RESIDENTIAL LOW IMPACT DEVELOPMENT PRACTICES: LITERATURE REVIEW AND MULTICRITERIA DECISION ANALYSIS FRAMEWORK FOR DETACHED HOUSES

RESIDENTIAL LOW IMPACT DEVELOPMENT PRACTICES: LITERATURE REVIEW AND MULTICRITERIA DECISION ANALYSIS FRAMEWORK FOR DETACHED HOUSES

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A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfillment of the Requirements
For the Degree of
Master of Applied Science

McMaster University
Hamilton, Ontario, Canada

MASTER OF APPLIED SCIENCE (2021)
(Civil Engineering)

McMaster University
Hamilton, Ontario

TITLE	Residential Low Impact Development Practices: Literature Review and Multicriteria Decision Analysis Framework for Detached Houses
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NUMBER OF PAGES	xv, 106

ABSTRACT

Low Impact Development (LID) is a sustainable stormwater management approach that aims to control runoff close to its source, mimicking the natural hydrological processes such as infiltration and storage. It is being adopted by many cities, where its implementation is rapidly evolving. The LID practices are small-scale measures; therefore, they need to be widely implemented to impact significantly. The selection of LIDs depends on the land use and characteristics of the area of interest. This study focuses on residential LIDs. First, a systematic and bibliometric literature review is conducted on the residential LIDs articles published up to the year 2020; a total of 94 papers were found in the Web of Science. This review resulted that LID implementation in residential areas still needs to be investigated. To assist the City, engineers, and policy-makers in implementing the suitable LIDs for detached houses, a multi-criteria decision analysis framework incorporating a hydrological model is developed in this study. The commonly used LIDs were identified, which are rain gardens, permeable pavement, rain barrels, soakaways. Seven criteria were selected – runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetical view. For the properties of the single-detached house and LIDs, the standards of *Credit Valley Conservation* (CVC) and *Toronto and Region Conservation Authority* (TRCA) were followed. The proposed decision-making framework also was applied to a case study. This framework is still in the preliminary stage, thus holds the potential to convert into a tool that will be handy enough for the homeowners and consume less time.

Dedicated to My Beloved Family

ACKNOWLEDGEMENTS

I would like to offer my sincerest gratitude to my supervisor, Dr. Sonia Hassini, for learning and grow under her wings. I greatly appreciate her continuous inspiration, guidance, involvement, and support throughout graduate studies. I am genuinely grateful for everything she taught me about water resources engineering as a course instructor and supervisor. Her deep understanding, valuable insights, and guidance in LIDs and other stormwater management practices made it possible to reach the end of this research work. She always inspired me to explore new fields of study and offered me her valuable advice.

My sincere appreciation extends to my defence committee members Dr. Yiping Guo, and Dr. Zoe Li, for their time and helpful comments to improve my research.

I also thank my lab mates Arpita Islam and Rikin Patel for providing me with technical and moral support whenever I needed it. Thank you for always believing in me and being a constant support system of mine in this journey. Without your assistance, it would be tough for me to reach the finishing line. I would also like to thank Zakia Sultana for being a constant mentor and providing me with valuable suggestions. Thank you for the assistance and wisdom that you have passed along to me.

I am most thankful to my beloved family for believing in me, encouraging me, and always keeping me in your prayers. You always inspire me to set higher goals and help me to reach the finishing line. Thank you for making all the sacrifices for me. I am also thankful to my niece – Nurat, and nephew- Mahrus for extending your love from Bangladesh. I am grateful to have you in my life to lighten my mood instantly and keep me sane during this stressful time.

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Abbreviations

Acronyms

RWH	Rainwater Harvesting
LCC	Life Cycle Cost
PAH	Polycyclic Aromatic Hydrocarbon
SW	Stormwater
TSS	Total suspended solids
TKN	Total Kjeldahl Nitrogen
NH3-N	Ammonia–Nitrogen
TP	Total Phosphorus
Z_n	Zinc
P_b	Lead
C_u	Copper
CFW	Constructed Floating Wetlands
HRT	Hydraulic Residence Times
AHP	Analytic Hierarchy Process
GI	Green Infrastructures
LCA	Life Cycle Assessment
SCMs	Source Control Measures
MOEA	Multi-Objective Evolutionary Algorithm
GSHP	Ground Source Heat Pump
DCIAs	Directly Connected Impervious Areas
HFM	High-Flow Media

TMDL	Total Maximum Daily Load
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
VELMA	Visualizing Ecosystems for Land Management Assessments
DSD	Downspout Disconnection
WoS	Web of Science
RB	Rain Barrel
PP	Permeable Pavement
SA	Soakaways
RG	Rain Garden
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
MCDA	Multicriteria Decision Analysis
CVC	Credit Valley Conservation
STEP	Sustainable Technologies Evaluation Program
TRCA	Toronto and Region Conservation Authority
MTO	Ministry of Transportation of Ontario

DECLARATION OF ACADEMIC ACHIEVEMENT

This thesis was prepared on the “sandwich” format following the School of Graduate Studies guidelines at McMaster University. The author, Ummay Sumaiya, with the supervision of Dr. Sonia Hassini, worked on the research work presented in this thesis. Chapters 2 and 3 are individual papers and going to be submitted to suitable peer-reviewed journals for publication.

1.0 Introduction

In urban and semi-urban areas, stormwater runoff generated from impervious surfaces is the primary stressor on the surface water sources (Roy et al., 2008). Different approaches and practices have been developed to control the stormwater resulting from an urbanized watershed. The oldest and the most popular measure is to route the stormwater runoff directly to the streams, which results in degradation of the natural freshwater ecosystem (Paul & Meyer, 2001b; Roy et al., 2008). Besides, these conveyances transfer the problems related to excess stormwater to downstream waterbodies. Moreover, conventional stormwater management is highly costly in construction, operation, and retrofitting (Bassut, 2016). To overcome the limitations of the traditional management of stormwater approach, the Low Impact Development (LID) approach has been introduced. This approach aims to mimic natural hydrologic processes and substantially reduce the operation and maintenance cost of the conventional approach by 25-30 % (Coffman, 2000). LIDs in urban residential areas are highly recommended as the residential areas contain a low level of pollutants, heavy metal, and petroleum hydrocarbons, thus are suitable for infiltration (Credit Valley Conservation & Toronto Region Conservation Authority, 2010). Currently, the LIDs are widely implemented at the lot level as they are aesthetically attractive, cost-effective, and sustainable (Bassut, 2016).

For the planning, design, implementation, maintenance, and performance-evaluation of LID practices, Credit Valley Conservation (CVC) and Toronto and Region Conservation Authority (TRCA) have developed planning and design guidelines. These reports are based on literature reviews of published research documents and local studies (Credit Valley Conservation & Toronto Region Conservation Authority, 2010). However, no extensive literature reviews or research have been conducted on LIDs implementation in residential areas. The neighborhood scale application of LID requires customized guidelines as the design specifications depend on the site of interest and cost constraints. Furthermore, LIDs implemented in private properties are expected to be financed and maintained by the owners. Therefore, when they are interested in implementing LIDs in their properties, the homeowners will select the LIDs that suit their budgets. There are no support systems that can help homeowners and decision-makers choose the most suitable LIDs. This study aims to conduct a comprehensive literature review on residential LIDs and develop a multi-criteria decision analysis framework to select the proper LIDs for a detached house. This study's two research parts are reported in Chapter 2; a scientific literature review (meta-research) on residential LIDs has been conducted using bibliometric analysis and Text Mining (TM). The use of TM in this study is innovative as it was not previously performed in the water-resources research area. From this meta-research, (1) latent and emerging topics were discovered, (2) homeowners' concerns related to the LID application in the residential area were recognized, and (3) the most appropriate LIDs types and properties for residential areas were identified.

Based on chapter 2, a framework was developed to facilitate selecting adequate LIDs for detached houses. It includes Multiple-Criteria Decision Analysis (MCDA) that incorporates the homeowner preferences.

2.0 Literature Review on Residential Low Impact Development: Bibliometric Analysis and Text Mining

Abstract: Stormwater management Low Impact Development (LID) is a multidisciplinary field with extensive research history. The focus of this paper is to perform a literature review on residential LIDs. To familiarize with the previous practical studies and current research trends, scientific approaches and modern techniques need to be applied to attain maximum information within minimum time and effort. This study has adopted a meta-research approach by using bibliometric visualizing software (VOSviewer) and text mining in the form of topic modelling to discover the latent topics with corresponding statistical distributions. The Web of Science database was used to collect the relevant publications from 1976-2020 (mid-August). Bibliometric analysis was done to identify the influential authors, publications, countries, and trending keywords. Subsequently, a qualitative study was performed to discover latent topics for better understanding and to provide an overview of the previous research. Both bibliometric analysis and text mining helped identify the significant research gaps in LIDs applications in urban residential areas. This literature review aims to provide a steppingstone for future research in residential Low impact development.

Keywords: Systematic literature review, Text mining, Bibliometric analysis, Low impact development, Urban stormwater management, Residential area.

2.1 Introduction

"The wars of this century have been on oil, and the wars of the next century will be on water ... unless we change the way we manage water" Ismail Serageldin, former vice president, World Bank, 1995 speech in Stockholm (Serageldin, 2009). This is a famous statement that has been quoted in media since 1995 to acknowledge the increasing scarcity of water.

Although water is considered a renewable resource, it has constrained abundance in society (Vargas-Parra et al., 2013). Due to climate change, the frequency and intensity of rainfall events have been incessantly escalating, which has consequential effects on the environment (Lo & Koralegedara, 2015). Moreover, the increasing population growth is directly related to continuous urbanization that leads to more impervious surfaces (Rivers et al., 2018). The gradual changes of impermeable covers are responsible for the exploitation of watershed, and natural ecosystems result in decreasing infiltration, increasing peak flows, quicker rainfall–discharge lag times, unwanted urban flooding, and mobilization of nutrients, metals, pollutants, and pesticides (Caparrós-Martínez et al., 2020; Fletcher et al., 2013; Paul & Meyer, 2001a; Yang & Li, 2013). Though climate change has yet to be addressed, the risk induced by increasing surface water runoff can be controlled by improving infiltration, drainage systems, and water quality. Thus, implementing urban stormwater management is a significant part of sustainable development (J. J. Zhang et al., 2019).

The history of urban stormwater management has started in Crete, Aegian Island, and in Indus Valley from 3200-1100 BC (Angelakis et al., 2012; Burian & Edwards, 2002; T. Fletcher et al., 2015; J. J. Zhang et al., 2019). Then, Germany has started to develop an organized drainage system to drain away polluted water in the commencement of 19th century. Later on, at the starting of the 20th century, United States created an integrated municipal pipe network to flow away polluted water produced by industries (Zhang et al., 2019). Since then, the urban stormwater systems have undergone various levels of changes and developments. In recent decades, more systematic and practical stormwater management systems are planned to be adopted. The literature reviews related to these have adopted new evolutionary terminologies (T. Fletcher et al., 2015). The United States of America proclaimed and amended legislation in the 1940s and 1980s, among which the Federal Water Control Act, Clean Water Act, and Water Quality Act were notable (Zhang et al., 2019). Gradually, Best Management Practices (BMPs) has introduced for controlling and improving the runoff quality of urban stormwater. However, it was discovered later that BMPs were not capable of controlling downstream pollution (Roesner et al., 2001; Zhang et al., 2019). To overcome the drawbacks of BMPs, the idea of low impact development (LID) was proposed by Prince George's County's Department of Environmental Resources (PGDER) in the 1990s (Coffman, 2000; Zhang et al., 2019). In 1997, PGDER issued the design manual which includes certain guidelines, objectives, and procedures regarding LIDs to ascertain its effectiveness (Peng et al., 2019). Meanwhile, New Zealand also has adopted all the guidelines of LIDs and finally suggested Low Impact Urban Design and Development (LIUDD) as it follows a catchment-based structural development (van Roon, 2011; Zhang et al., 2019).

Based on the definition of Coffman (2000), LID can be defined as a stormwater management strategy that is applied in the traditional site design for constructing an environmentally and hydrologically stable watershed regime and can mimic natural hydrologic conditions. The efficient application of LIDs can substantially reduce the operation and maintenance cost of traditional stormwater management systems (pipes, inlets, curbs, and gutters) up to 25-30%, depending on the construction and site constraints. Thus, LID has been gaining popularity in recent years (Coffman, 2000). The design criteria of LIDs mainly focus on infiltrating, storing, detaining, and improving the quality of urban runoff, which reduce the adverse effect of urban development (Wong et al., 2002).

LID practices can be both structural (wetlands, swales, bioretention cells, rainwater harvesting systems, filter strips) and non-structural (reduction of contaminant sources, creating alternative representations of roads and buildings to reduce the usage of concrete surfaces, increasing the use of vegetative lands and pervious soils, introducing educative programs) measures. LID features were mainly developed as an on-site small-scale source control system (Elliott & Trowsdale, 2007). Generally, most of the municipal residential areas built up a long time ago barely considering water sustainability, drainage systems, landform patterns of the associated site and were characterized mainly by unplanned urban expansion (Brito et al., 2020). Thus, necessary guidelines, studies and procedures need to be developed to facilitate the planning and design of LIDs in urban residential sites. This task can be initiated by a bibliometric literature review on residential LIDs.

Although there are several literature reviews that have been conducted on the evolution, application, and impact of stormwater management (Brown et al., 2009; Collins et al., 2010; Fletcher et al., 2015; Hamel et al., 2013; J Marsalek & Chocat, 2002; Tsihrintzis & Hamid, 1997; Zhou, 2014), there are only two bibliometric literature reviews (Du et al., 2019; Zhang et al., 2019) on stormwater management. There are also several literature review studies on different aspects of LIDs, e.g., the effectiveness (Ahiablame et al., 2012), functional models for simulation (Elliott & Trowsdale, 2007), bioretention research for cold climate (Kratky et al., 2017) and environmental impact for using permeable pavement (Sanicola et al., 2018). However, no literature review has been conducted yet on residential LIDs. Moreover, so far, there are no published bibliometric analysis on LIDs.

A bibliometric analysis helps to understand the correlation among the published scientific papers and their topics. It also provides insights on the impact of an article on other studies through the analysis of the article's total number of citations (Phulwani et al., 2020). Due to the vigorous technological development, many information visualization generation software has appeared recently. These software packages can evaluate the research structure to identify the existing research field, research trends, influential categories (authors, journals, countries) in a systematic way. For this purpose, different bibliometric tools, such as Gephi, CiteSpace, BibExcel and VOSviewer are used by many researchers (e.g., Rashidi et al., 2020; Van Eck & Waltman, 2010, 2014; Waltman et al., 2010; Waltman & Van Eck, 2013) on different study areas other than LIDs.

Besides the bibliometric analysis, Text Mining (TM) can unearthing valuable information on the latent topics (i.e., under investigated topics), research trends and gaps in research. TM accesses both structured (e.g., name of the authors, journals, publishers information and titles) and unstructured (e.g., abstracts and textual data fields) data of the publications in a specified field of interest (Ezzeldin & El-Dakhakhni, 2020). Text Mining (TM) has been used in this study to cope with the diversification and understanding of the critical context from the textual data format. TM is a data mining (DM) field that directs to discover meaningful information or latent patterns of interest from a large textual dataset (Blei et al., 2003; Gupta & Lehal, 2009; Y. Zhang et al., 2015) of a multidisciplinary field of research (Ezzeldin & El-Dakhakhni, 2020).

TM aims to identify the topics, within the analyzed data, which is known as topic modelling. Topic models are generative models in a probabilistic framework, to identify the term frequencies in the relevant documents and extract the subsequent insights (Hornik & Grün, 2011). Latent Dirichlet allocation (LDA) is a widely used topic model that scrutinizes each document as a distribution of topics and each topic as a distribution of words using its Dirichlet distribution

(Blei et al., 2003; Campbell et al., 2015). TM and associated topic modelling have a considerable potentiality for extensive research for any multidisciplinary field. For the last couple of years, text mining has been used to identify the latent topics for different research fields, such as – marketing and business (Amado et al., 2018), chemistry (Schneider et al., 2017) and transportation (Das et al., 2016). However, no TM studies were done on LIDs, neither on any other areas of stormwater management.

The objective of this study is to conduct a bibliometric literature analysis and TM on residential LIDs to identify the research topics, trends, and frontiers. The analyses are done on the relevant published articles, which are available on the Web of Science (WoS) database from the year 1976-2020. The VOSviewer software will be used for the bibliometric analysis and the TM will be performed using the LDA technique.

2.2 Research Methodology

2.2.1 Data gathering

For this research, data were collected from the Web of Science (WoS), which is popular for its enormous citation database with Journal Citation Reports (JCR) and InCites. WoS core collection comprises leading journals of all disciplines from where the publications are selected after rigorous screening by experts (Analytics, 2017). As the goal was to choose maximum papers in the relevant field, the search domain needs to be as comprehensive as possible; thus, 20 keywords were selected that include "LID" or specific names of individual LIDs, residential or residence or related words and urban stormwater or associated words. These keywords have been classified into three groups as described in Table 2.1.

Table 2.1 *Used keywords for selecting relevant documents*

LID-related keywords	"low impact development" OR "bioretention*" OR "rain garden*" OR "green roof*" OR "harvesting system*" OR "barrel*" OR "cistern*" OR " permeable pav*" OR "porous pav*" OR "pervious pav*" OR "infiltration basin*" OR "planter*"
AND	
Residence-related keywords	"hous*" OR "urban building*" OR "residen*" OR "driveway*"
AND	
Stormwater-related keywords	"urban stormwater" OR "urban drainage" OR "urban runoff" OR "urban rainwater"

(The asterisk (*) represents any group of characters, including no character)

Using the keywords listed in Table 2.1 and selecting a period of 44 years (1976 to August 15, 2020), the WoS search engine resulted in a total of 97 documents. After manually screening the connectivity of these documents to the research topic of this study, three papers were excluded. Therefore, bibliometric and text mining was performed on a total of 94 related documents. The overall methodology of this review (Figure 2.1) starts with a research scope identification, followed by document collection and then bibliometric analysis and text mining.

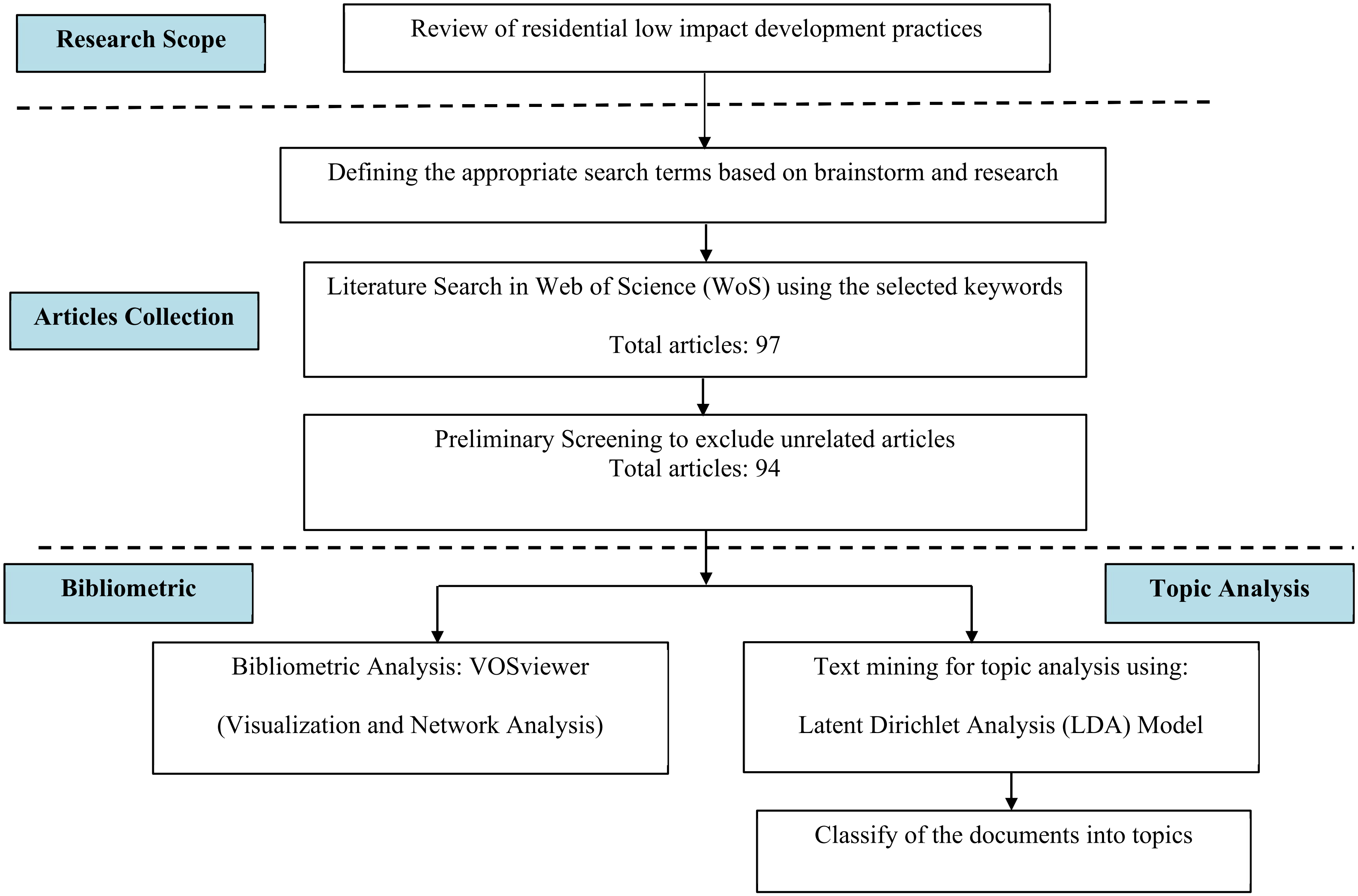


Figure 2.1 *Research Methodology*

2.3 Refinement and filtering

Even though the period was set for since 1976, however, the preliminary search came up with documents ranging from 1993 to 2020. In the first phase, all the papers were rigorously investigated for the title, abstracts, and keywords. This step is essential to exclude irrelevant articles to this study topic of interest, “residential low impact development.” As the keywords were selected meticulously, the reduction number of papers was deficient.

