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Research Article

A Multi-criteria Decision-making Approach for Characterizing the Best Low Impact Development (LID) Techniques for Stormwater Management

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Abstract: Low impact development (LID) techniques are known as a novel stormwater management approach designed to mitigate the adverse effects of stormwater runoff and nonpoint source pollution. This study proposes a methodology for selecting the best LIDs based on multi-criteria decision analysis (MCDA) while incorporating different stakeholder priorities. The proposed methodology comprises analysis of alternatives, stakeholder analysis, and application of the MCDA methods. The results show that most LID techniques received ratings of more than three from the Weighted Average Method (WAM; performing well) other than green roofs and constructed filters, and no techniques averaged lower than 2.29 out of five. There is a general consensus on how vegetated filter strips and infiltration practices would perform, while there is little consensus on bioretention, level spreaders, and porous pavements. The ratings show that the majority of stakeholders thought most LIDs would perform well (a rating of more than three). The findings of this study provide an initial insight into how to support effective and widespread LID implementation for all decision-makers such as planners, designers, engineers, and stormwater managers.

***Keywords*: multi-criteria decision analysis (MCDA), green roof, bioretention, stormwater

1. Introduction

Urban infrastructure management needs to be integrated, beginning with a definition of land-use that aims to preserve natural functions such as infiltration and the natural drainage system [1-3]. This approach to development has been termed Low Impact Development (LID) in the United States or Water-Sensitive Urban Design (WSUD) in Australia [4]. The LID approach is based on managing stormwater at its source by using planning techniques (called non-structural LID) and microscale controls (called structural LID) that are distributed throughout the site to maintain the pre-project hydrologic function of the site [5,6].

LID has the potential to mitigate some of the negative impacts of urban development that conventional stormwater management techniques have not been able to address adequately [7,8]. LIDs vary significantly in performance across different criteria [9]. Appropriate LID techniques can be selected according to the project objectives, capabilities, and limitations of the study area [7]. Reduction in the peak and volume of runoff, improvement of stormwater quality, and water conservation are the main goals of the LID implementation. Meanwhile, some influential factors that should be considered in the selection of proper LID techniques are basin slope, climate, groundwater depth, operation and

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maintenance of existing facilities, and cost [6].

Additionally, the stakeholders can have various views and priorities, adding to the complexity of the situation [10]. Conflicting views from the stakeholders may lead to a complicated selection procedure [11,12]. It is important to note that the effective implementation of LID will not occur without the support of all the main stakeholders [12].

Therefore, this study aims to propose a methodology for selecting the best LIDs for urban areas by comparing and applying multi-criteria decision analysis (MCDA) under different stakeholder scenarios. First, all main stakeholders were identified so that their influences could be assessed. Second, relevant main criteria and sub-criteria were selected. Third, a stakeholder analysis was carried out to obtain social performance values and criteria priorities. Finally, two MCDA methods were applied to obtain the final LID rankings. Note that while these kinds of problems are not new in water resource management and the use of the MCDA method, itself, has been investigated in different studies [13], the direct application of MCDA for selecting the best LIDs has rarely been investigated.

2. Materials and methods

The Weighted Average Method (WAM) and the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) method were applied as two common scoring mechanisms of the MCDA tool. Each of the selected MCDA methods was evaluated based on their ability to match the desired criteria. The procedure for evaluating the differing methods of MCDA followed a step-by-step technique as explained in the following sections. The selection and identification of stakeholders, criteria, and LID alternatives were based on reviewing several LID manuals, resources, and guidelines [6,14-19].

2.1 *Stakeholder identification*

Successful LID implementation requires the involvement of a wide group of stakeholders, such as local government, the local water authority, stormwater practitioners, elected officials, landscape architects, and representatives from the community [10,11]. In this study, the main stakeholder groups within the watershed are considered as below:

i. Municipal governments
ii. Building and land developers
iii. Planner (i.e., architect, urban planner)
iv. Private homeowner
v. Local business owner (i.e., restaurant, supermarket, etc.)
vi. Organizations (non-profit organizations [NGOs])

Various views and priorities of all the main stakeholders should be considered in the application of LID techniques. The proposed methods took each stakeholder into account separately and carried out a single evaluation of the LID alternatives.

