Resilience Quantification of Low Impact Development (LID) Practices

Resilience Quantification Approaches
of Low Impact Development (LID) Practices
Using Analytical and Continuous Simulation Models

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LAY ABSTRACT

There is a critical need to develop and implement optimal low-impact development (LID) practices in the field of stormwater management to mitigate the adverse effects of urbanization and climate change. This thesis is focused on developing quantitative resilient measurement approach of LID designs. A comprehensive literature review is first carried out, focusing on identifying various optimization methodologies, relevant gaps, and resilience assessment techniques. Subsequently, a novel resilience evaluation approach is developed, using bioretention (BR). By constructing a new reliability index, the entire BR system's reliability can also be assessed. Finally, a cost-effective, resilient and reliable design guideline for BR system is proposed. Although bioretention (BR) is used as an example in this study, the developed approach opens the gate to quantify the resilience of all types of LID practices.

ABSTRACT

Implementing optimal Low Impact Development (LID) practices has grown in popularity as a means of mitigating the adverse effects of urbanization and climate change. As such incorporating aspects of resilience for optimal LID design has become paramount. This study focuses on identifying the current LID optimization strategies and associated research gaps as well as assessing whether a quantitative approach to measure LID resilience exists. To do so, a systematic and bibliometric literature review on LIDs optimization and resilience is first conducted, based on which resilience, climate change, and uncertainty are recognised as hotspot keywords. The review also showed that no LID resilience quantification technique was available. Based on the latter outcome and to facilitate LID's optimal design in future, this research proposes a new resilience quantification approach of LID by developing set of equations using Analytical Probabilistic Approach (APA) and continuous simulation approach using SWMM. The equations consider LID's functionality and assess resilience using three indices: robustness, rapidity and serviceability. A new overall resilience index (the product of robustness and serviceability) and reliability index (the product of volumetric, occurrence, and temporal reliability) are proposed using different area ratios between contributing catchment and LID area to assure a resilient and safe LID system. LID costing tool of the Sustainable Technologies Evaluation Program (STEP) is subsequently utilized to estimate the capital cost of LID. Finally, a user-oriented design guideline is proposed for a cost-effective, resilient, and reliable LID system. Although this study adopts bioretention (BR) as a demonstration of the approach utility, the developed approach is applicable to any form of LID practices.

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

Nomenclature

Acronyms

AHP	Analytical Hierarchy Process
APA	Analytical Probabilistic Approach
BMP	Best Management Practices
BC	Bioretention Cell
BR	Bioretention
CC	Climate Change
CSO	Combined Sewer Overflow
DSS	Decission Support System
DT	Detention Tank
GA	Genetic Algorithm
GCM	Global Circulation Model
GI	Green Infrastructure
GR	Green Roof
GS	Grass Swale
HS	Harmony Search Algorithm
IT	Infiltration Trenches
IUWM	Integrated Urban Water Management
LCCT	Life Cycle Costing Tool
LID	Low Impact Development
LIUDD	Low Impact Urban Design and Development
LUC	Land Use Change
MCGS	Marginal Cost-Based Greedy Strategy
MIET	Minimum Inter-Event Time
MOALOA	Multi-Objective Antlion Optimization Algorithm
NSGA II	Non-dominated Sorting Genetic Algorithm II
PDF	Probability Distribution Function
PP	Permeable Pavement
PSO	Particle Swarm Optimization
RB	Rain Barrel
RG	Rain Garden

RWH	Rainwater Harvesting System
SCMs	Stormwater Control Measures
SUDS	Sustainable Urban Drainage Systems
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Storm Water Management Model
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
UDS	Urban Drainage System
VS	Vegetative Swales
WSUD	Water Sensitive Urban Design

Symbols

b	interevent dry period (h)
$\bar{b}$	mean of interevent dry period (h)
C	total capacity of LID (mm)
C_e	stormwater capture efficiency (%)
D	drying time (day)
D_2	thickness of soil layer of LID (mm)
D_3	thickness of storage layer of LID (mm)
D_4	thickness of pavement layer of LID (mm)
E_a	evaporation rate (mm/h)
$E(F_{iw})$	expected value of infiltrated water volume to wet fill media layer (mm)
$E(S_{dw})$	expected value of retained water in the surface depression of BR (mm)
F	functionality (%)
F_e	functionality at the end of an event (%)
F_i	initial functionality (%)
F_l	failure state
f_m	maximum infiltration rate of native soil (mm/h)
F_{min}	minimum functionality (%)
F_s	functionality at the start of an event (%)
f	infiltration rate (mm/h)
f_c	minimum infiltration rate (mm/h)

f_{LID}	infiltration from LID (mm/h)
h_s	surface level of LID (mm)
h_p	pavement level of LID (mm)
h_{sg}	storage level of LID (mm)
K	infiltration capacity decay constant (1/h)
L	functionality loss hour
N	number of cases where LID's functionality reaches its minimum value at t_{min} and restores its initial functionality
N_t	total number of time steps in SWMM
n	number of events
n_w	number of events at which water is stored in S_d
R	unitless constant
R_d	robustness (%)
RI	reliability index (%)
R_{occ}	occurrence reliability (%)
R_{tem}	temporal reliability (%)
R_{vol}	volumetric reliability (%)
r	ratio of the contributing catchment area to the BR area
r_p	poisson ratio
S_d	surface depression storage depth of BR (mm)
S_{dc}	surface depression storage capacity of the contributing catchment (mm)
S_{di}	impervious sub-area of sub-catchment A
S_{dp}	pervious sub-area of sub-catchment A
S_{dw}	stored water within LID (mm)
S_f	recovered state
S_I	serviceability index
S_0	original state
S_r	ruptured state
S_t	states of the LID system at each time-step
S_v	vulnerable state
s_{wLID}	water into LID (mm)

T	duration of the entire simulation period (h)
T_j	duration when the LID system remains in the satisfactory mode (h)
T_R	rapidity (h)
t	rainfall event duration (h)
$\bar{t}$	mean rainfall event duration (h)
t_d	drying time (h)
$\overline{t_d}$	average drying time (h)
t_{Fi}	time at which LID restores its initial functionality (h)
$t_{F(S)}$	duration of storm events at which LID remains in satisfactory state
t_0	time of event occurrence (h)
t_{min}	time at which minimum functionality (h)
t_s	time of recovery initiation (h)
t_t	time when full functionality recovered (h)
v	rainfall event volume (mm)
$\bar{v}$	mean rainfall event volume (mm)
v_i	inflow into LID (mm)
v_{min}	minimum threshold volume of rainfall(mm)
v_r	runoff from BR (mm)
v_{rA}	total runoff from sub-catchment A (mm)
v_{rain}	total rainfall volume (mm)
X_t	parameter corresponding to satisfactory state, S and failure state, F_l
ζ	inverse of the mean rainfall event volume (1/mm)
λ	inverse of the mean rainfall event duration (1/hr)
ψ	inverse of the mean rainfall episode's interevent time (1/hr)
θ	soil moisture content
ϕ	runoff co-efficient
η_1	porosity of the soil layer of LID
η_2	porosity of the storage layer of LID
η_3	porosity of the pavement layer of LID
я	overall resilience index

Declaration of Academic Achievement

In accordance with McMaster University's School of Graduate Studies regulations, this thesis was prepared in a sandwich format. The research conducted in this thesis was carried out by Arpita Islam under the supervision and guidance of Dr. Sonia Hassini and Dr. Wael El-Dakhakhni. Chapter 2 was published in the Journal of Hydrology on May 15, 2021, and Chapter 3 was submitted for publication in the Journal of Sustainable Water in the Built Environment on October 29, 2021.

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1. Introduction

The rapid increase of impervious surfaces due to urbanization, as well as climate change induced intensified and frequent precipitation generates excessive surface runoff, leaving drainage systems unable to handle this excessive runoff volume (Guo and Guo, 2018; Becciu and Raimondi, 2015). Different approaches and strategies have been adopted to control the excessive stormwater. Conventional stormwater management is one of the oldest and widely used methods of directing stormwater into streams as quickly as possible through a centralised system (Paul and Meyer, 2001; Wu et al., 2019). However, by transporting this extra water downstream, this circumstance puts downstream residents at risk, as well as deteriorating the natural freshwater eco-system. Building, operating, and retrofitting this ancient technology is also exceedingly costly (Bassut, 2016). As a result, in recent decades, there has been a shift toward employing Low Impact Development (LID) practices rather than the traditional strategy (Damodaram et al., 2010). These approaches strive to retain predevelopment hydrology, drain stormwater more sustainably, boost ecological benefits, and give both quantity and quality control benefits (Liu et al., 2015; Vogel et al., 2015).

These practices were built using deterministic design factors and static climatic assumptions, and as a result, they are unable to handle these unpredictable future events. Therefore, in the present debate about climate change and adaptation, resilience has emerged as a prominent concern in stormwater management (Islam et al., 2021; Brown et al., 2020). Following the concept of Hashimoto et al., (1982), a LID system can be considered as a resilient if it can go back to its original steady or equilibrium state after enduring stress due to any shock event (extreme rainfall). Resilience needs to be considered also as one of the optimization goals during LIDs optimal design to minimize the resulting aftereffect of uncertain future events.

Therefore, resilience analysis technique needs to be known before incorporating it as one of the optimization objectives and reviewing prior studies can aid this understanding. This study addresses these concerns through a two-part analysis which is detailed in the following chapters.

In Chapter 2, a detailed bibliometric and network analysis and a systematic literature review were carried out based on the evaluation, optimization and resilience of LIDs, to provide insights into the intrinsic structure and advancement across the defined research field. From this review, research clusters were identified, and their themes were designated using text mining feature. Furthermore, emerging study areas with hot topics and cross-cutting research gaps are recognized. In addition, this review found no quantified resilience assessment technique for LID systems.

Based on the findings of the previous chapter, Chapter 3 proposes a resilience quantification method for LID systems. As a first step, resilience assessing indicators were identified based on literature review. Then a set of new equations were developed by using both Analytical Probabilistic Approach (APA) and continuous simulation technique (SWMM) to evaluate them and quantify a new resilience index. Additionally, the overall LID system's reliability is measured by introducing a new reliability metric, as a system cannot be resilient if it is not reliable. Finally, Sustainable Technologies Evaluation Program’s (STEP) LID Costing Tool is used to determine the most cost-effective design criteria for a LID system. This newly proposed approach has the potential to provide a trustworthy tool for quantifying the resilience of any LID system, as well as providing additional knowledge for LID design optimization.

CHAPTER 2

A Systematic Bibliometric Review of Optimization and Resilience within Low Impact Development Stormwater Management Practices

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2. A Systematic Bibliometric Review of Optimization and Resilience within Low Impact Development Stormwater Management Practices

Arpita Islam, Sonia Hassini and Wael El-Dakhakhni

Abstract: The implication of optimal low impact development (LID) implementations has been attracting researchers' attention, aiming to alleviate the detrimental impacts of urbanization and climate change and enhance resilience. The rapidly increasing number of publications on LID optimization over recent years makes it one of the leading-edge research areas in the field of urban stormwater management. This study aims to conduct a systematic bibliometric review of the optimization and resilience within LID stormwater management practices. LID related publications of 17 years (2004–2020, August) were retrieved from the Web of Science database and thoroughly analyzed. This review looks into the progression of current research themes, previous work outcomes, and key research gaps. Using a clustering tool, four main research clusters have been identified. Employing text mining, each cluster's reflecting research theme is identified based on the analysis of the top fifteen papers. The cluster's themes are outlined as (1) optimizing LID type and size, (2) spatial layout optimization with parameter uncertainty and climate and land-use change impacts, (3) hydraulic LID parameter optimization and adoption of multicriteria analysis and (4) experimental studies on bioretention for quantity and quality assessment. Subsequently, the cross-cutting research gaps are identified considering all articles. Climate change and resilience are identified as key hot topics from authors' keyword analysis, highlighting current research frontiers and laying out the directions for future research thrust in this critically important emerging research field.

Keywords: Low impact development, Optimization, Bibliometric analysis, Research cluster, Climate change, Resilience.

2.1 Introduction

Urbanization, industrialization, and climate-change impact the intensity, frequency, and duration of extreme weather events such as floods, droughts, waterlogging (Seneviratne et al., 2012). Urban areas and their drainage systems have been significantly affected by this change from past decades, degrading urban resilience. The proliferation of impervious surfaces disrupts the natural hydrological cycle that results in excessive runoff (Guo and Guo, 2018), crippling drainage systems' ability to convey high runoff-volumes and increasing the potential for urban floods (Becciu and Raimondi, 2015). Urban stormwater management thus emerged to address pressing concerns to mitigate such risks. The goal of the traditional stormwater management approaches (gray infrastructures such as tunnels, gutters, curbs) is to drain the stormwater through a centralized system as soon as possible (Wu et al., 2019: Eckart et al., 2017). However, in recent decades, a shift towards a decentralized system known as Low Impact Development (LID) started to immerge, aiming to preserve predevelopment hydrology or to mimic the natural water cycle (Damodaram et al., 2010).

Across New Zealand and North America, the term LID is most widely used to indicate a control measure. Although this study focuses explicitly on LID, it is worth mentioning that some other terms are used to refer either to the LID approach or LID-like approaches such as water sensitive urban design (WSUD) in Australia, urban design and development in New Zealand (LIUDD), and sustainable urban drainage systems in Europe (SUDS) (Fletcher et al., 2015). These approaches aim to maintain hydrological restoration, manage stormwater close to its source and drain stormwater more sustainably than conventional approaches. A stormwater management approach can be sustainable if it encompasses water quantity and quality management and provides co-benefits like increasing biodiversity, feasibility, and amenity.

LID was first conceptualized in the early 1990s by the Environmental Resources department of Prince George's County, USA (Wu et al., 2019). However, the term was first used by Burrill and Nolfi (1977) in their study on reducing stormwater management costs. Prince George's country then developed a manual on LID to increase its adaptability across the world (Coffman, 2000). The overall aim of LID implementation is to i) provide quantity (Guo and Guo, 2018; Jia et al., 2012) and quality controls of stormwater (Liu et al., 2015), ii) treat runoff as close to the source as possible, iii) increase natural hydrological processes such as evaporation, infiltration, and storage (Ahiablame et al., 2013; Dolowitz et al., 2012; Dhalla and Zimmer, 2010; USEPA, 2000), and iv) enhance ecological benefits (Vogel et al., 2015). Some commonly used LID practices include rain barrel (RB) or cistern, green roofs (GR), bio-retention cell (BC) or bioretention (BR), rain gardens (RG), soakaways, permeable pavement (PP), vegetative swales (VS), infiltration trenches (IT), infiltration basins (IB), rooftop downspout disconnection, tree box filters, and other green infrastructures (GI). However, the combined application of LID and other BMP (Best Management Practice), such as detention pond, detention tank (DT), pipe systems, can serve as the best option to satisfy stormwater management goals (Ashley et al., 2011a, 2011b; Damodaram and Zechman, 2013).

Nowadays, optimal design of LID is a key in stormwater management, where the overall goal is to achieve a specified objective with limited available resources. The optimization objective can take many forms, such as reducing runoff volume, peak flow, combined sewer overflow (CSO) volume, pollutant load, first flush volume or minimizing cost. Optimal design of LIDs such as appropriate LID selection, spatial layout, and size can be obtained by either taking one individual LID or considering a range of LIDs under different design storm scenarios or probabilistic rainfall events.

As LID implementation is gaining popularity in recent decades, many optimization approaches are evolving to facilitate the design of optimal LID systems. Moreover, stormwater management infrastructures are exposed to more frequent extreme precipitation events due to climate change. Therefore, resilience needs to be considered in the design of LID systems. Although there are several review papers on LIDs as discussed in section 2.1.1, none of them has focused on optimization and resilience within LIDs. Moreover, the bibliometric review approach is a new technique that can add important information about publications in a specific research field. Therefore, this paper aims to provide a systematic and bibliometric literature review on LIDs optimization and resilience. Further details about this study’s scope and approach are provided in section 2.1.2.

