally, the development of LID-BMPs with high environmental, economic, and social benefits of regional scale application should lead to future progress to satisfy the requirements of sustainability. In brief, joint experimental, computational, and practical investigations can provide comprehensive insight into LID-BMPs.

Acknowledgement

This work was supported by the National Water Pollution Control and Treatment Science and Technology Major Project of China (Grant No. 2017ZX07103–002 and 2017ZX07205), Beijing Nature Science Foundation Project (Grant No. 8161003), the National Nature Science Foundation of China (Grant No.51778319), and Tsinghua University (School of Architecture) CIFI Group Joint Research Center for Sustainable Community (Grant No. R201). The research is also supported by Jiangsu Collaborative Innovation Center of Technology and Material of Water Treatment (Suzhou 215009, China)..

References

Baek, S.S., Choi, D.H., Jung, J.W., Lee, H.J., Lee, H., Yoon, K.S., Cho, K.H., 2015. Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: experimental and modeling approach. Water Res. 86, 122–131. https://doi.org/10.1016/j.watres.2015.08.038.

Bianchini, F., Hewage, K., 2012a. How “green” are the green roofs? Lifecycle analysis of green roof materials. Build. Environ. 48, 57–65. https://doi.org/10.1016/j.buildenv.2011.08.019.

Bianchini, F., Hewage, K., 2012b. Probabilistic social cost-benefit analysis for green roofs: a lifecycle approach. Build. Environ. 58, 152–162. https://doi.org/10.1016/j.buildenv.2012.07.005.

Brown, R.A., Hunt, W.F., 2011. Impacts of media depth on effluent water quality and hydrologic performance of undersized bioretention cells. J. Irrigat. Drain. Eng. 137, 132–143. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000167.

Carretero-Ayuso, M.J., García-Sanz-Calcedo, J., 2018. Comparison between building roof construction systems based on the LCA. Revista de la Construcción. Journal of Construction 17 (1), 123–136. https://doi.org/10.7764/RDLC.17.1.123.

Carter, T., Keeler, A., 2008. Life-cycle cost–benefit analysis of extensive vegetated roof systems. J. Environ. Manag. 87 (3), 350–363. https://doi.org/10.1016/j.jenvman.2007.01.024.

Casal-Campos, A., Fu, G., Butler, D., Moore, A., 2015. An integrated environmental assessment of green and gray infrastructure strategies for robust decision making. Environ. Sci. Technol. 49, 8307–8314. https://doi.org/10.1021/es506144f.

Chapman, C., Horner, R.R., 2010. Performance assessment of a street-drainage bioretention system. Water Environ. Res. 82, 109–119. https://doi.org/10.2175/106143009X426112.

Chen, T., Li, W., Zhang, Y., 2014b. Cost-benefit analysis of low rainfall impact development (LID) measures in typical cities. Southwest Water & Wastewater 36 (2), 41–46 (in Chinese).

Chen, W.Y., 2015. The role of urban green infrastructure in offsetting carbon emissions in 35 major Chinese cities: a nationwide estimate. Cities 44, 112–120. https://doi.org/10.1016/j.cities.2015.01.005.

Chen, X., Peltier, E., Sturm, B.S., Young, C.B., 2013. Nitrogen removal and nitrifying and denitrifying bacteria quantification in a stormwater bioretention system. Water Res. 47, 1691–1700. https://doi.org/10.1016/j.watres.2012.12.033.

Chen, Q.F., Shan, B.Q., Yin, C.Q., 2006. Application of eco-concrete for controlling stormwater pollution from urban sloping-land. Tech. Equip. Environ. Pollut. Control 7 (11), 23–28 (in Chinese).

Cheng, J., Yang, K., Huang, M.S., 2009a. Reduction effect of sunken green space on urban rainfall-runoff pollution. China Environ. Sci. 29 (6), 611–616 (in Chinese).

Cheng, J., Lv, Y.P., Huang, X.F., 2009b. Environmental effects of combined sewage detention tank in central Shanghai. Environ. Sci. J. Integr. Environ. Res. 30 (8), 2234–2240 (in Chinese).