2.3.1 Initial data statistics

Based on the 94 refined and filtered documents, the primary illustrative analysis was done considering the yearly aggregated level publications and citations which is shown in Figure 2.2. The publications include 1,614 total citations (excluding self-citation), 17.21 average citations per document, and 22 h-index. The number of yearly published articles is illustrated as a line graph plotted on the secondary axis in the diagram. Total global citation (TGC), which is the total number of yearly citations cited by the articles of the entire WoS database; and total local citation (TLC), which are the total yearly citations received from the sample of 94 articles. Both LGC and TLC are depicted as a bar chart in the primary axis in Figure 2.2. There is a sharp rise in articles in 2006 and onwards; however, the graph is very fluctuating over the years. The maximum number of articles published in the year 2019, even though the number of citations is less than other years, takes some time for articles to create impact after publication. On the other hand, 2020 is incomplete in this graph.

The selected documents are combinations of multidisciplinary research fields (Figure 2.3). The records 51.02% of documents focused on environmental science ecology, 44.89 % on water resources, and 40.82 % on engineering application. Along with these, public administration, development studies, and urban studies also play a notable role in analyzing household stormwater management systems.

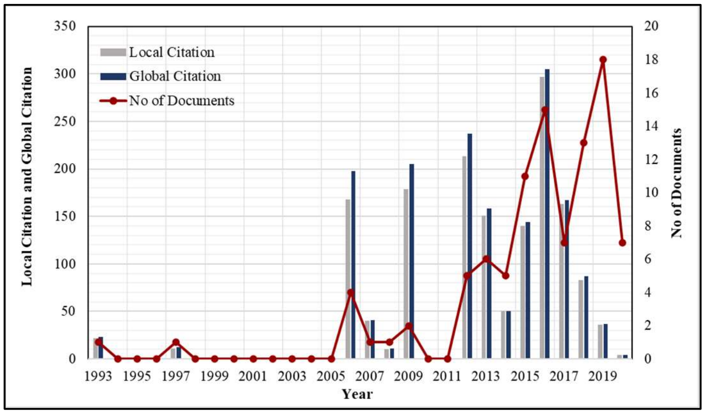


Figure 2.2 *Number of publications and citations*

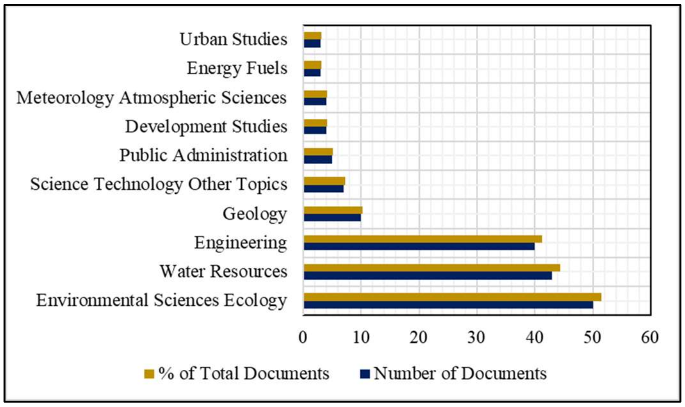


Figure 2.3 *Subject area of the publications*

2.4 Process of bibliometric analysis

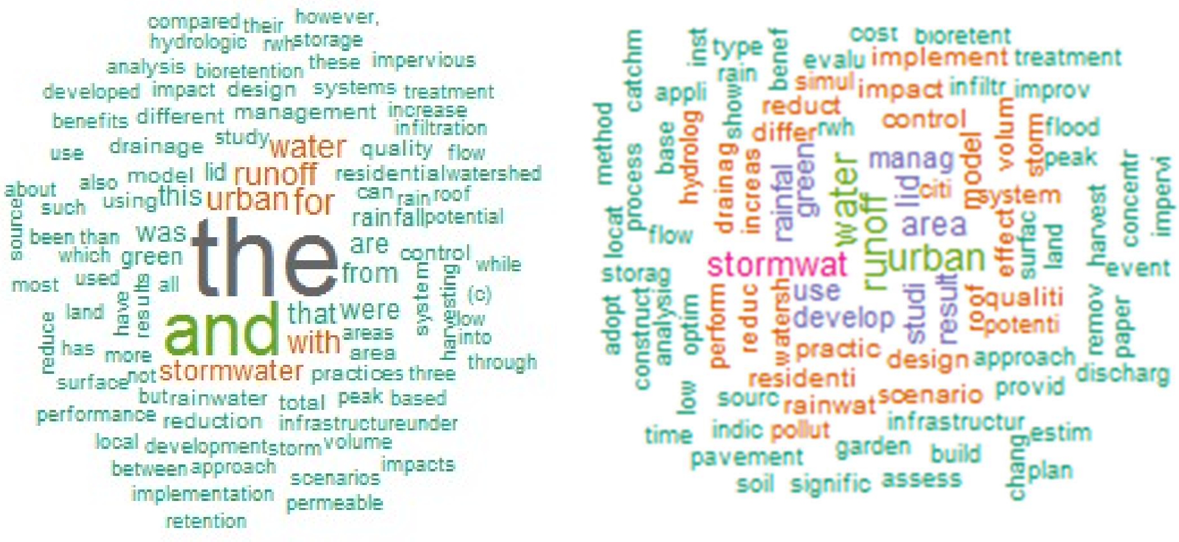
The bibliometric software package VOSviewer (van Eck & Waltman, 2010) was used in this study to retrieve the most influential authors and most cited papers. Along with these, the evolution of research in residential LIDs was identified by analyzing the publications, determining the countries that are playing significant contributions, and tracing innovative and new research streams. The output of this analysis will be discussed in section 2.6.

2.5 Process of topic modelling using text mining

2.5.1 Pre-processing of the dataset

Linguistic noise is a common complication that disturbs the statistical analysis within the application of text mining (TM) (Salloum et al., 2018). This linguistic noise has commonly occurred in many ways, such as word forms (e.g., optimize and optimization), variation in case of types (e.g., LID and lid), special characters (e.g., punctuation and whitespace), and frequently used words (e.g., the, a, an, is, etc.). Thus, the raw abstract data needs to be modified before starting to analysis.

The current research used the filtered and refined dataset derived from WoS. The raw abstract dataset was transformed into a so-called Corpus. Corpus is an abstract concept that collects large and unstructured sets of text used for various statistical and hypothetical testing (Feinerer, 2015). Then Corpus file went through the following processes : (1) Tokenization: converting unstructured text into words for further analysis; (2) Treatment: removing all commonly used word in English; (3) Transformation: changing capital letters to lowercase; (4) Stemming: converting the words to their root form; (5) Cleaning: eliminating all the numbers, punctuations, white spaces from the Corpus by using specific filters (Miner et al., 2012; Feinerer, 2015; Y. Zhang et al., 2015). Moreover, to avoid linguistic nuisances, non-technical words are removed from the Corpus using a custom-made “stop” list of 70 words. Figure 2.4 illustrates the word cloud before (a) and after (b) the pre-processing of the Corpus, respectively.



(a)

(b)

Figure 2.4: *Word cloud of the terms with the highest frequencies before Pre-processing (a) and after Pre-processing (b)*

2.5.2 Number of topic identification

Latent Dirichlet Allocation (LDA) uses three-level hierarchical Bayesian inference to generatively identify the model distribution using only the words present in the Corpus. To start the iteration procedures, LDA requires only one parameter: the number of latent topics (K) (K. Lee & Yu, 2018). Determining the optimal number of latent topics is a significant challenge in topic modelling (Ezzeldin & El-Dakhakhni, 2020). Thus, the perplexity analysis was introduced to predict the key topics from the abstract dataset. In the natural language statistical model, perplexity is used for the standard performance measurement (Ezzeldin & El-Dakhakhni, 2020; Blei et al., 2003). A lower perplexity score indicates better generalization performance (Blei et al., 2003). Apart from perplexity analysis, various processes are recommended by researchers to establish the value of K (Arun et al., 2010; J. Cao et al., 2009; Griffiths & Steyvers, 2004). All of these approaches are capable of providing a mathematically plausible range of possible K values. In the current research, ldatuning (Nikita, 2014) was applied with perplexity for further verifications.

2.6 Results and Discussions

2.6.1 Bibliometric Analysis

2.6.1.1 Productivity of authors, journals, and articles

The authors who have contributed significantly to the residential LIDs can be recognized from the bibliometric analysis. This information helps to identify the influential authors working in this field. A total of 314 authors and co-authors took part in the selected 94 papers. Figure 2.5 illustrates the collaboration network among the prominent authors based on co-authorship. Among these 314 authors and co-authors, 15 authors were interconnected with their publications. The main authors are divided into 3 clusters (Figure 2.5). Each cluster is prepared considering their collaborative publication, and the size of each node indicates the number of publications per author (Meseguer-Sánchez et al., 2020).

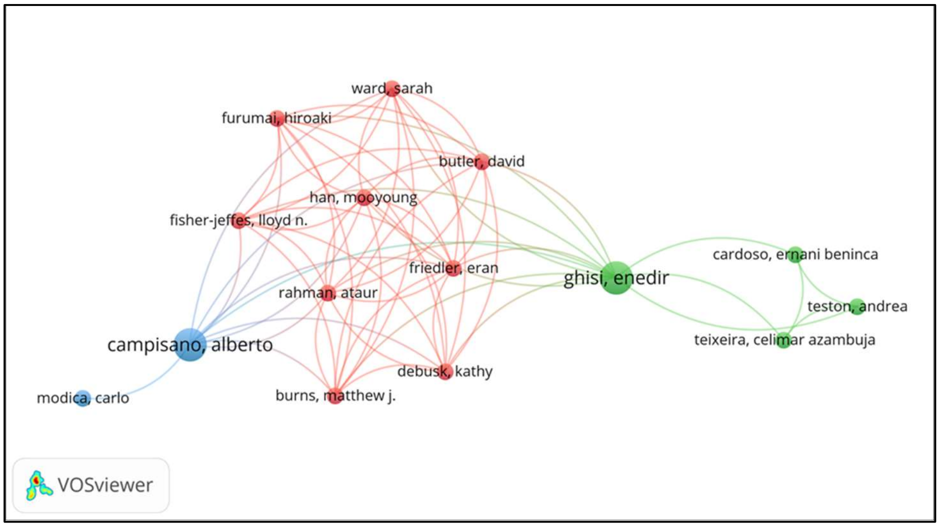


Figure 2.5: *Network of cooperation among authors based on co-authorship (1993-2020)]*

Table 2.2 indicates the top 10 contributing authors. At first, the authors were ranked based on their number of published articles; however, some of the authors have the same number of publications. To rank the authors, the "Factorization" method was applied (Rashidi et al., 2020). For a single-authored article, the author was awarded 1.0 credit, while in a multi-authored article, 1.0 would be divided by the total number of co-authors. For instance, if two authors publish an article, each author will be given 0.5 credit, and in a 3-author article, each author will be credited with 0.33.

Table 2.2: *Contributing authors*

#	Authors	No of Articles	Credits	Citation	Citation Ranking
1	Davis, Allen P.	2	0.750	88	4
2	Hu, Maochuan	2	0.750	64	5
3	Montalto, Franco A.	2	0.667	43	8
4	Jia, Haifeng	3	0.625	108	3
5	Campisano, Alberto	2	0.591	124	1
6	Zhang, Xingqi	2	0.583	64	6
7	Fletcher, Tim D.	2	0.583	49	7
8	Shuster, William D.	2	0.583	40	9
9	Green, Olivia Odom	2	0.533	40	10
10	Ghisi, Enedir	2	0.341	110	2

Table 2.3 depicts the top 10 most cited paper. Among these, 3 of the papers were published in the *Water Research* journal. Two of these three papers were the most cited ones. In Table 2.3, papers were ranked in two different methods: (1) the total number of citations, which means the cumulative number of citations of an individual paper from its publication year to mid-August of 2020, and (2) the average number of citations per year, i.e., the total number of citations divided by the number of years from publication to mid-August of 2020.

Table 2.3: *Top ten most cited publications statistics*

Title of the Paper	Authors	Year	Journal	Citation	Rank	Citation Per Year	Rank
Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut	Gilbert & Clausen	2006	Water Research	136	1	8.93	6
Urban rainwater harvesting systems: Research, implementation, and future perspectives	Campisano et al.	2017	Water Research	109	2	28.75	1
Planning of LID-BMPs for urban runoff control: The case of Beijing Olympic Village	Jia et al.	2012	Separation and Purification Technology	105	3	11.44	3
Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds(1)	Bedan & Clausen	2009	Journal of The American Water Resources Association	92	4	7.67	7
Removal and Fate of Polycyclic Aromatic Hydrocarbon Pollutants in an Urban Stormwater Bioretention Facility	Diblasi et al.	2009	Environmental Science & Technology	87	5	7.33	8
Assessing cost-effectiveness of specific LID practice designs in response to large storm events	Chui et al.	2016	Journal of Hydrology	80	6	16.20	2
Hydrological performance of extensive green roofs in New York City: observations and multi-year modelling of three full-scale systems	Carson et al.	2013	Environmental Research Letters	76	7	9.50	4
Assessing the effects of catchment-scale urban green infrastructure retrofits on hydrograph characteristics	Jarden et al.	2016	Hydrological Processes	47	8	9.40	5
Urban Rainwater Utilization and its Role in Mitigating Urban Waterlogging Problems-A Case Study in Nanjing, China	X. Zhang et al.	2012	Water Resources Management	44	9	4.89	10
Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review	Hashemi et al.	2015	Renewable & Sustainable Energy Reviews	40	10	6.67	9

2.6.2 Collaboration network analysis of countries

Table 2.4 shows the countries with the most published articles in the research field of residential LIDs, along with their total numbers of citations from 1990 to 2000. Heading the table is the United States with 44 articles and the highest number of citations (1016), meaning the average number of citations per document is 23.47. The majority of the papers have been published in the last decade. Besides, the United States also has the highest h-index (17). In second place comes China, which contributed by 17 publications with 289 total citations and seven h-index. Although Japan has publications in about 2% of this field, it has the highest number of citations per publication (6.85).

Table 2.4: *The most productive countries in the number of articles (1990–2020)*

Country	P*	TC**	TC/P•	h-Index••	Publications (%)	Number of Publication Per Year	
						2000-2010	2010-2020
USA	44	1016	23.47	17	46.81	4	43
China	17	289	17.22	7	18.09	0	18
Australia	10	240	24.55	9	10.64	1	9
England	5	184	38.4	4	5.32	0	5
Italy	4	129	34.5	3	4.26	0	4
South Korea	3	121	42.67	2	3.19	1	2
Brazil	3	110	39.33	2	3.19	0	3
Spain	3	24	8	2	3.19	0	3
Japan	2	129	68.5	2	2.13	0	2
South Africa	2	125	66	2	2.13	0	2

*P: number of publications; **TC: number of citations for all articles; •TC/P: number of citations by article; ••h-index: Hirsch index in the research topic

Figure 2.6 depicts the collaborative network among countries performing research on residential LID practices. The number of publications threshold was set to 1, and 29 countries were selected based on the co-authorships. The overall network includes 29 nodes (referred to as countries) and these nodes were classified as 4 different clusters depending on the collaboration network among the nations. The total link (the connection between two countries based on collaborations) strength is 114. Table 2.5 also depicts the top countries which worked together and published their research works. This analysis depends on the authors and the countries they represent.

Table 2.5: *Ten top collaborative countries*

Rank	Country	Links	Total Link Strength	Publications	Citations
1	USA	12	18	44	1016
2	Australia	11	13	10	240
3	England	11	12	5	184
4	South Korea	8	9	3	121
5	Japan	9	9	2	129
6	South Africa	8	8	2	125
7	Italy	8	8	4	129
8	Israel	8	8	1	109
9	Brazil	8	8	3	110
10	China	2	6	17	289

USA, Australia, and England were the top three most affiliated countries maintaining close cooperation, which proved by their high link strength of 18, 13, and 12, respectively. Japan and South Korea showed the same link strength, which was 9. They were followed by Brazil (link = 8, total link strength =8), Spain (link = 3, total link strength =3), and Japan (link = 9, total link strength =9).

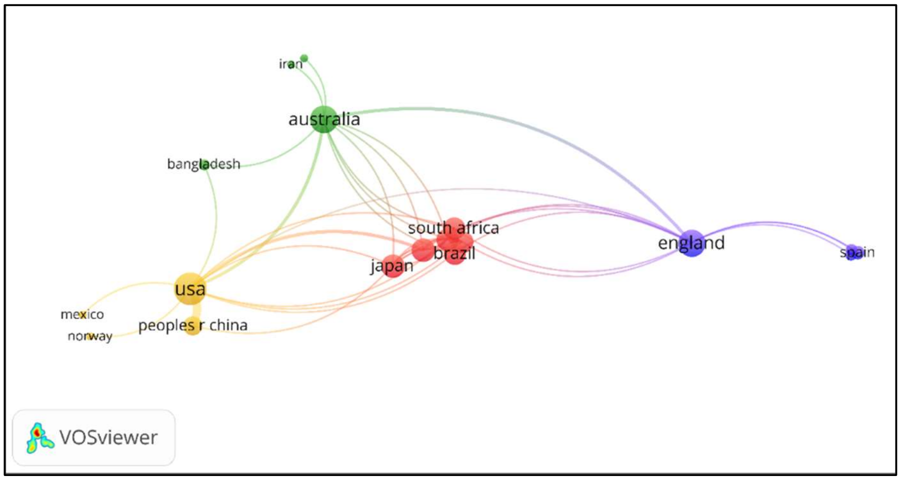


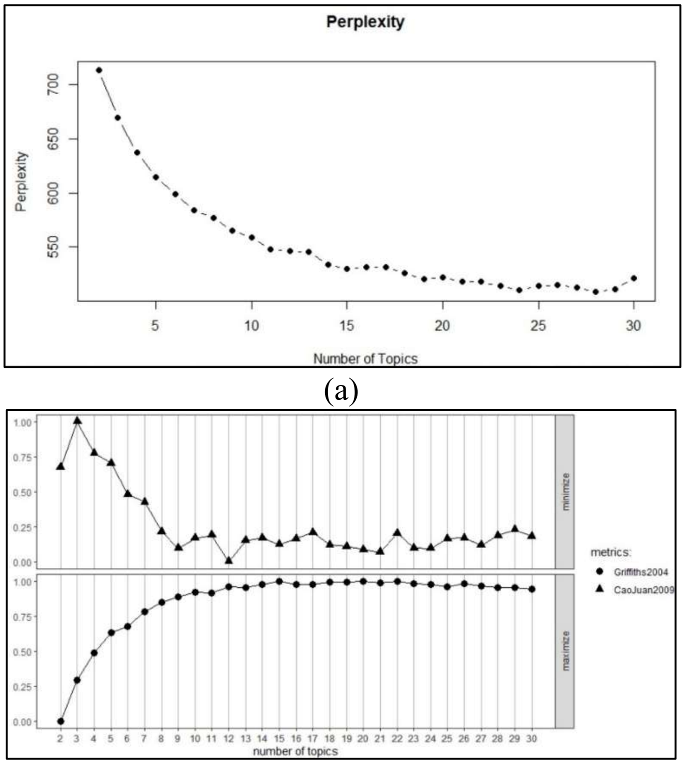
Figure 2.6: *Co-authorship diagram showing cooperation between countries*

Based on table 2.5, it is evident that the USA, Australia, and England were involved in joint research projects. From figure- 2.6, same-colored countries had interrelationships among them for each other for research purposes.