2.1.1 Categories of LID Review Papers

There are currently some literature review articles in the LID approach area, and they can be classified into three categories. The first category mainly deals with literature review papers that focus on the evolution, scope, goal, implication of several terminologies used in urban drainage management and several perturbations and possibilities in implementing LIDs or GIs. For example, Fletcher et al. (2015) described the development over time of several urban drainage terms such as LID, WSUD, BMP, SUDS, IUWM, SCMs and classified them based on underpinning principles and scopes of each term. A systematic literature review is conducted by Huang et al. (2020) in which the evolution of nature-based solutions (based on their terminologies) is described along with their benefits and limitations. Vogel et al. (2015) discussed thirteen critical questions on the LID or GI at the individual level or whole in climate change and socio-economic context. Similarly, Jayasooriya et al. (2020) reviewed the concerns and possibilities in implementing GI optimally in the industrial area and identified their potential benefits, limitations, and threats.

The second category deals with reviews primarily based on the performance evaluation of LIDs at different scales (i.e., numerical, field and experimental). As an illustration, Eckart et al. (2017) provided a synopsis of infiltration-based and retention-based LID's execution. They evaluated their performance in terms of quantity and quality as a stormwater management approach. Different modelling techniques, as well as hurdles towards LID implementation, were also discussed. Ahiablame et al. (2012) presented a comprehensive review to evaluate the efficacy (hydrologic and water quality aspects) of different LID practices, especially BR, RG, PP, GR, and swale systems using field and experimental studies. Beneficial uses of LID in terms of quantity and quality are the central research theme of the review article of Shafique and Kim (2015). Beecham et al. (2019) evaluated the quantitative and qualitative performance of intensive and extensive green roofs and living walls. They described several optimization methods for plant performance based on numerous numerical and experimental studies. Vogel and Moore (2016) conducted a review on stormwater quantity and quality, performance determination considering runoff control and runoff quality improvement and execution, and evaluation of LID-GI measures at a watershed scale. The review paper of Kaykhosravi et al. (2018) discussed eleven types of models used to evaluate LID and GI's performance, their features and hydrological and hydraulic modelling aspects.

In the third category, reviews are conducted based on optimization approaches on several LIDs. Zhang and Chui (2018) mainly focused on the location optimization of several LID, BMP, and GI measures, along with the factors that impact LID allocation. They also discussed various spatial-allocation optimization-tools, classified them based on their goals and allocation components, and evaluated the impacts of LID distribution patterns (centralized or decentralized) on optimization objectives. Shishegar et al. (2018) identified different optimization problems using eighty articles from the SCOPUS database and divided them in terms of objective functions, static and dynamic control approach, stormwater management approach and uncertainty considerations. They identified the publication trend graph of the last ten years on this field and found that sustainable urban drainage system requires further research to make them climate-resilient.

2.1.2 Current study focus and approach

As can be inferred from the above overview, all review papers focused on a specific part of the LID and optimization field. The bibliometric literature review approach is gaining popularity to explore the intrinsic structure and progression across many research fields (Haggag et al., 2020; Ezzeldin and El-Dakhakhni, 2020; Munoz-Ecija et al., 2017; Portillo-Salido, 2010). It helps determine the prolificacy of authors, institutions, countries, and international affiliations through analyzing the networks of articles, keywords, and authors (Romero and Portillo-Salido (2019). The analysis helps investigate research frontiers and hotspots. This approach has been used in several research areas such as city interdependence (Haggag et al., 2020), structural (Ezzeldin and El-Dakhakhni, 2020), supply chain management (Gelsomino et al., 2016; Xu et al., 2018a), economics and sociology (Korom, 2019) and medical and health sciences (Tranfield et al., 2003). In the context of water resources management, Troian and Gomes (2020) carried out a bibliometric analysis on a multicriteria approach to manage water resources and paved a way to deal with water pollution and water distribution management. This approach was also adopted in China to ensure water security and minimize conflict between water demand and supply (Zhu et al., 2019). They provided an overview through network analysis to quantify blue, green and gray water approaches using two frameworks: water footprint assessment and life cycle cost assessment. A bibliometric analysis was also conducted in several studies on drinking water and wastewater quality (Dura´n-S´anchez et al., 2020; Wambu and Ho, 2016; Wang et al., 2010), integrated water resources management (Dur´an- S´anchez et al., 2018) and stormwater management (Wu et al., 2019).

This study illustrates a bibliometric analysis and a systematic review of LID focusing on optimization and resilience. It provides insights into the inherent structure and emerging research areas in the specified study topic (i.e., LID optimization and resilience). To the best of the authors' knowledge, there are no published LID bibliometric reviews and no systematic reviews on LID optimization and resilience. The bibliometric analysis of extensive literature-database provides unabridged affiliation data of authors, institutions and countries. The analysis output acts as a potential information source for identifying collaboration trends and build a procreation tool for future international collaboration (Moed and Halevi, 2014). The bibliometric analysis helps determine the contents of research clusters and identify gaps and future research areas.

This study aims to explore the trends of approximately 17 years of research output in the field of LID optimization and resilience and identify research opportunities by answering the following questions:

i) How diverse the LID optimization research output is?
ii) Which authors and publications are prominent in the field?
iii) What is the extent of related collaborative work?

Focusing on LID performance evaluation and optimization, a systematic literature review and comprehensive bibliometric and network analysis are carried out using different tools. BibExcel is applied to generate the necessary data file employed by Gephi to perform citation analysis by determining the Page Rank score and carrying out co-citation analysis through cluster formation using the Louvain algorithm. VOSviewer is employed to facilitate the identification of the most prominent authors, countries, and sources or journals in this field using text mining. Text mining can extract essential information from unstructured or semi-structured data that helps to identify the main research topics and their categorization, underlying research themes and interconnections. The following section provides the methodology details of this literature review study.

2.2 Methodology

This review combines systematic and bibliometric approaches that enable critical analysis through information integration (Tranfield et al., 2003; Rowley and Slack, 2004; Manalo et al., 2004). As such, the review discerns the dominant articles and authors, identifies current research topics, and paves the way for future research directions by highlighting ongoing research interests and trends (Figure 2.1).

The Web of Science core collection database is used to retrieve articles focusing on resilience and optimization of Low Impact Development. Although the search period contains 44 years (from 1976 to 2020), publications in the LID field began only in 2004. Therefore, articles that are published during the period of 17 years (2004 to 2020, August) are collected and considered for further analysis. The selected topic, “resilience and optimization of Low Impact Development,” consists of three terms. Therefore, three search strings are selected to ensure that the keywords capture all features of the topic. The first search string contains the term ‘Low Impact Development; the second string contains optimization related terms, i.e., “optimization” or “optimisation” or “multi-criteria” or “multicriteria” or “multi-objective” or “multiobjective,” and the last or third string contains resilient related terms such as “resilience” or “resilient.”

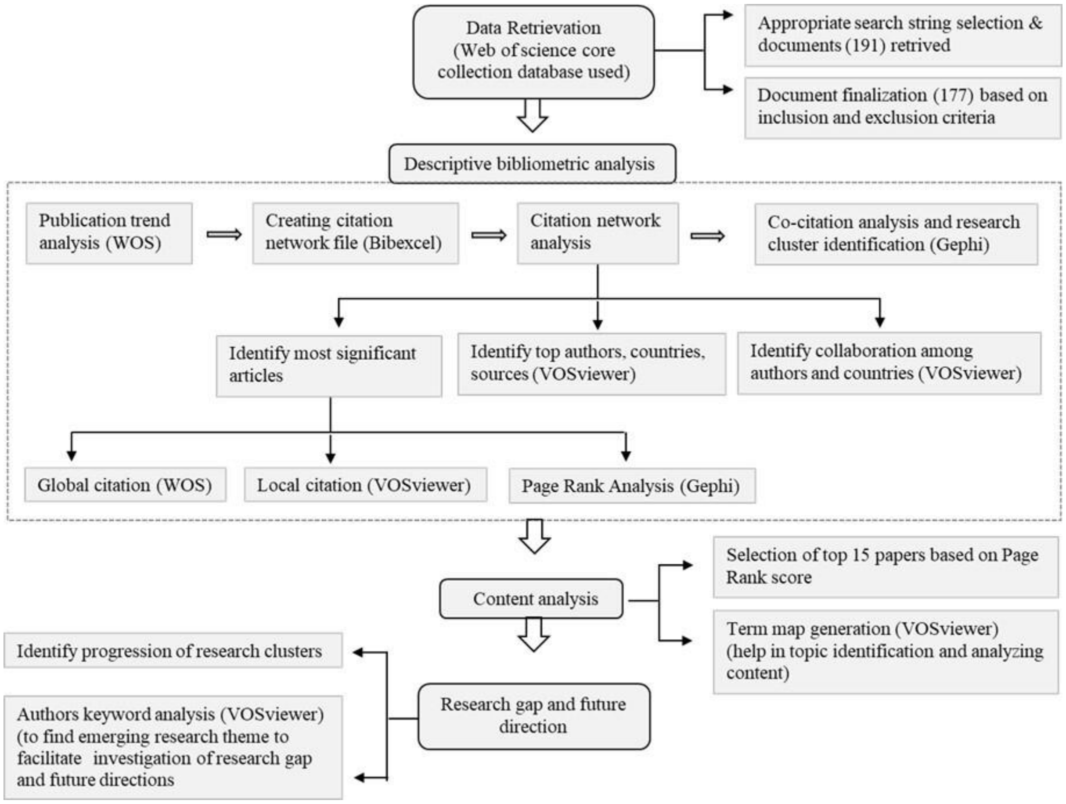


Figure 2.1: *Flowchart of research methodology*

Using these finalized keywords, the search resulted in 191 papers. These papers cover several topics, especially LID performance assessment, LIDs optimal design, and resilience assessment by incorporating climate and land-use change impacts. Some articles also mentioned the guidelines and strategies adopted by several countries to implement LIDs. The primary aim underlying these publications is to manage urban stormwater effectively using different LID practices (single/combined) to gain the maximum benefit at minimum cost, which is the intrinsic aim of the optimization process.

Some inclusion and exclusion criteria are considered for the final selection of the most relevant articles from 191 papers. Both titles and abstracts were carefully reviewed to identify the most relevant ones based on the selected criteria. Studies related to LID performances (quantity, quality), optimal design, the impact of climate change on performance were included. In contrast, studies about cities' guidelines and challenges that are not related to LID implementation strategies were excluded. Some performance criteria such as thermal effect determination in the LID application area and the articles that mainly focused on flood risk or environmental risk assessment were also excluded. Finally, 177 papers out of 191 are selected for further network and content analyses.

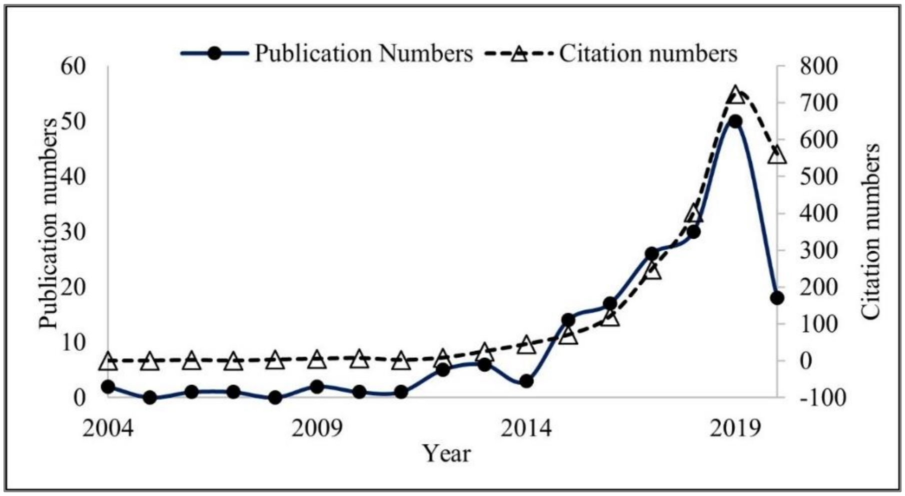


Figure 2.2: *Publication and citation trend per year*

Figure 2.2 depicts the evolution of publications and citations number per year available in the database on LID and its optimal design. As can be inferred, prior to 2004, no articles were published on this topic. From 2004 to 2014, publication number lies in the range of 1 to 6 per year. After 2014, an increasing trend is observed, reaching its peak in 2019 with 50 publications. Similarly, for citations, a surge is observed from 2013, and in 2019 citation number is maximum, which is 724. Citation and publication numbers continue to increase with time. As data for the year 2020 is incomplete, both graphs showed a decline in the trend that may not be representative of actual trends.

2.3 Bibliometric Review

Traditional literature reviews use a comprehensive approach for analyzing theories based on examining methodologies, results and discussions of every research article and ultimately provide a framework for future work (Jesson et al., 2011). In contrast, the bibliometric analysis uses quantitative and statistical approaches of published articles to describe the connections between them based on a specific topic or research field by assessing the co-citation time by other published papers (Melewar et al., 2012). In 1969, Alan Pritchard used the term “Bibliometrics” in his article based on scientific bibliography (Garfield, 2009). The analysis mainly focused on the research area of authors, the paper’s content, and citation network, which help find data statistics, such as keywords and affiliation (Xu et al., 2018a). Among various techniques, Social Network Analysis (SNA) is the most frequently used method in bibliometric analysis. It helps to visualize and describe community structures, emphasizing the importance of selecting the most frequent keywords and citations through this network (Al et al., 2012; De-Miguel-Molina et al., 2015). Various software packages such as Excel, BibExcel, Histcite and Sitkis have been used in bibliometric analyses for a long time, where each one has multiple advantages and disadvantages (Persson et al., 2009). In this study, BibExcel is used for bibliographic analysis and both Gephi and VOSviewer are used for visualization. BibExcel is selected for bibliometric and statistical perusal because it allows importing data from all databases such as Web of Science and Scopus. It also enables data coupling with network analysis and visualization tools like Citespace (Wu et al., 2019), Gephi, VOSviewer and CitNet Explorer (Van Eck and Waltman, 2017), Histcite and Pajek (Mrvar and Batagelj, 2016), and Ucinet and Igraph in R (Kolaczyk and Csa´rdi, 2014).

To analyze the networks and visualize them graphically, Gephi and VOSviewer are chosen because of their ability to handle extensive network data and format, visualization alternatives, improved filtering ability, built-in network analysis tool and enhanced clustering ability (Bastian et al., 2009; Gephi, 2013; Van Eck and Waltman, 2013). In this paper, local citations, influential authors and countries are identified using VOSviewer. However, Gephi is used for citation and co-citation analysis by page rank and clustering methods. Subsequently, content analysis is conducted for each cluster for better comprehension of the research theme. VOSviewer is also used for term map generation based on a corpus of documents using the same functional procedure as text mining (Van and Waltman, 2011). A '.NET' file from BibExcel is used as an input in Gephi, which results in 167 nodes (articles) with 5,337 edges (i.e., ways by which articles are connected).

2.3.1 Citation Analysis

Citation analysis maps the significance or popularity of a publication (Tsay, 2009; Ding and Cronin, 2011). Figure 2.3 shows the studies with a threshold of a minimum of 20 citations each. The analysis resulted in 31 articles; each article is represented by a node, where the node size increases with the number of citations of the corresponding article. Table 2.1 summarizes the top ten articles in the field of LID and its optimal design based on local and global citations.