Clar, M.L., Barfield, B.J., O'Connor, T.P., 2004. Stormwater Best Management Practice Design Guide Volume 2 Vegetative Biofilters. Environmental Protection Agency. http://nepis.epa.gov/Adobe/PDF/901X0B00.PDF(2/28/2010).

Chui, T.F.M., Liu, X., Zhan, W., 2016. Assessing cost-effectiveness of specific LID practice designs in response to large storm events. J. Hydrol. 533, 353–364. https://doi.org/10.1016/j.jhydrol.2015.12.011.

Cubi, E., Nicholas, F.Z., Sarah, J., Joule, B., 2015. Sustainability of rooftop technologies in cold climates: comparative life cycle assessment of white roofs, green roofs, and photovoltaic panels. J. Ind. Ecol. 249–262. https://doi.org/10.1111/jiec.12269.

Currie, B.A., Bass, B., 2008. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. Urban Ecosyst. 11 (4), 409–422. https://doi.org/10.1007/s11252-008-0054-y.

Clark, C., Adriaens, P., Talbot, F.B., 2008. Green roof valuation: a probabilistic economic analysis of environmental benefits. Environ. Sci. Technol. 42 (6), 2155–2161. https://doi.org/10.1021/es0706652.

Dabbaghian, M., 2014. Water Quality and Lifecycle Assessment of Green Roof Systems in Semi-arid Climate. Doctoral dissertation. University of British Columbia.

De Sousa, M.R., Montalto, F.A., Spatari, S., 2012. Using life cycle assessment to evaluate green and grey combined sewer overflow control strategies. J. Ind. Ecol. 16 (6), 901–913. https://doi.org/10.1111/j.1530-9290.2012.00534.x.

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A.G., Mittal, N., Feliu, E., Faehnle, M., 2014. Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. J. Environ. Manag. 146, 107–115. https://doi.org/10.1016/j.jenvman.2014.07.025.

Dietz, M.E., 2007. Low impact development practices: a review of current research and recommendations for future directions. Water, Air, Soil Pollut. 186 (1–4), 351–363. https://doi.org/10.1515/eces-2015-0032.

DiMuro, J.L., Guertin, F.M., Helling, R.K., Perkins, J.L., Romer, S., 2014. A financial and environmental analysis of constructed wetlands for industrial wastewater treatment. J. Ind. Ecol. 18, 631–640. https://doi.org/10.1111/jiec.12129.

Eckart, K., McPhee, Z., Bolisetti, T., 2017. Performance and implementation of low impact development - a review. Sci. Total Environ. 607–608, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254.

El Bachawati, M., Manneh, R., Belarbi, R., Dandres, T., Nassab, C., El Zakhem, H., 2016. Cradle-to-gate Life Cycle Assessment of traditional gravel ballasted, white reflective, and vegetative roofs: a Lebanese case study. J. Clean. Prod. 137, 833–842. https://doi.org/10.1016/j.jclepro.2016.07.170.

Elo, S., Kyngäs, H., 2008. The qualitative content analysis process. J. Adv. Nurs. 62 (1), 107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2014. SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. Urban Water J. 12, 525–542. https://doi.org/10.1080/1573062X.2014.916314.

Flynn, K.M., Traver, P.R.G., 2011. Evaluation of Green Infrastructure Practices Using Life Cycle Asessment. Doctoral dissertation. Villanova University.

Flynn, K.M., Traver, R.G., 2013. Green infrastructure life cycle assessment: a bio-infiltration case study. Ecol. Eng. 55, 9–22. https://doi.org/10.1016/j.ecoleng.2013.01.004.

Gargaria, C., Bibbianib, C., Fantozzia, F., Alberto, C., 2016. Environmental impact of Green roofing: the contribute of a green roof to the sustainable use of natural resources in a life cycle approach. Agriculture and Agricultural Science Procedia 8, 646–656. https://doi.org/10.1016/j.aaspro.2016.02.087.

Güneralp, B., Lwasa, S., Masundire, H., Parnell, S., Seto, K.C., 2017. Urbanization in Africa: challenges and opportunities for conservation. Environ. Res. Lett. 13 (1), 015002.

