Applying multi-criteria decision analysis to select WSUD and LID technologies

Faisal Ahammed, Guna Alankarage Hewa and John R. Argue

ABSTRACT

Water Sensitive Urban Design (WSUD) and Low Impact Development (LID) principles were investigated in Dhaka’s drainage network using ‘Regime in Balance’ strategy for Average Recurrence Interval (ARI), Y = 100 years. Three feasible alternatives, such as, leaky-well, soak-away and infiltration trench were identified and designed to improve Dhaka’s present unsatisfactory stormwater drainage system into one which is sustainable. For selecting the best one, we applied a multi-criteria decision analysis approach and chose the Analytic Hierarchy Process (AHP) model. Eleven criteria under three categories (technical, economic and social) were considered to quantify relative priorities of alternatives. Pair-wise comparisons of alternatives were performed against each criterion and ranked using a scale from 0 to 9. During the process of applying AHP model, consistency of ranking was thoroughly checked and a reasonable level of inconsistency was accepted due to the nature of human judgement. After the analysis, it was found that leaky-well (percentage priority 43%) followed by soak-away (38%) was the most appropriate technology for improving urban stormwater management system in Dhaka, Bangladesh. The proposed model can also be used in better selecting WSUD and LID technologies in other geographic locations.

Key words | analytic hierarchy process, Dhaka, low impact development, multi-criteria decision, stormwater management, water sensitive urban design

INTRODUCTION

The conventional stormwater management system in urban planning process considers stormwater as a little useful resource. Its main focus was collecting the stormwater as completely and as quickly as possible and discharging it directly to local waterways (Wong 2000). Although the system was successful in preventing flooding in some contexts, it was altering the natural hydrological cycle of urban catchment and hence, the capacity of this in large socio-economic regime is currently questioned (Pahl-Wostl et al. 2007). Newman (2001) termed this conventional system as ‘19th century solution’. For considering long term sustainability, a new approach of urban stormwater management was initiated in the early 1990s in Australia, which was expressed as Water Sensitive Urban Design (WSUD) (Coombes et al. 1999). It is the approach towards urban planning and design that integrates the management of the total water cycle into the urban development process (Kunapo et al. 2009). A parallel concept has also been developed and applied in North America termed as Low Impact Development (LID) (Elliott & Trowsdale 2007). According to Bachmann et al. (2009), ‘LID refers to stormwater management techniques that reduce the hydrological impact of new development or redevelopment at the site scale.’ Presently, WSUD and LID are identified as the most beneficial philosophies for holistic management of urban water resources in reducing the impact of both existing and new urban development (Shepherd 2008) and hence, urban cities have been started to treat as water sensitive...
cities. Argue (2011) mentioned that this paradigm shift could be the solution of everyday problems of small scale stormwater management: flood control, pollution control and stormwater harvesting. The typical WSUD and LID technologies include infiltration systems (leaky-well, soak-away and trench), bio-retention basin, vegetated swale, permeable pavement, wetland, pond and rainwater tank (Beecham 2003). Selection of the most appropriate technology for a particular catchment is challenging and multi-criteria decision analysis (MCDA) is required. This paper describes the application of MCDA using the Analytic Hierarchy Process (AHP) model for selecting the most appropriate WSUD and LID technology for Dhaka, Bangladesh.

Dhaka, the capital city of Bangladesh, has annual average rainfall of 2,076 mm and the rainfall intensity for Average Recurrence Interval (ARI) of 10 years and 1 hour duration is 98 mm/h (Ahammed & Hewa 2012). The stormwater drainage system of the city is centralized and conventional; its main focus is collecting and removing the stormwater from urban landscape. The system has proven unsatisfactory for three major reasons: (i) it leads to severe flooding in low lying areas and rivers, (ii) it results in pollution of waterways and rivers and (iii) it represents waste of water resource which could be put to good use. WSUD and LID principles were investigated into Dhaka’s drainage network to improve the situation and three feasible alternatives: leaky-well, soak-away and infiltration trench were identified and designed. To select the most appropriate option, we applied the AHP model developed by Saaty (1980).