2.2 *Criteria*

In this study, a list of sub-criteria was selected based on the requirement that the criteria can be quantified according to the literature. The following are the most important factors that influence LID techniques [6,11,19].

i. Stormwater quantity function
    - Volume
    - Groundwater recharge
    - Peak rate
ii. Stormwater quality function
    - Total suspended solids (TSS)
    - Total phosphorus (TP)
    - Total nitrogen (TN)

- Temperature

iii. Cost

iv. Maintenance

v. Winter performance

2.3 *LID alternatives*

The next step is to develop the various LID alternatives for consideration. In this study, the following ten LID techniques were selected [6].

i. Bioretention

ii. Vegetated swale

iii. Vegetated filter strip

iv. Permeable pavement

v. Rainwater harvesting

vi. Green roof

vii. Infiltration practices

viii. Level spreaders

ix. Constructed filter

x. Soil restoration

For more detailed investigation, effective quality parameters were quantified according to Table 1. According to the Army LID Technical User Guide manual [6], each LID technique was rated against the main criteria. Tables S1 to S10 show the ratings of criteria for each LID alternative according to their importance and impact.

Table 1. Rating of alternative function

Function	Rating	Rating for maintenance and cost
Low	1	5
Low/Medium	2	4
Medium	3	3
Medium/High	4	2
High	5	1

2.4 *Criteria weighting*

The stakeholders' interests or priorities were analyzed in this section to obtain separate LID rankings [10]. Every stakeholder was considered separately to obtain a single evaluation of the LID techniques [4].

2.4.1 *Stormwater quantity function*

Volume reduction is the most important factor from the engineers' perspective, while planners and citizens are equally concerned [11,12]. However, NGOs are less concerned about the volume reduction in comparison with planners and municipal governments. Most stormwater systems are on city property or within city setbacks; therefore, municipal governments are mainly responsible for controlling the runoff. For municipal governments, increasing groundwater recharge can be an important factor, which is also important for NGOs. LID reduces water supply demand and encourages natural groundwater recharge [4,20], so more attention should be given to the LID techniques in response to the rapidly worsening water crisis [21,22]. Nevertheless, compared to NGOs and governments, groundwater recharge does not have any importance for building and land developers, private homeowners, and local business owners.

Planners are located somewhere between the two aforementioned groups. Peak flow reduction has the same priority for planners, citizens, developers, and municipal governments [11,12]. However, NGOs are less concerned about this factor. The stakeholders' interests and priorities were quantified in terms of the stormwater quantity function as shown in Table 2.

Table 2. Stormwater quantity function

Stakeholders	Rating
Municipal governments	4
Building and land developers	3
Planner	3
Private homeowner	2
Local business owner	1
Organizations (NGOs)	2

2.4.2 *Stormwater quantity function*

For private homeowners and NGOs, LIDs protect site and regional water quality by reducing sediment, nutrient, and toxic loads to water bodies [9,11,12,23]. TSS removal is an incentive factor for citizens, engineers, and municipal governments. Planners are also concerned about this factor, but it is less than the three aforementioned groups [11]. As mentioned in the previous section, stormwater quality improvement is the most important factor for NGOs. Therefore, for all stormwater quality sub-criteria, NGOs have the highest rating. Planners usually do not care about TP removal. However, citizens are usually more sensitive in this case. Engineers, municipal governments, and developers are somewhere between these two groups [11]. Stakeholders' opinion about TP removal is very similar to that of TN removal [11]. Stormwater temperature reduction is another benefit of the LID technique. As mentioned in previous sections, for NGOs, stormwater quality has more importance than other stakeholders. Furthermore, it was assumed that the temperature of stormwater has the least importance for planners and land developers among all stakeholders [10]. Table 3 quantifies the stakeholders' interests and priorities in terms of the stormwater quality function.

Table 3. Stormwater quality function

Stakeholders	Rating
Municipal governments	3
Building and land developers	1
Planner	1
Private homeowner	2
Local business owner	2
Organizations (NGOs)	4

2.4.3 *Cost*

Quantifying the economic benefits of LIDs implementation is not a simple task because some benefits, such as aesthetics, recreational opportunities, and environmental impacts, are not monetary or cannot be obtained directly [11]. LIDs reduce land clearing, grading, infrastructure costs (streets, curbs, gutters, sidewalks) and stormwater management costs for developers [6]. For municipal governments, it reduces system-wide operations and maintenance costs of infrastructure and costs of combined sewer overflows. For private homeowners, LID provides shading for homes, which decreases monthly energy bills for cooling. It also saves money through water conservation [2,16,23,24]. Economic net present value (NPV) has greater importance, respectively, for developers, citizens, and planners [12]. For NGOs, cost has the least rating. The stakeholders' interests and priorities were quantified in terms of cost, as shown in Table 4.