Gwak, J.H., Lee, B.K., Lee, W.K., Sohn, S.Y., 2017. Optimal location selection for the installation of urban green roofs considering honeybee habitats along with socio-economic and environmental effects. J. Environ. Manag. 189, 125–133. https://doi.org/10.1016/j.jenvman.2016.12.022.

Hadjimichael, A., Morera, S., Benedetti, L., Flameling, T., Corominas, L., Weijers, S., Comas, J., 2016. Assessing urban wastewater system upgrades using integrated modeling, life cycle analysis, and shadow pricing. Environ. Sci. Technol. 50, 12548–12556. https://doi.org/10.1021/acs.est.5b05845.

Hasik, V., Anderson, N.E., Collinge, W.O., Thiel, C.L., Khanna, V., Wirick, J., Piacentini, R., Landis, A.E., Bilec, M.M., 2017. Evaluating the life cycle environmental benefits and trade-offs of water reuse systems for net-zero buildings. Environ. Sci. Technol. 51, 1110–1119. https://doi.org/10.1021/acs.est.6b03879.

Houng Li, A.P.D., 2008. Urban particle capture in bioretention media. I laboratory and field studies. J. Environ. Eng. 134, 409–418. https://doi.org/10.1061/(ASCE)0733-9372(2008)134:6(409).

Huang, M.S., Zhu, Y., Xie, B., 2010. The lower concave green space is used to purify the urban runoff. Construction Technology (1), 65–67 (in Chinese).

ISO (International Organization for Standardization)14040, 2006. Environmental Management-life Cycle Assessment-general Principles and Framework. ISO 14040, Geneva, Switzerland.

Jaffal, I., Ouldboukhitine, S.-E., Belarbi, R., 2012. A comprehensive study of the impact of green roofs on building energy performance. Renew. Energy 43, 157–164. https://doi.org/10.1016/j.renene.2011.12.004.

Jia, H., Wang, X., Ti, C., Zhai, Y., Field, R., Tafuri, A.N., Cai, H., Yu, S.L., 2015. Field monitoring of a LID-BMP treatment train system in China. Environ. Monit. Assess. 187, 373. https://doi.org/10.1007/s10661-015-4595-2.

Jia, H., Yu, S.L., Qin, H., 2017. Low impact development and sponge city construction for urban stormwater management. Front. Environ. Sci. Eng. 11 (4), 20. https://doi.org/10.1007/s11783-017-0989-4.

Jin, K.L., Zhao, L.B., Chen, J., Luo, F.Z., 2008. Research on BMPs of non-point sources pollution in xikeng reservoir watershed. Journal of Water Resources & Water Engineering 19 (5), 94–97 (in Chinese).

Kosareo, L., Ries, R., 2007. Comparative environmental life cycle assessment of green roofs. Build. Environ. 42, 2606–2613. https://doi.org/10.1016/j.buildenv.2006.06.019.

Kumari, A., Kumar Sharma, A., 2016. Infrastructure Financing and Development: a Bibliometric Review. International Journal of Critical Infrastructure Protection. https://doi.org/10.1016/j.ijcip.2016.11.005.

Law, E.P., Diemont, S.A., Toland, T.R., 2017. A sustainability comparison of green infrastructure interventions using emergy evaluation. J. Clean. Prod. 145, 374–385. https://doi.org/10.1016/j.jclepro.2016.12.039.

Li, H., Deng, N., Yang, Y.Q., 2010. The purification effect of vegetation filter belt on pollutants in surface runoff. Journal of Agricultural Engineering (7), 81–86 (in Chinese).

Li, H., Wei, P., Huang, Y., 2014. Study on the purification effect of transmission type vegetation shallow gully under heavy rainfall. Chinese Water Supply and Drainage 30 (1), 99–103 (in Chinese).

Lu, L., Chen, T., Fu, W.X., Liu, N.W., 2013. Analysis of life cycle assessment of LID—raingarden and permeable pavement + permeation tube/well. Journal of Green Science and Technology 5, 287–291 (in Chinese).

Lu, L., 2013. Life Cycle Assessment of Two Typical Rainwater LID. Beijing University of Architecture, Master thesis (in Chinese).