Several MCDA models have been proposed in the literature, such as AHP, fuzzy AHP, revised fuzzy AHP, Simple Additive Weighting Model, Weighted Product Model, Artificial Neural Network, Computational Neural Network, etc., and the most popular one is the AHP model. It is a weight evaluation method and it can compare different alternatives and attributes using a scale of relative importance (Belton & Gear 1985). The main advantage of this method is that it can handle a complex problem by preparing a hierarchy of choices explaining the reasons of such choices through decomposing and synthesis (Kangas 1993). Existing literature suggests several applications of the AHP model in water resources planning and management. Opricovic (2009) termed this as ‘compromised based solution’ in water resources planning. Kang & Lee (2011) applied the AHP to evaluate water resources sustainability of watersheds in the Geum River basin of South Korea. They employed four criteria (economic efficiency, social equity, environmental conservation and maintenance capacity), 16 sub-criteria and evaluated that water resources sustainability of the watersheds in the upper basin was better than other areas due to superior environmental condition. Ennaouri & Fuamba (2011) considered 15 criteria (e.g. pipe age, diameter, soil type, traffic load, infiltration, etc.) to apply AHP on assessing degradation state of sewer network in Saint-Hyacinthe, Quebec, Canada and remarked that hydraulic capacity had the most significant impact on degradation; meanwhile, exfiltration had the lowest impact. Levy (2005) used AHP for developing flood risk management decision support system of the Yangtze River, China. Four different alternatives were selected for flood risk management including: (i) Jianli evacuation and destroying dikes, (ii) Jingjiang evacuation and destroy dikes, (iii) evacuation only and (iv) not destroying dikes anywhere. He used four attributes (economic, environment, safety and social) for selecting the best alternative and analysis showed that the second option was the most appropriate for flood risk management in the middle reach of the Yangtze River. Montazar & Zadbagher (2010) applied AHP for assessing global water productivity of the irrigation network in Iran. An integrated benefit assessment model for urban water resource related policies was also established using AHP by Xiaoqin (2009). Lovelady & El-Halwagi (2009) applied this model for designing an eco-industrial park to manage water resources. However, existing literature suggests that the application of the AHP model in WSUD and LID is currently very rare (possibly, unavailable) and the authors believe that this is probably the first work of its kind.

In this study, we considered three alternatives, leaky-well, soak-away and an infiltration trench, for improving urban stormwater management situation in Dhaka, Bangladesh and selected 11 criteria including size, emptying time, clearance distance from domestic footings, soil hydraulic conductivity, constructability, maintenance, land value, construction cost, maintenance cost, land acquisition problem and ownership problem. We provided weights and prepared priority matrix for three alternatives using the AHP model.
METHODOLOGY

Study area

The climate of Dhaka, the study area (Figure 1) is classified into six major seasons in a year, but three seasons, namely, winter, summer and monsoon are prominent. Rainfall mainly occurs during the summer and monsoon seasons. According to Bangladesh Bureau of Statistics (2012), the annual average temperature of the city is 25°C and annual rainfall varies from 1,429 to 4,338 mm. Statistical analysis of 57 years (1953 to 2009) daily rainfall data shows that number of annual rainy days of the city varies from 95 to 144 (mean = 116, STD = 11). Rainfall intensity is also sometimes very high and annual average frequency with rainfall intensity greater than 100 mm/day is 2 (STD = 1.5). The highest amount of daily rainfall was recorded as 341 mm on September 14, 2004 followed by 333 mm on July 28, 2009.

Haq (2006) reported that the drainage of Dhaka City is divided into two different systems: one is for domestic and industrial wastewater and the other is for stormwater. The whole drainage system is owned, operated and maintained by three different organizations: Dhaka Water Supply and Sewer System, Dhaka City Corporation and Bangladesh Water Development Board. Khan & Siddique (2000) indicated that poor communication among organizations hinders the performance of the drainage system in Bangladesh. An effective decision support system could help the policy makers to take the right decision for stormwater management.

Selection of WSUD and LID technologies

Selection of WSUD and LID technologies requires several preliminary steps including:

- selecting a study area which is representative of Dhaka’s urban area and where installations of WSUD and LID technologies are possible;
- identifying the dimensions of a typical allotment area;
- measuring soil hydraulic conductivity for the study area;
- developing the rainfall Intensity–Frequency–Duration (IFD) relationship at sub-daily scale for Dhaka, required in the design process;
• deciding an appropriate ARI for application to Dhaka’s stormwater drainage network;
• designing appropriate WSUD and LID technologies and assessing their feasibility as a solution to be applied widely in Dhaka.

