Urban Forestry & Urban Greening 20 (2016) 295–304

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Evaluating the life cycle net benefit of low impact development in a city

Wenting Zhan, Ting Fong May Chui*

Department of Civil Engineering, Haking Wong Building, The University of Hong Kong, Room 6-18A, Pokfulam, Hong Kong

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
26 September 2016
Accepted 26 September 2016
Available online 28 September 2016

Keywords:
Economic benefits
Environmental benefits
Life cycle net benefit
Social benefits
Sustainable drainage systems
Water sensitive urban design

ABSTRACT

Low impact development (LID) practices (e.g., green roofs, bioretention systems, and porous pavements) offer multiple benefits to urban eco-systems. They reduce the expenses associated with water treatment, grey infrastructure, and energy consumption and thus generate economic benefits. They also benefit the environment by mitigating air pollution and climate change, and they provide social benefits such as enhancing livability, urban green space, and educating and improving the health of the public. Many studies have attempted to calculate the monetary value of these benefits. However, few have considered all three types of benefits (i.e., economic, environmental, and social) or considered all of the different LID practices at a city-scale. This study develops a life cycle quantification framework to determine the monetary values of the three types of benefits and the life cycle net benefit of LID practices for a city. Applying the proposed framework to a case study of Hong Kong, the 30-year economic and environmental benefits are 5.3 billion USD and 1.2 billion USD, respectively. The mean and median social benefits are 35.1 billion USD and 49.6 billion USD, respectively. Subtracting the 30-year LID implementation cost (55.8 billion USD) produces a median positive net benefit of 2.3 billion USD with an annual unit value of 1.05 USD/m^2 yr, and a mean negative net benefit of 12.2 billion USD with an annual unit value of −5.58 USD/m^2 yr. Sensitivity analyses show that the net benefit is sensitive to the willingness to pay (WTP) of Hong Kong people, especially the WTP of the private sector, and the land cost of green roofs. Overall, this study provides a framework for quantifying and evaluating the life cycle cost, benefits, and net benefit of LID practices. The assumptions in the framework can be modified based on local information and applied to many other cities worldwide.

1. Introduction

In the past decade, there has been increasing interest worldwide in implementing small-scale best management practices (BMPs) throughout urban areas to promote sustainable stormwater management and to reduce the environmental impact of stormwater on the bodies of water that receive it. This approach to stormwater management is referred to as low impact development (LID) in the U.S. and Canada, water sensitive urban design in Australia, and sustainable drainage systems in Europe (Ahiablame et al., 2012). LID makes use of several techniques such as green roofs, bioretention systems and porous pavements. It mimics or restores natural hydrologic processes by managing stormwater at the source (Vogel et al., 2015; Trinh and Chui, 2013), and provides many economic, environmental, and social benefits (US EPA, 2010). The economic benefits include reduction in water treatment and grey infrastructure costs, reduction in energy consumption and costs, etc. (Wise et al., 2010; Gallet, 2011). The environmental benefits are of two main types: CO$_2$ emissions reduction through carbon sequestration (Getter et al., 2009; Wise et al., 2010; Gallet, 2011; Bouchard et al., 2013; Peng and Jim, 2015) and avoided CO$_2$ emissions (Wise et al., 2010; Gallet, 2011); and air quality improvement through pollutants reduction (Wise et al., 2010; Gallet, 2011). The social benefits include the enhancement of livability and urban green space, public education in stormwater management, public health improvement (US EPA, 2010; Wise et al., 2010; Gallet, 2011), etc.

To implement, not only does LID need to be technically feasible and effective, it also has to be socially and economically beneficial. However, although there are many technical studies, there are very few economic, environmental, and social analyses of LID due to the challenges in quantifying the benefits and the uncertainties related to the cost, operation, and maintenance of LID practices (US EPA, 2013). One exception is Wossink and Hunt's (2003) study of the pollutant removal effectiveness of some BMPs such as wet ponds, stormwater wetlands, bio-retention areas, and sand filters. They calculate the construction and maintenance costs for those

---

* Corresponding author.
E-mail address: maychui@hku.hk (T.F.M. Chui).

http://dx.doi.org/10.1016/j.ufug.2016.09.006

four elements, and the monetary value of removing pollutants such as total suspended solids, total phosphorus, and total nitrogen, nitrate, and zinc. However, they do not consider the social benefits of these practices. Roseen et al. (2015) examine the economic advantages of LID and the metrics used in municipal decision making in a number of case studies. Tomalty et al. (2010) also quantify the monetary value of the soft benefits of green roofs in both individual properties and the community using heuristic methods, but do not consider some of the hard benefits such as the cost reductions in water treatment and grey infrastructure or energy savings. The benefits of combinations of LID practices have been evaluated in Milwaukee (MMSD, 2007), Seattle, West Union, Iowa (US EPA, 2013), etc. However, the EPA project in West Union does not quantify the non-market benefits of LID practices even though it recognizes the importance (Thurston, 2011). The US EPA (2007) finds that implementing well-chosen LID practices protects and restores water quality, and also reduces total project costs due to the reduction in the need for other stormwater drainage and management facilities.