Liu, W., Chen, W., Peng, C., 2015. Influences of setting sizes and combination of green infrastructures on community's stormwater runoff reduction. Ecol. Model. 318, 236–244. https://doi.org/10.1016/j.ecolmodel.2014.11.007.

Lopsik, K., 2013. Life cycle assessment of small-scale constructed wetland and extended aeration activated sludge wastewater treatment system. Int. J. Environ. Sci. Technol. 10, 1295–1308. https://doi.org/10.1007/s13762-012-0159-y.

Ma, H.S.X.,T., Zhao, L.B., Liu, Q., 2013. Cost benefit analysis of low impact development (LID) value engineering. Value Eng. 12, 287–289 (in Chinese).

Mangangka, I.R., Liu, A., Egodawatta, P., Goonetilleke, A., 2015. Performance characterisation of a stormwater treatment bioretention basin. J. Environ. Manag. 150, 173–178. https://doi.org/10.1016/j.jenvman.2014.11.007.

Martin, P., Turner, B., Waddington, K., Pratt, C., Campbell, N., Payne, J., Reed, B., 2000. Sustainable Urban Drainage Systems: Design Manual for Scotland and Northern Ireland. C521. CIRIA, London, UK.

Martin, P., 2001. Sustainable Urban Drainage Systems: Best Practice Manual for England, Scotland, Wales and Northern Ireland. CIRIA Report No. CR086A, London, United Kingdom.

Maria Raquel, C.d.S., Montalto, F.A., Palmer, M.I., 2016. Potential climate change impacts on green infrastructure vegetation. Urban For. Urban Green. 20, 128–139. https://doi.org/10.1016/j.ufug.2016.08.014.

Meng, Y., Wang, H., Zhang, S., 2013. Experimental study on the effluent purification effect of urban road rain water retention based on biological detention. J. Beijing Normal Univ. (Nat. Sci.): natural science edition 49 (2/3), 286–291 (in Chinese).

MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China), 2014. Sponge City Sponge City Construction Technology Guide. Beijing (in Chinese).

O'Sullivan, A.D., Wicke, D., Hengen, T.J., Sieverding, H.L., Stone, J.J., 2015. Life Cycle Assessment modelling of stormwater treatment systems. J. Environ. Manag. 149, 236–244. https://doi.org/10.1016/j.jenvman.2014.10.025.

Ou, L., Che, W., 2001. Study on the infiltration and purification of rainwater and greenbelt in urban roof. Urban Environment & Urban Ecology 14 (6), 24–27 (in Chinese).

Pan, L., Chu, L.M., 2016. Energy saving potential and life cycle environmental impacts of a vertical greenery system in Hong Kong: a case study. Build. Environ. 96, 293–300. https://doi.org/10.1016/j.buildenv.2015.06.033.

Peng, L.L.H., Jim, C.Y., 2015. Economic evaluation of green-roof environmental benefits in the context of climate change: the case of Hong Kong. Urban For. Urban Green. 14, 554–561. https://doi.org/10.1016/j.ufug.2015.05.006.

Prince George's County, (Md, 1999a. Department of Environmental Resources. Programs and Planning Division. Low-impact development: an integrated design approach. The Department.

Prince George's County, (Md, 1999b. Department of Environmental Resources. Programs and Planning Division. Low-impact development hydrologic analysis. Department of Environmental Resources.

Pyke, C., Warren, M.P., Johnson, T., LaGro, J., Scharfenberg, J., Groth, P., Freed, R., Schroeer, W., Main, E., 2011. Assessment of low impact development for managing stormwater with changing precipitation due to climate change. Landsc. Urban Plann. 103, 166–173. https://doi.org/10.1016/j.landurbplan.2011.07.006.

Qi, H., 2013. Study on the Design and Effectiveness of the Development of Rainwater Management Measures. Beijing University of Architecture, Master thesis (in Chinese).

Santos, J., Flintsch, G., Ferreira, A., 2017. Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. Resour. Conserv. Recycl. 116, 15–31. https://doi.org/10.1016/j.resconrec.2016.08.025.

Schueler, T.R., 1987. Controlling Urban Runoff: a Practical Manual for Planning and Designing Urban BMPs. Water Resources Publications.

