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Assessment of stormwater management options in urban contexts using Multiple Attribute Decision-Making

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A B S T R A C T

This paper addresses the problem of selecting the most sustainable stormwater management alternative in developing countries in a dense urban context. Firstly, suitable Low Impact Development (LID) stormwater management measures for dense urban areas in developing countries were identified based on critical review of literature. Alternatives have been formulated as varying percentages (degree of adoption) of these suitable measures to manage the stormwater sustainably. Further, a novel decision-making framework is developed which generates the hierarchy for selection of the most sustainable stormwater management alternative. Four main criteria (technical, economic, environmental and social) comprising three quantitative and eight qualitative indicators have been used for evaluating seven alternatives. The regional and local societal priorities are captured through criteria-weightings and are translated into a decision-making methodology. Experts' opinions have been included using Analytical Hierarchy Process (AHP). One of the most widely used Multiple Attribute Decision-Making (MADM) method, TOPSIS, is used to rank the alternatives and to identify the most sustainable alternatives. Various scenarios to represent different stakeholders' perspectives have been articulated. Alternative with medium level of cost implication and satisfactory level of performance is chosen by the decision making method in most of the scenarios. The proposed decision making approach can be used for selecting sustainable stormwater management options in densely populated areas of developing countries.

1. Introduction

As a consequence of urbanization and climate change, urban water managers have to rethink the ways in which water is managed today, taking into account economic, environmental and social factors (Willuweit and O'Sullivan, 2013). The urban population is estimated to increase from 3.6 billion to 6.3 billion by 2050 (UN, 2012). Such a high population density will lead to unprecedented pressure on water resources. The changes in the land cover associated with high urbanization are responsible for the problems of water scarcity as well as increased flood risks faced by today's cities (Bradshaw et al., 2007; De Roo et al., 2003). Increase in impervious areas and decrease in vegetated surfaces causing characteristic changes in the surface runoff hydrology (increase in runoff volumes and peak flows) are the results of such urbanization (Barbosa et al., 2012; Goonetilleke et al., 2005).

The massive urbanization in India has resulted in generation of huge quantities of stormwater which are unutilized and for which there do not exist any treatment strategies in the current urban water infrastructure. Although, stormwater drainage is being addressed in the development plan, it does not receive enough attention since India has a seasonal monsoon and stormwater becomes a prominent problem only after a significant failure has taken place (NIH, 2001). Current financial resources are not sufficient to address this huge challenge. The primary factor leading to mismanagement of stormwater in India is uncontrolled urban expansion resulting into inadequate infrastructure and other basic facilities. This gets further exacerbated by secondary factors including socio-political and institutional, inadequacy of available data and lack of a technological basis (Gogate and Rawal, 2015a;

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Nair, 2007; Silveira, 2002).

1.1. Need for change in the approach to manage stormwater

The adverse impacts of the traditional practice of urban stormwater management have raised growing concerns about the natural environment. A number of investigators have also critiqued outdated urban stormwater management practices ignoring the importance of stormwater as an alternative source of water (Chong et al., 2013; Fielding et al., 2015; Goonrey et al., 2009; Leinster et al., 2010). The balancing of water shortages and flood risks is a challenging task for urban planners (Yang and Cui, 2012). Traditional stormwater management removes runoff from developed areas, as completely and as quickly as possible. To cater to the needs of the growing urban population, urban water managers typically provide additional centralized stormwater infrastructure. Sustainability aspects cannot be incorporated in the management of stormwater by following this practice (Brown et al., 2009). Traditional strategies of stormwater management do not focus on reducing the runoff at source or prevent or control stormwater pollution. Better water resources management of the urban water cycle is essential in order to address increasing water demands without further environmental deterioration (Hatt et al., 2006). The new alternative sustainable approach comprises basically a combination of the conventional approach (providing a drainage network and modifying existing water courses) complemented or substituted by different concepts including recycling and reuse of stormwater. Stormwater harvesting is an important strategy for improving management of urban water resources to tackle the increasing stresses on the water resources throughout the world (Yang and Cui, 2012).