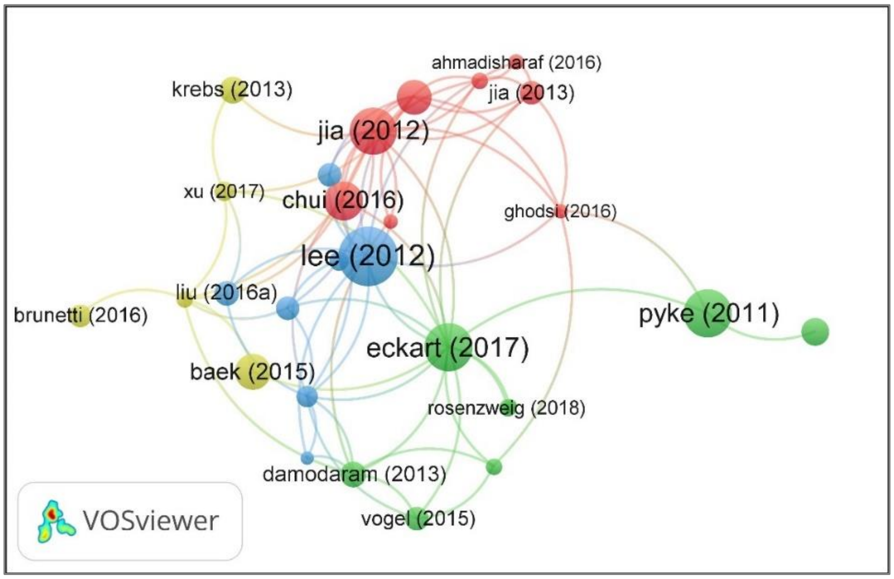


Figure 2.3: *Citation network*

Table 2.1 *Top ten articles based on global and local citation*

Article	Local citations	Global citations
Lee et al. (2012)	140	151
Jia et al. (2012)	105	125
Eckart et al. (2017)	108	111
Pyke et al. (2011)	107	109
Chui et al. (2016)	81	82
Jia et al. (2015)	71	75
Baek et al. (2015)	72	73
Lucas and Sample (2015)	53	56
Krebs et al. (2013)	51	52
Damodaram and Zechman (2013)	48	48

Local citation indicates the number of citations within the 167 node-network. On the other hand, global citation implies the overall citation number across all databases considering other research fields and areas (Goyal and Kumar, 2020). According to a local citation, Lee et al., (2012) rank as first with 140 citations, followed by Eckart et al. (2017) and Jia et al. (2012) with 108 and 105 citations, respectively. Considering global citations, Lee et al. (2012) rank first with 151 citations, and Jia et al. (2012) rank second with 125 citations, followed by Eckart et al. (2017) and Pyke et al. (2011) with 111 and 109 citations, respectively. Among them, Lee et al. (2012), Jia et al. (2012), and Eckart et al. (2017) are the most influential studies with the highest citations based on the two citation categories.

2.3.2 Page rank analysis

Brin and Page (1998) introduced the page rank algorithm as a measure of prestige and eminence. This algorithm alleviates the drawback of citation analysis (Ding et al., 2009). Citation from an ambiguous paper and a very highly cited paper carries the same citation analysis weight

(Maslov and Redner, 2008). However, page rank gives more value to a paper if other prestigious articles cite it. Originally, page rank is introduced to give precedence to the webpages based on keyword search in any search engine such as Google (Brin and Page, 1998). But now, it is used to identify the linkage between articles. The top ten articles based on page rank are listed in Table 2.2.

Table 2.2 *Top ten articles based on page rank*

Article	Page rank
Eckart et al. (2017)	0.012965
Zhang and Chui (2018)	0.012023
Li et al. (2018)	0.011246
Zhou et al. (2019)	0.010878
Mani et al. (2019)	0.010847
Baek et al. (2019)	0.010395
Ercolani et al. (2018)	0.010206
Yang and Chui (2018)	0.010196
Alamdari and Sample (2019)	0.010017
Irvine and Kim (2018)	0.00997

From Table 2.2, a disparity is observed, while the top ten papers are compared based on page rank and both local and global citations. Only two papers, i.e., Eckart et al. (2017) and Vogel et al. (2015) are the common papers among the categories. The other four eminent articles (top) based on page rank are Zhang and Chui (2018), Li et al. (2018), Zhou et al. (2019), and Mani et al. (2019). These four papers mainly dealt with optimization strategies in LIDs such as allocation and scenario optimization to evaluate hydrological performance considering cost and runoff reduction.

2.3.3 Author and Country Analysis

In the finalized datasets, 610 authors from 38 countries published 167 articles. VOSviewer software is used to find the top ten authors and countries, where the minimum number of publications per author or country is considered three.

Table 2.3 *Top ten authors*

Author	Publication number	Citation number
Haifeng Jia	8	312
Shawl Yu	6	278
Jenny Zhen.	3	208
Leslie Shoemaker	3	178
Ting Fong May Chui	4	136
Engel Bernard A	5	121
Yaoze Liu,	4	116
Xuhui Mao	3	78
Giuseppe Brunetti	3	71
Patrizia Piro,	3	71

In Table 2.3, the top ten authors are listed based on the maximum number of citations, whereas in Table 2.4, countries are listed based on the maximum number of published studies. Among the authors, Haifeng Jia ranks first with 312 citations, followed by Shawl Yu and Jenny Zhen with 278 and 208 citations. Haifeng Jia and Shawl Yu also published the highest number of articles 8 and 6, respectively. As these two authors have the maximum number of documents with higher citations, they are considered experts in the area of LID practices.

Table 2.4 *Top ten countries*

Country	Publication number	Citation number
USA	69	1218
China	63	699
Iran	12	98
Canada	11	212
South Korea	11	122
Australia	9	54
England	8	34
Italy	6	92
Singapore	6	11
Taiwan	6	20

As shown in Table 2.4, the USA ranked first, whereas China ranked second with 69, and 63, respectively, as the most contributing countries in the LID, resilience and optimization field. After analyzing these three countries' major research themes, it is found that all of them experienced major LID benefits such as quantity and quality control of stormwater runoff.

2.3.4 Co-authorship-Country network map

VOSviewer visualization tool is used to map a network of co-authorship and country relationships. This network provides information about prospective partners working in a specific area. The map is made based on a threshold value of 5 (minimum documents) of a country; eleven countries out of 38 countries meet this criterion. Figure 2.4 depicts a collaborative country-coauthor map consisting of nine countries in four clusters. Two countries among eleven are not included in the map as they have no links with the other nine countries.

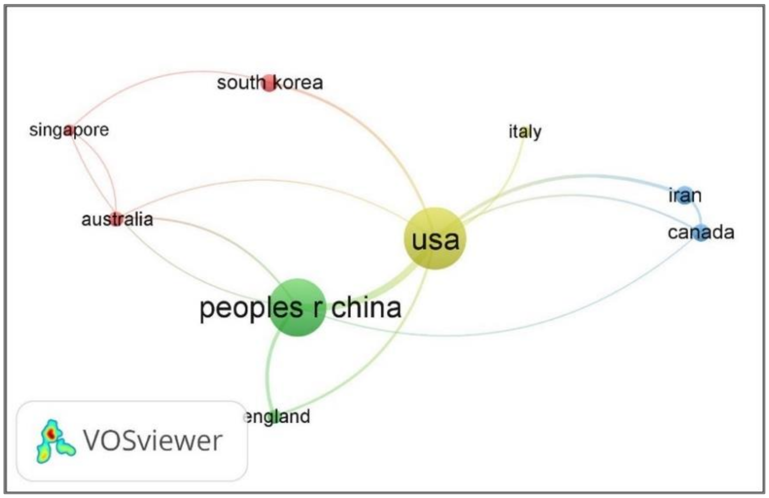


Figure 2.4: *A network map of co-authorship and country.*

Cluster formation is based on the measurement of concurring term recurrency of each country (Romerio & Portillo-Salido, 2019). For example, the yellow cluster (Figure 2.4) shows that the USA and Italy worked in the same research field. The nodes in Figure 2.4 represent the number of documents per country, where the node size increases with the number of published articles. However, the curved lines represent collaboration, the thicker the line, the more co-authorships between the connected countries. Considering this, the USA node is the largest with 69 articles, followed by China and Iran with 63 and 12 papers, respectively. Line thickness between the USA and China is the greatest with link strength 15; however, link strength between the USA and Australia is one, which shows minimum collaboration. Among all countries, the USA worked most with other countries with link strength 31, followed by China and Iran with link strength 15 and 5, respectively. Collaborative networks or links help to identify collaboration between authors from different countries. For example, researchers from Canada collaborated most with Iran (link strength 3), followed by the USA and China with link strength 2 and 1, respectively. China is the leading country in the green cluster, which showed an associated work with the USA (link strength

15) followed by England (link strength 5), Australia (link strength 2), Singapore and Canada (link strength 1), respectively.

2.3.5 Co-citation analysis

Co-citation analysis results in a network that comprises nodes and edges representing, respectively, articles and concurrence of pairs of articles in another article (Barnett, 2011). The primary purpose of co-citation analysis is to measure the recurrency of cited articles together in other documents (Trujillo and Long, 2018). This type of analysis presents a comprehensive approach to investigating a research area's inner structure in a bibliometric study. The similarity in the research area or concept depends on the frequency of citations between two papers (Xu et al., 2018a). Gephi is used for co-citation analysis using the '.NET' file created by Bibexcel. After importing this file, it is found that 167 papers are co-cited by other articles in the 177-node network, and the arrangement of these nodes in this co-cited map is randomly generated.

In bibliometric research, the clustering technique has been widely used for determining a group of related articles or authors (Radicchi et al., 2004). A network of 167 articles is partitioned into several clusters where each cluster is formed by the dense connection between nodes (Blondel et al., 2008). Edge density or weight is smaller between nodes of different clusters and higher between the same cluster nodes (Ley- desdorff et al., 2017). Here, co-citation analysis is conducted through cluster formation where relevant articles with similar themes are grouped in one cluster. Each cluster is further investigated to identify the publications' intrinsic characteristics, evaluate the topics, and analyze the content of each topic's top articles. Nowadays, the clustering mechanism is gaining eminence in network analysis and was used by many researchers. The network structure is measured by modularity, the thicker nodes' connection, the higher the modularity. Cluster quality is measured by the modularity index (Brandes et al., 2007). Louvain algorithm vanquished other methods in optimizing modularity while dealing with computation time and large networks. This method uses optimization techniques to determine the optimal number of clusters by iterative optimization, where the modularity index is escalated. The Louvain method follows an iterative approach consisting of two phases to determine the optimal cluster number. In the first phase, a different cluster is allotted for each node, which results in numerous clusters. Then neighbours j of each node i is considered and determined gain of modularity by eliminating i from its cluster and replacing it in j cluster. If a positive increase is achieved in the second phase, node i is placed in the cluster where the maximum gain is evaluated. The overall mechanism is repeated sequentially and stops when the local modularity value is maximum. Applying this algorithm on the final 167 filtered articles resulted in four clusters (Figure 2.5), where Cluster 1 contains 65 articles and Clusters 2, 3, 4 comprises 56, 25 and 21 articles, respectively.

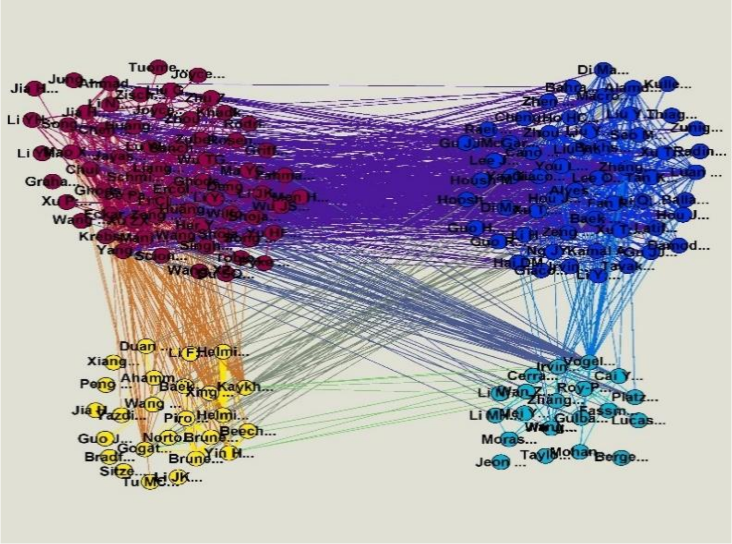


__Figure 2.5:__ Cluster formation.

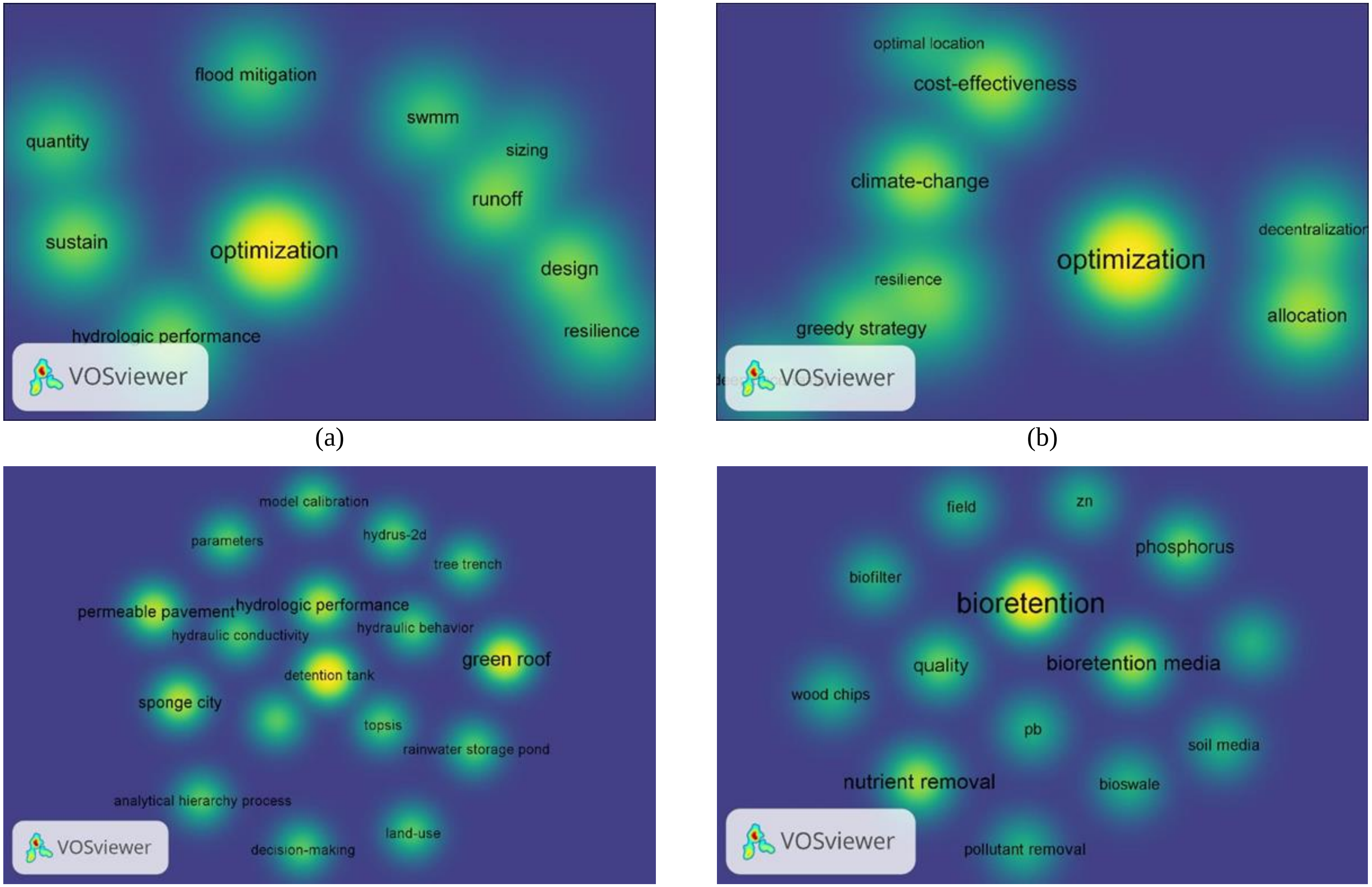
Each cluster's research focus is identified through the analysis of the top 15 papers based on page rank (Table 2.5). The selected leading papers are also analyzed using the VOSviewer text mining function for term map generation. The term map provides a general direction of actively developing research areas (Romero & Portillo-Salido, 2019). After that, the content analysis of each cluster is conducted to assess the main research insights.