2.6.2 Topic modelling by using text mining

2.6.2.1 Appropriate model selection

The lowest perplexity score that corresponds to our dataset is 28 (Figure 2.7 a). This score is relatively high given that the dataset consists of 94 articles only. Moreover, there is a high chance that this analysis may result in redundant topics. Therefore, the range of topics can be estimated from the steady-state after facing a steep slope. Thus, for this dataset, the number of topics is between 11 and 15 (Figure 2.7 a).



(a)

(b)

Figure 2.7: *Determination of the number of latent topics (K) using (a) Perplexity analysis, (b) Minimization (top chart), and Maximization (lower chart) methods*

These results are further confirmed using the minimization (Griffith 2004) and maximation (CaoJuan 2009) methods. The minimization method (Figure 2.7 b, top chart) indicates that the minimum value is at topic 12, and the maximization method (Figure 2.7 b, lower diagram) shows that the maximum value is at topic number 15. Based on the above analyses, research objectives, and the number of publications considered, 12 is selected as a reasonable number of latent topics. Due to their latent nature, the extracted topics usually express multi-dimensional semantics (K. Lee & Yu, 2018).

2.6.2.2 Topic identification

The LDA model outputs the word distribution, the probability of word occurrence, and the relevant documents for each topic. The set of words with a higher likelihood for a specific topic K can be connected with a particular research field (Ezzeldin & El-Dakhakhni, 2020; Griffiths & Steyvers, 2004). The probabilistic interpretation of words for each topic can be represented as "beta." the Beta distribution (per-topic-per-word probabilities) of the top eight frequently used words within each topic is shown in Figure 2.8.

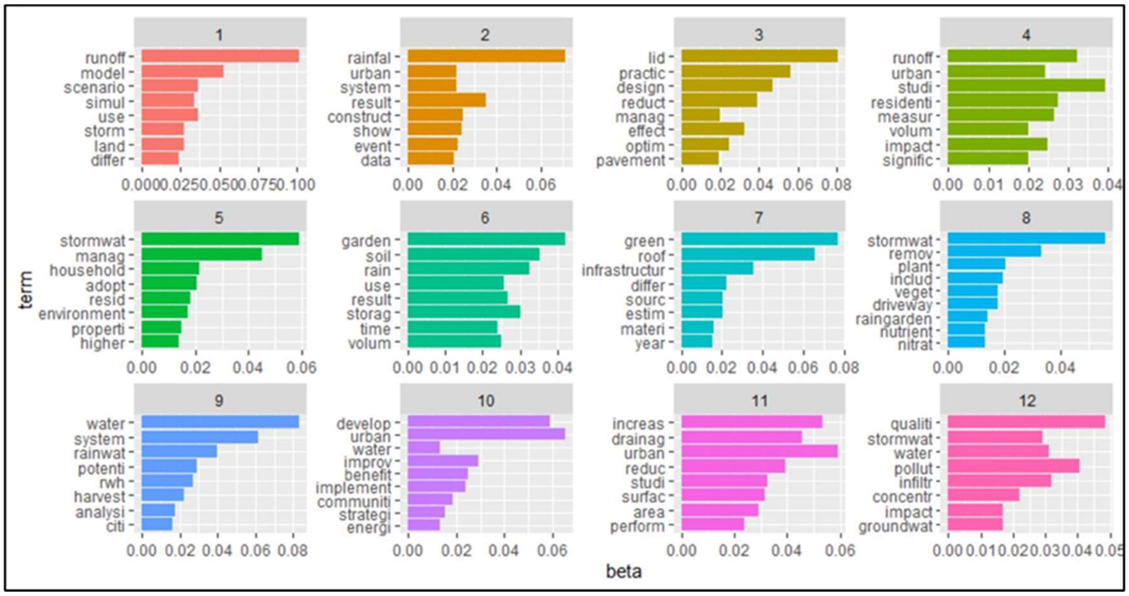


__Figure 2.8:__ Beta distribution of extracted latent topics

For each topic, the most frequent word has a higher beta value compared to other words. Therefore, the most frequent words play a crucial role in identifying the topics. For example, in topic 1, "*runoff*" has the highest beta value (0.101), which means topic 1 has formed based on runoff with other associated areas. Similarly, topic 2 has been created with "*rainfal*" as this word has the highest beta value (0.0706).

The related publications for each topic were also determined using the LDA model. Therefore, the research theme for each topic was identified based on the content of these papers. Following is table 2.6, showing the publications for each of the topics and corresponding titles for further detailed investigations.

Table 2.6: *Identified topics*

Notation	Topics
Topic 1	Runoff scenarios based on model simulation
Topic 2	Impact of rainfall
Topic 3	Design of LID practices
Topic 4	Impact of impervious cover
Topic 5	Public perception
Topic 6	Effect of core material of specific LIDs
Topic 7	Green infrastructures
Topic 8	Stormwater quality assessment
Topic 9	Water saving potentiality of rainwater harvesting systems
Topic 10	Green Infrastructure based management strategies
Topic 11	Studies on SUDS*
Topic 12	Groundwater quality

*SUDS: Sustainable Urban Drainage Systems

2.6.3 Residential low impact development overview based on topic modelling

This section will shed light on some studies related to residential LIDs for each topic listed in Table 2.6.

Topic 1: Runoff Scenarios Based on Model Simulation

The increase in impervious areas provokes recurring flood disasters, which tend to impact the water environment. To reduce the negative impact of urbanization, urban stormwater flood management focusing on LIDs has gained popularity among planners and engineers (J. Zhang et al., 2019). Model-based simulation is an effective way to mimic the actual urban runoff situation. Researchers have used different types of models over the years. Some of those are mentioned below with their ability to perform runoff scenarios.

The Storm Water Management Model (SWMM), the Windows version of the Source Loading and Management Model (WINSLAMM), the PCSWMM, the L-THIA LID are the most available numerical models for stormwater management. Many researchers (e.g., Zhang et al., 2019, Guan et al., 2015, Lee et al., 2018 and Zhu et al., 2019) used the SWMM model various residential LID practices. Zhang et al. (2019) analyzed the runoff control measures for LID practices under different rainfall scenarios. They reported that LID practices had the most influence on runoff rate reduction even during rainfall with high intensity. Chen et al. (2019) developed a runoff hydrograph for a specific rainfall scenario to avoid the risks and uncertainties. Zhang and Peralta (2019) used the WINSLAMM model to quantify runoff for three different scenarios with green infrastructures (grass swales, pervious areas, and permeable pavement). PCSWMM was used on seven LID scenarios to check their water quality and quantity control performance under different rainfall return periods, intensities, and durations (Peng et al., 2019). SCS-CN method was used with other models (WINSLAMM, L-THIA LID, and GIS tool) infiltration, relative runoff reduction, and rainfall-runoff scenarios for different land-use types (Eaton, 2018; Liu et al., 2013; Zhang and Peralta, 2019).

Topic 2: Impact of Rainfall

Urbanization and modernization, construction of complex grey infrastructures, and changes in rainfall patterns make municipality areas endangered to water-related issues (Lo & Koralegedara, 2015). Moreover, climate change is another opposing driving force which has a considerable impact on rainfall pattern. Following this, historical rainfall data of 1981-2010 has been taken to predict long-term future rainfall from 2011-2099 by using the Long Ashton Research Station Weather Generator (LARS-WG). The results showed that severe weather conditions with heavy rainfall events might occur at the end of this century (2080-2099) (Lo & Koralegedara, 2015). Cao et al. (2020) found that water depth at the water collection points increases with building coverage ratio even for rainfall events with low return periods. However, if the drainage capacity is increased, water depth depicted a decreasing trend for rainfall events with high return periods. Xiang et al. (2019) used six design storms that correspond to return periods between 2 to 100 years to calculate the inundation risks for SCMs. They found that the risk values fell under 0.2 when the rainfall return period was less than ten years. Moreover, Carson et al., 2013 monitored data of 12 months to simulate a characteristic runoff equation for each green roof. The derived model was then applied to estimate the total rainfall retention, using 40 years of precipitation record.

Topic 3: Design of LID Practices

Low impact development is a comparatively modern and practical approach in urban stormwater management, which possesses a notable impact on urban surface runoff management and pollutant loadings (Seo et al., 2017; You et al., 2019). Thus, the LID needs to be implemented carefully considering some crucial factors such as cost-effectiveness, improving water quality, runoff volume reduction, runoff peak reduction, etc. (Y. Chen et al., 2019; You et al., 2019; Di Matteo et al., 2017; Hoghooghi et al., 2018; Tuomela et al., 2018). Applying different optimization techniques (NSGA-II, MOEA, and manual optimization) to select the appropriate LID is a general approach (You et al., 2019; Cheng et al., 2018; Di Matteo et al., 2017). Various software packages, e.g., SUSTAIN, PCSWMM, BMPDSS, include an optimization module. Table 2.7 shows the criteria for selecting LID techniques based on previous studies.

Table 2.7: *LIDs selection criteria*

Source	LIDs	Used Model	Optimization Techniques	Performance evaluation	Selection Criterion
(J. Chen et al., 2019)	Rain barrels/cisterns, green roofs, porous pavements, and bioretention	L-THIA-LID 2.1		runoff volume and water quality (TSS, TN, and TP)	Cost-effectiveness, improving hydrology and water quality
(You et al., 2019)	Bioretention, porous pavement, green roof, rain barrel, grassed swale	SUSTAIN version 1.2	NSGA-II	runoff volume, peak, coefficient, and control rate, pollutant control (COD, SS, TN, TP)	cost-effectiveness and reduction rate of annual runoff volume
(Tuomela et al., 2018)	Permeable pavements, bioretention cells	SWMM 5.1	Manual	Runoff volume and pollutant load reduction	pollutant load reductions
(Hoghooghi et al., 2018)	Rain garden, permeable pavement, and riparian buffer	VELMA		subsurface runoff and infiltration, evapotranspiration, and decreases in peak flows and surface runoff	Peak flow and surface runoff reduction
(Cheng et al., 2018)	Green roof, bioretention, permeable pavement, and vegetative swale	SWMM and SUSTAIN	Genetic Algorithm	Runoff reduction	Cost-effectiveness
(Di Matteo et al., 2017)	Biofilter, sediment basin, wetland, storage pond	MUSIC	NSGA-II	cost, supply volume, and water quality improvement	type, size, and spatial distribution, pollutant reduction
(Seo et al., 2017)	Rainwater harvesting system, permeable pavement, rain gardens, and detention ponds	SWAT	Manual	Runoff volume and pollutant load	minimize cost and reduce runoff
(Chui et al., 2016)	Green roof, bioretention, and porous pavement	SWMM	Manual	Runoff peak and cost	reduce 20% runoff and cost-effectiveness
(Giacomoni, 2015)	Green roof	SWMM	Multi-Objective Evolutionary Algorithm	Runoff volume and peak, Hydrologic Footprint Residence (HFR)	surface runoff volume and peak flow reduction, cost-effectiveness
(H. Jia, Lu, Shaw, et al., 2012)	Green roof, bioretention, infiltration trench, and rain barrel	BMPDSS and SWMM		Runoff volume and runoff peak	Controlling maximum runoff (20% reduction of volume from scenario 3) and total minimum system cost

Topic 4: Impact of Impervious Cover

Increasing impervious cover elevates the runoff quantity, peak discharges, and chances of pollutant load discharge towards streams. Consequently, the nearby waterbody of impervious surface faces water quality degradation and ecological imbalance (Page et al., 2015b). Several LIDs (Bioretention cell, street retrofit, permeable pavement, tree filter device) were installed to control and treat street runoff, as retrofitting SCM has a significant impact on hydrology conditions and water quality improvement in residential areas (Page et al., 2015a, 2015b). Again, urbanization increases directly connected impervious areas (DCIA), which is also a significant concern from the ecological and environmental perspective (Sadeghi et al., 2017). To balance with this expanding DCIA, downspout disconnections were installed in 4 different locations for calculating runoff volume and peak flow reduction for various factors, which results in a decrease of 57-99% and 49-99%, respectively (Sadeghi et al., 2017). In another study, the impact of LID on an alleviated DCIA was investigated for five different land-use types by using Sutherland's equations (Sohn et al., 2017). The result indicated that DCIA is greater in commercial areas than residential areas and land-use type has a significant impact on reducing DCIA (Sohn et al., 2017). A carefully selected LID combination could maximize the benefit of DCIA, which could be very helpful in minimizing runoff volume (Sohn et al., 2017).

Topic 5: Public Perceptions

Decentralized stormwater management has been gaining popularity, and residents are becoming more concerned about the urban stormwater runoff. Thus, residents’ perceptions and participation need to be monitored and ensured. Surveys (Cockerill et al., 2019; Dean et al., 2016; Sun & Hall, 2016), formal and informal interviews (H. L. Brown et al., 2016), and statistical analysis (Gao et al., 2018) have been conducted to assess residents involvement, knowledge, and interests. Surveys were done to identify residents’ knowledge on stormwater management and the responsible payee for management (Cockerill et al., 2019), understanding public's openness towards GI implementations (Sun & Hall, 2016), assess people's consciousness towards community-based stormwater management (Dean et al., 2016). The survey results showed that residents have limited knowledge about stormwater impacts. Even though some of them implemented stormwater control measures, they are unsure about the responsible payee of the management (Cockerill et al., 2019). Residents were more interested in implementing rain barrels and rain gardens in their private properties for stormwater management (Sun & Hall, 2016). A survey conducted in Australia showed that older, educated, and non-urban living respondents possessed a better understanding of the effect of household activities on stormwater management than non-English speakers at home (Dean et al., 2016).

Topic 6: Effect of Core Material of Specific LIDs

Some of the studies have been conducted considering the base materials of different LIDs and how they affect the performance of LIDs. These studies were performed on bioretention cells, rain gardens, permeable pavement, and rainwater harvesting systems.

To understanding the hydrologic performance of rain garden relying on in-situ soil infiltration, Anderson (2018) examined the performance of 11 residential rain gardens (surface and subsurface storage capacity, ponding depth, etc.) by applying a variable-rate stormwater runoff simulator and a design storm of 3 cm to generate an SCS Type II runoff hydrograph. Garza et al. (2016) compared the performance of rain gardens using engineered soil versus native soil; they suggested using native soil if its infiltration capacity is sufficient. Kazemi and Hill (2015) researched permeable pavements using basecourse aggregates (basalt, quartzite, and dolomite) for cheeking water quality improvement (DO, EC, pH, and turbidity**)**. The study, as mentioned above, was a significant one for ensuring sustainability in irrigation management (Kazemi & Hill, 2015).

Topic 7: Green Infrastructures

In water-sensitive urban design systems, the green roof plays a substantial role in boosting the urban runoff quality, decreasing energy consumption, adding cooling effects in buildings, and alleviating aesthetical values (Hashemi et al., 2015). Green roofs can drop the roof's surface temperature by 30–60 °C which can balance the indoor air temperature and save energy cost (Hashemi et al., 2015). Even though the green roof is counted as an environmentally sustainable LID feature, it may have detrimental effects on runoff quality when the roof contaminates the runoff water depending on multiple factors, e.g., the type of roofs, species of plants, fertilizer types, climate condition, and depth of the growing medium (Hashemi et al., 2015). Roofing materials can potentially degrade the quality of rain falling on the roof. As a result, metals from the roof such as arsenic, copper, and zinc may leach into the runoff water in varying concentrations, depending on the roof's life span (McIntyre et al., 2019). McIntyre et al. (2019) found that residential roofs are a significant source of arsenic and copper and that commercial roofs mainly contribute zinc. To facilitate the implementation of green roofs, which are gaining popularity, Zellner et al. (2016) developed a process-based model, L-GriD. The model allows comprehending the impact of design structures of green infrastructures on a proximity scale by considering the magnitude of storm events and different types of land covers (Zellner et al., 2016). The study revealed that generally, green infrastructures could capture the majority of runoff volumes resulting from small storms. However, the coverage needs to be doubled or tripled to capture runoff from more significant events (Zellner et al., 2016).

Impervious surface runoff that reaches water bodies negatively impacts the aquatic life; therefore, disconnecting impervious surfaces from the stream and controlling urban runoff using decentralized green infrastructures, adequately designed and constructed, can decrease these adverse effects (Jarden et al., 2016). Connecting streets to bioretention cells, rain gardens, and rain barrels in an experimental study, Jarden et al. (2016) found that roads with smaller lots reduced runoff volume up to 40% and peak discharge up to 33%; however, streets with larger lots did not show any worthy of mention results.

Topic 8: Stormwater Quality Assessment

Urban stormwater is a significant source of non-point pollution and entirely accountable for the various pollutants, pesticides, toxic metals, and bacteria. The most pollutants originating from urban residential stormwater are- nitrogen (N), phosphorus (P), potassium (K), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), orthophosphate (PO_4^{-3}), ammonia (NH_3), nitrate (NO_3^-), copper (C_u), lead (P_b), and zinc (Z_n). Controlling such pollutants will improve the runoff quality (Bedan & Clausen, 2009; Diblasi et al., 2009; Landsman & Davis, 2018; Milandri et al., 2012; Schwammberger et al., 2020). Different researchers worked on minimizing the pollutant quantity and enhancing the runoff quality by adopting various approaches.

A field experiment showed that tall sedge (Carex appressa) plants planted on a large scale in Constructed Floating Wetlands (CFWs) had impressive adaptability in changing nutrient availability (Schwammberger et al., 2020). Another worth mentioning study revealed that High-Flow media (HFM) are the excellent exclusion of TSS, and the higher the organic content present in HFM, the higher the tendency of removing N (Landsman & Davis, 2018). Milandri et al. (2012) reported that local plant species (Agapanthus, Stenotaphrum, and Pennisetum and turf grasses) lowered the concentration of PO_4^{-3}, NH_3, NO_3^- on an average of 81%, 90%, and 69%, respectively. Another research demonstrated that polycyclic aromatic hydrocarbons (PAHs), present in urban stormwater, had a powerful affinity towards TSS. Bioretention containing a 90 cm mixed layer of soil, sand, organic matter, and vegetation was highly influential in removing PAHs (Diblasi et al., 2009). Gilbert and Clausen (2006) compared the quality and quantity of runoff from the driveway of asphalt, permeable paver, and crushed stone. They found that runoff from the paved driveway was the most successful in lowering the concentration of pollutants.

Topic 9: Water Saving Potentiality of Rainwater Harvesting Systems

In urban areas, rainwater harvesting (RWH) systems help store rainwater used as a non-potable source (Lúcio et al., 2020; Tavakol-Davani et al., 2019). However, the effectiveness of the RWH system in an urban residential area is dependent on various factors. Lúcio et al., 2020 used a balance equation model and found that depending on the buildings' characteristics and water usage pattern, the capability of RWH systems varies from 16 to 86%. Tavakol-Davani et al. (2019) analyzed the uncertainty in RWH systems in life cycle assessment (LCA). The result showed that rainfall depth was the most responsible (more than 86%) parameter on uncertainty; however, only 7% uncertainty was produced by life cycle impact assessment (LCIA) parameters. Apart from these, the cost-effectiveness of RWH systems was investigated by Bashar et al.(2018) and Stec and Słyś (2018). Freni and Liuzzo did an exciting study building a relationship between reliability and stormwater retention using the FLO-2D model on 400 single-family houses. The study showed that the average reliability was between 63-86%, and the average overflow ratio was between 38-62%. Teston et al. (2018) used the German Practical Method to find the tank capacity. Foo et al. (2017) studied RWH systems in commercial areas that possess more impervious covers than urban residential lands, and Vargas-Parra et al. (2013) analyzed the exergy of RWH systems for eight different scenarios. They found that the highest energy was consumed while transporting the materials of the RWH system construction. Apart from all of the studies mentioned above, a considerable number of research works were focusing on reducing surface runoff and peak flow (Campisano & Modica, 2016; Rostad et al., 2016; X. Zhang et al., 2012a).

Topic 10: Green Infrastructure Based Management Strategies

The rapid growth of the urban population and consequential impervious areas are primarily responsible for the decreasing infiltration rate, increasing runoff peak and volume, sediment, and pollutant mobilization (Garcia-Cuerva et al., 2018; Giner et al., 2019). To minimize the adverse impact of poor stormwater management on the environment and socio-economy, the Border Environment Cooperation Commission (BECC) took four years of strategic planning to increase resiliency by integrating Green Infrastructures (GI) public areas. GIs help to cope with global warming, ecological imbalance, and land-use change (Giner et al., 2019). Traditionally, the concept of "Sustainability" is most favored for the privileged society; however, marginalized and underprivileged communities are constantly deprived of social and environmental benefits (Garcia-Cuerva et al., 2018). GI-based (e.g., RWH and bioretention cells) management approaches were adopted in neglected communities after simulating their effect on runoff volume and peak (Garcia-Cuerva et al., 2018). Improving sustainability by utilizing GI has an impact on food, water, and energy. Chang (2015) investigated the possibilities of implementing LID practices in urban areas on a larger scale, harmonizing both planning and design approaches.