In general, there are established methods for evaluating the economic and environmental benefits. For example, Gallet (2011) provides a two-step valuation method to estimate the monetary value of proposed LID investments. However, some benefits, in particular the social ones, are relatively abstract and do not have market values. Gallet (2011) also does not address the non-market ecosystem benefits such as the mitigation of the urban heat island effect, enhancement of community livability, and public education (Gallet, 2011). Fortunately, there are techniques available that can assign market values to non-market ecosystem services or related environmental attributes to the price or asset market value of individual properties (Guo et al., 2014; Chui and Ngai, 2016). For example, the stated preference method determines the price people are willing to pay for a good/service or the compensation people expect for harm (i.e., willingness to pay (WTP) and willingness to accept (WTA) compensation).

Among the different studies, cost-effectiveness and benefit-cost analyses are often performed on a life cycle scale. For example, Seattle Public Utilities (SPU) conducted a cost-effectiveness analysis of the Seattle Natural Drainage Systems' project options using life cycle costs, but did not quantify many of the environmental and social benefits due to the lack of resources and expertise (US EPA, 2013). A comprehensive benefit-cost analysis should also include a calculation of the life cycle net benefit, also referred to as the net present value (NPV) of a project, which is the difference between the present value (PV) of the benefits and the PV of costs (US EPA, 2010). For example, the West Union project compared the life-cycle costs (i.e., capital and operation and maintenance (O&M) costs) of porous and traditional pavements. The comparison indicated that although porous pavements are initially more expensive, the lower O&M costs result in cost savings in the long run (US EPA, 2013). The cumulative savings over a 57-year period were estimated to be about 2.5 million USD (US EPA, 2013).

The extant literature lacks a comprehensive framework for quantifying economic, environmental, and social benefits in a life cycle analysis. Furthermore, existing studies on quantifying the costs and benefits of LID focus on single LID practices (Blackhurst et al., 2010; Tomalty et al., 2010) and only a very few studies, such as that in West Union and SPU (US EPA, 2013), consider the benefits of larger-scale implementations. This paper therefore has three specific objectives:

1. to formulate an overall framework for quantifying the life cycle economic, environmental, and social benefits of large-scale (i.e., citywide) LID implementation;

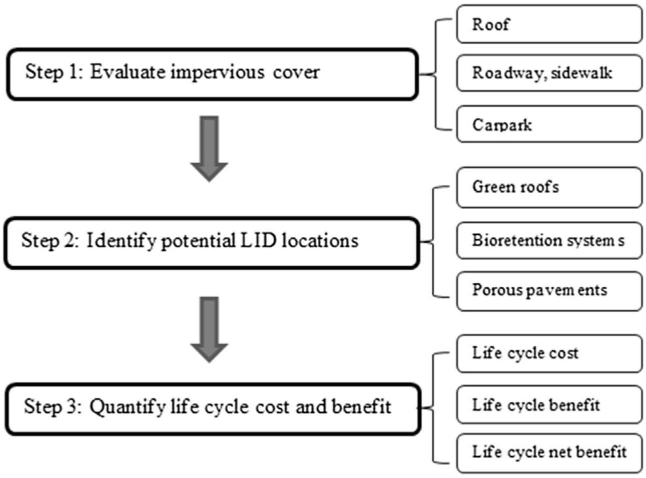

Fig. 1. Three-step life cycle cost and benefit quantification procedure.

2. to propose specific quantification and valuation approaches for each benefit; and
3. to demonstrate the proposed framework using Hong Kong as a case study

1.1. Methods

To quantify the citywide benefits of LID implementation, a three-step quantification procedure is proposed (Fig. 1). For demonstration purposes, three main LID practices are considered: green roofs, bioretention systems, and porous pavements.

Step 1: Estimate area of each impervious cover type.

Step 2: Identify potential locations for each LID practice.

Step 3: Quantify life cycle cost and benefit.

To determine the monetary value of all of the benefits, the last step of the three-step process is further broken down into four substeps:

a define types of costs and benefits;
b determine an evaluation method for each type of cost and benefit;
c calculate life cycle cost and benefit for a specific service time; and
d evaluate the life cycle net benefit.

The method developed by Gallet (2011) is used to quantify the system's economic and environmental benefits (blue circles in Fig. 2), and the stated preference method is used to quantify the WTP and thus the social benefits (red circle in Fig. 2). This paper combines the two methods to evaluate the three benefits and weight them against the costs. The explanations on the evaluation of the three benefits are given below, and the equations for quantifying them are summarized and listed in Table 1.

1.2. Evaluation of economic benefits

The economic benefits include cost reductions in water treatment and grey infrastructure, as well as energy savings. Cost reductions in water treatment and grey infrastructure are only available to cities with combined sewer systems in which stormwater runoff is combined with wastewater for treatment. McPherson et al. (2007) suggest that single-family residential sewer service fees can be used to estimate the value of rainfall intercepted and thus the potential cost reductions in stormwater management control. Gallet (2011) suggests using the marginal cost of treating wastewater and stormwater to estimate the reduction in water treatment costs. He also proposes methods for estimating the total runoff reduction of green roofs, bioretention systems, and porous