Table 2.5 *Top fifteen articles based on Page Rank*

Cluster	Articles
1	Eckart et al. (2017), Li et al. (2018), Mani et al. (2019), Ercolani et al. (2018), Yang and Chui (2018), Zeng et al. (2019), Alamdari and Sample (2019), Huang et al. (2020), Li et al. (2020), Her et al. (2017), Jia et al. (2015), Mao et al. (2017), De Paola et al. (2018), Zhu and Chen (2017), Jayasooriya et al. (2020)
2	Zhang et al. (2018), Zhou et al. (2019), Baek et al. (2019), Alamdari and Sample (2019), Alves et al. (2016), You et al. (2019), Latfi et al. (2019), Bakhshipour et al. (2019), Luan et al. (2019), Minh Hai (2020), Hou and Yuan (2020), Xu et al. (2018), Xu et al. (2019), Giacomoniet and Joseph (2017), Fan et al. (2017)
3	Helmi et al. (2019), Kaykhosravi et al. (2018), Baek et al. (2015), Gogate et al. (2017), Xing et al. (2016), Brunetti et al. (2016), Brunetti et al. (2017), Yin et al. (2019), Li et al. (2019), Piro et al. (2019), Duan et al. (2016), Tu et al. (2020), Xiang et al. (2019), Ahammed et al. (2012), Wang et al. (2017)
4	Cai et al. (2018), Platz et al. (2020), Wu et al. (2017), Jiang et al. (2019), Zhang et al. (2018), Lucas and Sample (2015), Morash et al. (2019), Li et al. (2018), Gulbaz et al. (2019), Roy-Poirier et al. (2015), Li et al. (2014), Wan et al. (2018), Fassman et al. (2015), Berger et al. (2019), Mei et al. (2013)

2.3.1 Term map

VOSviewer tool is used to detect major research trends and explore dissimilarities within the top 15 papers of each cluster, which eventually helps in topic identification (Zahedi and Van Eck, 2015). The papers' content is analyzed using a text mining function within VOSviewer to generate a two-dimensional term map (Van and Waltman, 2011). The connectedness between terms is illustrated by the distance between two terms, and the term occurrence is represented by the term size (Figure 2.6). This relatedness is measured based on co-occurrences of the term in the articles. Each text in the term map (density map) is expressed by its label and colour. As VOSviewer circumvents label overlapping, only some terms are represented by their labels. The default colour range, blue-green-yellow, is used for map visualization. If the term's frequency is high, it carries greater weight, and the yellow colour reflects it with a larger label size. Whereas the blue colour presents the less frequent term with a smaller label size (Van and Waltman, 2018). Figure 2.6 represents the term map where the research clusters are mapped separately. In ClusterSUSTAIN, SWMM, runoff, design and hydrological performance are the most frequent terms as they lie in the yellow zone. Cluster 2 represents spatial allocation and cost-effectiveness of LID considering climate change. In Cluster 3, the frequently used terms are related to LIDs and their performance, such as detention tank, permeable pavement, green roof, hydrological performance and hydraulic conductivity. Some decision-making approaches such as The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchy Process (AHP) are also present in the Cluster 3 articles. Terms such as field experiments, pollutants removals such as phosphorus, Zn and Pb using bioretention are the focus of Cluster 4. A combination of terms in each cluster is further used for topic identification.



(a) (b)

(c) (d)

Figure 2.6: *Term maps of research clusters (a) cluster 1; (b) cluster2; (c)cluster3; (d)cluster 4.*

2.3.2 Clusters content analysis

The four clusters' content based on 60 articles (15 articles per cluster) are shown in Tables 2.6–2.9. Review articles are shown separately in Table 2.10. A brief description of the content analysis is given below:

2.3.2.1 Cluster 1: Design optimization (type, area) and performance evaluation of multiple LIDs

Cluster 1 has emerged in 2011 and it has the largest number of articles (65 articles). This research cluster's primary focuses on optimal LID unit and type selection from multiple LID options. SWMM and SUSTAIN models are mainly used, along with an optimization algorithm for this purpose. Among the 15 studies, seven studies focused on optimization, three papers provide reviews about LID aspects, and the other five articles evaluate hydrological performance (Table 2.6). In the review papers, factors, benefits, and limitations of several LIDs and optimal GI approaches in residential areas are discussed. SUSTAIN with the Non- dominated Sorting Genetic Algorithm II (NSGA II) is used in three studies to determine optimal combination LID scenarios, especially for GR, BR, and RB. SWMM with different algorithms such as MOALOA, HS, R toolbox is applied in three articles to select LIDs optimally. The other five studies analyzed the hydrological performance (i.e., runoff and peak reduction) of LIDs.

2.3.2.2 Cluster 2: Cost optimization for LID deployment considering climate change and parameter uncertainty

It is the second-largest cluster with 56 papers. Publications in Cluster emerged in 2006. This cluster mainly examines LIDs allocation. Among the top 15 articles in this cluster, eleven articles focused on allocation strategies considering cost as an objective function to reduce runoff volume, runoff peak and pollutant loads (Table 2.7). The rest of the three studies determined optimal drainage schemes to achieve runoff and pollution control targets. One review paper of this cluster mainly discussed the factors affecting LID placement and evaluated the impacts of numerous LID distribution patterns. The most used LIDs in this cluster are PP, BR and GR. Climate change and uncertainty in model parameters and rainfall were also considered in the articles of this cluster.

2.3.2.3 Cluster 3: Calibration parameter optimization and analytic hierarchy process adaptation

This cluster contains 25 papers, where the first publication appeared in 2004. Apart from size and location optimization, this cluster dealt with several LID optimization applications. Six studies (out of fifteen) use multicriteria approaches such as AHP, TOPSIS, index ranking system for optimal selection of LIDs type and placement and three studies focusing on several LID parameter optimization (Table 2.8). This cluster’s papers contain one review paper, which focuses on the different LID models used to evaluate LIDs performance. Four of the fifteen top studies have also discussed LIDs allocation incorporating combined detention facilities and storage tanks with other LIDs, while Cluster 2 considers only LIDs except for any end of pipe facilities. Apart from the cluster’s main focus, two studies discussed the factors causing plant stress for tree trench and GR’s hydrological performance.

2.3.2.4 Cluster 4: Experimental studies on Bioretention performance

This cluster emerged in 2007. It contains 21 papers. Nine out of the top 15 papers in this cluster discuss the bioretention’s performance in terms of quantity (volume, peak discharge, peak delay time) and pollutant removal efficiency (Table 2.9). Bioretention (BR) is the commonly used LID measure in this cluster (twelve studies), and it is used both individually and in conjunction with other LIDs such as PP, GR, swale, etc. Unlike other clusters, experimental analysis and water quality improvement are the main focus of this research cluster.

Table 2.6 *Content details of cluster 1*

Source	Objective of Paper	LID Type	Model & Algorithm	Performance					Optimization						
									Purpose	Objective					
				Quantity			Quality	Others		Quantity			Quality	Cost	Others
				RV	RP	TP				RRV	PR	LPT			
Li et al. (2018)	Determine optimal combination of LID scenario	PP, GR, BR, RB	SUSTAIN + NSGAII	x			x		Optimize different LID configuration (unit) with scenario optimization	x					
Mani et al. (2019)	Find optimal combination of LID types	PP, BC, IT, VS	SWMM + MOALOA	x	x	x			Determine optimal combination of LID types	x				x	Reduction of service performance
Ercolani et al. (2018)	Determine green roof performance	GR	Mobidic-U	x	x										
Yang and Chui (2018)	Optimize BR area	BR	SWMM + R toolbox						Optimize BR area	x	x			x	First-flush reduction
Zeng et al. (2019)	Evaluate effects of GR by adopting placement strategies	GR	SWMM					Urban flooding, CSO volume, shock loading							
Alamdari and Sample (2019)	Multi-objective optimization tool is developed	GR, PP, BR, dry swale	SWMM + NSGAII	x			x		Selection of LID unit and Size	x			x	x	
Li et al. (2020)	Analyze RV & PF performance & estimate cost-effectiveness to select suitable solution	BR, PP, GS	SWMM	x	x										
Her et al. (2017)	Evaluate RV & PF reduction using SWAT	GR, RG, PP, RB	SWAT	x	x										
Jia et al. (2015)	Evaluate performance of LIDs and select optimal scenario	BR, GR, GS, RB, wet pond	SUSTAIN + NSGAII	x	x		x		Identify optimal scenario (LID unit)	x				x	
Mao et al. (2017)	Evaluate performance of LIDs and select optimal scenario	RB, GR, BR, PP, swales, wet pond	SUSTAIN + NSGAII	x	x		x		Identify optimal scenario (LID unit)	x				x	
De Paola et al. (2018)	DSS is applied to find optimal combination of LID	PP, BR, GR with storage tank	SWMM + HS	x					Optimize LID combination and area	x				x	
Zhu and Chen (2017)	Determine effectiveness of RG and BS on flooding	RG, bioswale	SWMM + Projected pursuit method					Flood volume	Assess flood volume, rate and duration	x					Duration of flooding

Note: RV = Runoff Volume; PF = Peak Flow; TP = Time to Peak; RRV = Reduction of Runoff Volume; PR = Peak Reduction; LPT= Lengthening Peak Time; DSS= Decision Support System.

Table 2.7 *Content details of cluster 2*

Source	Objective of Paper	LID Type	Model & Algorithm	Performance					Purpose	Optimization					
										Objective					
				Quantity			Quality	Others		Quantity			Quality	Cost	Others
				RV	RP	TP				RRV	PR	LPT			
Zhou et al. (2019)	Synergistic effects of LID and pipe system is investigated	PP, GR, IT, VS	SWMM + GA	x	x			Ecosystem protection, landscape amenity, quality of life & environmental impacts	Identify optimal combination and placement strategies of LIDs & pipe system	x				x	Increase additional benefit
Baek et al. (2019)	Simulation tool is proposed for sizing Bioretention	BR	K-LIDM + NSGAII					Infiltration	Sizing BR based on spatial allocation						
Liang et al. (2019)	Evaluate effectiveness of BR and PP in peak reduction	BR, PP	SWMM + GA		x		x		Find optimal spatial distribution of LIDs		x				
Alves et al. (2016)	Optimal methodology is proposed to select gray green infrastructure retrofitting with drainage system	PP, GR, RWH, IT	SWMM + NSGAII					CSO reduction	Optimal drainage scheme selection based on spatial allocation & storage		x			x	
You et al. (2019)	Identify optimal cost-effective solution to meet control target criteria	PP, RB, GR, GS, BR	SUSTAIN + NSGAII	x	x		x		Find optimal location and cost-effective solution				x		
Latfi et al. (2019)	Find optimal solution considering uncertain parameters of SWMM model	BR, VS	SWMM + NSGAII	x			x		Find optimal solution based on stake-holders demand	x			x		
Bakhshipour et al. (2019)	Select suitable Green blue measure & find their optimum distribution	RB, IT	SWMM + Binary GA						Find optimal distribution of green blue measures					x	
Helmi et al. (2019)	Location optimization based on cost benefit analysis	PP, RG, GR	WetSpa-Urban	x	x				Layout optimization					x	
Hou et al. (2019)	Find optimal layouts of LIDs	RB, PP, RG, VS, BR, detention pond	P-median model + ACO	x			x		Determine optimal layout of LIDs	x			x	x	
Hou and Yuan (2020)	optimal selection of LID layout and unit using SUSTAIN and NSGAII	PP, BR, RB, GS, vegetative filter strip	SUSTAIN + NSGAII						Find optimal placement and unit of each LID	x				x	
Xu et al. (2018b)	Find optimal allocation of LID	PP, BR	SWMM + MCGS						Find optimal placement ratio of LID	x	x			x	
Xu et al. (2019)	Find optimal solution to achieve acceptable phosphorus control target considering climate change	PP, BR, RB	L-THIA + MCGS				x		Find optimal solution to achieve phosphorus control target	x	x				
Giacomoni and Joseph. (2017)	Evaluate LID placement strategy in an optimal way using Monte Carlo simulation	PP, GR	SWMM + NSGAII	x	x	x		HFR	Optimal location selection for LID placement	x	x			x	Minimize HFR
Fan et al. (2017)	Find optimal arrangement of LID placement under climate change	BR, IT	SUSTAIN + BMP siting tool	x					Select optimal type, unit and placement location of LID					x	

Note: RV = Runoff Volume; PF = Peak Flow; TP = Time to Peak; RRV = Reduction of Runoff Volume; PR = Peak Reduction; LPT= Lengthening Peak Time; TSS= Total Suspended Solid; HFR= Hydrological Footprint Residence; ACO=Ant Colony Optimization.

Table 2.8 *Content details of cluster 3*

Source	**Objective of Paper**	**LID Type**	**Model & Algorithm**	**Performance**					**Optimization**						
				Quantity			**Quality**	**Others**	**Purpose**	**Objective**					
										Quantity			**Quality**	**Cost**	**Others**
				RV	RP	TP				RRV	PR	TP			
Luan et al. (2019)	Investigate performance of different LIDs with detention basin	PP, BR, GR, GS, detention basin	SWMM + TOPSIS	x	x		x							x	
Jia et al. (2013)	Select appropriate LIDs using multicriteria index ranking system	PP, BR, RB, GR, GS, VFS, IT	MCIS+BMPSELEC	x	x		x	Co-benefits							
Gogate et al. (2017)	Multi-criteria analysis is adopted to select best stormwater control measure	Leaky well, RG, GR	AHP, TOPSIS					Environmental & social impact							
Xing et al. (2016)	Determine optimal layout of runoff storage & infiltration and its effects	Runoff storage+ infiltration facility	SWMM + Integrated ranking index	x	x		x		Layout optimization	x					
Brunetti et al. (2016)	Describe unsaturated flow mechanism of PP	PP	HYDRUS 1D +PSO					Unsaturated flow	Identify unsaturated flow parameter						
Brunetti et al. (2017)	Analyze hydraulic behavior of stormwater filter	Stormwater filter	HYDRUS 2D +PSO					Hydraulic behavior	Identify shape & hydraulic parameter						
Yin et al. (2019)	Evaluate hydrological performance of GR	GR	Experimental work		x	x									
Li et al. (2019)	Find optimal combination of LID and DT	GR, PP	SWMM + PSO + NSGAII		x		x		Find optimal combination of DT & LID				x	x	Flooding risk
Piro et al. (2019)	Determine flooding event impact &hydraulic behavior of PP	PP, BR, GR, GS, detention basin	SWMM +HYDRUS 1-D, HYDRUS 3-D+ PSO	x	x			CSO volume, hydraulic behavior	Identify hydraulic parameters						
Duan et al. (2016)	Identify optimal implementation strategy of DT & LIDs	BR, RG, GR, PP, DT	SWMM + PSO	x					Identify optimal design & implementation of DT & LIDs	x				x	
Tu et al. (2020)	discuss and identify factors causing plant stress using tree trench	Tree trench	HYDRUS 2-D												
Ahammed et al. (2012)	Multi-criteria analysis to select appropriate LIDs	IT, leaky well, soakaway	Rational method	x											
Wang et al. (2017)	Determine optimal number and location of storage tank	Storage tank	SWMM + Genealized pattern search						Identify optimal number and location of storage tanks	x			x	x	
Song and Chung (2017)	Determine location of LIDs using multicriteria analysis	IT, PP	SWMM+TOPSIS	x	x										

Note: RV = Runoff Volume; PF = Peak Flow; TP = Time to Peak; RRV = Reduction of Runoff Volume; PR = Peak Reduction; LPT= Lengthening Peak Time ; FF= First Flush; MCIS= multi-criteria selection index system

***Table 2.9** Content details of cluster 4*

Source	Objective of Paper	LID Type	Model & Algorithm	Performance				
				Quantity			Quality	Others
				RV	RP	TP		
Cai et al. (2018)	Determine optimal selection order of LID measures	BC, PP, GS, GR	Inexact fuzzy chance-constrained programming	x				
Platz et al. (2020)	Examine accuracy of LID modules in SWMM	GR, PP, BS, BR	SWMM	x	x	x		
Wu et al. (2017)	performance of biofilter in terms of pollutant removal efficiency is measured	Biofilter	Experimental				x	
Jiang et al. (2019)	Assess removal efficiency of heavy metals and COD	BR	Experimental				x	
Zhang et al. (2018)	Evaluate hydrological performance of BR	BR	SWMM	x	x	x		
Lucas and Sample (2015)	Assess effectiveness of several LIDs	BR, PP, GR, Tree planter	SWMM	x			x	CSO volume
Morash et al. (2019)	Assess plant species tolerance in adverse environment and their pollutant removal capacity	RG, BR	Experimental				x	
Li et al. (2018)	Performance evaluation of several LIDs	RG, PP, GS, Tree box	SWMM +Principal Component Analysis	x	x		x	
Gulbaz et al. (2019)	Propose an empirical formula to determine peak outflow rate	BR			x			
Roy-Poirier et al. (2015)	Propose hydrological model to design BR	BR		x	x			
Li et al. (2014)	Evaluate performance of BR considering the presence and absence of internal storage layer	BR	Experimental		x	x	x	
Wan et al. (2018)	Evaluate nitrogen removal efficiency of a woodchip BR	Woodchip BR	Experimental				x	
Fassman et al. (2015)	Impact assessment of composite media on hydraulic conductivity and water holding capacity of BR	BR	Experimental					Hydraulic conductivity & water holding capacity
Berger et al. (2019)	Assess nitrate removal capacity of biofilter using biochar	Biofilter	Experimental				x	
Mei et al. (2013)	Determine best mulch material to improve pollutant removal efficiency of BR	BR	Experimental				x	

Note: RV = Runoff Volume; PF = Peak Flow; TP = Time to Peak.