All of the above steps were undertaken in 500 m² allotment in Banani suburb of Dhaka, where the soil hydraulic conductivity was $1.53 \times 10^{-5}$ m/s. We considered ‘Regime in Balance (RIB)’ strategy for ARI, $Y = 100$ years to design leaky-well, soak-away and infiltration trench. According to Argue (2011), in RIB, the stormwater runoff volume after the urbanization site is considered to be equal to its green-fields (before urbanization) discharge in adopted critical design storm duration. So, the difference of stormwater volumes of a catchment ‘after’ and ‘before’ of urban development is treated as the critical runoff to be removed from urban landscape to minimise flooding risk. We considered rational method (Pilgrim 2001) for the estimation of runoff volume and only the runoff beyond the capacity of existing drainage system (around 60%) was considered in the design process. Equations (1)–(3) (Argue 2011) show the formula for designing leaky-well, soak-away and infiltration trench respectively.

$$D = \sqrt{\frac{V}{\pi (H + 120. Kh. \tau. U)}}$$  \hspace{1cm} (1)

$$A = \frac{V}{e. H + 60. Kh. \tau. U}$$  \hspace{1cm} (2)

$$L = \frac{V}{e. b. H + 60. Kh. \tau. \left( b + \frac{H}{2} \right). U}$$  \hspace{1cm} (3)

where $D =$ diameter of leaky-well, $A =$ area of soak-away, $L =$ length of infiltration trench, $b =$ width of infiltration trench, $H =$ height of leaky-well/soak-away/infiltration trench, $V =$ stormwater runoff volume of critical duration, $K_h =$ soil hydraulic conductivity, $\tau =$ critical storm duration ($t_e$) + site time of concentration ($t_a$), $U =$ moderation factor; 0.5, 1.0 and 2.0 for sandy, sandy clay and clay soil respectively.

It is always important to ensure that the stored runoff of the system is empty before the arrival of a succeeding significant storm (Tennakoon & Argue 2011). Emptying times of leaky-well, soak-away and infiltration trench were estimated using Equations (4)–(6) respectively (Argue 2011). The recommended value is around 1 day for New Zealand (Auckland City Council 2005) and 3 days for the USA (Browne et al. 2008). In Australia, this value varies from 12 hours to 3.5 days depending on the frequencies of ARI (Argue 2011).

$$T_e = -\frac{4.6}{4 Kh \log \left[ \frac{D/4}{H + D/4} \right]} \text{ sec}$$  \hspace{1cm} (4)

$$T_e = \frac{2 H e}{K_h} \text{ sec}$$  \hspace{1cm} (5)

$$T_e = -\frac{4.6 L b e}{2 Kh (L + b)} \log_{10} \left[ \frac{L b}{L b + 2 H (L + b)} \right] \text{ sec}$$  \hspace{1cm} (6)

Figure 2 shows the WSUD and LID technologies with necessary dimensions designed for Dhaka, Bangladesh.

Selection of criteria

One of the major steps in MCDA is to select criteria and sub-criteria. Available alternatives are assessed based on selected criteria. The importance of all criteria is not equal and hence, it is also necessary to give weight to them. We evaluated 11 criteria under three categories, including technical, economic and social. These criteria were selected based on literature review and our practical judgements. Table 1 shows the description of all criteria selected for applying MCDA to choose the most appropriate WSUD and LID technology for Dhaka.

Applying AHP model

Applying AHP model consists of several steps which are shown in Figure 3. It starts with setting the goal followed by selection of alternatives. Practical judgement is necessary for criteria selection. Pair-wise comparisons are required in...
two stages: (i) among criteria and (ii) among alternatives using each criterion. These comparisons were made using Saaty’s discrete 9 value scale (Table 2). Comparisons of alternatives were evaluated by a joint effort of two members; one was the stormwater practitioner in context of Bangladesh and the other one was the expert in the areas of WSUD and LID.