Seib, M., 2009. Life Cycle Assessment of a Cluster System Constructed Treatment Wetland.

Shan, B.Q., Chen, Q.F., Yin, C.Q., 2006. On-line control of stormwater pollution by pond-wetlands composite system in urban tourist area. Acta Sci. Circumstantiae 26 (7), 1068–1075 (in Chinese).

Shafique, M., Kim, R., Rafiq, M., 2018. Green roof benefits, opportunities and challenges—A review. Renew. Sustain. Energy Rev. 90, 757–773. https://doi.org/10.1016/j.rser.2018.04.006.

Shi, W.J., Liu, H., Zhang, X.H., 2007. Application of artificial wetland for controlling stormwater runoff pollution. Southwest Water & Wastewater 29 (2), 20–23 (in Chinese).

Spatari, S., Yu, Z., Montalto, F.A., 2011. Life cycle implications of urban green infrastructure. Environ. Pollut. 159, 2174–2179. https://doi.org/10.1016/j.envpol.2011.01.015.

Standards Australia/StandardsNew Zealand, 1999. AS/NZS 4536:1999 Life Cycle Costing - an Application Guide, Standards Australia. Sydney and Standards New Zealand, Wellington.

Sun, S.M., Shan, B.Q., Peng, W.J., 2009. Roles of urban lawn system in controlling rainfall-induced runoff nitrogen pollution. Chinese Journal of Ecology 28 (1), 23–26 (in Chinese).

Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: a code of practice. Int. J. Life Cycle Assess. 16, 389–391. https://doi.org/10.1007/s11367-011-0287-5.

Timothy, O., Daniel, W.M., 2018. A scientometric review of global research on sustainability and sustainable development. J. Clean. Prod. 183, 231–250. https://doi.org/10.1016/j.jclepro.2018.02.162.

Thome, A.M., Ceryno, P.S., Scavarda, A., Remmen, A., 2016. Sustainable infrastructure: a review and a research agenda. J. Environ. Manag. 184, 143–156. https://doi.org/10.1016/j.jenvman.2016.09.080.

Tiwary, A., Kumar, P., 2014. Impact evaluation of green-gray infrastructure interaction on built-space integrity: an emerging perspective to urban ecosystem service. Sci. Total Environ. 487, 350–360. https://doi.org/10.1016/j.scitotenv.2014.03.032.

Trowsdale, S.A., Simcock, R., 2011. Urban stormwater treatment using bioretention. J. Hydrol. 397, 167–174. https://doi.org/10.1016/j.jhydrol.2010.11.023.

Tupper, F., 2012. A Cost Comparison of a Low Impact Development to Traditional Residential Development along the South Carolina Coast. Doctoral dissertation, Masters Thesis. University of South Carolina, Columbia, SC).

Vacek, P., Karel, S., Libor, M., 2017. Life-cycle study on semi intensive green roofs. J. Clean. Prod. 154, 203–213. https://doi.org/10.1016/j.jclepro.2017.03.188.

Vandermeulen, V., Verspecht, A., Vermeire, B., Van Huylenbroeck, G., Gellynck, X., 2011. The use of economic valuation to create public support for green infrastructure investments in urban areas. Landsc. Urban Plann. 103, 198–206. https://doi.org/10.1016/j.landurbplan.2011.07.010.

Vijayaraghavan, K., 2016. Green roofs: a critical review on the role of components, benefits, limitations and trends. Renew. Sustain. Energy Rev. 57, 740–752. https://doi.org/10.1016/j.rser.2015.12.119.

Vineyard, D., Ingwersen, W.W., Hawkins, T.R., Xue, X., Demeke, B., Shuster, W., 2015. Comparing green and gray infrastructure using life cycle cost and environmental impact: a rain garden case study in cincinnati, OH. JAWRA Journal of the American Water Resources Association 51, 1342–1360. https://doi.org/10.1111/1752-1688.12320.

Wang, T., Liu, R., O'Meara, K., Mullan, E., Zhao, Y., 2018. Assessment of a field tidal flow constructed wetland in treatment of swine wastewater: life cycle approach. Water 10 (5), 573. https://doi.org/10.3390/w10050573.