Table 4. Cost

Stakeholders	Rating
Municipal governments	4
Building and land developers	4
Planner	2
Private homeowner	3
Local business owner	3
Organizations (NGOs)	1

2.4.4 *Maintenance*

LID techniques should be maintained to retain their effectiveness. The costs of maintaining a LID technique are easily recouped in reduced flooding, reduced home energy heating and cooling costs, increased amenity values, and improved water quality [5,9,15,25]. Most property owners would prefer and are looking for their municipal government to take on their stormwater drainage system maintenance and repairs for obvious reasons [26]. The stakeholders' interests and priorities were quantified in terms of maintenance, as shown in Table 5.

Table 5. Maintenance

Stakeholders	Rating
Municipal governments	2
Building and land developers	2
Planner	4
Private homeowner	1
Local business owner	1
Organizations (NGOs)	2

2.4.5 *Winter performance*

Stakeholders' opinions about winter performance are considered to be similar to maintenance considerations [6,11,23,27,28]. The stakeholders' interests and priorities were quantified in terms of winter performance, as shown in Table 6.

Table 6. Winter performance

Stakeholders	Rating
Municipal governments	1
Building and land developers	2
Planner	4
Private homeowner	1
Local business owner	1
Organizations (NGOs)	2

2.5 *Multi-criteria Decision Analysis (MCDA) Method*

The WAM approach and PROMETHEE analysis were considered in this study as a scoring mechanism for the MCDA tool [4,26]. The WAM of MCDA is a value-based method where the rating assigned to each criterion is a value along a discrete pre-determined range. The overall ratings for criteria are determined by the following equation [4,26]:

$$Sj = \sum W_i * R_j \tag{1}$$

where Sj is the overall rating for technology, W_i is weight, and R_j is the relative importance of criteria.

3. Results and discussion

The ratings of one to five were assigned by the users according to the importance of each main criterion, with one representing little to no importance and five representing very important criteria [4,11,12,26]. The importance of each criterion was measured on a scale from one to five, as each analysis considers five technologies, and this scale is considered simple for users to understand. Table 7 summarizes the rating of each technology for each criterion in the absence of weighting. Infiltration practices have the best rating for stormwater quantity function. Bioretention, vegetated filter strips, rainwater harvesting, and soil restoration are the best LID techniques in terms of stormwater quality function. As a result, environmentally, they should be the best alternatives. In addition, vegetated filter strips, permeable pavement, level spreaders, and soil restoration require less maintenance. According to Table 7, vegetated filter strips, permeable pavement, level spreaders, and soil restoration have the highest ratings for winter performance. In terms of cost, vegetated filter strip, permeable pavement, and level spreader are the best LID practices. As a result, they can be acceptable for municipal organizations. However, varying levels of performance across a wide range of criteria and conflicting stakeholder views could complicate the selection process of these practices.

Table 7. Summary of each technology's rating for each criterion

Resource criteria	Bioretention	Vegetated swale	Vegetated filter strip	Permeable pavement	Rainwater harvesting	Green roofs	Infiltration practices	Level spreaders	Constructed filter	Soil restoration
Stormwater quantity function	3.7	2.0	1.0	1.0	2.3	2.7	4.0	1.0	3.0	2.3
Stormwater quality function	4.0	3.3	4.0	1.0	4.0	3.5	3.8	1.0	3.0	4.0
Cost	3.0	4.0	5.0	5.0	4.0	1.0	4.0	5.0	2.0	3.0
Maintenance	3.0	4.0	5.0	5.0	3.0	3.0	4.0	5.0	1.0	5.0
Winter performance	3.0	3.0	5.0	5.0	3.0	3.0	4.0	5.0	3.0	5.0

The results of this study provide a greater insight into the opinions and concerns of stakeholders in stormwater management.

3.1 *Weighted Average Method (WAM)*

As shown in Table 8, for municipal governments, infiltration practices and constructed filters are the best and worst techniques, respectively. It seems logical because infiltration practices have some distinct advantages, mainly in stormwater quantity function and cost, and it is exactly this that is more important for municipal governments. For building and land developers, in addition to infiltration practices, vegetated filter strips also have a high rating for the same reasons. In fact, stormwater quality function has less importance for these groups. For planners, vegetated filter strips and constructed filters have the highest and lowest ratings, respectively. Maintenance and winter performance are two things that planners are more sensitive about, and as it is mentioned in previous sections, vegetated filter strips need less maintenance and better winter performance than other LID alternatives. For private homeowners, infiltration practices are the best techniques. However, vegetated filter strips have more importance for NGOs than infiltration practices. That is because these techniques have high stormwater quality functions, which is the most important factor for environmental organizations.