The comparison matrix (A) of WSUD and LID alternatives based on single criterion of ‘emptying time’ is given below:

\[
A = \begin{bmatrix}
L & S & T \\
1 & 1 & 1 \\
4 & 3 & 0.67 \\
2 & 1 & 1 \\
\end{bmatrix}
\]

where \(L = \) leaky-well, \(S = \) soak-away and \(T = \) infiltration trench.

**Determination of weights**

The relative ranks of \(L, S\) and \(T\) were determined from matrix \(A\) by normalizing it into a new matrix \(N\). This process required dividing the elements of each column by the sum of the elements of the same column. The desired relative rank \(N_w\) of three alternatives were then computed as row average:

\[
\begin{align*}
L & = [0.13, 0.14, 0.10] \\
S & = [0.50, 0.57, 0.60] \\
T & = [0.58, 0.29, 0.30] \\
\end{align*}
\]

and

\[
N_w = \begin{bmatrix} 0.56 \\ 0.32 \end{bmatrix}
\]

**Consistency check**

The columns of \(N\) were identical, meaning that the comparison exhibited perfect consistency in specifying the entries of the comparison matrix \(A\). Mathematically, the matrix \(A\) is consistence if

\[a_{ij} \cdot a_{jk} = a_{ik} \text{ for all values of } i, j \text{ and } k\]

It was abnormal for all comparisons to be consistent. A reasonable level of inconsistency was expected and accepted due to the nature of human judgement. To determine whether or not the level of inconsistency was
reasonable, we applied following methodology developed by Saaty (1980):

- Estimate the Consistency Index (CI) using Equation (7).

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1}
\]  

Here, \(n\) is the size of matrix \((n \times n)\) and \(\lambda_{\text{max}}\) is defined as the product of \(A\) and \(N_w\).

\[
\lambda_{\text{max}} = A \times N_w = \begin{bmatrix} 1 & 1 & 1 \\ 4 & 1 & 2 \\ 3 & 2 & 1 \end{bmatrix} \times \begin{bmatrix} 0.12 \\ 0.56 \\ 0.36 \end{bmatrix} = 3.0056
\]

- Consistency Ratio (CR) was estimated using Equation (8). As a rule of thumb, if CR value was equal or less than

### Table 1 | Description of selected criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sizes of WSUD and LID technologies</td>
<td>The proposed sizes of leaky-well, soak-away and infiltration trench for urban stormwater management in 500 m² allotment of Dhaka are:</td>
</tr>
<tr>
<td>Leaky-well</td>
<td>Soak-away</td>
</tr>
<tr>
<td>Number = 2</td>
<td>Number = 1</td>
</tr>
<tr>
<td>Diameter = 2.1 m</td>
<td>Length = 5.4 m</td>
</tr>
<tr>
<td>Depth = 2.0 m</td>
<td>Width = 5.3 m</td>
</tr>
<tr>
<td>Depth = 0.5 m</td>
<td>Depth = 1.2 m</td>
</tr>
<tr>
<td>Emptying (drain) time</td>
<td>The estimated emptying times of leaky-well, soak-away and infiltration trench were 1.25 days, 17.25 hours and 20.4 hours respectively.</td>
</tr>
<tr>
<td>Clearance distance</td>
<td>The recommended minimum clearance distance between WSUD/ LID technology and domestic footing depends on soil types as 1, 2, 4 and 5 m for sand, sandy clay, medium clay and heavy clay respectively.</td>
</tr>
<tr>
<td>Soil hydraulic conductivity</td>
<td>It has an impact on emptying time of the device. Argue (2011) mentioned the ranges of hydraulic conductivity for different soil types as:</td>
</tr>
<tr>
<td>Soil type</td>
<td>Hydraulic conductivity (m/s)</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>(1 \times 10^{-5}) to (5 \times 10^{-5})</td>
</tr>
<tr>
<td>Medium clay</td>
<td>(1 \times 10^{-6}) to (1 \times 10^{-5})</td>
</tr>
<tr>
<td>Heavy clay</td>
<td>(1 \times 10^{-6}) to (1 \times 10^{-6})</td>
</tr>
<tr>
<td>Constructability &amp; Construction includes suitability of installation of WSUD and LID technologies in the site conditions. High water table, low permeability, steep terrain greater than 5%, wind-blown, availability of saline and acid in the soil, etc. can hinder satisfactory performance.</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>Routine and periodic maintenances of WSUD and LID technologies are required in cleaning, removal of sediment, replacement of geo-textile fabric, weeding of surface vegetation, etc.</td>
</tr>
<tr>
<td>Land value</td>
<td>The higher the area required, the higher the value of land cost, which is expensive in urban areas.</td>
</tr>
<tr>
<td>Construction cost</td>
<td>Design cost, materials cost, excavation cost, labour cost, etc. are included.</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>It depends on life cycle of WSUD and LID technologies. In many cases, life cycle is unknown and determining the accurate maintenance cost is challenging.</td>
</tr>
<tr>
<td>Land acquisition</td>
<td>Land acquisition difficulties may limit the opportunity to implement WSUD and LID technologies.</td>
</tr>
<tr>
<td>Ownership</td>
<td>Community may resist the installation due to unavailability of suitable land and the problem of its ownership.</td>
</tr>
</tbody>
</table>
The Random Consistency (RC) of the matrix $A$ was estimated using Table 3; it depends on the size of matrix. The RC value for matrix $A$ was 0.58, as it was $3 \times 3$ matrix.