***Table 2.10** Review papers within the four clusters*

Clusters	Source	Main Focus
1	Eckart et al. (2017)	Review about several factors affecting LID specially infiltration and retention based, their performance (quantity, quality). This paper also discussed about several models used for LID performance evaluation and optimization.
	Huang et al. (2020)	Review about different nature-based solutions such as GR, PP, IT, VS, RB; its functions and limitations to minimize flood risk.
	Jayasooriya et al. (2020)	Deal with optimization approaches of GI to manage runoff in terms of volume, peak and time to peak.
2	Zhang and Chui (2018)	Review focuses on factors that impacts LID allocation, suitable LID selection based on several condition and evaluate impacts of LID distribution pattern.
3	Kaykhosravi et al. (2018)	A comparison and evaluation of different LID models are done to assess LID’s performance in terms of quantity and quality.

2.3.3 Research cluster Progression

The evolution of the four research clusters is developed to identify the progress of research on LIDs optimization and LIDs resilience. Figure 2.7 represents the total number of published articles in each cluster from 2004 to 2020. It shows that Cluster 1 emerged in 2011 and developed steadily with time.

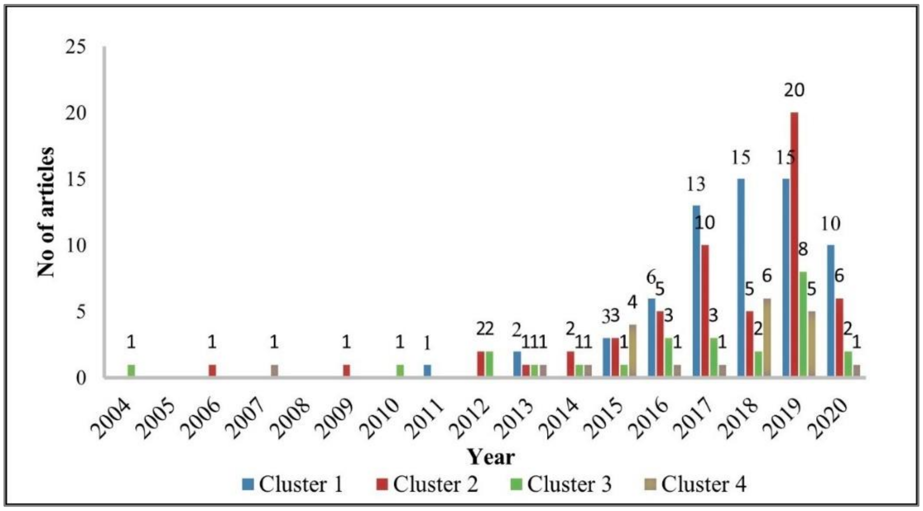


Figure 2.7: Progression of research cluster with time.

Research related to Clusters 2 started in 2006. Steady development is observed in Cluster 2 from 2006, but a sudden drop is observed in 2018 (from 10 to 5 articles). However, it continued to rise again in 2019 with 20 articles. Cluster 3 emerged at the earliest stage, 2004, and showed continuous growth in publications with time. Although Cluster 4 appeared in 2007, with seldom publications (three papers only) until 2015, where four studies are documented. Then in 2016 and 2017, the number of publications dropped to one, but in 2018, it increased to six. To recapitulate, Cluster 1 had the highest number of papers between 2004 and 2020, followed by Clusters 2, 3, then 4. Clusters 1 and 2 continue to grow in recent years with many publications compared to Clusters 3 and 4, which implies that research themes under Cluster 1 and 2 are the hotspot topics in the LID field. In the following section, the author's keywords are analyzed to understand the emerging trends of keywords, which eventually determine the hotspot research theme.

2.4 Emerging research theme and gap identifications

2.4.1 Emerging themes

The author's keywords are selected as a criterion for evaluating the emerging research theme. Comerio and Strozzi (2019) used this criterion to identify the main thread of research articles. The VOSviewer is used in this study to analyze the author's keywords. An author's keyword is considered a frequent one if it occurs at least five times in all abstracts and titles. Among 554 keywords, 21 meet the threshold category. In these 21 keywords, similar words like "LID" or "low impact development" and irrelevant words such as "city," "sponge," and "urban" are eliminated. This filtering resulted in 13 keywords, as listed in Table 2.11.

Table 2.11 *Top thirteen keywords on LID and optimization field based on occurrences*

Keyword	Occurrences	Publication Year
Low impact development	50	2017
Optimization	32	2017
SWMM	24	2017
Green infrastructure	16	2017
Bioretention	13	2016
Climate change	12	2018
Best management practices	7	2014
Genetic algorithm	6	2017
NSGA II	6	2017
Uncertainty	6	2017
Cost	5	2014
Multi-objective optimization	5	2017
Resilience	5	2018

Among this list, "low impact development" is the most recurrent keyword with 50 occurrences. The three subsequent most frequent words are "optimization" (32 occurrences), "SWMM" (24 occurrences), and "Green Infrastructure" (16 occurrences).The evolving nature of the keywords with timescale is shown in Figure 2.8. which depicts that best management practices and their costing were the main research area in 2014. Bioretention was the most investigated LID in the year between 2016 and 2017. After 2017, the major research fields were green infrastructures and multi-objective optimization approaches using mainly genetic algorithm (GA), NSGA-II. From 2018, climate change impact and resilient design were becoming prominent and still worth investigating areas.

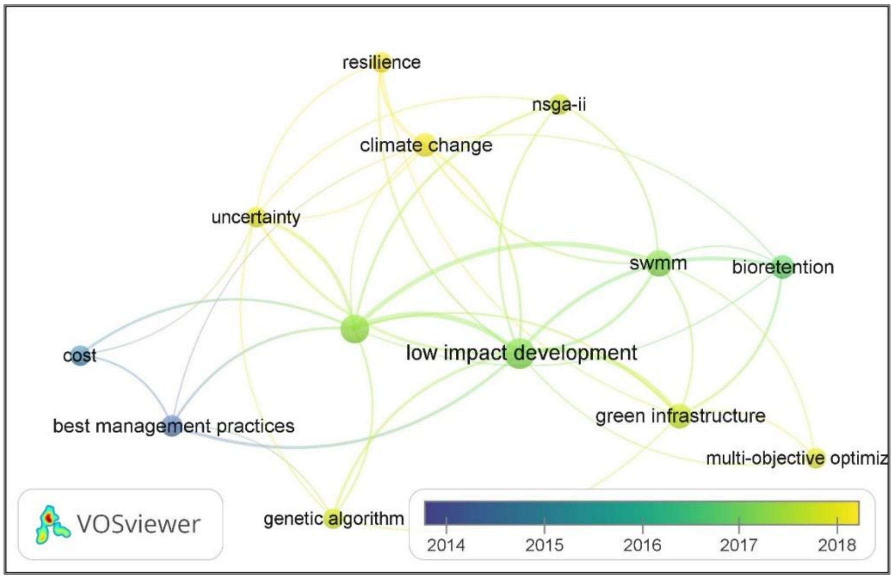


Figure 2.8: *Author's keyword network*

2.4.2 Research gaps

The author's keyword analysis is used to exhibit research theme progression and discover the research gaps and future hotspot topics, where all documents under each cluster (167 articles) are considered. Based on the author's keyword analysis, "resilience," "climate change," and "uncertainty" are the hotspot keywords in recent years. Clusters 1 and 2 deal with several optimization approaches where the number of documents showed an increasing trend. Therefore, gaps and directions for future work for Clusters 1 and 2 are combined.

Based on Cluster 1 and 2, optimization of LID type and the area was performed for PP, GR, RG, RB, VS, BR, IT based on either quantity improvement (runoff volume and peak-volume reduction) or quality improvement (pollutant load reduction) at a minimum cost (Xu et al., 2019, Xu et al., 2017, Mani et al., 2019). Overall optimal scenario (selection of LID type, size and location) was determined for PP, GR, BR, RB, RG and IT to minimize volume and cost (Seo et al., 2017; Ghodsi et al., 2020; Fan et al., 2017; Xu et al., 2019). All performance criteria (quantity, quality, cost) can be combined as optimization objectives for several LIDs in the future. Also, the hydrological performance can be assessed based on this combined approach for both single LID and a combination of multiple LIDs.

For resilient LID design, both climate change (CC) and land-use change (LUC) are considered, and optimal type, area, location are determined for multiple LIDs such as PP, BR, GR, RB, VS (Liu et al., 2016, 2017; Xu et al., 2018b). Optimal IT design is investigated under the CC scenario. In the future, this design can be optimized considering either LUC or combined CC and LUC scenarios.

The uncertainty in parameters such as infiltration rate, release rate, build up and wash off coefficient, impermeability (Latifi et al., 2019; Raei et al., 2019) and rainfall characteristics (Latifi et al., 2019; Gu et al., 2018, 2020; Ng et al., 2020) were considered for selecting optimal LID type and area from VS, BR, percolation well, catch basin, RB, GR, PP and IT. For PP, GR, and BC, the Monte Carlo approach was used for spatial location optimization (Guo et al., 2018, September). Design optimization of RG considering uncertainty was not done in the previous studies. So, incorporating uncertainty of both parameters and rainfall characteristics in RG’s optimal design and other LIDs such as RB, GR, PP, IT will be a worth investigating research area in future.

In Cluster 3, parameter optimization is conducted using the PSO algorithm to determine hydraulic properties for PP and GR (Brunetti et al., 2016; Piro et al., 2019) and shape parameters for the stormwater filter (Brunetti et al., 2017). So, optimal parameter values for other LIDs such as BR, RG, RB, VS, IT can be considered in future studies. Several multicriteria decision analysis approaches such as AHP, TOPSIS, index ranking system were applied for leaky well, RG, GR, soakaway, infiltration facility to select optimal LID type (Ahammed et al., 2012; Gogate et al., 2017; Luan et al., 2019; Xing et al., 2016). Multicriteria approaches can be used in conjunction with the optimization techniques for other LIDs to get the overall optimal solution in the future.

The most used LID in Cluster 4 is bioretention. Experimental studies are conducted in the majority of the articles lying in this cluster to evaluate the performance (quantity, quality) of BR (Fassman-Beck et al., 2015; Jiang et al., 2019; Li et al., 2014; Mei et al., 2013; Morash et al., 2019; Wan et al., 2018). SWMM is used as a hydrologic-hydraulic model in two of the studies to measure these performances (Zhang et al., 2018; Lucas and Sample, 2015; Platz et al., 2020). Experimental investigations on other LIDs can be done in future studies, and the results can be used for numerical model validation.

2.5 Discussion

An evolutionary increase in the number of research articles in the stormwater management field provides an opportunity to conduct meta-research on the LIDs optimization field. To conduct this review, first, the related articles were retrieved from the Web of Science core collection database. A publication trend graph is generated to show the emergence and growth rate of these articles. Later, BibExcel is used to create an appropriate file format coupled with other visualization software analysis tools such as Gephi and VOSviewer. Citation analysis is done on a local and global basis, as well as Page Rank analysis to identify highly cited and prominent articles in this research field. VOSviewer is also used to determine the most influential authors based on citations and find the top countries based on document numbers. Co-citation analysis is performed through clustering using Gephi to group-related articles, where four clusters are identified. For each cluster, using VOSviewer, text mining was applied on the top 15 papers based on page rank scores to identify the research subthemes. A term map was generated to help in naming the research theme of each cluster and uncover its inherent concept. Analyzing the latent topics within each cluster and considering the identified keywords help in providing recommendations for future research works. Finally, the analysis of authors' keywords is performed using all four clusters' documents to discover the emerging research themes.

Clusters 1 and 2 showed a steady development rate with greater publications compared to the other clusters. A boost in the publication is observed in 2006 for both Clusters 1 and 2. The analysis illustrates that the research themes under these two clusters are the current research frontiers. So, LID optimization research can be divided into three major streams. Cluster 1 and Cluster 2 form one stream where type, unit and area optimization are the main focus. The second stream contains Cluster 3, where parameter optimization of several LIDs and adaptation of multicriteria decision analysis is observed. The last stream deals with Cluster 4 where several experimental studies, especially on BR are discussed.

Cluster 1 contains the highest number of articles although it appeared later than the other clusters. This cluster mainly deals with optimal LID type and LID unit selection. It contains three review papers; i) factors impacting LIDs performance, ii) infiltration and retention-based LIDs and the models that are used for assessing LIDs performance, and iii) issues and challenges related to implementing GI in industrial areas. Besides, BC, PP and GR are the mainly used LIDs in these studies. The majority of the studies applied SWMM with several multi-objective algorithms, while some studies used SUSTAIN and its integrated algorithms to get the optimal solutions. Some other studies focused on improving drainage systems' performance using GR, BC, PP,RG and RB.

Cluster 2 is the second-largest cluster. The majority of the articles in this cluster illustrate several deployment strategies of LIDs, such as centralized, distributed or combined. The rest of the articles focused on selecting optimal scenarios based on quantity and quality-control criteria. This cluster's research articles also considered the uncertainty of input parameters such as rainfall, imperviousness co-efficient, build up and wash off co-efficient and determined the optimal scheme under different climate change scenarios. Previously, flow control was the major criteria to obtain the optimal solution; however, shifting towards the incorporation of CC and LUC along with different uncertain parameters is observed from this cluster progression.

Both Clusters 1 and 2 dealt with design optimization (type, unit, area, location); however, Cluster 2 focused on uncertainty and combined LUC and CC scenarios. In these studies, the objective function was either volume or peak flow or cost-minimization. In the future, multi-objective functions can be considered, using two or more objectives, including reducing the time of concentration, FF volume, and hydrological residence footprint. Also, LUC and CC impacts can be incorporated into optimization techniques to get the climate-resilient solution. The combined uncertainty effect lying under rainfall and hydraulic soil properties can be also considered for the LIDs such as GR, RG, RB, PP in the future.

Cluster 3 focuses on multi-criteria approaches and LIDs parameter optimization. Six out of fifteen studies applied various multicriteria techniques such as AHP, TOPSIS to select the appropriate LID type and placement. Parameter optimization was done on PP, GR, BR and stormwater filter only; therefore, there is an opportunity to perform parameter optimization on other LIDs. The results can be used as constraints or decision variables to determine the optimum solution that satisfies all design objectives. A combined multicriteria analysis and optimal solutions (obtained from several climate change scenarios) can be used in the future to get the best solution and make the drainage infrastructure climate resilient.

Cluster 4 articles included experimental studies focusing on assessing the performance of BR, both quantitively and qualitatively. In these studies, BR was used as a single measure or as part of other LIDs. In the future, similar studies can be conducted on several different LIDs to assess their performance and collect data to help in validating numerical models.

The prevailing and emerging thread of research articles is obtained using authors' keywords evolution. The progressive nature of keywords with a timespan showed that BMP was previously used as a stormwater management measure in 2014. Later, BR was used as a subset of BMP measure during 2016–2017. After 2017, a shift towards using GI with multi-objective optimization is observed. Finally, the analysis revealed that climate change and resilience are cutting-edge research themes that also support the steady development and progression of Clusters 1 and 2. Therefore combining optimization of LID size (e.g.,

length, width, depth) with LUC and CC analyses can be considered to make climate-resilient drainage infrastructure.

2.6 Limitations of the study

In this study, only the top fifteen papers (selected based on page rank score) of each cluster are considered for topic identification and content analysis. This selection is made because the lead papers can illustrate the main research focus of the clusters (Fahimnia et al., 2015). However, as the rest of the articles are not considered, each cluster's overall topic determination gets affected. Future studies can perform the analysis by including all articles underlying each cluster to facilitate more accurate topic identification and content analysis. Besides, articles from recent years, such as four or five years, can be chosen for keyword analysis to map the recent influential and prominent themes in this field (Paul et al., 2017). The results obtained from this mapping can help further content analysis through clustering and enable researchers to identify the current hotspot topics and their corresponding gaps. Moreover, this field's publications can be classified based on several study methods such as review analysis, meta-analysis, empirical and conceptual study. This data will help future researchers to select and carry out proper study methods in their specified fields.