Topic 11: Studies on SUDS

SUDS is a promising solution for dealing with the consequences of urbanization and the climate change process; however, its impact on the urban fabric is different depending on the urban ecosystem (La Rosa & Pappalardo, 2020). Thus, selecting an appropriate location for the SUDS installment is highly important to attain the maximum advantage from the watershed and reduce the risk of urban pluvial flooding (Ariza et al., 2019; La Rosa & Pappalardo, 2020). Ariza et al.(2019) developed a relationship between the urban flooding risk reduction and location optimization for different planning scenarios of the densely populated cities. La Rosa and Pappalardo (2020) conducted a study to determine the most appropriate SUDS measures for public and residential areas considering different aspects, such as minimizing runoff, improving water quality, and generating amenity. Scholz (2013) found that permeable pavements have minimal water quality control. Lestari and Irawan (2019).found that an artificial small bioretention cell was highly capable of treating roof and surface runoff.

Topic 12: Groundwater Quality

As stormwater runoff has the pollution concern in the nearby streams and groundwater , LID has introduced to reduce the pollutants coming from urban runoff and improve groundwater quality (Sadeghi et al., 2017). The Broadway Neighborhood Stormwater Greenway (Project) was built to cure, capture, and infiltrate the stormwater using LIDs (rain gardens/infiltration swales, dry wells, infiltration swales, and underneath parking) and to ensure meeting the requirements for the pollutant removals set by Los Angeles River Total Maximum Daily Load (TMDL) before infiltrating (Sadeghi et al., 2017). The Avalon Green Alley Network is another established project in South Los Angeles (Sadeghi et al., 2016). This project was installed in a public alley of high-density neighborhood blocks, which slowed, infiltrated, and retained the stormwater using dry wells, rain gardens/infiltration trenches, and infiltration swales before percolating to groundwater. Monitored water quality showed that the pollutant level was reduced to 90% after the LIDs installation (Sadeghi et al., 2016). Pollutant levels from the sediments of different implemented BMPs, such as stormwater ponds, infiltration basin, constructed wetlands, biofilter, three-chamber oil, and grit separators. The results revealed that chromium ($C_{r)}$, copper (C_u), zinc (Z_n), cadmium (C_d), lead (P_b), manganese (M_n) were highest in level (Jiri Marsalek et al., 2006). Apart from the pollution penetration into the groundwater, artificial stormwater infiltration has some adverse effects on the groundwater ecology (Datry et al., 2007). Increasing artificial infiltration increases the local fluxes of organic material into the underground ecology, which results in an ecological imbalance of groundwater (Datry et al., 2007).

2.7 Research Recommendations

The LID stormwater management approach in residential areas is a multidisciplinary field. Although there are many publications on this subject, this study shows that this research field did not appropriately emerge. In this study, both bibliometric analysis and topic modelling were used to strengthen the idea and identify future research opportunities.

Visual representation (Figure 2.9) was prepared using VOSviewer, where keywords from each cluster were evaluated. This figure detects the significant keywords used in the dataset of publications based on their importance according to time. For example, the violet cluster (Figure 2.9) represents the period 2012-2018 (this time frame has taken for clear representation), where the most important keywords are concentration, runoff, sediment, solid, nutrient, organic matter, infiltration basin, driveway, paver, etc. The yellow cluster is the most recent one where the most prominent keywords are suds (Sustainable Urban Drainage System), scms (Source Control Measures), uncertainty, reliability, information, inundation risk, etc. These are the recently emerged words for the period 2016-2018.

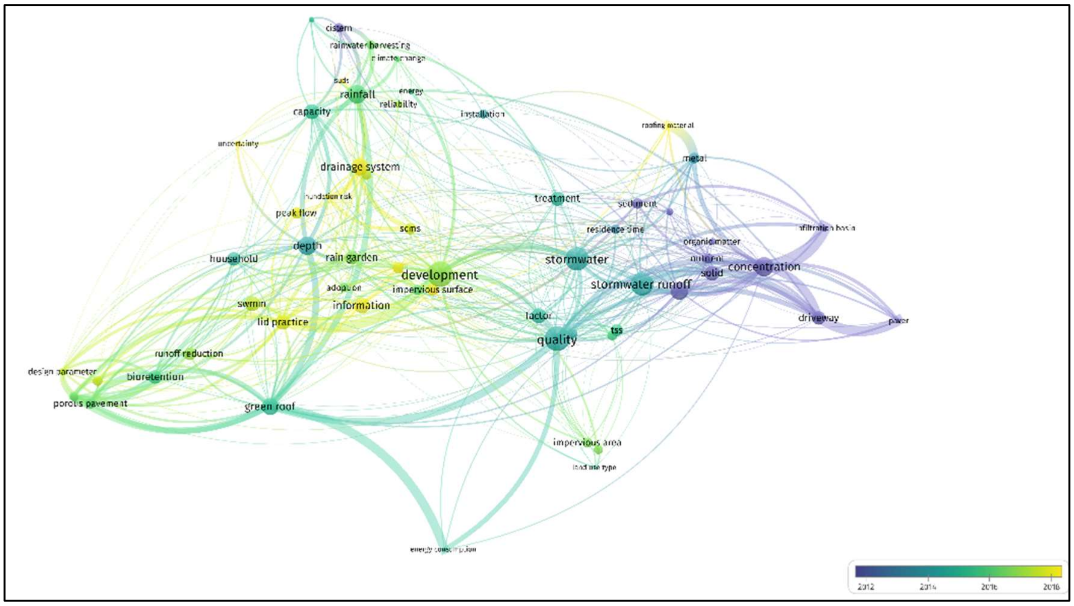


Figure 2.9: Evaluation of keywords network based on co-occurrence

Thus, the current research trends mainly focus on sustainability, reliability, and uncertainty assessment of the stormwater management systems. The size of the nodes indicates the total number of publications, so smaller nodes mean those topics are less discussed ones, and hence, subsequent research can be done targeting those fields. Considering this, SCMC, SUDS, roofing material, land use type, climate change, energy consumption, design parameters, inundation risk, uncertainty can be adopted as future research topics.

Another important observation can be emphasized from figure 2.6, where the countries mostly being influential in this research area have portrayed. The overall statement from figure 2.6 indicates that LID implementation in a residential area is not a common research area for most Middle Eastern and African countries. So, this field yet to be explored in these countries.

Before moving forward to research gaps discovered from the text mining, the sum of gamma values (i.e., per-document-per-topic probability) is estimated to measure the contribution of each topic towards the publication used in the LDA topic model.

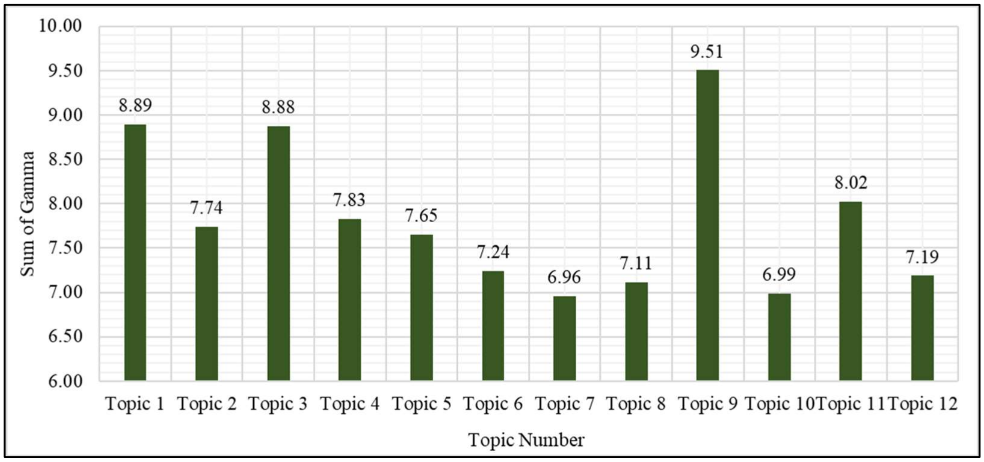


Figure 2.10: *Cumulative distribution of the documents in each topic*

In figure 2.10, the gamma probabilities of each document are accumulated for each topic, which shows that Topic 9 (Water Saving potentiality of rainwater harvesting systems), Topic 1 (Runoff scenarios based on model simulation), and Topic 3 (Design of LID practices) have the highest gamma score, which means these topics were investigated over the years.

Based on the qualitative assessment of the identified latent topics shown in figure 10, the main research gaps are summarized.

Gap 1: it is related to the *base materials of the LID* (Topic 6). Every LID is different based on its functions and design properties/parameters. The design and material of individual LID which is used for a subwatershed scale, might not be appropriate for residential areas or a single house. So, design criteria, material selection, implementation, construction, and maintenance will vary depending on the location, geophysical characteristics, economic perspective, and LID function. The overall observation showed that a considerable variety of LIDs were applied in the residential context (Figure 2.11). However, only a few studies have explored the impact of soil characteristics on rain gardens, permeable pavement, and RWHs systems. And the results strongly evident that the performance of these LIDs is highly affected by altering soil types. So, a similar analysis can be executed for other LIDs. The study can be extended using different construction materials (porous pavement, permeable pavement, cistern, etc.) and plant species (green roof, bioretention, grass swales, biofilter, etc.) from the point of view of residential areas. Though LID designs and components follow the authorities' guidelines, the behavior, impact, and outcome can be changed in the residential context. Cost is also an essential factor for implementing LIDs, so using eco-friendly and locally available elements can be a practical option. Thus, an extensive study can yet be conducted focusing on individual LID.

Gap 2: This gap is related to Topic 10, *Green Infrastructure based management strategies*. Low impact development is still a new concept in most communities. Appropriate design, effectiveness, construction, and maintenance of LID are still under the process of improvement. Subsequent surveys and interviews were conducted to evaluate the public's understanding and perception of LIDs. Some survey-based analysis was also carried away to understand people's preference in selecting the type of LIDs and their financial limit for investing in LID. LID measures are popular among privileged communities, and all the constructed LIDs are located in those communities. It is still a new concept to many people, which needs to be redefined. To discover more appropriate and effective LID measures for underprivileged societies ground-breaking research should be carried out.

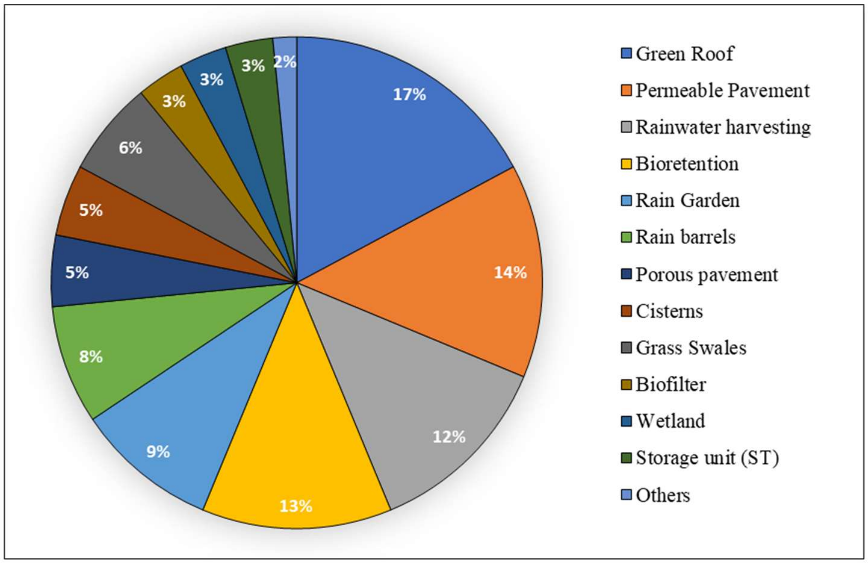


Figure 2.11: *Most used LIDs in residential areas*

2.8 Conclusions

A famous Chinese proverb says, “The water can bear the boat and can swallow it too.” The saying means depending on the attitude towards water may result in constructing or destructing the natural water (Wu et al., 2013). The cities are currently experiencing rapid changes due to urbanization and unhealthy site development; hence extreme adverse events, such as floods, waterlogging, and pollution, become frequent. New technologies and concepts in stormwater management, such as LID, SUDS, and GI are gaining popularity in many countries to cope with these situations. Though many related studies were conducted, no comprehensive research is done on implementing the LID approach in residential areas.

The current research is an attempt to apply the meta-research technique to assess previous works qualitatively and quantitatively. A bibliometric analysis is also implemented to get a comprehensive idea about the selected publications (influential authors, journals, publications, countries). Topic modelling was used to identify 12 latent topics - runoff scenarios based on model simulation, the impact of rainfall, design of LID practices, the result of impervious cover, public participation, the effect of the core material of specific LIDs, Green Infrastructures, stormwater quality assessment, water saving potentiality of rainwater harvesting systems, Green Infrastructure based management strategies, studies on SUDS and groundwater quality. After topic extractions, several relevant studies were reviewed from the previous research. The Bibliometric analysis identified the future prominent research topics- SCMC, SUDS, different land-use types, the effect of climate change, energy consumption, various design parameters, inundation risk, and uncertainty. This analysis also discovered that African and Middle Eastern countries have not yet started research on residential LIDs. So, tremendous research opportunities are still available there. Text mining found that appropriate and specified design guidelines, types, materials need to develop for LIDs in the residential context. Local materials and plant species can be considered while formulating design guidelines. The LIDs application needs to be available for all classes of people regarding the economic feasibility and preferences. Such gaps and recommendations are likely to be addressed in future studies on LID.

3.0 Multi-criteria Decision Analysis Framework Supporting the Selection of Low Impact Development Practices for a Detached House

Abstract: Application of Low Impact Development (LID) stormwater management practices has gained popularity due to their sustainability, economic stability, and resilience. The authorities are developing appropriate design guidelines, policies, and standards for LIDs to increase their acceptability, suitability, and performance. However, there are no specific framework/guidelines for selecting the LIDs for single-detached houses. This study aims to develop a framework, using Multi-Criteria Decision Analysis (MCDA), to identify the most suitable LID alternatives for a single-detached house. Moreover, guidelines for residential LIDs used in Ontario are collected and documented. The framework is developed based on seven different criteria (runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetics) and four LIDs – rain barrel, permeable pavement, soakaways, and rain garden. The runoff peak and volume are generated using the Stormwater Management Model (SWMM). Costs are estimated using the in this framework, two Multicriteria Decision Analysis methods are adopted, first the Analytic Hierarchy Process (AHP) is used to assign weights for the seven selected criteria. Then the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied for scoring the LID alternatives. This framework was applied for an actual case study, a single-detached house as a case study located in a Flamborough residential area, Ontario. The area of the house lot is 386 m^2 with a 40 % impervious surface. The results revealed that when costs are given higher weights, one 378 L rain barrel and one soakaway with an area equivalent to 10% of the impervious area. However, when the runoff reduction rate is given a priority then a permeable pavement with an area of 20% of the impervious area, one 378 L rain barrel and a soakaway with an area equivalent to 20% of the impervious area.

Keywords: Multi-Criteria Decision Analysis, Analytic Hierarchy Process, Technique for Order of Preference by Similarity to Ideal Solution, Stormwater Management Model, Residential LID practices, detached house

3.1 Introduction

Urban stormwater management is an element of local water management, and they are accountable for supporting, operating, and maintaining it. For the past century, the local government focused on constructing grey infrastructures to convey stormwater from the urbanized impervious land to the nearby streams through pipes and culverts. However, this traditional approach harms the receiving water bodies and highly costly to maintain, retrofit, and upgrade (Bassut, 2016). For instance, the City of Mississauga spent $1.7 billion on stormwater management infrastructures in 2011, and then in 2012, the city invested $15 million on the improvements, operations, and maintenance of the projects. Besides, the authority needs to spend almost $40 million to fulfill the project goals (AECOM, 2013).

More than 60-70% of the greater Toronto area (GTA) was developed before the standard stormwater management practices, which implies that the stormwater management systems need to be upgraded (Valderrama & Davis, 2015). In some older neighborhoods, stormwater management facilities do not exist. For example, in Kitchener's older downtown neighborhood, no stormwater management facilities were built; thus, the runoff from this area cause sedimentation problems in the nearby Victoria Park Lake (Bassut, 2016). Considering the abovementioned facts, the local governments face challenges in finding stormwater management solutions that are cost-effective, sustainable, resilient, and accepted by the residents (Bassut, 2016).

Municipalities are implementing stormwater management facilities at the lot level to control runoff on a neighborhood scale. These facilities (e.g., bioretentions, vegetative swales, and infiltration trenches) are designed to manage stormwater and enhance the aesthetic view (Toronto and Region Conservation, 2020). These approaches are environmentally friendly, but they are only part of the solution. For a more effective stormwater management approach, it is recommended to include implementing stormwater management practices on a small scale in both public and private sectors. These facilities are known as low impact development (LID) in North America. "*Effective management of urban flooding will require adapting infrastructure and homes to extreme rainfall events. By addressing stormwater flows and reducing the impact of extreme rainfall events in new and existing subdivisions, LID, in combination with other lot level and infrastructure risk reduction measures, can help to provide a long-term solution to urban flood losses for the insurance industry.*" (Credit Valley Conservation, 2018)

The low impact development (LID) approach aims to control the runoff close to its source, mimicking the natural hydrological processes (e.g., infiltration, filtration, evapotranspiration, and storage). It can eliminate the pathogens, pollutants, nutrients, metals from the stormwater (Weitman et al., 2009). It is an integral element of the stormwater treatment train (TT) approach (Credit Valley Conservation & Toronto Region Conservation Authority, 2010). Implementing LIDs on private homes can reduce basement flooding and increase the possibility of reserve clean water by residence (Credit Valley Conservation, 2015; Credit Valley Conservation & Toronto Region Conservation Authority, 2010).

One of the obstacles in implementing the LID practices on private property is the high installation, operations, and maintenance cost. Even when stormwater credits are available, the payback period is limited (Credit Valley Conservation, 2015). Addressing this issue, a study was executed in the City of Philadelphia revealed that retrofitting on one acre of impervious area of private property can be 67% cheaper than the cost of stormwater management retrofitting on the public road right of way (Valderrama & Davis, 2015). The implementation of LID in private sectors can also avoid the cost of managing downstream impacts and upgrading stormwater infrastructure.

In general, municipalities are the owners of conveyance and end-of-pipe controls, where the operations and maintenance of these controls are handled as public infrastructures. However, property owners are responsible for the functions and maintenance of the LIDs on private property. The success of these LIDs are entirely depends on the municipality and homeowners' commitments. Thus, owners' training and legal agreements are needed to ensure the stormwater facilities' standards, feasibility, and longevity (Credit Valley Conservation & Toronto Region Conservation Authority, 2010). Municipalities need to take more deliberate actions to foster LID implementation in the private sector. Such plans should consider the property owners' preferences and address their concerns in selecting the appropriate LID alternatives.

Overall, In water sources planning and management, decision-making under multiple conflicting criteria is a complex task as it involves economic, social, technical, and environmental factors (Keeney & Wood, 1977). Making suitable decisions require integrating data sources, model developments, and different priority-based criteria (Eggimann et al., 2017). To the authors' best of knowledge, no such analysis is conducted focusing on the single-detached house in a residential area.

Addressing these issues, this study focuses on residential LID alternatives that are suitable for detached houses. A framework integrating the Stormwater Management Model (SWMM) and multiple-criteria decision-analysis (MCDA) is developed to support finding suitable LID alternatives for a detached house (private property) in Ontario. These criteria include technical, economic, and social choices- runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetics. The developed framework was applied to a case study in Flamborough, Ontario.

3.2 Framework Development Methodology

The Framework is developed based on information from the literature review (Sumaiya and Hassini, 2021), Ontario guidelines (Credit Valley Conservation & Toronto Region Conservation Authority, 2010; Ontario Ministry of Transportation, 2009) data from the City of Hamilton in Ontario (City of Hamilton, 2012, 2020), and the storm water management model user's manual (Rossman, 2010). This framework incorporates STEP for cost estimation, AHP for criteria weighting, and TOPSIS for scoring LIDs alternatives. The framework development methodology is summarized in Figure 3.1, and the details for each step are provided as follows.