Thereafter, the CR value of the matrix $N$ was estimated as $0.0048 (<0.10)$, which was accepted.

### Ranking of WSUD and LID technologies

The final step of AHP application started giving the ranks of WSUD and LID alternatives. It was executed by multiplying the decision matrix with criteria (or sub-criteria) judgement matrix as:

$$\text{Rank of WSUD and LID alternatives} = \begin{bmatrix} L_p & L_q & L_r \\ S_p & S_q & S_r \\ T_p & T_q & T_r \end{bmatrix} \times \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

where $L, S, T$ are three possible WSUD and LID alternatives and $p, q, r$ are three selection attributes.

### RESULTS

Table 4 shows the relative weights of criteria and ranks of WSUD and LID alternatives using different criteria. It was
noticed that technical feature (percentage priority 66%) was the most important attribute followed by social aspect (19%). The least important attribute was economic (15%). There were six criteria under technical attribute and emptying time (32%) was the most important under this category. Land value (78%) was the most important criteria in economic attribute and all criteria under social aspect were equal weights.

The final WSUD and LID decision matrix D and final criteria judgement matrix J were identified from Table 4 and overall ranking of alternatives was determined as the product of D and J.

The final WSUD and LID decision matrix,

\[
D = \begin{bmatrix}
0.43 & 0.68 & 0.24 \\
0.38 & 0.14 & 0.56 \\
0.18 & 0.19 & 0.21
\end{bmatrix}
\]

The final criteria judgement matrix,

\[
J = \begin{bmatrix}
0.66 \\
0.15 \\
0.19
\end{bmatrix}
\]

It was noticed from Table 4 that, considering technical and economic criteria, leaky-well was the most preferred alternative (percentage priority was 43% and 68%, respectively); however, social criteria indicated that soak-away was the most preferred option (56% percentage priority). Combination of technical, economic and social criteria together, leaky-well (43%) followed by soak-away (38%) was the most preferred WSUD and LID technology for improving stormwater situation of Dhaka. Meanwhile, the least preferred alternative was infiltration trench with percentage priority as 19%. Figure 4 shows the rankings of WSUD and LID technologies for Dhaka, Bangladesh.

### CONCLUSIONS

The AHP is an established model in MCDA; however, its application in WSUD and LID is very limited and possibly unavailable. We applied this model as a first kind of work to select the most appropriate WSUD and LID technology for Dhaka, Bangladesh. This process started designing three alternatives including leaky-well, soak-away and infiltration trench. Thereafter, we considered 11 criteria under three attributes (technical, economic and social) to give ranks to alternatives. Consistencies of weights and ranks were also checked thoroughly. After the analysis using the AHP model, we found that leaky-well followed by
soak-away was the most preferred WSUD and LID technology for urban stormwater management in Dhaka, Bangladesh.

The model used in this study can also be applied for water resources planning and management in other geographical locations. Potential WSUD and LID technologies can be site specific and criteria can be selected based on its geo-hydrologic and socio-economic conditions. Hence, this paper is the beginning of a new dimension of decision support system to WSUD and LID technologies.

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