1.2. Alter natives for sustainable stormwater management and suitability in Indian context

Alternative sustainable urban stormwater drainage systems are recommended to mitigate the effects of landuse changes and restore water quality (Parker et al., 2009). These novel stormwater management approaches designed to control runoff at source and prevent pollution are known as Low Impact Development (LID) in USA and New Zealand; Water Sensitive Urban Design (WSUD) in Australia (Roy et al., 2008) and Sustainable Urban Drainage Systems (SUDS) in the UK. The water managers should utilize a variety of LID/WSUD options to integrate the concept of sustainability in stormwater management (Brown et al., 2009). The current spectrum of such technologies include stormwater retention and detention ponds, pervious pavements, bio-retention, swales, green roofs, rain barrels, rain gardens, vegetated filter strips and some local erosion control measures. Many researchers have investigated different aspects such as design (Schwartz, 2010; She and Pang, 2009; Zheng et al., 2006) and effectiveness in reducing runoff and pollutants (Weiss et al., 2006). Stormwater systems have also been considered as valuable elements for landscaping apart from diverting undesired water from urban areas (Galuzzi and Pflaum, 1996; Lin et al., 2006). Stormwater harvesting has the potential to mitigate a number of detrimental impacts of urbanization like increased frequency of surface runoff, increased peak flows and an increase in total runoff (Fletcher et al., 2007).

Bioretention is known for its efficiency in reducing runoff volume and in treating the first flush of stormwater (USEPA, 2000). Grass swales are also effective for both pollutant removal and runoff volume reduction. Permeable pavements and vegetated rooftops can be employed to reduce total impervious surface area. The USEPA (2000) report highlights the possibility of retrofitting these systems into older highly urbanized areas of the United States. Though permeable pavements reduce impervious surfaces, their comparatively higher initial and operation & maintenance cost may inhibit their adoption particularly in developing countries.

Many researchers worldwide are exploring the opportunities of applying Rain Water Harvesting (RWH) as a potential urban runoff management tool and as an alternative resource and are in the process of developing planned strategies and models for its implementation (Alam et al., 2012; Fletcher et al., 2007; Hamdan, 2009; Mahmoud et al., 2014; Mankad et al., 2015; Steffen et al., 2013; Ward et al., 2012). Different RWH configurations can be formulated depending on local guidelines, environment, stakeholders and expertise (Roy et al., 2008). Table 1 provides detailed information about available sustainable storm water management options.

However, the effective implementation of the sustainable urban stormwater approach may be challenging particularly in developing countries (Silveira and Goldenfum, 2004; Silveira et al., 2001). Initiation and implementation of sustainable drainage schemes are inhibited by uncontrolled urban development, leaving very few open spaces to accommodate infiltration and detention devices. Highly contaminated nature of runoff further restricts the adoption of infiltration based stormwater management options. Thus, the factors hindering the adoption of centralized retention and detention approaches for stormwater management in developing countries may include maintenance tasks (McCuen and Moglen, 1988), space constraint (Burns et al., 2012; Clar, 2001) and non-point source pollution (USEPA, 1996). Providing detention reservoirs may be challenging in densely urbanized environments. Thus, detention or retention techniques have limited scope, particularly in highly urbanized cities. Decentralized stormwater management approaches can be advantageous in such conditions. Techniques which promote artificial recharge of groundwater may avoid such problems.

Harvesting at the site scale may prove to be more beneficial as the collected rainwater can either be used for multiple purposes or infiltrated into ground. Retrofitting of site-scale watersheds with LID measures is one of the latest techniques for site scale harvesting. The benefits of implementing RWH as a stormwater control measure and as an alternative source of water for US cities and individual residents are evident from the results presented by Steffen et al. (2013).

Thus micro scale, infiltration based LID techniques, applied in a decentralized way, promise significant benefits for cities in developing countries like India. Table 1 describes the advantages and disadvantages of alternative stormwater management options along with their suitability in Indian context.

1.3. Motivation and problem definition

Decision making in urban environmental management is complex and there is a need for decision support to Urban Local Bodies (ULBs) and planning agencies. The selection of appropriate strategies for stormwater management often involves multiple criteria, such as costs, environmental performance, safety, ecological risks and community perception.

However, the ongoing and planned stormwater projects in many cities in India at present tend to be based on conventional approaches, regardless of the fact that these may be inconsistent with improving the sustainability of urban environments. This stormwater which otherwise creates complex problems can be diverted and used for artificial recharge. Given climate change and other pressing environmental issues, it is essential to adopt solutions that have low impact on the environment and that are appropriate for local conditions. While this has been generally recognized, currently in India there is no appropriate decision support tool that