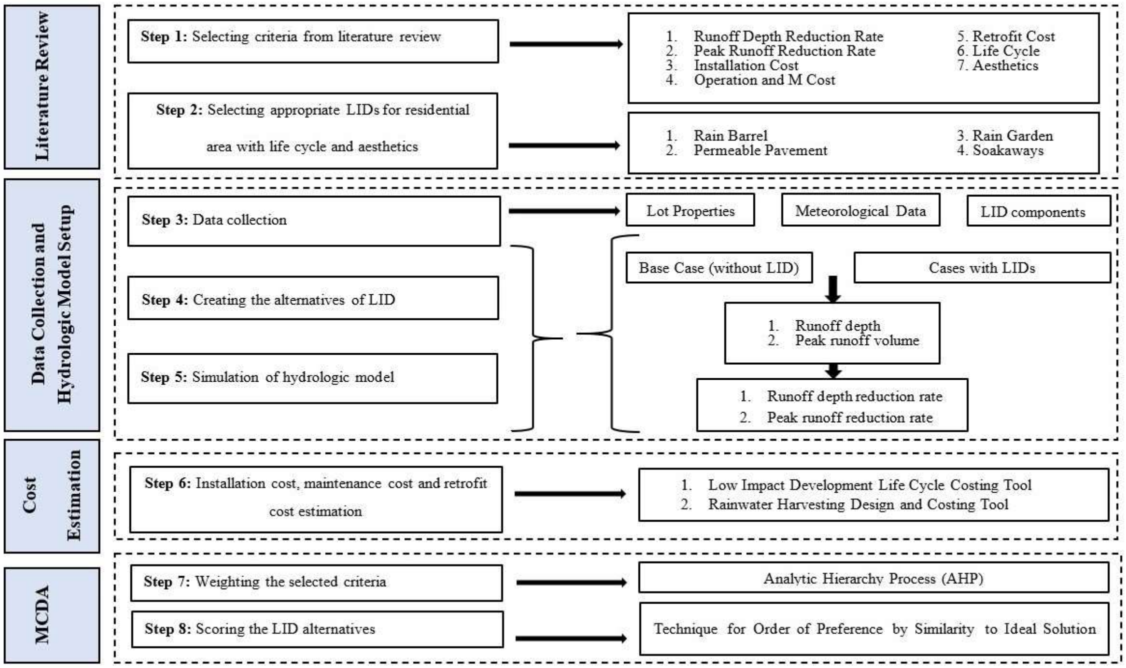


Figure 3.1: *Framework Methodology*

3.2.1 Criteria and LIDs selection

The mainly used criteria and LIDs for residential areas are identified based on the extensive literature review on residential LIDs done by Sumaiya and Hassini (2021). The selected criteria for this study are runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetic benefits. These seven criteria are the most influential ones on the implementation of LIDs in residential areas. Although the literature review (Sumaiya and Hassini, 2021) revealed that there are many options for LIDs that are suitable for residential areas, rain barrels, rain gardens, permeable pavements, and soakaways are the only LIDs used in this study as they are the most appropriate LIDs for houses.

3.2.2 Data Collection

The data collected are classified into three categories as follows.

3.2.2.1 Lot Properties

A unit lot that has a single-detached house is treated as a single catchment. It is divided into two components- impervious area and pervious area. This catchment contains different parameters such as- roughness coefficient, depth of depression storage, the width of the overland flow, infiltration rate, and average percent stope. Several studies (Baffaut & Delleur, 1989; Ibrahim & Liong, 1992; Muleta et al., 2013) showed that among these parameters- the percent impervious area, the characteristic width of sub-catchment, average percent slope, and depression storage for impervious areas have significant impact on the runoff. These parameters may vary from one catchment to another.

According to the Ministry of Transportation of Ontario (MTO) guidelines, percent imperviousness for a single lot is permitted in between 20-50% (Ontario Ministry of Transportation, 2009). The characteristics width of the catchment depends on the lot area and the location of the outlet. Based on the guidelines provided by the city of Hamilton (City of Hamilton, 2012), the slope of a lot area for a single detached house is between 2-7%. The roughness coefficient and depression storage depend on the impervious surface (roof, driveway, and walkway) and pervious surface (lawn/pasture) (Rossman & Huber, 2016). The lot data and guidelines are summarized in Table 3.1.

Table 3.1: *Data for lot property*

Criteria	Notations	Guidelines	References
Area of Lot	A_L (m^2)	SD	
Roof area	R_A (m^2)	SD	
Area of driveway	A_{DW} (m)	SD	
Area of walkway	A_{WW} (m)	SD	
Pervious area	A_p (m^2)	SD	
Impervious area	A_I (m2)	SD	
Width	W (m)	SD	
% Slope	S	2-7%	City of Hamilton, 2012
% Imperviousness	Imp (%)	20-50%	Ontario Ministry of Transportation, 2009
Manning's number for impervious area	n_i	0.01-0.023	Yen, 2001
Manning's number for pervious area	n_p	0.01-0.32	Engman, 1986
Depression storage depth on impervious area	d_{si} (mm)	1.27-2.54	Rossman, 2010
Depression storage depth on pervious area	d_{sp} (mm)	2.54-5.08	Rossman, 2010
% of impervious area with no depression storage	Imp_0 (%)	25% ≥	Rossman, 2010
Curve Number	CN	Soil Dependent	Rossman, 2010
Soil infiltration rate	I_S	Soil Dependent	
Time of concentration	t_c (mm)	Timestep of the design storm	City of Hamilton, 2020

*SD = Site Dependent

3.2.2.2 Meteorological Data

Depending on the data availability, rainfall, evaporation, wind speed, snow melt, areal depletion can be inserted as input data. Design storms for different return periods or continuous time series can be used as rainfall data. For an urban area, it is recommended to use Chicago (Keifer & Chu, 1957) design storm of 3hr or 4hr duration (Ontario Ministry of Transportation, 2009). Therefore, in this study the design storm approach is used. Meteorological data source and criteria for the design storm in the Hamilton area as well as the expected output are given in table 3.2.

Table 3.2: *Meteorological Data*

Data	Notation	Criteria	Reference
Rainfall intensity	i (mm/hr)	Rainfall Station Dependent	City of Hamilton, 2020
Duration	d (hour)	Rainfall Station Dependent	City of Hamilton, 2020
Time interval	I_t (min)	Rainfall Station Dependent	City of Hamilton, 2020
Return period	T (years)	Rainfall Station Dependent	City of Hamilton, 2020
Total runoff depth	v_r (mm)	Computed	
Runoff peak	Q_P (cms)	Computed	
Total runoff depth with LIDs	v'_r (mm)	Computed	
Runoff peak with LIDs	Q'_P (cms)	Computed	
Runoff depth reduction rate	R_{vr}	Computed	
Peak runoff reduction rate	R_{Qp}	Computed	

3.2.2.3 LIDs Data

Rain Barrel

The rain barrel is one of the popular stormwater management systems in residential areas (Sun & Hall, 2016). A rain barrel (Figure 3.2) is installed to capture rainwater from the roof area. This practice has gained popularity in urban areas as it can conserve rainwater that can be used for irrigation purposes. According to the guideline (Credit Valley Conservation & Toronto Region Conservation Authority, 2010), the sizes of rain barrels for residential land uses are typically 190 to 400 liters. Market analysis (Home Depot, Lowe's, and Canadian Tire) showed that 13 different sizes of rain barrels ranging from 132 to 378 liters are commonly available in Canada. Considering the guideline of (BASMAA & NAPA, 2012), if the roof area is between 1250-1750 ft^2 (116.13 – 162.58 m^2), 3-4 rain barrels of 55 gallons (208 L) are required to use. The features associated with rain barrels are given in Table 3.3.

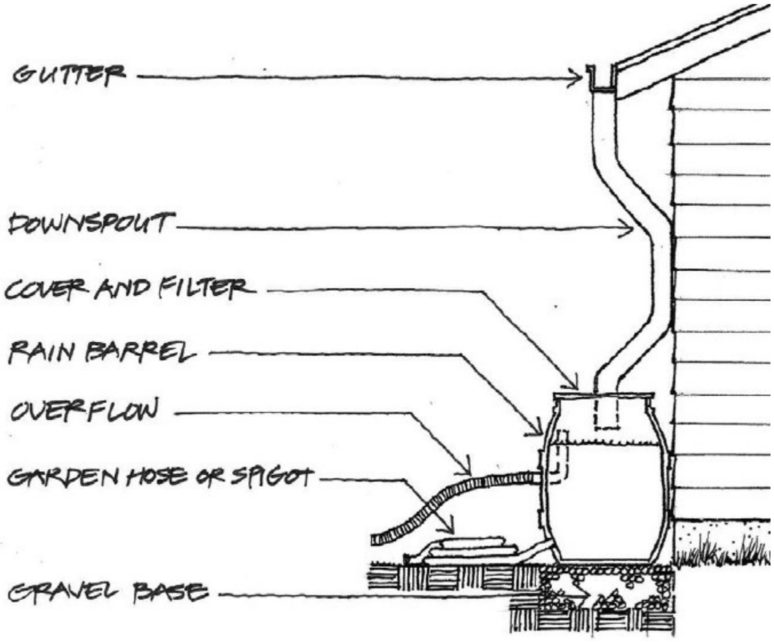


Figure 3.2: *Schematic of a rain barrel (Clark & Acomb, 2008)*

Table 3.3: *General guidelines for rain barrel (RB)*

Criteria	Notation	Guidelines	Reference
Capacity	C_B (L)	190 to 400	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
		Market sizes: 378, 302, 283, 249, 247, 234, 208, 200, 189, 185, 170, 151, 132	Canadian Tire, 2021; Home Depot Canada, 2021; Lowes, 2021
Storage	S_B (mm)	508-1238.25	Canadian Tire, 2021; Home Depot Canada, 2021; Lowes, 2021
Bottom area	A_B (m^2)	$\frac{C_B}{S_B}$ (approx.)	

Rain Garden

A rain garden (Figure 3.3) is designed to capture rainwater from the roof, front yard, back yard, driveway, or walkway from medium to low-density residential lots. The permissible slope for the rain garden is within 1-5%. The stormwater draining time is usually 24 to 72 hours (X. Zhang et al., 2012b). Rain gardens work efficiently for small drainage areas less than 1000 m^2.

The dimensions of the rain garden are allowed to be between 6.67 and 20% of the impervious drainage area (Credit Valley Conservation & Toronto Region Conservation Authority, 2010). The appropriate guidelines for rain gardens are summarized in table 3.4.

Table 3.4: *Design parameters of rain garden (RG)*

Criteria	Data	Notation	Guidelines	Reference
Size	Surface area	A_G (m^2)	6.5-20% of I_A	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
Surface	Berm height	h_G (mm)	150-300	Cappiella, 2006
	vegetation volume fraction	F_{vegG}	0.1-0.2	Rossman, 2010
Soil	Thickness	T_G (mm)	450-900	Rawls et al., 1983
	Porosity	$ø_G$	0.437-0.475	Rawls et al., 1983
	Field capacity	C_G	0.062-0.378	Rawls et al., 1983
	Wilting point	W_{PG}	0.024-0.265	Rawls et al., 1983
	Conductivity	K_G (mm/hr)	120.39-0.25	Rawls et al., 1983
	Conductivity slope	K_{sG}	30-60	Rawls et al., 1983
	Suction head	ψ_G (mm)	1.93-12.6	Rawls et al., 1983
Storage	Thickness	S_G (mm)	150-450	Rossman, 2010
	Void ratio	RV_G	0.5-0.75	Rossman, 2010
	Seepage rate	S_{rG} (mm/hr)	Site dependent	Rossman, 2010

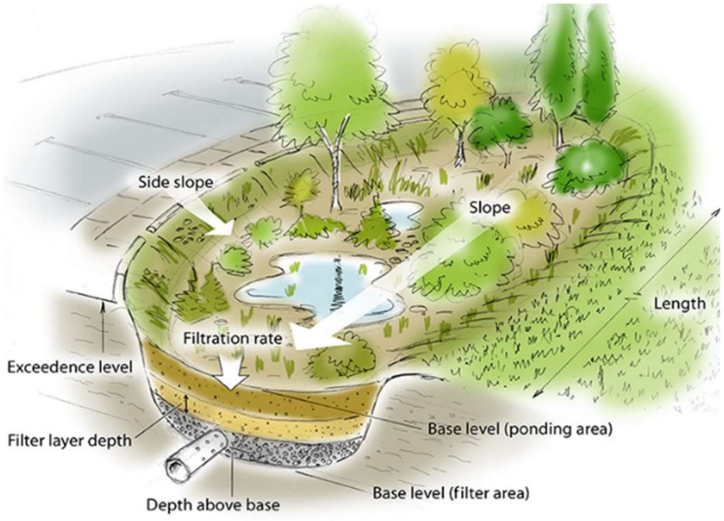


Figure 3.3: *Schematic of a rain garden (Innovyze, 2016a)*

Permeable Pavement

Permeable pavement (Figure 3.4) is constructed to drain stormwater over its surface towards the stone reservoir, where the infiltration occurs through the native soil. It is expected to drain stormwater within 48 hours. Clogging is one of the major concerns for permeable pavements, which can be avoided by using 2.5 mm of gravel or clear stone in both bedding layer and joint filler (Credit Valley Conservation & Toronto Region Conservation Authority, 2010). Permeable pavements are effective in parking lots, driveways, walkways, low traffic roads, etc. (Credit Valley Conservation & Toronto Region Conservation Authority, 2010).

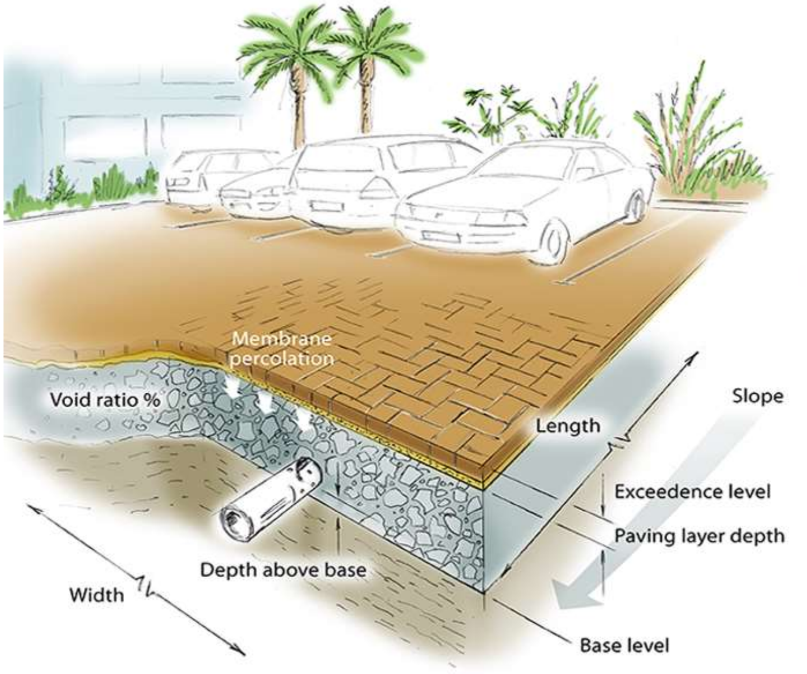


Figure 3.4: *Schematic of permeable pavement (Innovyze, 2016b)*

The appropriate values of the components of permeable pavements in residential sites are given in table 3.5.

Table 3.5: *Design parameters of permeable pavement (PP)*

Criteria	Data	Notation	Guidelines	Reference
Size	Surface area	A_P (m^2)	80-100% of I_A	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
Surface	Berm height	h_P (mm)	N/A	Rossman, 2010
	Vegetation volume Fraction	F_{vegR}	0.1-0.2	Rossman, 2010
	Surface roughness (Manning's n)	n_{PP}	0.01 – 0.02	Rossman & Huber, 2016
	Surface slope	S_P (%)	1-5	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
Soil	Thickness	T_P (mm)	450-900	Rawls et al., 1983
	Porosity	$ø_P$	0.437-0.475	Rawls et al., 1983
	Conductivity	K_P (mm/hr)	120.39-0.254	Rawls et al., 1983
	Conductivity slope	K_{sP}	30-60	Rawls et al., 1983
Storage	Thickness	S_P (mm)	150-450	Rossman, 2010
	Void ratio	V_P	0.5-0.75	Rossman, 2010
	Seepage rate	S_{rP} (mm/hr)	Not specified	Rossman, 2010
Pavement	Thickness	S_{PP} (mm)	Vehicle: 80, Pedestrian: 60	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
	Void ratio	R_{vP}	0.12-0.21	Rossman, 2010
	Impervious surface Fraction	I_{fP}	0, if continuous	Rossman, 2010
	Permeability	P_{rP} (mm/hr)	Dependent on the material used	Rossman, 2010

Soakaways

Soakaways are stormwater infiltration systems (Figure 3.5), which are excavated in a rectangular or circular shape. They are designed to be filled with 30-40% void-creating material, usually granular material of 50 mm clear stone. They are suitable for private property as they can infiltrate stormwater in narrow strips. Soakaways are constructed in a unit lot to receive stormwater from the roof, walkway, and overflowing water from rainwater harvesting systems. They are not permitted to install in areas with slopes more than 15%. Based on the guideline, the size of a Soakaway should be 5-20% of the total impervious area (Credit Valley Conservation & Toronto Region Conservation Authority, 2010). The appropriate guidelines for soakaways that are suitable for residential sites are given in table 3.6.

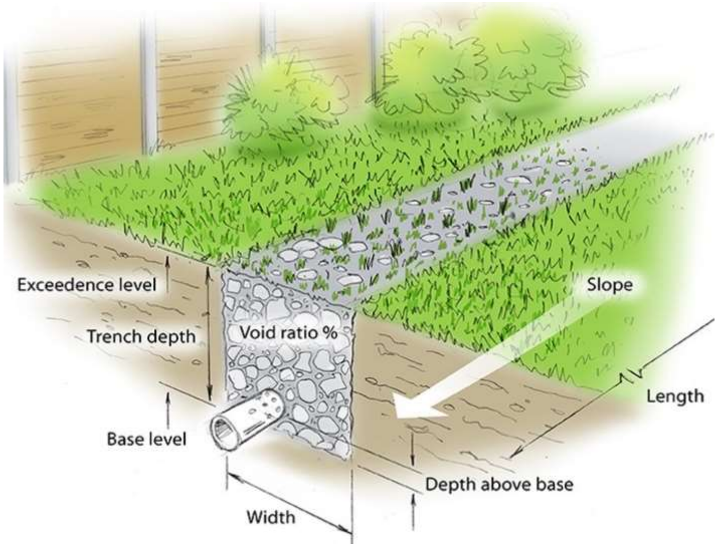


Figure 3.5: *Schematic of soakaways (Innovyze, 2015)*

Table 3.6: *Design guidelines for soakaways (SA)*

Criteria	Data	Notation	Guidelines	Reference
Size	Surface area	A_S (m^2)	5-20% of I_A	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
Surface	Berm height	h_S (mm)	150-300	Rossman, 2010
	Vegetation volume fraction	F_{vegS}	0.1-0.2	Rossman, 2010
	Surface Roughness (Manning's n)	n_S	0.03-0.07	Rossman, 2010
	Surface slope	S_S (%)	Not Specified	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
Storage	Thickness	S_S (mm)	150-450	Rossman, 2010
	Void ratio	V_S	0.4-0.75	Credit Valley Conservation & Toronto Region Conservation Authority, 2010
	Seepage rate	S_{rS} (mm/hr)	Not Specified	Rossman, 2010

3.2.2.4 Hydrological Model Setup

For the criteria of runoff depth and peak runoff reduction rates, a hydrologic model is required to simulate the total runoff depth and peak runoff discharge from the source site with and without LIDs. In this study, the design storm approach within the Stormwater Management Model (SWMM) is used and the lot area is assumed to have one outlet, which is not always the case for a house lot. This assumption may have an impact on the runoff peak estimation but not on the runoff depth reduction rate, which is the main purpose of an LID implementation. However, a defined outlet point is required for locating the flood peak estimation. When there is no single outlet, the runoff peak reduction rate can be neglected by giving it a weight of zero.

SCS Curve Number Method:

$$R = \frac{(P - Ia)^2}{P - Ia + S} \qquad \text{Eq 1}$$

$$S = \frac{1000}{CN} - S \qquad \text{Eq 2}$$

$$Ia = 0.2 * S \qquad \text{Eq 3}$$

Where, R = cumulative runoff volume (mm), P = cumulative rainfall (mm), I_a = initial abstraction (mm), S = soil moisture storage capacity (mm), and CN = curve number.

Runoff depth reduction rate: Eq 4

$$R_{vr} = \frac{v_r - v'_r}{v_r} \times 100\%$$

Peak runoff reduction rate: Eq 5

$$R_{Qp} = \frac{Q_P - Q'_P}{Q_P} \times 100\%$$

The hydrological model is simulated for the base case (i.e., the site has no LIDs) and for each LIDs alternative (i.e., the site has one LID or a combination of LIDs). The relevant techniques, equations, input and output are summarized in tables 3.7 and 3.8 for the site without and with LIDs, respectively.