Wang, M., Zhang, D., Adhityan, A., Ng, W.J., Dong, J., Tan, S.K., 2016. Assessing cost-effectiveness of bioretention on stormwater in response to climate change and urbanization for future scenarios. J. Hydrol. 543, 423–432. https://doi.org/10.1016/j.jhydrol.2016.10.019.

Wang, R., Eckelman, M.J., Zimmerman, J.B., 2013. Consequential environmental and economic life cycle assessment of green and gray stormwater infrastructures for combined sewer systems. Environ. Sci. Technol. 47, 11189–11198. https://doi.org/10.1021/es4026547.

Wang, R., Li, J., Wan, J.B., 2008. The application of BMPs in source pollution control. Jiangxi Energy (3), 44–48 (in Chinese).

Wang, X., Zhang, Y., Ou, Y., 2009. Cost-benefit evaluation and optimization of non-point source pollution control management measures in watershed. Journal of Ecological Environment 18 (2), 540–548 (in Chinese).

Wei, P., 2014. Evaluation on the Operation Effect of Shallow Vegetation and the Improvement of Design Research. Beijing University of Architecture, Master thesis (in Chinese).

Whelans, C., Maunsell, H.G., Thompson, P., 1994. Planning and Management Guidelines for Water Sensitive Urban (Residential) Design. Department of Planning and Urban Development of Western Australia, Perth, Australia.

Wong, T.H.F., 2007. Water sensitive urban design-the journey thus far. Aust. J. Water Resour. 110 (3), 213–222. https://doi.org/10.1080/13241583.2006.11465296.

Woodward, D.G., 1997. Life cycle costing—theory, information acquisition and application. Int. J. Proj. Manag. 15 (6), 335–344.

Xiao, H.W., Yan, N.F., Zhai, J., 2010. Study on the effect of artificial wetland on lead removal in urban residential area. J. Environ. Eng. 8, 1799–1804 (in Chinese).

Xu, C., Chen, W., Hong, J., 2014. Life-cycle environmental and economic assessment of sewage sludge treatment in China. J. Clean. Prod. 67, 79–87. https://doi.org/10.1016/j.jclepro.2013.12.002.

Xu, C., Hong, J., Jia, H., Liang, S., Xu, T., 2017. Life cycle environmental and economic assessment of a LID-BMP treatment train system: a case study in China. J. Clean. Prod. 149, 227–237. https://doi.org/10.1016/j.jclepro.2017.02.086.

Xu, P., Li, J.Q., Guo, J., 2005. Research on removal of pollutants from stormwater using artificial soil and plant system by experimentation in beijing. Journal of Beijing Institute of Civil Engineering and Architecture 21 (4), 45–50 (in Chinese).

Yan, S., 2011. Demonstrative research on rainfall utilization of the residential community of in the water side of qinhuangdao city. Journal of EMCC 21 (4), 29–31 (in Chinese).

Yang, J., Yu, Q., Gong, P., 2008. Quantifying air pollution removal by green roofs in Chicago. Atmos. Environ. 42 (31), 7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003.

Ye, M., Lei, A., Guo, L., 2004. Research on the technology and management of rainfall runoff control in new area. Proceedings of the 4th International Conference on Watershed Management and Urban Water Supply 706–710 (in Chinese).

Zeng, H.H., 2003. Design of rainwater reuse in a community. Proceedings of south China youth geoscience symposium 202–205 (in Chinese).

Zhan, W., Chui, T.F.M., 2016. Evaluating the life cycle net benefit of low impact development in a city. Urban For. Urban Green. 20, 295–304. https://doi.org/10.1016/j.ufug.2016.09.006.

Zuo, J., Pullen, S., Rameezdeen, R., Bennetts, H., Wang, Y., Mao, G., Zhou, Z., Du, H., Duan, H., 2017. Green building evaluation from a life-cycle perspective in Australia: a critical review. Renew. Sustain. Energy Rev. 70, 358–368. https://doi.org/10.1016/j.rser.2016.11.251.

Zhou, K., Gao, F., Hu, Y.H., 2011. The technology of grassed swale based on porous concrete. Water Supply and Drainage (S1), 269–274 (in Chinese).