Table 8. Ratings of LID alternatives for selected stakeholders (WAM method)

Resource criteria	Bioretention	Vegetated swale	Vegetated filter strip	Permeable pavement	Rainwater harvesting	Green roofs	Infiltration practices	Level spreaders	Constructed filter	Soil restoration
Municipal governments	3.40	3.20	3.64	3.00	3.31	2.44	3.95	3.00	2.43	3.45
Building and land developers	3.25	3.27	3.92	3.67	3.25	2.29	3.98	3.67	2.33	3.58
Planner	3.21	3.23	4.07	3.86	3.07	2.68	3.98	3.86	2.29	4.07
Private homeowner	3.37	3.28	3.89	3.22	3.41	2.37	3.94	3.22	2.44	3.52
Local business owner	3.30	3.39	4.33	3.67	3.48	2.41	3.94	3.67	2.44	3.81
Organizations (NGOs)	3.48	3.18	3.91	2.82	3.33	2.94	3.91	2.82	2.55	3.97

Finally, the summary of this project using the WAM method can be seen in Table 9. Using this method, infiltration practices and vegetated filter strips can be considered the best techniques for these stakeholder groups. Also, according to stakeholders' preferences and main criteria, green roofs and constructed filters are not recommended here. Selection of permeable pavement, level spreaders and bioretention heavily depends on stakeholders' preferences.

Table 9. Ratings of LID alternatives (WAM method)

	Bioretention	Vegetated swale	Vegetated filter strip	Permeable pavement	Rainwater harvesting	Green roofs	Infiltration practices	Level spreaders	Constructed filter	Soil restoration
Worst	8	7	2	8	8	10	3	8	10	5
Best	4	6	1	3	4	7	1	3	9	1
Average	5.83	6.17	1.67	5.50	5.83	9.17	1.67	5.50	9.5	2.67

3.2 *Preference Ranking Organization Method (PROM)*

As illustrated in Table 10, infiltration practice is still the best technique for municipal government. However, according to the PROM method, green roofs have the lowest rating. Vegetated filter strips and infiltration practices have the highest ratings among LIDs for most stakeholders. On the other hand, green roofs and constructed filters have the lowest rating for different groups of stakeholders.

Table 10. Ratings of LID alternatives for selected stakeholders (PROM method)

Resource criteria	Bioretention	Vegetated swale	Vegetated filter strip	Permeable pavement	Rainwater harvesting	Green roofs	Infiltration practices	Level spreaders	Constructed filter	Soil restoration
Municipal governments	-0.04	-0.21	0.27	-0.05	0.04	-0.41	0.54	-0.05	-0.30	0.23
Building and land developers	-0.25	-0.21	0.35	0.23	-0.13	-0.54	0.46	0.25	-0.38	0.21
Planner	-0.25	-0.21	0.41	0.30	-0.25	-0.50	0.32	0.29	-0.50	0.39
Private homeowner	-0.14	-0.25	0.36	0.03	0.00	-0.47	0.50	0.06	-0.36	0.28
Local business owner	-0.31	-0.31	0.53	0.19	-0.11	-0.56	0.39	0.25	-0.50	0.42
Organizations (NGOs)	0.05	-0.30	0.39	-0.16	0.02	-0.32	0.41	-0.18	-0.15	0.55

Finally, the summary of this project using the PROM method can be seen in Table 11. Using this method, vegetated filter strips and infiltration practices can be considered the best techniques for these stakeholder groups. The rank of the vegetated filter strip is also more variable compared to the WAM method. According to stakeholders' preferences and main criteria, green roofs are not recommended here. The installation of green roofs has very little impact on the overall watershed response.

Table 11. Ratings of LID alternatives (PROM method)

	Bioretention	Vegetated swale	Vegetated filter strip	Permeable pavement	Rainwater harvesting	Green roofs	Infiltration practices	Level spreaders	Constructed filter	Soil restoration
Worst	8	8	3	6	7	10	3	7	10	5
Best	4	6	1	4	4	9	1	3	9	1
Average	6.33	7.33	1.83	5.00	5.67	9.67	1.83	4.83	9.17	2.67

When averaged across the group, infiltration practices and vegetated filter strips received the best ratings, while green/living roofs and constructed filters came in last. However, other techniques received ratings of more than three out of five from the WAM method (performing well), and no techniques averaged lower than 2.29. It is also important to note how the stakeholders rated each technique. For example, it appears that there is a general consensus on how vegetated filter strips and infiltration practices would perform here, while there is little consensus on bioretention, level spreaders, and porous pavements. The ratings showed that the majority of stakeholders thought most LIDs would perform well, with a rating of more than three.