Table 3.7: *Hydrological Model (SWMM) Input and Output for the base case (without LIDs)*

Description	Technique	Input	Output
Base Case: Runoff depth and peak runoff simulation	Unit Hydrograph	Lot Property: A_p, A_I, W, S, Imp, n_i, n_p, d_{si}, d_{sp}, Imp_0, CN, I_S, and t_c	Q_P (cms)
	SCS Curve Number Eqs 1-3	Meteorological Data: i, d, I_t, and T	v_r (mm)

Table 3.8: *Hydrological Model (SWMM) Input and Output for cases with LIDs*

Description	Technique	Input	Output
Scenarios with LIDs: Runoff depth and peak runoff simulation	Unit Hydrograph	Lot Property: A_p, A_I, W, S, Imp, n_i, n_p, d_{si}, d_{sp}, Imp_0, CN, I_S, and t_c Meteorological Data: i, d, I_t, and T	Q'_p (cms)
	SCS Curve Number Eqs 1-3	Rain Barrel: S_B and A_B Rain Garden: A_G, h_G, F_{vegG}, T_G, $ø_G$, C_G, W_{PG}, K_G, K_{Sg}, ψ_G, S_G, RV_G, and S_{rG} Permeable Pavement: A_P, h_P, F_{vegR}, n_{PP}, S_P, T_P, $ø_P$, K_P, K_{sP}, S_P, V_P, S_{rP}, S_{PP}, R_{vP}, I_{fP}, and P_{rP} Soakaways: A_S, h_S , F_{vegS}, n_S, S_S (%), S_S, V_S, and S_{rS}	v'_r (mm)
Runoff depth reduction rate and peak runoff reduction rate calculation for each of the combinations	Eqs 4-5	Q_p (cms) and Q'_p (cms) v_r (mm) and v'_r (mm)	R_{vr} and R_{Qp}

Since only rain barrels (RB), rain gardens (RG), permeable pavements (PP) and soakaways (SA) are used in this study, therefore there are only 14 possible LID alternatives (Listed in Table 3.9) that can be used based on the LID type. However, more alternatives are possible based on the LID types and sizes.

Table 3.9: *LIDs alternatives*

Description	Input	Alternatives
LID alternatives (Combinations of different sizes of RB, RG, PP, and SA)	RB, RG, PP, and SA	1. RB 2. RG 3. PP 4. SA 5. RB + RG 6. RB + PP 7. RB + SA 8. RG + PP 9. RG + SA 10. SA + PP 11. RB + RG + PP 12. RB + RG + SA 13. RG + PP + SA 14. RB + RG + PP + SA

3.2.3 Cost Estimation

In this study, LIDs installation, maintenance, and retrofit costs are included in the development of the framework. These costs are estimated using STEP (TRCA, 2019b, 2019a). To estimate the installation cost (CI) and the maintenance cost (MI), the input data required by STEP are mainly the household number and lot and LIDs properties. Then the retrofit cost (CR) is estimated by STEP as 16% of the installation cost (Eq 6).

$$C_R = 0.16C_I \qquad \text{Eq 6}$$

3.2.4 Multicriteria decision analysis (MCDA)

In water resources management and planning, various criteria need to be evaluated to identify the most suitable specifications. Multiple criteria decision making (MCDA) have been used in many water resources studies to construct complex problems considering the overall uncertainties (Gogate et al., 2017; Song & Chung, 2017). The Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) were used as MCDA methods in this study.

3.2.4.1 Analytic Hierarchy Process (AHP)

The AHP is used to quantify the criteria using the pairwise comparison technique by calculating and distributing the weights of the significance of each of the requirements through preparing a judgment matrix (W. Chen et al., 2016; Debnath et al., 2015; Y. Jia et al., 2018; Saaty, 1987). The steps to determine the criteria weights using AHP are as follows.

a) Hierarchical Structure Model:

A complex problem is designed by disintegrating into hierarchical criteria, including all the elements required by the decision-makers to achieve the intended goal (Chao, 1993). The model is constructed, including a destination layer, criterion layer, and schematic layer. The destination layer is the target objective which is the most suitable solution. The criteria layer includes different criteria, and the schematic layer includes sub-criteria for achieving the target (Li et al., 2017).

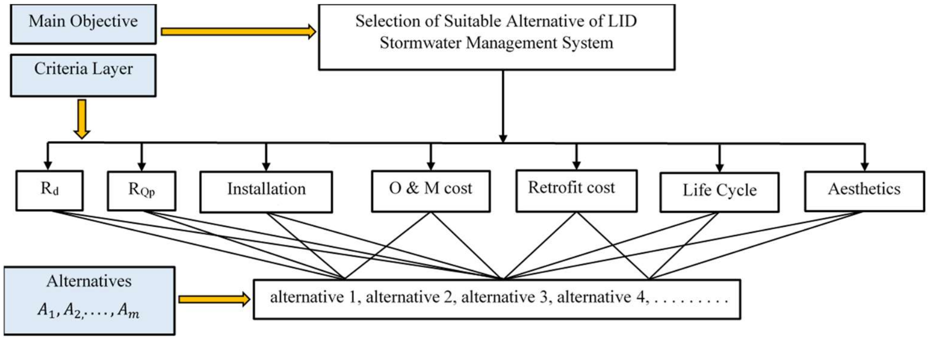


Figure 3.6: *Suitable LID alternatives selection hierarchy*

In this research, the target objective is to select the most suitable LID from the different alternatives. The criteria layer includes seven other criteria –runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetics (Figure 3.6.). The criteria and sub-criteria can be customized based on the homeowner's preferences.

b) Pairwise Comparison and Judgment Matrix:

The homeowners/decision-makers preferences are taken into consideration. The homeowner can rank the criteria based on their preferences. Then this ranking can be used in the AHP development trough through pairwise comparisons of the criteria (Camarinha-Matos et al., 2016). The importance each two elements under each layer (Figure 3.6) is determined using a qualitative scale of 1 to 9 (table 3.10) as recommended by Saaty (1987). Therefore, each criterion (i) has a preference value c_i varying between 1 and 9 (table 3.10)

Table 3.10: *Qualitative comparison scale*

The intensity of importance between two elements	Definition
1	Two elements hold equal importance
3	One element is moderately important over another
5	One element is strongly important over another
7	One element is very strongly important over another
9	One element is extremely important over another
2, 4, 6, 8	Medians of the in-between judgment

The ratios of each criteria pair (*i, j*) form the elements $a_{ij} = \frac{c_i}{c_j}$ of the judgement matrix *A* (Eq 7), where n is the total number of criteria. The lower-triangular part of the matrix are the reciprocals of the upper-triangular matrix (Camarinha-Matos et al., 2016; Li et al., 2017).

$$A = \begin{bmatrix} \frac{c_1}{c_1} & \frac{c_1}{c_2} & \cdots & \frac{c_1}{c_n} \\ \frac{c_2}{c_1} & \frac{c_2}{c_2} & \cdots & \frac{c_2}{c_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{c_n}{c_1} & \frac{c_n}{c_2} & \cdots & \frac{c_n}{c_n} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} = [a_{ij}], \quad i,j = 1,2,3,\dots,n \qquad \text{Eq 7}$$

c) Criteria Weights:

To estimate the weights of criteria, the judgment matrix needs to be normalized by dividing each column entry by the sum of the column (Chen et al., 2010). The following equation shows the normalized matrix, B:

$$B = [b_{ij}], \quad i,j = 1,2,3,\ldots,n \qquad \text{Eq 8}$$

Therefore, B is the normalized matrix of judgment matrix A comprising of each of the elements b_{ij} where:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \quad i,j = 1,2,3,\ldots,n \qquad \text{Eq 9}$$

Finally, the average of each of the row is calculated from the normalized matrix B and hence, a set of weights $w_i = \frac{\sum_j^n b_{ij}}{n}$, which represent the element of the eigen vector of matrix B, where $\sum_{i=1}^{n} w_i = 1$ (Nü & Soner, 2007).

d) Consistency Checking:

The largest eigen value (λ_{max}) can also be determined from matrix B using the following equation:

$$Bw_i = \lambda_{max} w_i \qquad \text{Eq 10}$$

Then the consistency ratio (CR) is quantified using Eq (11) to verify the consistency of the pairwise comparisons.

$$CR = \frac{\lambda_{max} - n}{(n-1)RI} \qquad \text{Eq 11}$$

Where, RI is the random index of n. The value of RI for matrices of order 1to 15 are available in the study done by Saaty (1987). If the CR value is below 0.1 then the judgements are consistent, and the weight values are acceptable. If a CR value is greater than 0.1, then the pairwise comparisons are insufficient for consistent decision, thus, judgement matrix needs to be reconstructed (Chao, 1993; Y Chen et al., 2010).

3.2.4.2 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is a MCDA tool that aims to find the most suitable alternatives that have the shortest geometric distance from the positive ideal solution (PIS), i.e., the best solution, and longest geometric distance from the negative ideal solution (NIS), i.e., the worst solution (Tzeng & Huang, 2011; Ye & Li, 2014). Then the relative closeness of a solution to the ideal solution is used to rank the alternatives (Song & Chung, 2017). TOPSIS can handle conflicting issues, therefore, it is considered the most efficient technique for ranking options in water and environmental decision-making problems (Gogate et al., 2017; Kalbar et al., 2016).

Many researchers (e.g., Jozaghi et al., 2018; Nü & Soner, 2007; Yue, 2011) have described TOPSIS procedures. The main steps are summarized as follows

Step 1: Identify the weights of all the criteria

The weight of each criterion needs to be estimated. For this study, the criteria weights were calculated using AHP as described in section 2.2.3.1.

Step 2: Calculate the normalized decision matrix

For a MCDA problem, the criteria may have different dimensions/units. For instance, in this study, the criteria cost and life cycle are measured in currency and years, respectively. It is hard to compare two criteria with different units. To facilitate the comparison of criteria, it is crucial to quantify all the criteria as into non-dimensional using a standardizing equation (Eq 12).

$$r_{ki} = \frac{f_{ki}}{\sqrt{\sum_{k=1}^{m} f_{ki}^2}} \qquad \text{Eq 12}$$

Where r_{ki} is the standardized value of the i^{th} criterion for the k^{th} alternative, f_{ki} is value of the i^{th} criterion for the k^{th} alternative and m is the total number of alternatives.

Step 3: Calculate the weighted normalized decision matrix

The weighted normalized decision matrix $[v_{ki}]$, is simply determined by multiplying the standardized value of the k^{th} alternative of the i^{th} criterion (r_{ki}) by the weight of the i^{th} criterion (w_i) as follows

$$v_{ki} = r_{ki} * w_i \qquad \text{Eq 13}$$

Where $k = 1, \dots, m)$ (LID alternative) and $i = 1, \dots, n$ (criterion, e.g., runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetics).

Step 4: Determine the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS)

The positive ideal solution (PIS) maximizes the runoff depth reduction rate, peak runoff reduction rate, life cycle, and aesthetics benefit criteria. However, the negative ideal solution maximizes installation cost, maintenance cost, and retrofit cost. For each LID alternative k $(k = 1, \dots, m)$, the maximum (max) values of runoff depth reduction rate, peak runoff reduction rate, life cycle, and aesthetics benefit criteria are considered as PIS (v_k^+) and the minimum (min) values are NIS (v_k^-) as expressed in Eq 14.

$$\begin{cases} v_k^+ = max_i \{v_{ki}\} \\ v_k^- = min_i \{v_{ki}\} \end{cases} \qquad \text{Eq 14}$$

Where, $i =$ runoff depth reduction rate, peak runoff reduction rate, life cycle, and aesthetics benefit criteria.

Similarly, for each LID alternative k $(k = 1, \dots, m)$, the minimum values of installation cost, maintenance cost, and retrofit cost-benefit criteria are considered as PIS (v_k^+) and the maximum (max) values are NIS (v_k^-) as described by Eq 15.

$$\begin{cases} v_k^+ = min_i \{v_{ki}\} \\ v_k^- = max_i \{v_{ki}\} \end{cases} \quad \text{Eq 15}$$

Where, i represents any of the cost criteria.

Step 5: Measure distances between each alternative and ideal solutions

The aim of this step is to estimate the distances S_k^+ and S_k^- of each LID alternative (k) from PIS and NIS, respectively as follows

$$S_k^+ = \{\sum_{i=1}^{n}(v_{ki} - v_k^+)^2\}^{0.5} \quad \text{Eq 16}$$

$$S_k^- = \{\sum_{i=1}^{n}(v_{ki} - v_k^-)^2\}^{0.5}$$

Where $i = 1, \dots, n$ and n is the total number of criteria, which are runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetics, in this study.

Step 6: Calculate the relative closeness to the negative ideal solution

The relative closeness of kth alternative (C_k^*) is calculated usingthe following equation:

$$C_k^* = \frac{S_k^-}{S_k^+ + S_k^-} \quad \text{Eq 17}$$

where $0 \leq C_k^* \leq 1$, $k = 1, \dots, m$, m is the total number of LID alternatives.

Step 7: Rank the alternatives based on the relative closeness values

Based on Eq 17, the relative closeness value is proportional to the geometric distance from the NIS. Therefore, the best LID alternative is the one that results in the highest relative closeness value.

3.2.5 Case Study

The developed framework is applied to a single-detached house in a residential area Flamborough is taken for the implementation of framework (figure 3.7). The size and the percent imperviousness of the house were determined from Google Earth.

Figure 3.7: *A Single-detached house from a residential area in Flamborough*

For infiltration, the Curve Number (CN) method is used as it is widely applied (Rossman & Huber, 2016). The values of the lot area are given in Table 3.11.

Table 3.11: *Lot properties for model setup*

Criteria	Notations
Area of Lot	386 m^2
Roof area	123.52 m^2
Area of driveway	21.62 m^2
Area of walkway	9.26 m^2
Pervious area	231.6 m^2
Impervious area	154.4 m^2
Width	12 m
% Slope	2 %
% Imperviousness	40 %
Manning’s number for impervious area	0.013
Manning’s number for pervious area	0.15
Depression storage depth on impervious area	1.5 mm
Depression storage depth on pervious area	5 mm
% of impervious area with no depression storage	80 %
Curve Number	74
Soil infiltration rate	10.92 mm
Time of concentration	10 min

The soil in the Flamborough area is sandy loam type (Ontario GeoHub, 2020). Based on the guideline of (Rossman & Huber, 2016), sandy loam soil has hydraulic conductivity of 0.43 in/hr, suction head of 4.33 in, porosity of 0.453, field capacity of 0.19 and wilting point of 0.085. These values were used for the model development.

The design storm data for different return periods (2, 5, 10 years) was collected from the City of Hamilton for Mount Hope station (City of Hamilton, 2020). The rational method was used for checking the model performance if the model is working well enough for further analysis. Coefficient of Determination (R^2), Root Mean Square Error (RMSE), and Nash–Sutcliffe efficiency were used for the evaluation. The results showed that all the values were within the range, and the values are provided in Table 3.12. The results showed that the values were 0.811, 0.99 and 0.0036 for NSE, R^2 and RMSE, respectively. The equations, interpretations and appropriate ranges of the Goodness-of-fit tests are given in table 3.12. The comparison in between the resultant values and the appropriate ranges showed that the resultant values are within the range. Therefore, this model is efficient for further analysis.

For hydrologic model development, Stormwater Management Model (SWMM) was used following section 3.2.2.4. Table 3.13 is provided here, showing different scenarios of LIDs based on their sizes (A(X%), A= Name of the LIDS, and x= % of the impervious area covered by that LID). Besides, the design parameters LIDs used in this study are provided in figure 3.14. These parameters were also used for the sensitivity analysis of the model. The investigation revealed that almost all of the parameters have negligible impact except permeability which is highly sensitive. The considered % of the impervious area covered by each LID alternative is presented in Table 3.15. The installation cost, maintenance cost, and retrofit cost of RB, PP, RG, and SA were estimated by following section 2.2.5, and the values are provided in table 3.16 (a, b).

Table 3.12: *Goodness-of-fit tests with appropriate range*

Goodness-of-Fit Tests	**Equation**	**Interpretation**
Nash-Sutcliffe Efficiency, NSE	$1-\frac{\sum_{i=1}^{n}(Qo,i-Qm,i)2}{\sum_{i=1}^{n}(Qo,i-Qo)2}$	Goodness-of-fit value ranges from -∞ to 1, where 1 means perfect fit and 0 means model validation is as accurate as the observed mean over the observed dataset. Less than 0 means the accuracy of the observed mean over the observed dataset is better than the simulated model. (Hossain et. al., 2019)
R^2	$\frac{[n\sum_{i=1}^{n}(Qo,i\times Qm,i)-\ \sum_{i=1}^{n}(Qo,i\times\ \sum_{i=1}^{n}Qm,i]2}{[n\sum_{i=1}^{n}(Qo,i)2-(\sum_{i=1}^{n}Qo,i)2\ \ ]\times[n\sum_{i=1}^{n}(Qm,i)2-(\sum_{i=1}^{n}Qm,i)2\ \ ]}$	Value ranging from 0 to 1 where 0 means poorest fit and 1 means best fit (Hossain et. al., 2019)
Root Mean Squared Error, RMSE	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Qo,i-Qm,i)2}$	Always non-negative, and a value of 0 (almost never achieved in practice) would indicate a perfect fit to the data. Lower values in RMSE indicate less simulation error (Zhao et. al.,2019)

Where, $Q_{o,i}$ = observed discharge values, $\overline{Q}_o$ = observed mean discharge values, $Q_{m,i}$= modelled discharge values, $\overline{Q}_o$ = modelled mean discharge values

Table 3.13: *Scenarios considered for different LIDs*

Categories	Dimensions (m^2)	% of the Impervious Area	% of the Lot Area	Notation
Permeable Pavement				
Scenario 1	30.88	20	8	PP (20%)
Scenario 2	21.62	14	5.6	PP (14%)
Scenario 3	10.808	7	2.8	PP (7%)
Rain Garden				
Scenario 1	30.88	20	7.2	RG (20%)
Scenario 2	23.16	10	6	RG (10%)
Scenario 3	18.528	6.67	4.8	RG (6.67%)
Infiltration Trenches				
Scenario 1	30.88	20	8	SA (20%)
Scenario 2	15.44	10	4	SA (10%)
Scenario 3	10.29	6.67	2.67	SA (6.67%)
Scenario 4	7.72	5	2	SA (5%)

Table 3.14: *Design parameters of LIDs used in this study*

Layers	Key Parameters	Rain Barrel	Rain Garden	Permeable Pavement	Soakaways
Surface	Berm Height (mm)	-	150	-	150
	Vegetation Volume Fraction	-	0.1	0.1	0
	Surface Roughness (Manning's n)	-	0.05	0.013	0.05
	Surface Slope (%)	-	2	2	2
Soil	Thickness (mm)	-	450	450	-
	Porosity	-	0.475	0.475	-
	Field Capacity	-	0.378	-	-
	Wilting Point	-	0.265	-	-
	Conductivity (mm/hr)	-	10.92	10.92	-
	Conductivity Slope	-	30	30	-
	Suction Head (mm)	-	12.6	-	-
Storage	Thickness (mm)	812.8 and 609.6	150	150	300
	Void Ratio	-	0.5	0.5	0.5
	Seepage Rate (mm/hr)	-	3.3	3.3	3.3
Pavement	Thickness	-	-	80	-
	Void Ratio	-	-	0.12	-
	Impervious Surface Fraction	-	-	0	-
	Permeability	-	-	127	-

Table 3.15: *Percent of impervious area considered for simulation*

Combination	Maximum Impervious Area Treated (%)					Notes
	RB	PP	SA	RG	SUM	
RB	80	0	0	0	80	RB captures the entire roof
RB	40	0	0	0	40	RB captures half of the roof
PP	0	54	0	0	54	PP captures 1/2 of the roof (front roof surface) and the entire driveway
PP	0	34	0	0	34	PP captures 1/4 of the roof (front roof surface) and the entire driveway
PP	0	20	0	0	20	PP captures from its own surface and walkway
PP	0	14	0	0	14	PP captures from its own surface
SA	0	0	80	0	80	SA captures the entire roof
SA	0	0	49.26	0	49.26	SA captures the back half of the roof and back walkway
SA	0	0	40	0	40	SA captures back half of the roof
SA	0	0	20	0	20	SA captures from driveway and walkway
RG	0	0	0	80	80	RG captures entire roof
RG	0	0	0	54	54	RG captures half of the roof and the entire driveway
RG	0	0	0	40	40	RG captures from half of the roof
RG	0	0	0	20	20	RG captures from driveway and walkway
RB+PP	40	54	0	0	94	RB captures from half of the roof, and PP captures from the rest of the impervious area
RB+RG	40	54	0	0	94	RB captures from half of the roof, and RG captures from the rest of the impervious area
RB+SA	40	54	0	0	94	RB captures from half of the roof, and SA captures from the rest of the impervious area
SA+PP	54	46	0	0	100	SA captures from half of the roof, and PP captures a slight part of the walkway and the rest
RG+SA	46	54	0	0	100	SA captures from half of the roof, and RG captures a slight part of the walkway and the rest
RG+PP	46	54	0	0	100	SA captures from half of the roof, and PP captures a slight part of the walkway and the rest
RG+PP+SA	35	30	35	0	100	RG, PP, and SA capture from the front roof, own surface and walkway, and back roof, respectively
RG+PP+RB	30	30	40	0	100	RG, PP, and RB capture from the front roof, own surface and walkway, and back roof,respectively
RG+SA+RB	30	30	40	0	100	RG, SA, and RB capture from driveway and walkway, back roof and, and front roof, respectively
PP+SA+RB	30	30	40	0	100	PP, SA, and RB capture from driveway and walkway, back roof and, and front roof, respectively
SA+PP+RG+RB	25	25	25	25	100	All LIDs take equal shares from the impervious area