2.7 Conclusion

LID implementation and its optimal design is an emerging topic in the stormwater management field, thus drawing several researchers' attention. This review employs systematic literature and bibliometric analysis on the field of LID practices and their optimization and resilience. The field's state-of-the-art development is summarized in this review paper to help researchers, preceptors, decision-makers, and several stakeholders. The consequent maps of authors, countries, and terms generated by bibliometric, network analysis and text mining techniques are useful and captivating appliances among the researchers' community.

The following key conclusions can be drawn out from the biblio- metric and content analysis:

(1) The publication trend graph depicts that articles in this field emerged from 2004, and the growth rate got its propulsion after 2014.

(2) Citation and page rank analysis revealed the paper entitled 'Performance and implementation of low impact development - A review' (Eckart et al., 2017) as the prestigious and popular paper (highest page rank score which is 0.01296) in the LID field, which has received 108 local and 111 global citations.

(3) Haifeng Jia is identified as the prominent author in this field with 312 citations, and the USA ranked first in publishing a larger number of articles in this research area (69 documents).

(4) Co-citation analysis identified four research clusters; Cluster 1, 2, 3 and 4 contains 65 56, 25 and 21 articles, respectively. Cluster 1 focuses on optimal LID size and unit selection from multiple options. Cluster 2 deals with the optimal allocation strategy of LIDs with cost minimization. Cluster 3 uses hydraulic parameter optimization for PP, GR, and stormwater filters. Several multi-criteria approaches were adopted in this cluster to get the optimal selection of LIDs. Finally, the main research theme of Cluster 4 is performance evaluation (quality and quantity) of BR at the experimental scale.

(5) The evolution of research clusters with time is identified. In addition, to exhibit research theme progression and discover future hotspot topics, the authors' keyword analysis revealed that climate change and resilience are now the major focus in this research era.

Based on the above discussions, the following recommendations can be adopted in the near future:

(1) Runoff volume and peak control, first flush reduction, minimizing hydrological footprint residence, lengthening the time of concentration or time to peak and life cycle cost – all together can be used to formulate a multiple-objective optimization problem to get the most effective solution.

(2) Combined CC and LUC impacts should be considered in optimizing the design of RG and IT.

(3) The combined uncertainty effect lying under rainfall and hydraulic soil properties (infiltration rate) can be considered for the LIDs such as PP, RG, GR and RB in the future.

(4) Parameter optimization can be considered for LIDs, especially RB, RG, IT, VS, and the results can be incorporated into optimization algorithms to determine the optimal solution that satisfies all design objectives.

(5) In the future, multicriteria approaches can be used together with optimization algorithms output to reach the best solution.

(6) Experimental studies can be conducted on various LIDs (except BR) to collect actual data of their performances (runoff volume, the concentration of pollutant loads) which can be used later for numerical model validation.

Finally, the analyses presented herein can benefit different stakeholders in the LID research and decision-making community, including 1) conference organizers (e.g., to prioritize the scope of their future conferences); (2) journal editors (e.g., to develop new interest within their journals); 3) researchers (e.g., to consider breakthrough and seminal work opportunities at the interface with other fields); 4) funding agencies (e.g., to prioritize and strategize research investments prudently and efficiently towards identified knowledge gaps and possible future opportunities for societal benefits); and 5) designers/regulators (e.g., to improve LID design, optimization, economy and resilience).

CHAPTER 3

Resilience Quantification of Low Impact Development Practices: A Demonstration Application on a Bioretention System

The chapter's content contains a manuscript text submitted to the Journal of Sustainable Water in the Built Environment on October 29, 2021—currently under review.

3. Resilience Quantification of Low Impact Development Practices: A Demonstration Application on a Bio-retention System

Abstract: The field of stormwater management has been experiencing increased demands for resilient low-impact development (LID) practices over the past few decades. During extreme uncertain events, a resilient LID system is expected to not only handle immediate shocks, but it is also expected to rapidly adapt to changes and regulates itself to ensure continuous functionality. This study presents a new resilience quantification approach applicable to different LIDs, and the approach utility is demonstrated on a bioretention system. A set of equations for the functionality of the considered LID is developed using two hydrological simulation approaches: the analytical probabilistic approach (APA) and continuous simulations using SWMM. These equations are subsequently used to evaluate resilience indices such as: robustness, rapidity and serviceability. In addition, the overall LID system's reliability is evaluated using a reliability index based on the product of volumetric, occurrence and temporal reliability. A similar range in the overall resilience and reliability index values is found based on the APA and SWMM simulation for different area ratios and surface depression storage depths. However, the average rapidity index is smaller in the APA compared to SWMM. This slight variation occurs due to APA's inability to measure functionality at small time increments since the approach only delivers information at the beginning and ending of an event. Further analysis using the Sustainable Technologies Evaluation Program (STEP)'s tool shows that an area ratio of 20 and 30 with surface depression storage depth varying from 300-600 mm is the most cost-effective design criteria to obtain a resilient and reliable BR system. The developed approach and findings of this study provide policymakers with a consistent approach to design resilient LID practices, as well as decision makers to strategize research investment through optimal LID designs.

Keywords: Stormwater Management, Low Impact Development, Resilience, Reliability, Robustness, Rapidity, Serviceability.

3.1 Introduction

Over the past few decades, different low impact development (LID) practices have been replacing conventional stormwater management approaches to overcome the limitations of this approach as well as to mitigate adverse hydrological impacts induced by urbanization and climate change (Guo and Guo, 2018). These LID practices aim at i) conserving the natural hydrologic processes such as infiltration, evaporation, and storage (USEPA, 2010 and Damodaram et al., 2010); ii) increasing natural hydrologic processes; and iii) enhancing ecological benefits such as stormwater quality control (Liu et al., 2015; Jia et al., 2012; and Vogel et al., 2015). Rain garden, bioretention (BR), green roof, rain barrel, infiltration trenches and permeable pavement are some examples of frequently used LID practices. These practices are typically designed based on deterministic assumptions of associated variables and static climate assumptions. However, the increased occurrence of extreme climatic events affects LID fragility to and perform during such events—creating the need to build resilience within LIDs to minimize the resulting aftereffect of uncertain future events (Brown et al., 2020).

Resilience is generally defined as a system's ability to endure stress and bounce back to its original state following a shock (Holling,1973&1986; PIEVC, 2020). As a concept, resilience is well established in various fields (e.g., manufacturing and structural engineering); however, it is relatively new to stormwater management. Since we are interested in runoff reduction, resilience in this study is defined as the ability of a LID system to store water from a rainfall event and subsequently return to a state where the LID is completely ready (fully available) to capture and store water from the next event. LID's resilience quantification thus depends on the amount of perturbation absorption and the recovery time to quantitatively measure LID's resilience to a rainfall event.

The resilience assessment approaches employed in previous studies can be classified into three categories. In the **first** category, a resilience evaluation framework was developed focusing on some principles such as i) diversity ii) redundancy, iii) flexibility and adaptability, iv) modularity, v) interdependency, vi) stabilizing and buffering factors, vii) mobility and viii) planning and foresight (Albres and Deppisch, 2013). Moores et al., (2017) applied this concept with a multicriteria decision support system (DSS) to assess urban aquatic system's resilience of Lucas Creek catchment. This approach was also applied to assess flood resilience of Tanzania water supply system (Sweya et al., 2020) and urban systems in Asia and Europe (Batica and Gourbesville, 2016) based on these principles (i.e., diversity) using some indicators (i.e number of multiple devices, effectiveness of the devices) and aggregated weighted value method was used to evaluate the indicator's scores and thereby assessed system's resilience.

Unlike the aforementioned resilience principles, the **second** category measured LID's resilience considering uncertainties associated with climate and land-use change (Liu et al., 2017; Xu et al., 2018); hydrological parameters (rainfall, infiltration rate) and economic factors (funds and unit price) (Gu et al. 2016; Gu et al., 2018; Latfi et al., 2019; Raei et al., 2019) to ensure resilient LID design. Therefore, first, future uncertain scenarios were generated utilizing several GCM model outputs (Ghodsi et al., 2020; Wang et al., 2019; Fan et al., 2017), a design storm technique (Chen et al., 2017), stochastic rainfall events (Ng et al., 2020), and including increased urbanization in land-use patterns (Luan et al., 2019). Then LIDs were implemented as an adaptive measure and they are termed resilient if they can endure the vigorous impacts of the developed scenarios and provide satisfactory performance (Herman et al., 2015; Mcphail et al., 2018).

Drainage infrastructure resilience was ensured using LIDs including green roof and permeable pavements with different area ratios in Gongming area of China based on the timing of concentrating floodwater and flooding duration, aiming to mitigate urban flooding risk of the study area (Song et al., 2019).

The **third** category considers two resilience goals: rapidity and robustness and has been applied in different research fields such as structural engineering (Salem et al., 2020), transportation (Barker et al., 2013, Mackie and stojadinovic, 2006, Berche et al, 2009), health care (Choi et al., 2017, Cimellaro and Pique, 2015) and water (Cimellaro et al., 2016, Chang and shinozuka, 2004). In addition to the aforementioned goals, vulnerability, survivability (Barker et al., 2013), reliability (Proag, 2016, Todini, 2000) and serviceability (Cimellaro et al., 2015) have also been considered in previous studies to quantify resilience. It should be noted that while some studies used reliability to measure system performance (Tahmasebi Birgani et al., 2013), others used it as a property of resilience assessing metrics (Mugume et al., 2015, Joyce et al., 2018, Hashimoto et al., 1982). Based on the widely used definition of reliability, this indicator should reflect a system's continued adequate performance (capacity) to its design (demand).

Based on the above review, resilience has been mainly assessed quantitatively for a whole urban drainage system (UDS) or to improve flood response within a watershed. In addition, LID's resilience was considered in past studies to ensure if LID can handle uncertain future events from the stormwater management perspective. To the best of the authors' knowledge, no quantitative approach for evaluating LID's resilience—focusing on the major resilience goals, is published as this is an emerging research topic.

The current study bridges prior research gaps and aims to quantify LID's resilience by developing a set of equations considering two main resilience goals: robustness and resilience and a new index termed as ‘serviceability’. The equation development of the three indices have considered the dynamic functionality of the LID system (variation of storage condition with time). Later, all the indices are used to develop an overall resilience index of a LID system. In addition, this study also assesses reliability of the overall LID system considering volumetric, occurrence and temporal reliability as reliability indices by proposing a new reliability index as without being reliable, a system fails to being resilient.

To demonstrate the utility of the proposed approached, first, a BR APA model (Zhang and Guo, 2014) is used to develop equations for functionality, resilience, and reliability indices. Subsequently the APA results are validated with the continuous simulation model SWMM, using long-term continuous rainfall data from Hamilton A station. The APA and SWMM models are then used to generate resilience quantification and reliability indices equations. More details of both models are given in Sections 3.2.1 and 3.2.2. Finally, LID Costing Tool of Sustainable Technologies Evaluation Program (STEP) is used to determine the most cost-effective design criteria (length to width ratio, surface depression storage depth) of BR system. The APA simulations are based on the probability distribution functions (PDFs) of the runoff-event characteristics obtained by transferring the rainfall-event characteristics pdfs through the rainfall-runoff transformation model. The rainfall-event characteristics are assumed to be exponentially distributed. Therefore, prior to applying the APA simulation, the corresponding rainfall data must satisfy these assumptions. Moreover, in this study, concepts of resilience and reliability indicators are assumed to be applicable to stormwater management field.

3.2 Methodology

3.2.1 Analytical Probabilistic Approach

3.2.1.1 Probabilistic Distribution of Rainfall Event Characteristics

At first, APA requires continuous rainfall record discretization into independent events that have characteristics of rainfall event volume (v), duration (t), and interevent dry period (b), respectively. Two thresholds: minimum rainfall volume (v_{min}) and minimum interevent time (MIET) are required for this discretization. MIET represents minimum dry hours between two rainfall episodes, and v_{min} depicts small events which produce no runoff. Following the procedure given in Hassini and Guo (2016), Guo and Baetz (2007), MIET ranging from 6-12 h and v_{min} ranging from 0 to 5mm is tested in this study. The distribution of the rainfall events is assumed to be exponential and Hassini and Guo (2016) developed a method to assess this exponentiality. Exponential PDFs and distribution parameters of rainfall characteristics are shown in Table 3.1.

Table 3.1 *Exponential PDFs and distribution parameters of rainfall characteristics*

Rainfall event characteristics	Exponential PDF	Distribution Parameter
Volume, v(mm)	$f(\upsilon)= \zeta \exp(-\zeta\upsilon); \quad \upsilon\geq 0$	$\zeta =\frac{1}{\bar{v}}$
Duration, t(h)	$f(t)= \lambda \exp(-\lambda t); \quad t \geq 0$	$\lambda =\frac{1}{\bar{t}}$
Interevent dry period, b(h)	$f(b)= \psi \exp(-\psi b); \quad b \geq 0$	$\psi =\frac{1}{\bar{b}}$

*$\bar{v}$, $\bar{t}$ and $\bar{b}$ are mean values of rainfall event volume, duration and inter-event dry period, respectively.

3.2.1.2 Hydrological processes of LID in APA

During a current rainfall-event (CRE), the amount of stormwater retained by BR (S_{dw}) depends on the inflow volume (v_i), infiltration (F_t), and evapotranspiration (ET) during the current cycle, and the system's available storage capacity (R_c) at the start of the CRE. Also, S_{dw} can not be greater than the BR’s (as the example LID considered for demonstration herein) total surface depression storage depth, S_d. The total inflow volume (v_i) is the sum of direct rainfall on BR (v) and surface runoff from contributing catchment. During a rainfall occurrence, the water balance equation of BR is as follows,

$$v_o = v_i - F_t - R_c \tag{1}$$

The ET is neglected as it is relatively very small during the rainfall event. R_c is controlled by S_{dw} at the end of previous rainfall event (PRE), ET and F_t during the dry period, b (h) between end of PRE and start of CRE. S_{dw} is calculated by Zhang and Guo (2014) as follows:

$$S_{dw} = \begin{cases} 0, & v_p \leq \frac{f_c t_p + r\phi S_{dc}}{r\phi + 1} \\ (r\phi + 1)v_p - r\phi S_{dc} - f_c t_p, & \frac{f_c t_p + r\phi S_{dc}}{r\phi + 1} < v_p \leq \frac{f_c t_p + r\phi S_{dc} + S_d}{r\phi + 1} \\ S_d, & v_p > \frac{f_c t_p + r\phi S_{dc} + S_d}{r\phi + 1} \end{cases} \tag{2}$$

where, v_p is the inflow volume into BR (mm/unit area); r is the ratio of the contributing catchment area to the BR area; f_c is the constant infiltration rate (mm/h); t_p is the duration (h) of PRE; ϕ= runoff-coefficient (dimensionless); S_{dc} is the surface depression storage capacity of the contributing catchment (mm per unit area of catchment). The approximate expected value of S_{dw} is also estimated by Zhang and Guo (2014) as:

$$\mathrm{E}\,(S_{dw}) = \frac{\lambda\,(r\phi+1)^2}{\varsigma[\lambda(r\phi+1)+\zeta f_c}\mathrm{exp}[-\frac{S_{dc}(\varsigma f_c+\lambda)}{f_c}][1-\mathrm{exp}(-\frac{\zeta S_d}{(r\phi+1)}] \tag{3}$$

S_{dw} decreases, through evaporation and infiltration, during the dry period following a current rainfall event. The infiltration rate in the BR is assumed to reach a constant value f_c (mm/h) at the end of PRE. Considering an average evapotranspiration rate, E_a (mm/h), the time needed to drain out all stored water after each event is calculated by Zhang and Guo (2014) as follows:

$$t_d = \frac{S_{dw}}{E_a + f_c} \tag{4}$$

The distribution parameter values along with these key governing equations [Eqs. (1)-(4)] and some previously developed analytical equations of BR (Zhang and Guo, 2014) are used to generate new equations for estimating resilience and reliability of LID.