Overall, there are some concerns and recommendations that should be considered. First, including LID combinations in the analysis can be highly relevant. Second, note that land-use cover and construction constraints can play an important role, as some LIDs are only suitable for certain specific urban contexts. Third, watershed modeling should be done to calculate the performance of each LID alternative. Finally, several sub-criteria were considered but eliminated due to the inability to find proper data on the corresponding metrics.

4. Conclusion

The purpose of this study was to investigate the concerns held by each stakeholder group regarding the implementation of LID practices. Characteristics and project objectives should be considered as the main influential factors in the planning, design, and construction of LID techniques. Generally, most stakeholders agreed that all the techniques were feasible if used in the intended climate and at proper functions. The findings of this study reveal how stakeholders' priorities and views can be affected according to the project objectives and criteria and in response to the implementation of various LID alternatives. The provided information regarding the involved stakeholders, main criteria and various LID alternatives can provide a background for planners, designers, engineers and stormwater managers to begin the site planning process to achieve stormwater management requirements.

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Conflict of interest

The author declares no conflict of interest.

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Appendix

Table S1. Bioretention

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Medium/High	4
Groundwater recharge	Medium/High	4
Peak rate	Medium	3
Stormwater quality functions		
TSS	High	5
TP	Medium	3
TN	Medium	3
Temperature	High	5
Cost	Medium	3
Maintenance	Medium	3
Winter performance	Medium	3

Table S2. Vegetated swale

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Low/Medium	2
Groundwater recharge	Low/Medium	2
Peak rate	Low/Medium	2
Stormwater quality functions		
TSS	Medium/High	4
TP	Low/High	3
TN	Medium	3
Temperature	Medium	3
Cost	Low/Medium	4
Maintenance	Low/Medium	4
Winter performance	Medium	3

Table S3. Vegetated filter strip

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Low	1
Groundwater recharge	Low	1
Peak rate	Low	1
Stormwater quality functions		
TSS	Medium/High	4
TP	Medium/High	4
TN	Medium/High	4
Temperature	Medium/High	4
Cost	Low	5
Maintenance	Low	5
Winter performance	High	5

Table S4. Permeable pavement

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Low	1
Groundwater recharge	Low	1
Peak rate	Low	1
Stormwater quality functions		
TSS	Low	1
TP	Low	1
TN	Low	1
Temperature	Low	1
Cost	Low	5
Maintenance	Low	5
Winter performance	High	5

Table S5. Rainwater harvesting

Criteria	Word	Rating
Stormwater quantity functions		
Volume	High	5
Groundwater recharge	Low	1
Peak rate	Low	1
Stormwater quality functions		
TSS	High	5
TP	Medium	3
TN	Medium	3
Temperature	High	5
Cost	Low/Medium	4
Maintenance	Medium	3
Winter performance	Medium	3

Table S6. Green roofs

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Medium/High	4
Groundwater recharge	Low	1
Peak rate	Medium	3
Stormwater quality functions		
TSS	Medium	3
TP	Medium	3
TN	Medium	3
Temperature	High	5
Cost	High	1
Maintenance	Medium	3
Winter performance	Medium	3

Table S7. Infiltration practices

Criteria	Word	Rating
Stormwater quantity functions		
Volume	High/Medium	4
Groundwater recharge	High	5
Peak rate	Medium	3
Stormwater quality functions		
TSS	High	5
TP	High/Medium	4
TN	Low/Medium	2
Temperature	High/Medium	4
Cost	Low/Medium	4
Maintenance	Low/Medium	4
Winter performance	High/Medium	4

Table S8. Level spreaders

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Low	1
Groundwater recharge	Low	1
Peak rate	Low	1
Stormwater quality functions		
TSS	Low	1
TP	Low	1
TN	Low	1
Temperature	Low	1
Cost	Low	5
Maintenance	Low	5
Winter performance	High	5

Table S9. Constructed filter

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Low/High	3
Groundwater recharge	Low/High	3
Peak rate	Low/High	3
Stormwater quality functions		
TSS	High	5
TP	Medium	3
TN	Medium	3
Temperature	Low	1
Cost	Medium/High	2
Maintenance	High	1
Winter performance	Medium	3

Table S10. Soil restoration

Criteria	Word	Rating
Stormwater quantity functions		
Volume	Medium	3
Groundwater recharge	Low	1
Peak rate	Medium	3
Stormwater quality functions		
TSS	High	5
TP	High	5
TN	Medium	3
Temperature	Medium	3
Cost	Medium	3
Maintenance	Low	5
Winter performance	High	5