SA*= Soakaways, RG**=Rain Garden, PP***=Permeable Pavement, and RB****= Rain Barrel

Table 3.16: (a) *Case study Input data for cost estimation*

LIDs	Input description	Data Input/Select
RB	Building Type	Residential
	Number of occupants	5
	Days occupied per week	7
	Total building roof surface area	123.52 m^2
	Rainwater catchment area	LID alternative dependent
	Roofing material	Asphalt shingle
	Type of rain barrel	Plastic (above-ground)
	Size of rain barrel	Sizes in table 3.3
	Rainwater treatment	Leaf Screen & First flush kit
	Outdoor fixtures	Hose watering and irrigation system
	Water usage duration	30 minutes
	Tank unused volume	15%
	Service pipe size	32 mm
	Supply pipe size	13 mm
	Supply pipe total length	6 m
	Pump head operating pressure	138/276 kPa [20/40 psi]
	Routine/Maintenance inspections and cleaning	Periodic
RG	Drainage area	Impervious area
	Native soil infiltration rate	10.92 mm/hr
	Design type	Partial infiltration
	Drainage period	48 hours
	RG surface area length to width ratio	4
	Filter media depth	0.75 m
	Ponding depth	0.2 m
	Safety factor	2.5
	Void ratio	0.5
	Mulch depth	0.075
PP	Drainage area	Impervious area
	Native soil infiltration rate	10.92 mm/hr
	Design type	Partial infiltration
	Drainage period	48 hours
	Total length of permeable area	3.048 m
	Time to fill stone bed	2 hr
	Bedding depth (2-5 mm dia clear stone)	25 mm
	Base depth (20 mm dia clear stone)	25 mm
	Safety factor	2.5
	Void ratio	40 %
	Height of pavers	80 mm
	Minimum sub-base depth (50 mm dia clear stone)	60 mm
SA	Roof drainage area	61.76 m^2
	Drainage period	12 Hours
	Inlet locations (manholes)	1
	Infiltration rate of the subgrade	10.92 mm/hr
	Rainfall capture target	32.67 mm
	Safety factor	2.5
	Void ratio	0.5
	Width of trench	1 m

Table 3.16: *(b) Cost derived from STEP tools and considered for the analysis*

Name of LID	SA*				RG**			PP***			RB****
Area (m^2)/Capacity (L)	30.88	15.44	10.29	7.72	30.88	15.44	10.29	30.88	21.61	10.80	378
Construction Cost	18724.31	14778.11	13760.02	13251.71	27184.29	21658.63	18807.20	12991.25	11715.45	10227.02	2719.26
Average Annual Maintenance Cost (30 Year evaluation period)	975.33	763.03	692.23	656.89	3881.73	3588.64	3352.81	27.27	23.84	19.85	321.78
Retrofit Cost	2995.89	2364.50	2201.60	2120.27	4349.49	3465.38	3009.15	2078.60	1874.47	1636.32	435.08

SA*= Soakaways, RG**=Rain Garden, PP***=Permeable Pavement, and RB****= Rain Barrel

3.3 Result and Discussions

The model simulation for the base case showed that for a 2-year return period, total runoff depth in the lot area was 14.31 mm, and total runoff volume was 5.53 m^3/s. From this runoff volume, 35.28 % was coming from the impervious area. Similarly, for 5-year and 10-year return periods, runoff volumes from the impervious area were 30.05 m^3/s and 22.43 m^3/s, respectively. So, LID practices were used to manage the runoff volume coming from impervious surfaces. Before applying the *Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)*, *Analytic Hierarchy Process (AHP)* was used for prioritizing the criteria. Six different choices were made at different levels of prioritizing the criteria. The considered events were:

Event 1: No preference is given, which means equal weightage is given to all the criteria

Event 2: Priority is given to runoff (runoff depth and peak runoff reduction rate)

Event 3: Priority is given to cost (installation cost, maintenance cost, retrofit cost)

Event 4: Priority is given to runoff life cycle

Event 5: Priority is given to runoff aesthetics

Event 6: Twice much priority is given to runoff, life cycle, and aesthetics than cost. The weightage value of each of the scenarios is presented in table 3.17.

***Table 3.17:** Weightage of criteria for different scenarios*

Criteria	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6
Runoff Depth Reduction Rate	0.143	0.25	0.125	0.083	0.083	0.182
Peak Runoff Reduction Rate	0.143	0.25	0.125	0.083	0.083	0.182
Installation Cost	0.143	0.10	0.167	0.083	0.083	0.091
Maintenance Cost	0.143	0.10	0.167	0.083	0.083	0.091
Retrofit Cost	0.143	0.10	0.167	0.083	0.083	0.091
Life Cycle	0.143	0.10	0.125	0.500	0.083	0.182
Aesthetics	0.143	0.10	0.125	0.083	0.50	0.182

In event 1, a scenario was created where all criteria (runoff volume reduction rate, peak discharge reduction rate, installation cost, maintenance cost, retrofit cost, and aesthetic) possess equal weightage. The reason behind this assumption is that the property owner's priority, expectations, and taste cannot be determined without executing extensive surveys/interviews. However, an overall idea is possible to comprehend finding the positive ideal solutions (PIS) and negative ideal solution (NIS). The geometric distance of each of the criteria from NIS and PIS will indicate the most influential criteria and how the effect of those criteria can be neutralized. In figure 3.8, NIS and PIS for each of the criteria are given for different return periods.

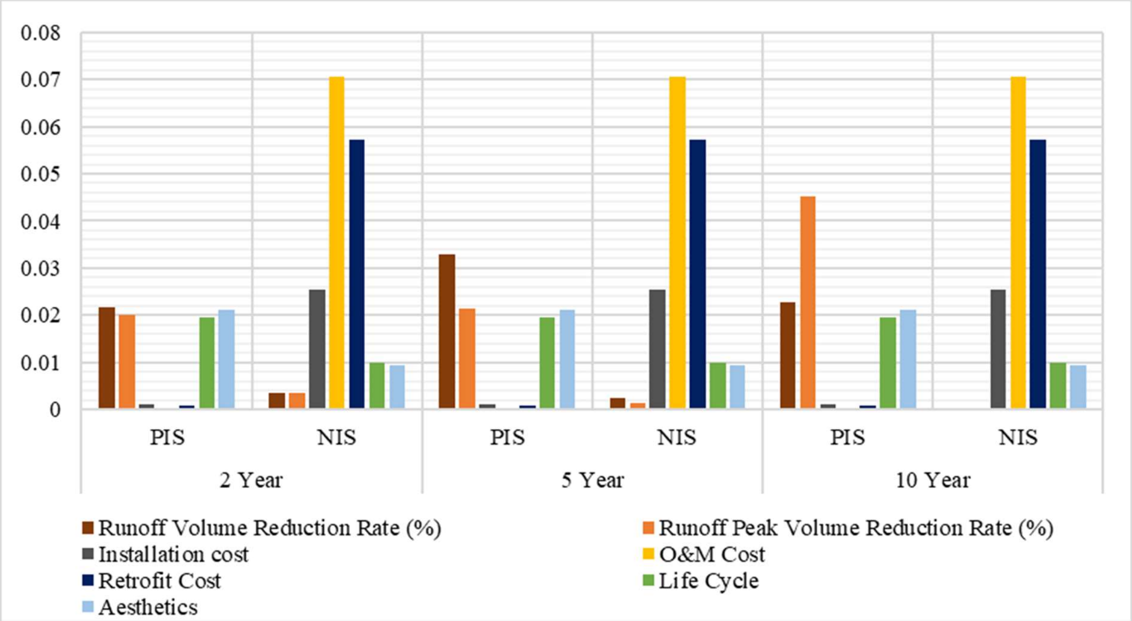


Figure 3.8: *Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) of all criteria for event 1 of different return periods*

The graphical illustration of figure 3.8 represented that for a 2-year return period, runoff depth reduction rate, peak runoff reduction rate, life cycle, and aesthetics hold higher PIS values (almost 20 times) than installation cost, maintenance cost, and retrofit cost. Similarly, in NIS, costs are dominant- nearly 35 times higher than reduction rate, peak runoff reduction rate, and seven times higher than life cycle and aesthetics. Dominant criteria remain the same (costs) for 5 – year and 10 – year return periods. However, in PIS for the 10-year return period, the peak runoff reduction rate (0.07) shows three times higher values than the runoff depth reduction rate (0.022). This sudden change is that for the 10-year return period, the precipitation amount is much higher, and so is the runoff. Thus, it becomes difficult to reduce higher runoff depth. However, the peak runoff discharge rate can be reduced substantially. The analysis indicates that providing higher weightage to runoff depth reduction rate, peak runoff reduction rate, life cycle, and aesthetics than installation cost, maintenance cost, and retrofit cost may result in a solution that balances all the criteria.

For all events, quantitative scores were derived for each of the alternatives by using TOPSIS. As the decision criteria analysis was applied for 94 different LID alternatives, thus top five LID alternatives are selected from each of the events for further research (Table 3.17). Along with these, normalized values of criteria for each of the events were illustrated in a radar graph in figure 3.9 for understanding the influence of criteria on a LID alternative.

Event 1: In this event, all the criteria have equal weightage (0.143). Based on the ranking combination of 378 l of a rain barrel and 30.88 m^2 of soakaways (RB (0.54%) + SA (20%)) was the best suitable LID alternatives to balance in between all the priorities, which is evident from table 3.18, figure 3.11 and 3.12. This alternative reduced 22.432% and 19.938% of runoff depth and peak runoff volume, respectively. Compared with other most suitable alternatives of LID in different events, it required an average installation, maintenance, and retrofit cost (26171.66 CAD). However, this alternative has the lowest life cycle than other alternatives.

Event 2: The most suitable alternative in event 2 was PP (20%) + SA (20%) + RB (0.54%). As per the priority, this alternative reduced the maximum percentage of runoff depth and peak runoff volume- 30.608 % and 25.234 %, respectively. However, this alternative took the highest costs (41351.79 CAD). So, this was not an economically feasible solution.

Event 3: RB (0.54%) + SA (10%) was the best economical alternative which needed less money for overall installation, maintenance, and retrofit cost (21381.77 CAD) compare to other LID alternatives in terms of runoff depth and peak runoff discharge reduction (19.217 % and 18.069 %, respectively). This alternative has the lowest life cycle and average aesthetics value. Considering all the criteria, this option could be regarded as a low-cost alternative after the alternative of RB (0.54%) + SA (20%).

Event 4: PP (20%) was the most suitable alternative having the most extended life cycle of 30 years. It required the lowest maintenance cost (27.276 CAD) and the second-lowest installation, retrofit, and total cost of 12991.255 CAD, 27.276 CAD, and 15097.13 CAD, respectively. However, it is not preferred by the homeowners for beautification purposes. Thus, it has the lowest aesthetic value of 4.

Event 5: In terms of aesthetics, rain barrels are the most preferred LID alternative by the homeowners. However, it has the lowest runoff depth and peak runoff discharge reduction, which were 14.396 % and 15.576 %, respectively. Even though 208 l of 4 rain barrels were used, this alternative has the lowest installation and retrofit cost. Overall, 13904.52 CAD was required for the installation, maintenance, and retrofit of this alternative. So, if the primary purpose of a homeowner is to beauty his/her house, this option would be the most suitable one.

Event 6: The most suitable alternative in events 1and 6 was RB (0.54%) + SA (20%), which applies. Even though lower weightage was given to the costs, this was the only solution to balance all the criteria. However, figure 239 of event 6 shows the next three of the alternatives of this event- RB (0.54%) + RG (6.67%), RB (0.54%) + RG (20%), and RB (0.54%) + PP (20%) were highly influenced by maintenance and retrofit cost, especially the ones with the rain garden.

Table 3.18: *five suitable alternatives of LID for different events for 2-year return period*

Rank	LID Alternatives	Score	LID Alternatives	Score
	Event 1		**Event 2**	
1	RB (0.54%) + SA (20%)	0.8447	PP (20%) + SA (20%) + RB (0.54%)	0.828
2	PP (20%) + SA (5%) + RB (0.54%)	0.8413	SA (20%) + PP (20%)	0.824
3	PP (20%) + SA (6.67%) + RB (0.54%)	0.8411	PP (14%) + SA (20%) + RB (0.54%)	0.812
4	PP (20%) + SA (10%) + RB (0.54%)	0.8404	SA (20%) + PP (14%)	0.809
5	RB (0.54%) + SA (10%)	0.8396	PP (20%) + SA (10%) + RB (0.54%)	0.805
	Event 3		**Event 4**	
1	RB (0.54%) + SA (10%)	0.8698	PP (20%)	0.845
2	RB (0.54%) + SA (20%)	0.8696	PP (14%)	0.838
3	RB (0.88%)	0.8687	RG (6.67%) + PP (20%)	0.820
4	RB (0.54%) + SA (6.67%)	0.8683	RG (6.67%) + PP (14%)	0.818
5	RB (0.54%) + SA (5%)	0.8674	PP (7%)	0.817
	Event 5		**Event 6**	
1	RB (0.88%)	0.865	RB (0.54%) + SA (20%)	0.792
2	RB (0.66%)	0.857	RB (0.54%) + RG (6.67%)	0.784
3	RB (0.54%)	0.828	RB (0.54%) + RG (20%)	0.782
4	RB (0.54%) + SA (20%)	0.751	RB (0.54%) + PP (20%)	0.778
5	RB (0.54%) + SA (10%)	0.750	SA (10%)	0.775

Figure 3.9: *Normalized values of criteria for different events 2-year return period*

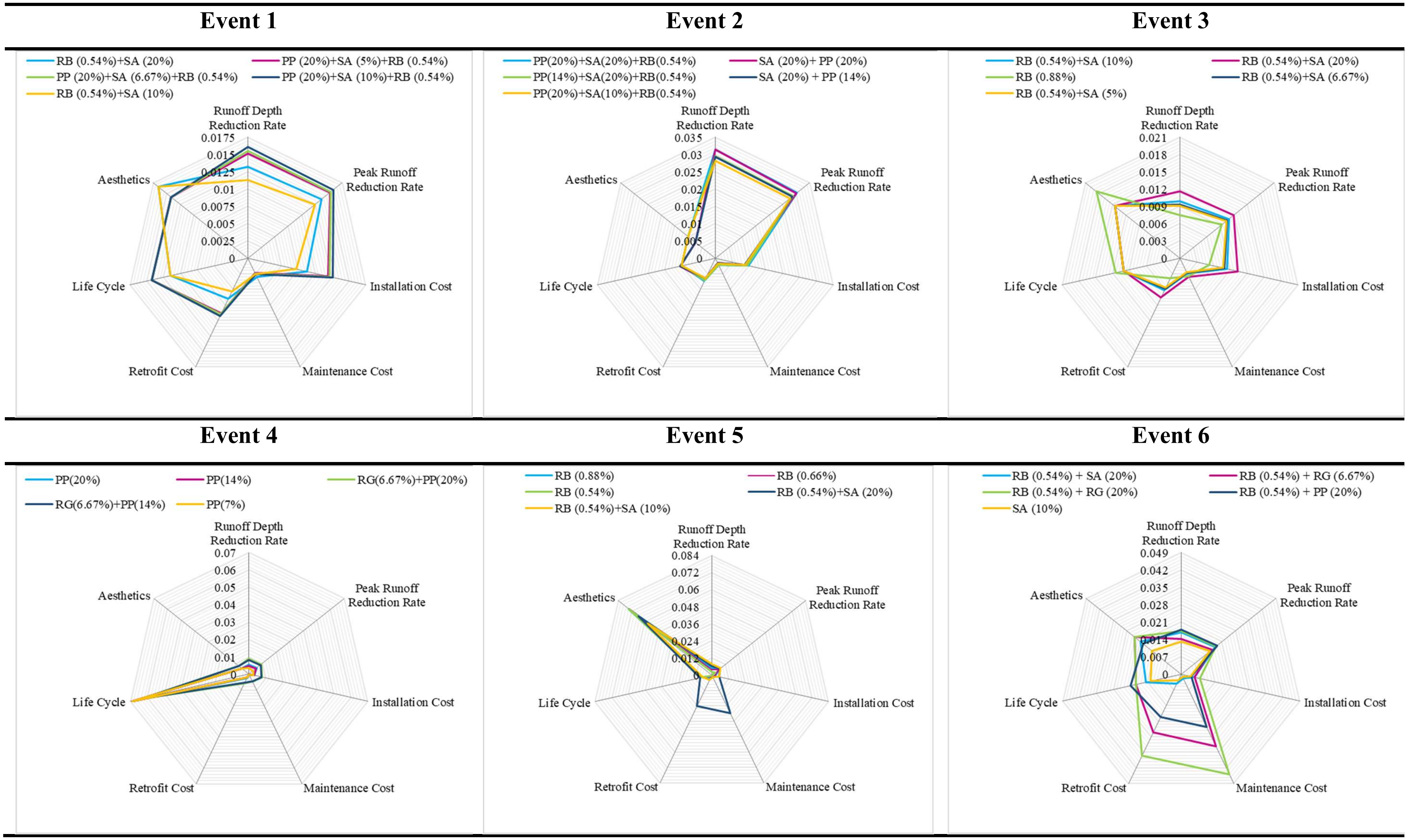


Table 3.19: *Qualitative (aesthetics) and quantitative (runoff depth reduction rate, peak runoff reduction rate, life cycle, installation cost, maintenance cost, and retrofit cost) values for the best alternative of each event*

Event No.	LID Alternatives	Runoff Depth Reduction Rate	Peak Runoff Reduction Rate	Installation Cost	Maintenance Cost	Retrofit Cost	Life Cycle	Aesthetics
1	RB (0.54%) + SA (20%)	22.432	19.938	21443.569	1297.120	3430.971	17.5	7
2	PP (20%) + SA (20%) + RB (0.54%)	30.608	25.234	34517.824	1324.395	5509.572	21.67	6
3	RB (0.54%) + SA (10%)	19.217	18.069	17497.365	1084.823	2799.578	17.5	7
4	PP (20%)	16.562	14.330	12991.255	27.276	2078.601	30	4
5	RB (0.88%)	14.396	15.576	10877.033	1287.158	1740.325	20	9
6	RB (0.54%) + SA (20%)	22.432	19.938	21443.569	1297.120	3430.971	17.5	7

🟧 = Balanced for all criteria
⬜ = Highest runoff depth and peak runoff reduction rate
🟥 = Lowest cost value
🟪 = Highest life cycle value
🟦 = Highest aesthetics value

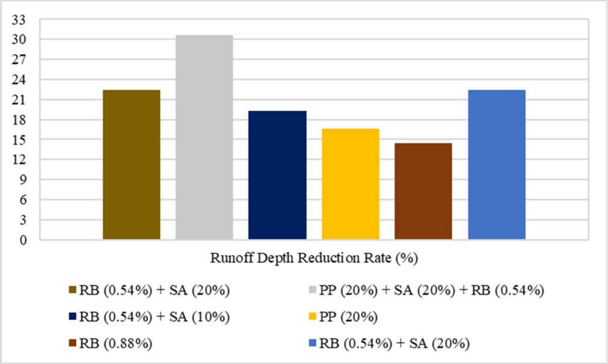


Figure 3.10: *Runoff reduction rate (%) of most suitable alternatives off all the events*

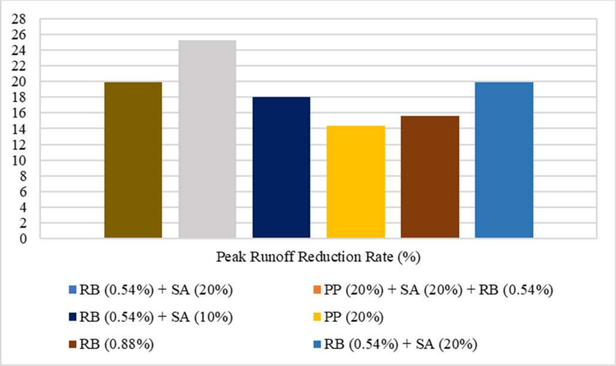


Figure 3.11: *Peak runoff volume reduction rate (%) of most suitable alternatives off all the events*

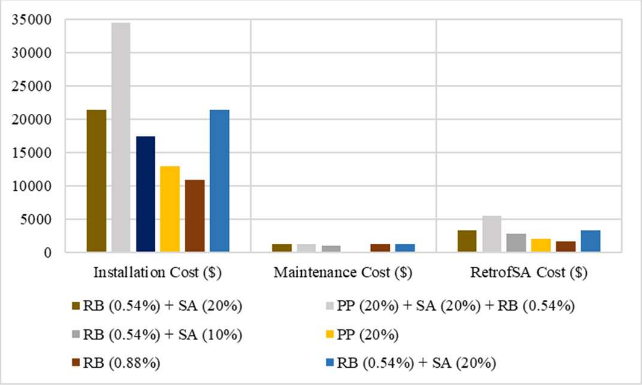


Figure 3.12: *Installation, maintenance, and retrofit cost of most suitable alternatives off all the events*

An important observation is that rain garden is the only LID alternative which was not present in any of the event of a most suitable alternative. One of the reasons is that the installation, maintenance, and retrofit cost of the rain garden is much higher than other alternatives. An area of 10.29 m2 of rain garden costs 1.83 and 1.37 times higher than permeable pavement and soakaways. The maintenance and retrofit costs are also much higher than other LID alternatives.