3.2.2 Continuous simulation models

To conform the admissibility of the assumptions adopted in APA to develop the equations illustrating rainfall-runoff transformations of BR and to demonstrate the accuracy of APA, a comparison is made between results from APA and continuous simulations. The difference between both models is given in Table 3.2.

***Table 3.2**. A comparison between APA and SWMM models*

APA	SWMM
• Event based model: calculations are done on event-by-event basis	• Continuous simulation model: calculations are done on timestep-by-timestep basis
• Rainfall input: average values of rainfall event volume, duration and interevent time, where rainfall event volume, duration and interevent are assumed to be exponential random variables	• Rainfall input: rainfall data series
• Lumped model: treats the study area as one catchment	• Study area can be subdivided into sub-catchment.
• Provides information of stored water amount only at the start and end of an event	• Provides information about stored water amount at small time steps during a rainfall occurrence
• Does not explicitly include antecedent soil moisture conditions	• antecedent moisture conditions are incorporated into the simulation
• Requires few hydrologic parameters	• Requires numerous hydrologic parameters
• Has closed-form Mathematical solutions	• Provides numerical solution

• Provides frequencies within the results	• Requires frequency analysis on the output
• Less time consuming and computationally efficient	• Data is scarce, time intensive and needs high expertise

3.2.2.1 LID modelled as a sub-catchment

To confirm that the contributing catchment and BR represented by APA is exactly same as that presented by SWMM, both are modeled in this study as a sub-catchment A and B respectively. As a lumped model, SWMM treats each sub-catchment as a single homogeneous entity with spatially uniform rainfall input in this study. Based on imperviousness, sub-catchment A is divided into pervious and impervious subareas with depression storage depth S_{dp} and S_{di} respectively. When rainfall occurs, a part of rainfall is trapped by S_{dp} and the rest of the rainfall is routed to sub-catchment B. Furthermore, sub-catchment-B receives all rainfall that falls directly on it (v) and has only a large surface depression storage, S_d with no impervious sub-area and highly permeable soil layer. Outputs at small time increments i.e. 30 min time-step for the overall simulation period of 38 years (1978-2015) such as: runoff from contributing catchment (v_{rA}), runoff from sub-catchment B (v_{rB}), infiltration rate (f), runoff-co-efficient (ϕ) are used to determine water into LID (s_{wLID}), infiltration from the LID (f_{LID}) and stored water within LID (S_{dw}), thus facilitating the determination of functionality and resilience and reliability indices. To be consistent with APA, ET effect is neglected in estimating S_{dw}. The units of all parameters are considered as mm of depth per area of LID. For example, storage within LID is calculated by the following equations:

$$s_{wLID} = (v_i - v_{rB}) \tag{5}$$

$$\text{where, } v_i = v + v_{rA}; \tag{6}$$

$$f_{LID(t)} = \min\left(f, S_{dw(t-1)} + s_{wLID(t)}\right) \tag{7}$$

$$S_{dw(t)} = \min\left(S_{dw(t-1)} + s_{wLID(t)} - f_{LID(t)},\ S_d\right) \tag{8}$$

In the above equations, v_i is the total inflow volume and the subscript *t* and *t-1* denote current and previous time step respectively.

3.2.2.2 LID modelled using LID control editor

Unlike treating LID as a sub-catchment, LID control under hydrology module can also be used for detail performance assessment of LID. Different layers such as surface, soil, storage, pavement, drain system and drainage materials are combined to represent each LID control and the total capacity (C) of the specific LID is measured by summing all layer's depth. All hydrological processes occurring in each layer can be estimated in this setting; however, only the amount of stored water in the surface layers can be determined in the first setting. The hydrological processes occurring in different layers of BR are schematically shown in Figure 3.1.

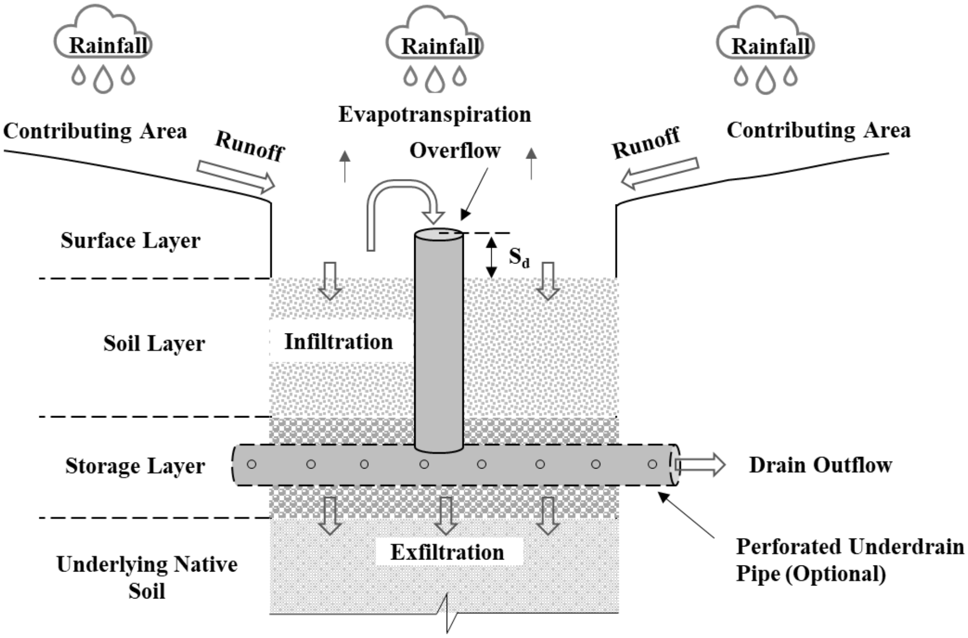


Figure 3.1: *A schematic representation of Bioretention system (Adopted from TRCA,2019)*

BR receives rainfall in the same manner as in the previous setting. Part of the rainfall is absorbed by the depressions of surface layer and the rest of the part is infiltrated downward through the soil layer into the storage layer. Some part of infiltrated water is then retained by the voids of the storage layer while the remainder either drained away through the perforated underdrain pipes as drain outflow or exfiltrates into the underlying native soil. To deal with heavy rain events, the design also includes an overflow or bypass pipe.

The detailed output (surface level, h_s; pavement level, h_p; soil m/c, θ; and storage level, h_{sg}) from the continuous simulation facilitates estimating the stored water amount in each layer (S_{dw}) at small time-steps. C and S_{dw} are determined by the following equations:

$$C = S_d * \eta_1 + D_2 * \eta_2 + D_3 * \eta_3 + D_4 * \eta_4 \tag{9}$$

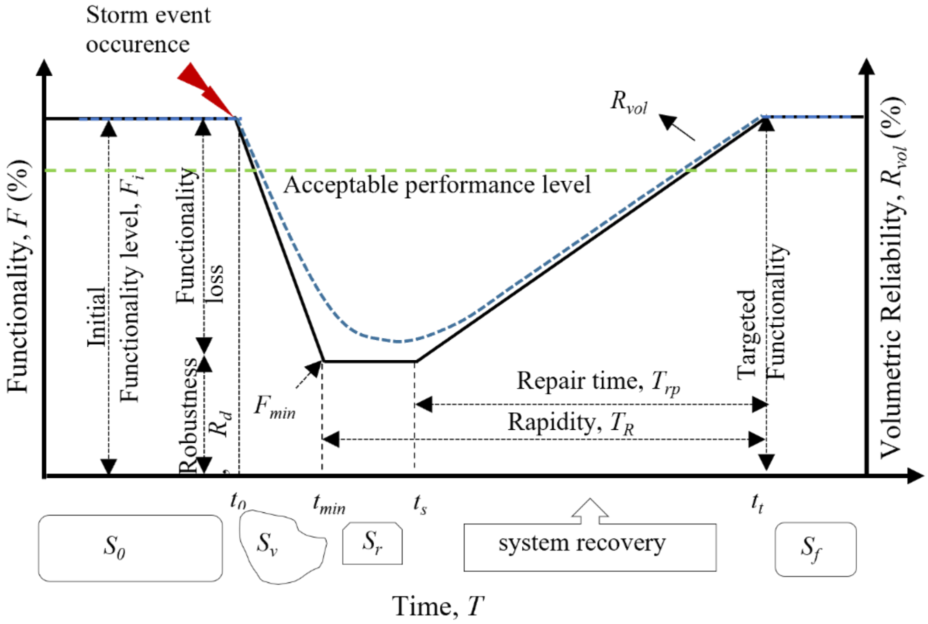
$$S_{dw} = h_s * \eta_1 + \theta * D_2 + h_{sg} * \eta_3 + h_p * \eta_4 \tag{10}$$

where D_2, D_3 and D_4 are the thickness of soil, storage and pavement layer respectively. All of the parameters are expressed in millimeters or inches. η_1 represents a void fraction of berm height not filled with vegetation and η_2, η_3 and η_4 represents porosity of the soil, storage and pavement layer respectively. The last terms $D_4 * \eta_4$ and $h_p * \eta_4$ of Eq. (9) and Eq. (10) are only applicable for permeable pavement. Eq. (9) and (10) is a general one that is applicable to any LID practices, thus facilitating the determination of stored water within LID at any time-step and other resilience assessing indicators described in sub-section 3.2.4.

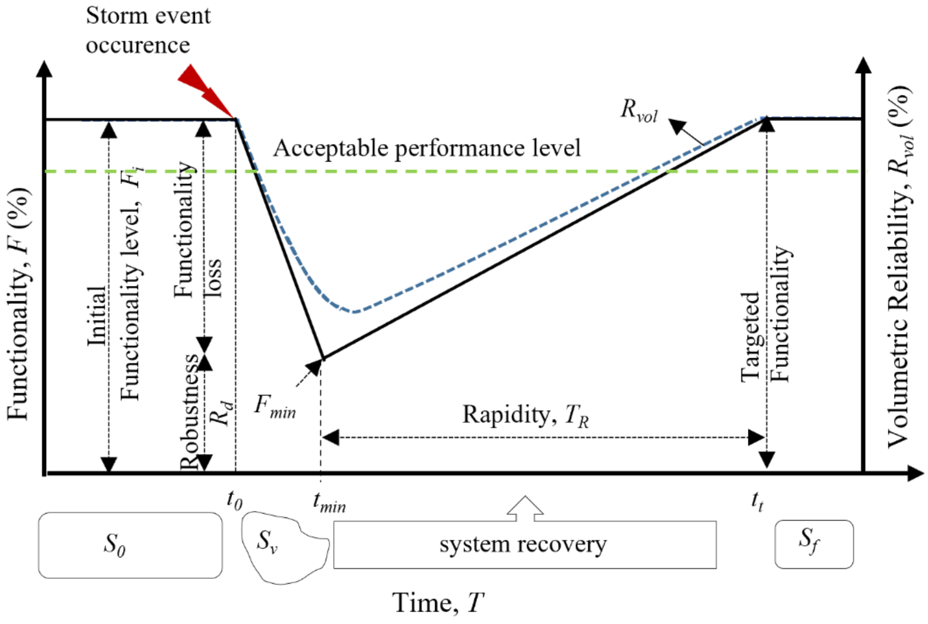
3.2.3 Relationship between LID Resilience and Reliability

A system is considered resilient if it absorbs stress from an uncertain disturbance and rapidly recovers to reach a satisfactory performance level. System reliability on the other hand indicates the probability of a system to perform its intended function adequately for a specified period of time without failure. This study considered three resilience indices: robustness, rapidity, and serviceability and three reliability indices including those: volumetric, occurrence-related and temporal. The indices' definitions are given in sub-sections 3.2.4 and 3.2.5. The indices' equations are developed based on the system's functionality (*F*). The functionality definition varies among fields due to its multi-attribute nature. In a LID system, the functionality is defined as the amount of storage availability to capture water from the next event. The factors affecting *F* and process of obtaining this parameter are discussed briefly in the following subsection 3.2.4.

The volumetric reliability measures the total captured water in LID compared to its total inflow volume and increases or decreases with the functionality during a storm. However, the occurrence and temporal reliability indices is just a number which is measured based on the probability of occurrence of satisfactory states (i.e., functionality is anything but zero), therefore, these two indices' variation over time cannot be graphically represented.



(a)



(b)

Figure 3.2: *Schematic of LID system behavior following a storm event (adapted from Salem et al., 2020): (a) Case 1; and (b) Case2]. Here,* t_0*= Time of event occurrence;* $t_{min=}$ *time at which minimum functionality (*F_{min}*)occurs;* t_s*= time of recovery initiation;* t_t*= time when full functionality recovered*

Figure 3.2. (a) depicts a general case describing four different operational states of LID starting from t_0 up to t_t . LID remains in its original state S_0 until storm occurred at time t_0 . From t_0 to t_{min} , LID pertains to a vulnerable state, S_v and minimum functionality occurs at the end of this state. LID remains in this damaged state, S_r up-to time period (t_s - t_{min}) before initiating its recovery. Recovery from its minimum functionality commences at t_s and after reaching t_t , LID's functionality fully recovered, thus reaching recovered state, S_f , which is continued thereafter. However, LID's operational states and the time of recovery initiation based on rainfall events depth and infiltration rate of the fill media of LID. For example, functionality may reach a minimum value just after the event occurrence (Figure 3.2.b), and the recovery process is initiated immediately if the rainfall event depth is less than the infiltration rate, making t_{min} = t_s and

$T_R = T_{rp}$. The system's recovery rate indicates the rate at which a disrupted system recovers to a satisfactory functionality level. However, literature investigated different recovery behaviors such as exponential, linear, trigonometric (Cimellaro et al. 2009), stepped (Burton et al., 2016; Cimellaro et al., 2016) of numerous systems; this study assumed a linear recovery behavior due to lack of information pertaining to the recovery rate of LID (Choi et al., 2019). Furthermore, the relationship between the two resilience goals is presented in Figure 3.2, where rapidity is attributed to the temporal robustness improvements. If a LID system shows higher robustness, recovery time will be shorter which means that the LID can recover quicky after a disruptive event thereby depicting higher resilience.

3.2.4 Resilience Assessment Indicators

Among the resilience indices, robustness and rapidity are parts of the resilience triangle (Figure 3.2) and serviceability definition is developed following the concept of resilience loss indicator by Salem et al., (2020). The concepts pertaining to the different indices is adopted from literature and a new equation for estimating overall resilience index of a LID system is proposed.

Functionality:

The variation of functionality of a LID with time depends on some factors such as i) available storage capacity of the surface depression of BR at a particular time step ii) magnitude and duration of the events, iii) infiltration and evaporation rate. A functionality value of F = 100% indicates BR's capacity is fully available to store water whereas F= 0% means BR's storage is completely filled with water. F in both APA and SWMM (using LID as a sub-catchment) can be determined using the following equation,

$$F = \left(1 - \frac{S_{dw}}{S_d}\right) * 100 \qquad (11)$$

In APA, each event has a starting and ending time, so F is calculated at each event's starting and ending time, however F is calculated in every timesteps (user specified) in SWMM. The process of obtaining S_{dw} in SWMM is described in section 3.2.2. F of LID using the LID control can be also calculated by replacing S_d with C.

Although functionality is considered as event specific, resilience indices are represented as mean value. This is attributed to the computation nature of both models and the derivation processes of these indices' from functionality. For example, rapidity is estimated for those events in which stormwater was stored whereas functionality provides information about storage availability per time step (i.e., SWMM) and per event (i.e., APA). In addition, robustness and serviceability cannot be estimated from mean functionality. Therefore, to ensure consistency in both model's results and to provide approximate values for the indices considering all events, per LID design, mean value of all indices is considered.

Robustness:

In general, robustness measures the system's resistance to any disruption without degrading or losing functionality. Robustness within the focus of the study indicates the system's post-event (minimum) functionality and is related to the system's pre-event functionality and the post-event functionality loss. Average robustness is calculated as follows:

In APA,

$$R_d = \frac{1}{n} \sum_{i=1}^{n} \left\{1 - \left(\frac{F_s - F_e}{F_s}\right)\right\} * F_s \tag{12}$$

In SWMM,

$$R_d = \frac{1}{n} \sum_{i=1}^{n} \left\{1 - \left(\frac{F_i - F_{min}}{F_i}\right)\right\} * F_i \tag{13}$$

Where n represents the number of events; F_s and F_e are the functionality at the start and end of an event, respectively; F_i and F_{min} are the system's initial functionality and minimum functionality (before recovery initiation) and the terms $(\frac{F_i - F_{min}}{F_i})$ or $(\frac{F_S - F_e}{F_S})$ represents the functionality loss.