The model simulation revealed that a combination of RG (20%) + PP (20%) + SA (20%) could reduce 34.94 % of the total runoff depth and 28.037 % of peak runoff discharge; however, due to its high costings (71724.82 CAD for installation, maintenance and retrofit cost) and comparatively low life cycle (23.33 years) and aesthetic beauty does not make this one an ideal LID alternative.

The analysis was also carried out for 5 and 10 -year return periods. The top five most suitable LID alternatives are listed in Table 3.20 and 3.21. Along with these, the normalized distance from NIS and PIS for each of the criteria are shown in figure 3.13 and 3.14. An important observation is that the RG of 20% imperviousness (RG (20%)) was the highest-scoring one in terms of no preference and preference given to runoff and costs for the 5-year return period. Similarly, for the 10-year return period, (RG (20%)) was the most suitable one in all events except for event 5 (preference was given to life cycle). Even though rain gardens are costly, they are effective for all the criteria and one of the preferred LID by the homeowners.

The comparison of each of the events for different return periods showed the dominance of runoff volume reduction rate and peak discharge reduction rate for 5 and 10 year periods, respectively. The graphical representations in Figures 3.13 and 3.14 also support and strengthen this idea. Addressing this, if event 1 is considered for the observation, Figure 3.13 showed 3.033 value for runoff volume reduction rate, which is the highest than other criteria. For the same event in Figure 3.14, the value for peak discharge reduction rate is significantly higher (0.044) than other criteria, and thus it is the dominant one. The dominance of runoff volume reduction rate is prominent for events 1,2 and 3 in 5-year return period. However, the peak runoff reduction rate is the highest one for all of the events.

Table 3.20: *five suitable alternatives of LID for different events for the 5-year return period*

Rank	LID Alternatives	Score	LID Alternatives	Score
	Event 1		**Event 2**	
1	RG (20%)	0.832	RG (20%)	0.798
2	RG (6.67%) + PP (14%)	0.808	RG (6.67%) + PP (14%)	0.753
3	PP (14%) + SA (20%) + RB (0.54%)	0.800	PP (14%) + SA (20%) + RB (0.54%)	0.713
4	SA (20%) + PP (20%)	0.787	SA (20%) + PP (20%) + RG (6.67%) + RB (0.54%)	0.703
5	PP (7%) + SA (10%) + RB (0.54%)	0.786	SA (20%) + PP (20%) + RG (10%) + RB (0.54%)	0.693
	Event 3		**Event 4**	
1	RG (20%)	0.841	PP (20%)	0.845
2	RG (6.67%) + PP (14%)	0.824	PP (14%)	0.838
3	PP (14%) + SA (20%) + RB (0.54%)	0.822	RG (6.67%) + PP (20%)	0.820
4	PP (7%) + SA (6.67%) + RB (0.54%)	0.820	RG (6.67%) + PP (14%)	0.818
5	PP (7%) + SA (10%) + RB (0.54%)	0.819	PP (7%)	0.817
	Event 5		**Event 6**	
1	RB (0.88%)	0.784	RB (0.54%) + SA (20%)	0.792
2	RB (0.66%)	0.773	RB (0.54%) + RG (6.67%)	0.784
3	RB (0.54%)	0.759	RB (0.54%) + RG (20%)	0.782
4	RG (20%)	0.744	RB (0.54%) + PP (20%)	0.778
5	RB (0.54%) + SA (20%)	0.720	SA (10%)	0.775

Figure 3.13: Normalized values of criteria for different events 5-year return period

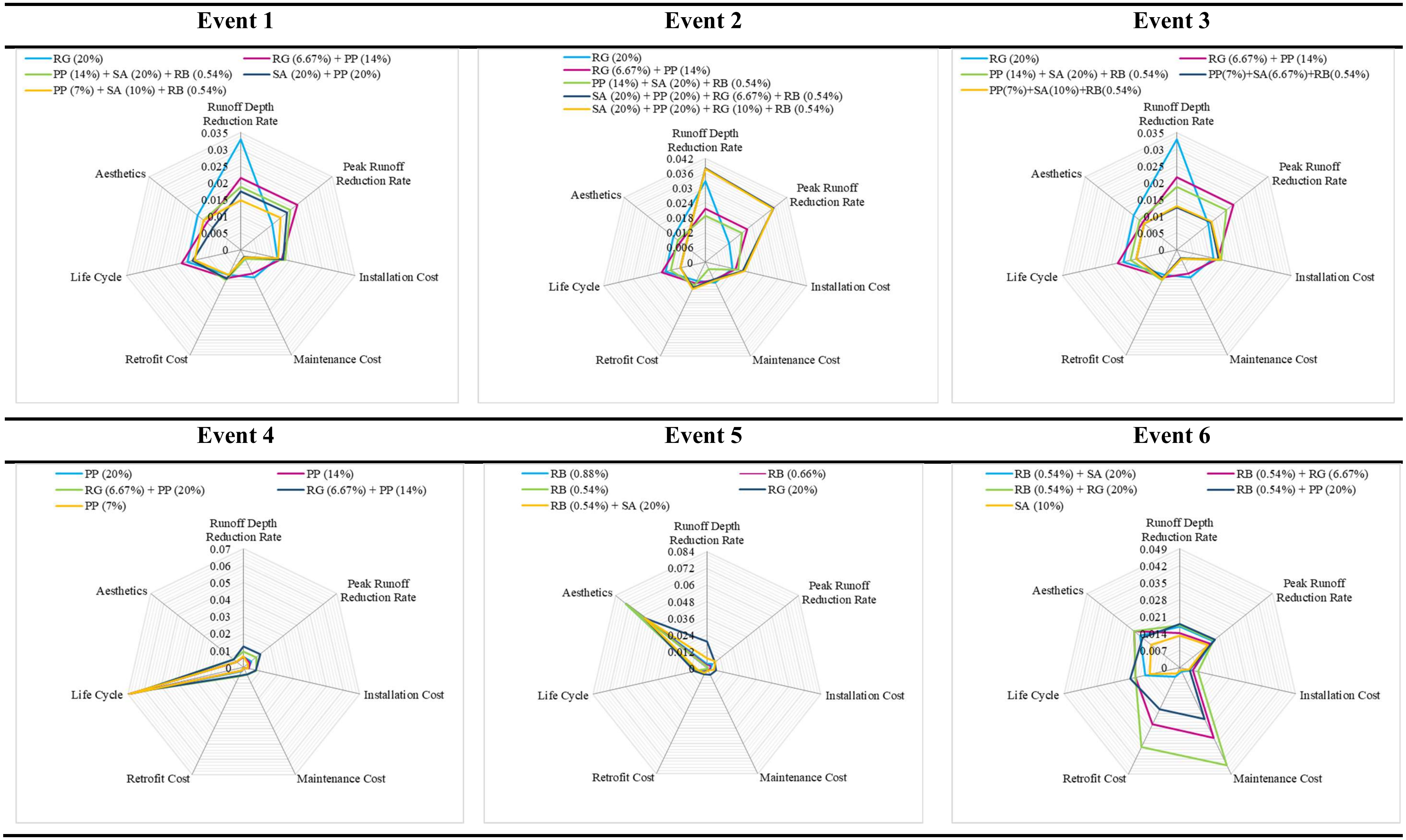
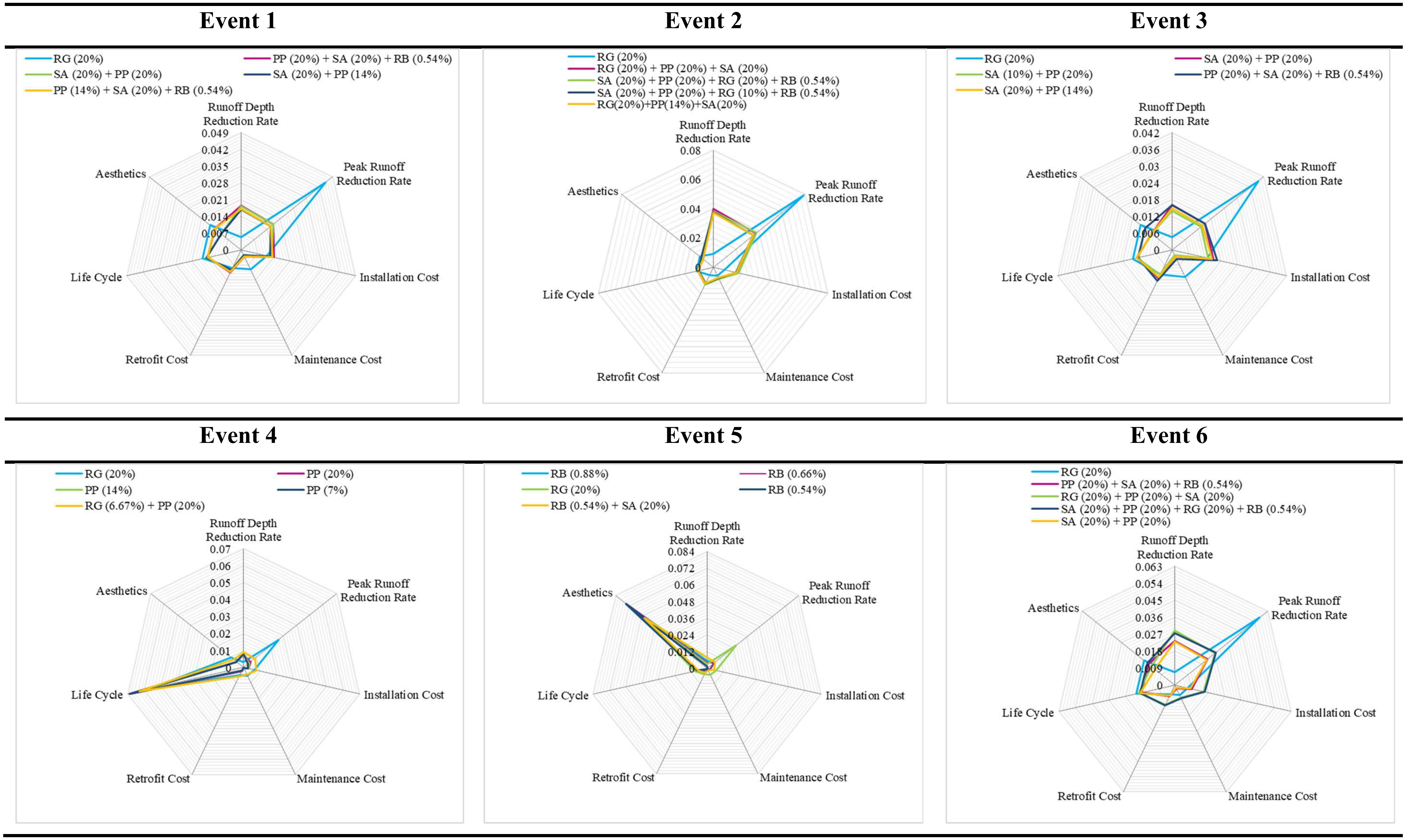


Table 3.21: *five suitable alternatives of LID for different events for 10-year return period*

Rank	LID Alternatives	Score	LID Alternatives	Score
	Event 1		**Event 2**	
1	RG (20%)	0.798	RG (20%)	0.737
2	PP (20%) + SA (20%) + RB (0.54%)	0.724	RG (20%) + PP (20%) + SA (20%)	0.598
3	SA (20%) + PP (20%)	0.724	SA (20%) + PP (20%) + RG (20%) + RB (0.54%)	0.596
4	SA (20%) + PP (14%)	0.718	SA (20%) + PP (20%) + RG (10%) + RB (0.54%)	0.583
5	PP (14%) + SA (20%) + RB (0.54%)	0.718	RG (20%) + PP (14%) + SA (20%)	0.582
	Event 3		**Event 4**	
1	RG (20%)	0.817	RG (20%)	0.766
2	SA (20%) + PP (20%)	0.766	PP (20%)	0.734
3	SA (10%) + PP (20%)	0.764	PP (14%)	0.728
4	PP (20%) + SA (20%) + RB (0.54%)	0.764	PP (7%)	0.720
5	SA (20%) + PP (14%)	0.763	RG (6.67%) + PP (20%)	0.720
	Event 5		**Event 6**	
1	RB (0.88%)	0.753	RG (20%)	0.746
2	RB (0.66%)	0.750	PP (20%) + SA (20%) + RB (0.54%)	0.608
3	RG (20%)	0.734	RG (20%) + PP (20%) + SA (20%)	0.607
4	RB (0.54%)	0.701	SA (20%) + PP (20%) + RG (20%) + RB (0.54%)	0.607
5	RB (0.54%) + SA (20%)	0.679	SA (20%) + PP (20%)	0.603

Figure 3.14: Normalized values of criteria for different events 5-year return period



Event 1 Event 2 Event 3

Event 4 Event 5 Event 6

3.4 Conclusions

Selecting the most suitable low impact development (LID) practices to manage the stormwater is a challenging issue. Source level stormwater management system (LIDs) is one of the effective ways; however, studies on the implementation of LID in private properties are limited. Moreover, the costs and maintenance of LIDs implemented in private sectors are the responsibility of the property owner, which further complicates the LID selection. Technical, economic, and social factors need to be considered to maintain a balance between the priorities of the property owners and the local government. As a first step, these issues are addressed in this study by developing an innovative framework to assist in identifying the most suitable Low LIDs for a single detached house, while prioritizing the essential criteria. Also, the guidelines for residential LIDs that are used in Ontario have been collected and provided in this report.

In this work, based on the literature review, rain barrels, permeable pavement, rain gardens, and soakaways are the focus of this study as they are the most suitable for residential sites. The literature review also revealed that the main criteria that have an impact on LID selection and implementation in private property, are runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle, and aesthetics. Therefore, the developed framework incorporates these criteria through hydrological modelling and multicriteria decision analyses. Runoff peak and depth reduction rates are simulated using SWMM for a base case with no LIDs and cases with LID alternatives. The costs are calculated from the cost estimation tools developed by the Sustainable Technologies Evaluation Program (STEP). Along with these, necessary guidelines are provided for the implementation of LID for a single-detached house.

The framework was applied in a single-detached house in Flamborough residential area. The area of the lot was 386 m^2 and the percent imperviousness is 40 %. The LID practices were installed as a percentage of the total impervious area, maintaining the appropriate guidelines. For the hydrological modelling, 3-hour Chicago design storms corresponding to 2-, 5-, 10-year return periods from the Mount Hope station were considered. Various economic features (construction cost, maintenance cost, and retrofit cost) were extracted from STEP tools for the assigned dimensions and properties of the individual LIDs. Life cycle and aesthetics were identified from the guidelines, manuals, and literature review. AHP and TOPSIS were used for estimating the criteria weights and ranking the LID alternatives. Six hypothetical criteria-weighting combinations were investigated. For 2-year return period, the highest scored LID alternatives were found to be RB (0.54%) + SA (20%), PP (20%) + SA (20%) + RB (0.54%), RB (0.54%) + SA (10%), PP (20%), RB (0.88%) and RB (0.54%) + SA (20%) for criteria weight-scenarios 1 to 6, respectively. The LID alternative, PP (20%) + SA (20%) + RB (0.54%), results in the highest runoff depth and peak reduction rates; however, it is the costliest one. The most economical LID alternative is PP (20%) with a life cycle of 30 years; however, it has poor runoff management. The LID alternative that balances all the criteria is RB (0.54%) + SA (20%) (378 l of a rain barrel and 20 % of the impervious area of soakaways). This alternative results in a 22.432 % runoff reduction rate and 19.938 % peak runoff discharge reduction rate, it costs 26171.66 CAD and has a life cycle of 17.5 years.

The developed framework can help in selecting the most suitable LIDs alternative for a single detached house. Although it accounts for the homeowner preferences, the application of this framework still requires the intervention of an engineer or technician. In the future this framework can be prepared as an interactive tool that can be applied by homeowners without the need for an expert. It can also be extended to include other types of stormwater sources such as schools, buildings, and parking lots. Moreover, this framework can be a starting point for a framework for a residential small catchment. Similarly, frameworks can be developed for industrial sites and highways.

4. Conclusions

This study focuses on finding the latent topics in Low Impact Development (LID) practices in residential areas and selecting suitable LID alternatives by prioritizing individual needs. An extensive meta-research has conducted using bibliometric analysis and text mining. The investigation revealed that LID in residential areas still holds ample opportunities to further exploration. Therefore, an attempt has taken in this study to develop a framework for selecting suitable LID in a private property.

The framework is developed using the Multiple-Criteria Decision Analysis (MCDA) and hydrologic model. The framework includes four steps. At first, selecting the criteria and LID alternatives that would be used for the analysis. Seven criteria- runoff depth reduction rate, peak runoff reduction rate, installation cost, maintenance cost, retrofit cost, life cycle and aesthetics, and four different LIDs - rain garden, permeable pavement, rain barrel, soakaways are selected for the investigations. In this study, an assumption is taken that the runoff peak reduction rate is calculated from the lot area considering the presence of a single outlet. However, in the practical scenario, there can be multiple active outlets contributing to the lot area. Besides, the peak runoff discharge reduction rate is essential for the flood peak estimation. In some cases, peak runoff discharge can be insignificant to consider. In that regard, zero needs to be included as weightage value. Secondly, collecting necessary data from the guidelines of Ontario and the study area. In this step, different alternatives are created based on the sizes and the combination of LIDs for the model simulation. Runoff depth reduction and peak runoff reduction rates are estimated for different alternatives of LIDs by using a hydrologic model (Stormwater Management Model (SWMM)). Thirdly, the Sustainable Technologies Evaluation Program (STEP) tools are used to calculate the installation cost, maintenance cost, and retrofit cost. In the last step, the Analytic hierarchy process (AHP) is used to calculate the weightage of each of the criteria, and the Technique for Order of Preference by Similarity

(TOPSIS) is used for calculating the ranking of the LID alternatives from the considered criteria weightage. This framework can identify the most suitable LID alternatives based on the priority of the selected criteria. It will also be advantageous to locate the most efficient LID alternatives and meet up with the sizing and cost restraints. The City can adopt this framework to be beneficial for the planners, homeowners, contractors, and real estate agents/brokers.

In terms of limitations, this framework is still under development, and so, it can be challenging for the homeowners to use. However, it has the immense potentiality to be converted as a tool in the future. Moreover, design storms are used in the study, which is effective for peak runoff estimation but not for runoff volume calculation. One option can be to use the continuous simulation to get the runoff values. More straightforwardly, the analytical probabilistic stormwater management model (APSWMM) can be the best way to get the most precise value.

5. Future Recommendations

This research work is still in the primary stage and still has the immense opportunity to further investigations and improvement. Firstly, a mathematical tool can be prepared based on this framework adopting different criteria and LIDs. This tool will be helpful for the homeowners to select the best LID alternatives.

Secondly, this framework needs modification after applying continuous simulation or the analytical probabilistic stormwater management model to get the most accurate result and save time.

Thirdly, extensive surveys and interviews need to be conducted in the area where LID will be implemented to know about the public's opinion on the selection process. These may help to create the hierarchy process in a precise way.

Fourthly, depending on the location, the section of LID alternatives can be varied. For instance, no green roof is applied in the framework even though the people highly appreciate it. The reason behind is that the roof shape of most of the house in Canada is a pyramid which is not convenient for the green roof. Therefore, depending on the location, the LID alternatives will vary.

Fifthly, this framework needs to be applied in any residential area to compare the result with the hypothetical one.

And lastly, the framework needs to be checked if any modification is required while applying in a semi-detached house and town house.

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