Rapidity:

Rapidity in this study refers to the recovery time estimated from the time of system's minimum functionality level after the occurrence of a storm event until reaching its initial or any satisfactory functionality level. In APA, it is assumed that F_{min} can occur at the end of a storm event because the F is completely restored at the start of a new event due to the presence of a large MIET (12 hr) between storm events. A drying time (t_d) denotes the time needed to drain out all stored water remaining in S_d at the end of each event, thus representing a similar concept of recoverability. So, average rapidity in this study is calculated as follows:

In APA,

$$T_R = \frac{1}{n_w} \sum_{i=1}^{n_w} (\frac{S_{dw}}{(f_c + E_a)}) \tag{14}$$

Where n_w represents the number of events at which water is stored in S_d.

In SWMM,

$$T_R = \frac{1}{N} \sum_{i=1}^{N} (t_{min} - t_{Fi}) \tag{15}$$

Here, N represents the number of cases where LID's functionality reaches its minimum value at t_{min} and restores its pre-functionality, F_i at t_{Fi}.

Serviceability Index:

This study defines serviceability index (S_I) as a ratio of LID's perfectly functional hour (h) to its total functional hour considering all storm events. It is expressed by,

$$S_I = 1 - \frac{\int_{t_0}^{t_t} (functionality\ lost\ history\ ) dt}{\sum (t_t - t_0) * F_i} \tag{16}$$

The numerator in Eq. (16) measures the cumulative loss of BR system's functionality, L and the denominator represents a total functional hr. Both are measured for all storm events (n= number of events) from time t_0 until recoverability at t_t. Based on the concept of resilience triangle and linear recovery history, L is calculated by estimating the area of a triangle in APA. In this approach, only triangular area is considered because functionality can be determined only at the start and end of an event, and drying time (t_d) is estimated when an event ends. However, numerous patterns of restoration history are observed in SWMM; only triangular and trapezoidal shapes are considered in this study because the resulting ratio of Eq. (16) from those shapes provides a minimal difference in the overall S_I compared to the adopted patterns. The functionality loss history along with S_I calculation process for both approaches are depicted in Figure 3.3 and Figure 3.4. Figure 3.3. represents an event in APA, where A denotes the event occurrence where the functionality is F_s. This event continues up to t hr and at its end (point B), the functionality decreases to F_e. From B, its functionality starts increasing and after t_d, it reaches its pre functionality level, F_s .

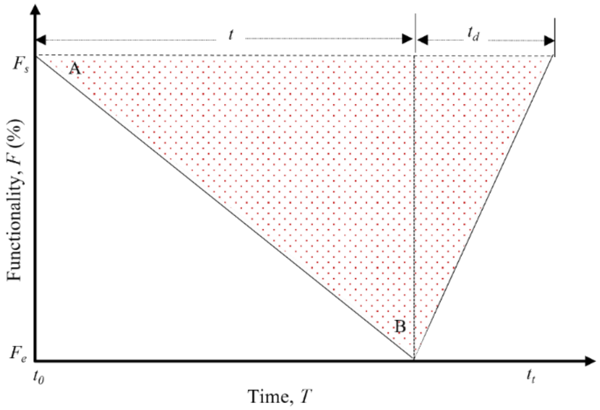


Figure 3.3: *Functionality loss hour calculation using APA*

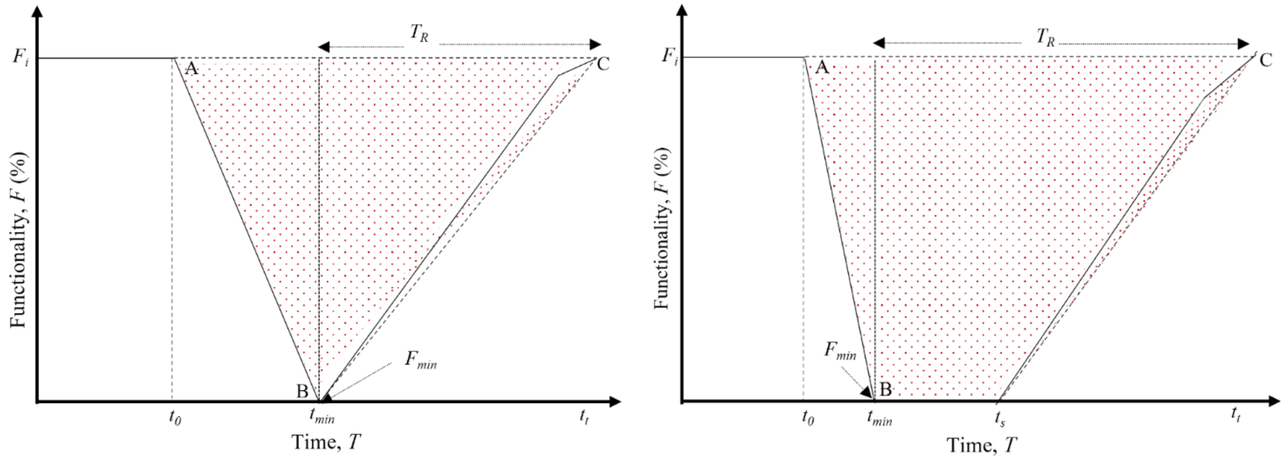
The following equations are used to determine L and S_I in APA:

$$L = \sum_{i=1}^{n} ½ * (F_s - F_e) * t + ½ * (F_s - F_e) * t_d \qquad (17)$$

$$\text{Total functional hour} = \sum(t + t_d) * F_s \tag{18}$$

$$S_I = 1 - \frac{\sum_{i=1}^{n} ½*(F_s - F_e)*t + ½*(F_s - F_e)*t_d}{\sum(t + t_d) * F_s} \tag{19}$$

Figure 3.4 presents two typical recovery histories from the SWMM Model in which, Figure 3.4 (a) calculates L using the area of the triangle where F reaches its minimum value after passing a degradation length $(t_{min} - t_0)$ and after rapidity (T_R), it reaches its pre functionality level, F_i . On the other hand, trapezoidal area is used in the L estimation process in Figure 3.4(b).



(a) (b)

Figure 3.4: *Functionality loss hour calculation using SWMM considering: a) triangular area; and (b) trapezoidal area*

SWMM uses the following equations to determine $L(F, t)$ and S_I for all storm events

For Triangular area,

$$L = \sum_{i=1}^{n} ½ * (F_i - F_{min}) * (t_{min} - t_0) + ½ * (F_i - F_{min}) * T_R \tag{20}$$

For trapezoidal area,

$$L = \sum_{i=1}^{n} ½ * (F_i - F_{min}) * (t_{min} - t_0) + ½ * (F_i - F_{min}) * [(t_s - t_{min}) + T_R] \tag{21}$$

$$\text{Total functional hour,} = \sum(t_t - t_0) * F_i \tag{22}$$

Overall S_I considering both recovery histories in SWMM is calculated as:

$$S_I = 1 - \frac{L}{\sum(t_t - t_0) * F_i} \tag{23}$$

Later, except for rapidity, the other two indices are combined (as they are dimensionless) to comprehensively evaluate overall LID's resilience using a newly developed index.

Overall Resilience Index:

This index is developed based on the product of two performance indices: robustness and serviceability index and can be expressed as,

$$я = R_d * S_I \quad (24)$$

The indices are multiplied here due to the susceptibility nature of this new resilience index when subjected to various storm events (Cimellaro et al., 2015). For example, some events may generate a lower R_d (i.e. 0%) indicating no functionality, and due to larger recovery time (i.e., 5hr), this may results a high S_I (i.e., 0.8); however, in spite of having a comparatively high R_d (i.e. 80%), the system may generate lower S_I value (i.e., 0.05) due to having shorter rapidity (i.e. 2 hr).

3.2.5 Performance Evaluation of LID System

Different aspects of system performance are measured through resilience and reliability. Resilience encompasses the system to recover quickly whereas reliability and safe to fail concept keep the system operational to ensure safe design of LID system. After ensuring system resilience, this study evaluate the overall system performance consistency considering its reliability.

Reliability

In the context of a LID system, reliability refers to the likelihood that the LID will continue to function as intended without failing or causing overflow. If a LID's functionality is greater than zero, it is considered satisfactory; otherwise, it is termed a failure state in this study. This study adopted three types of reliability indices: volumetric, occurrence, and temporal reliability (Kritskiy and Menkel, 1952) to evaluate overall system's performance. The definition and equations to evaluate three indices are developed based on the similar concept adopted by Binesh et al., (2019).

i)Volumetric Reliability

It is defined as the ratio of stormwater captured by the BR system to its total inflow volume. Zhang and Guo (2014) defined this as a stormwater capture efficiency, C_e, which has the following expression:

$$C_e = 1- \frac{(r+1)C_1C_3\ [C_2\ C_4\ (1-C_5)+\exp\ (-\Psi\overline{t_d})}{1+r\phi\ exp\ (-\varsigma S_{dc})} \tag{25}$$

Here C_1 through C_5 are dimensionless constants used to simplifying the above equation and these constants can be determined using the expressions such as $[C_1 = \frac{\lambda(r\phi+1)}{\lambda(r\phi+1)+\varsigma f_c}$; $C_2 = \frac{\Psi(r\phi+1)}{\Psi(r\phi+1)+\varsigma(f_c\ +E_a\ )}$; $C_3 = \exp\left\{-\frac{\varsigma(r\phi S_{dc}\ +S_d\ +E(F_{iw}\ )}{(r\phi+1)}\right\}$; $C_4 = exp\left[\frac{\varsigma E(S_{dw}\ )}{(r\phi+1)}\right]$, $C_5 = \exp\left\{-\frac{\Psi(r\phi+1)+\varsigma(f_c\ +E_a\ )}{(r\phi+1)}\overline{t_d}\right\}]$; where $E(F_{iw})$ represents the expected value of infiltrated water volume to wet fill media layer (mm) Analytical C_e depicts the same concept of volumetric reliability, R_{vol}; therefore, $C_e = R_{vol}$ is considered to determine volumetric reliability in APA.

For the continuous simulation approach, R_{vol} is calculated by,

$$R_{vol} = \frac{v_i - v_{rB}}{v_i} \tag{26}$$

where v_{rB} is the total runoff volume from BR. The process of obtaining v_i is described in section 3.2.1.1. All the terms used in the above equation are expressed in mm of water over the BR area.

ii) Occurrence Reliability

From a stormwater management perspective, the occurrence reliability of a LID system is defined as the number of times LID's functionality is greater than zero to its total simulated time steps. The following equation is used in both APA and SWMM to estimate this index.

$$R_{occ} = \frac{1}{N_t}\sum_{t=1}^{N_t} S_t \tag{27}$$

$$\text{where, } S_t = 1 \text{ when, } X_t \in S$$

$$\text{And} \quad S_t = 0 \text{ when, } X_t \in F_l$$

Here, S_t represents the states of the LID system at each time-step t; X_t is a parameter corresponding to satisfactory state, S and failure state, F_l and N_t is the total number of time steps in SWMM. In APA, each event exhibits a starting and ending time. So, $N_t = 2 * n$, where n represents the total number of events.

iii) Temporal reliability:

This reliability emphasizes on the time duration when the LID remains in the satisfactory state, S compared to the total simulated period and can be estimated as:

$$\text{In APA:} \quad R_{tem} = \frac{\sum t_{F(S)} + \sum b - \sum t_{d(F_l)}}{\sum b + \sum t} \tag{28}$$

$$\text{In SWMM: } R_{tem} = \frac{1}{T}\sum_{j=1}^{S} T_j \tag{29}$$

Here, $t_{F(S)}$ presents the total time duration of storm events at which LID remains in state S; b is the total inter-event dry period of all events, $t_{d(F_l)}$ is the total drying time when BR remains in failure state, and t is the total duration of storm events. In Eq. (29), T represents the duration of the entire simulation period; T_j is the duration when the LID system remains in the satisfactory mode S.

Overall Reliability Index:

The overall reliability index is defined as the product of the above three indices, which help engineers and planners to evaluate a system's condition (satisfactory or failure). This is expressed by,

$$RI = R_{vol} * R_{occ} * R_{tem} \tag{30}$$

3.2.6 Sustainable Technologies Evaluation Program’s LID Life Cycle Costing Tool

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program that was created to promote Canadian sustainable activities and technical advancements by providing data and necessary analytical tools (TRCA, 2019). STEP independently assesses new technologies to authenticate environmental assertion and helps developers, users and other interested parties to make enlightened decisions about applying and managing innovatory technologies (TRCA, 2019). STEP provides a realistic and accurate cost estimation of different LIDs such as green roof, bioretention, infiltration trenches, permeable pavers, vegetative filter strip, enhanced swale, rainwater harvesting etc. through employing the Low Impact Development Life Cycle Costing Tool (LCCT) (TRCA, 2019).

The primary goal of this tool is to look at the capital expenses of a LID project in Ontario, but it also considers the costs over a 30-year and 50-year life cycle along with retrofit cost which is 16% of capital cost. However, only the capital cost is considered in this study, as the ultimate goal is to evaluate BR’s resilience and reliability and its cost based on various area ratios. Pre-construction, excavation, materials and installation and inspection are the four primary areas of capital costs in the STEP tool. To account for the possibility of hiring a general contractor, a common total overhead of 10% in our costing method is employed. Despite the fact that the tool uses 2018 pricing, each LID capital cost spreadsheet has the option of entering an inflation rate. This option was not used in this study because it has no relevance on the cost-performance efficacy (resilience and reliability) relationship of BR. Inflation rates between 2018 and 2021 in Canada would adjust the projected costs to 2021 rates however the link between cost and sizing criterion would remain unchanged; the only difference would be that the costs would be higher.

The tool assumes a rectangular BR cell and completely new construction rather than a retrofit. There are two tables in the STEP tool section for BR, one for BR design and the other for capital cost calculation. Some mandatory fields need to fill up in the design table by the user which are drainage area, native soil infiltration rate, design type, drainage period and BR surface area length to width ratio. Design type depends on underdrain requirement by BR to sustain its operation and infiltration rate of the soil distinguishes this requisite. As the BR's soil infiltration rate is > 15mm/hr, this system is designed for full infiltration without any underdrain. The programme calculates a few more fields, but the user can change them to fit their own design demands. The capital cost table calculates pricing for each associated task when all inputs have been entered into the STEP programme. The parameters used in this study to calculate capital cost of BR are given in Table 3.3.

Table 3.3 *Parameter values for BR cost estimation*

Input Parameter	Value
Drainage Area	Impervious Area
Native soil infiltration rate	36 mm/hr
Design type	Full infiltration
Drainage period	48 hours
BR surface area length to width ratio	1.25-2.5
Max drainage area to surface area ratio	5-40
Void ratio	40%
Ponding depth	0.2m

3.3 Application Demonstration

The methodology described above is applied to BR system using historical rainfall data of Hamilton A (43.17°N, 74.94°W). The whole dataset is retrieved from Environment Canada (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html), covering the years from 1978 to 2015, including nine years of missing data (23.68% of missing data). An exclusion of snow months and inclusion of rainfall months are considered in this study based on the daily minimum temperatures. According to Environment Canada, rainfall months start from April 1st and continues up to November 30th in the test location and are therefore used as study months in developing the APA model.

In this study, APA and SWMM are used to estimate the hydrological information that is needed for resilience quantification. Prior to their applications to the case study of interest, and similar to any other hydrological models, APA and SWMM must first be calibrated and validated using observed data. However, as the current study considers a hypothetical catchment, APA and SWMM are not compared to field data. Instead, since continuous simulation models (e.g., SWMM) are reliable and widely trusted, the APA results are compared to SWMM to ensure that both models represent the same LID and contributing catchment by using the same or equivalent parameters (Zhang and Guo, 2013, Zhang and Guo, 2014; Zhang and Guo, 2015). To achieve so, first, contributing catchment and BR are modelled in SWMM as sub-catchments A and B respectively. Similar Horton model's parameters values (maximum infiltration rate, f_m(mm/h), minimum infiltration rate, f_c (mm/h), infiltration capacity decay constant, K (1/h), Drying time, D (day)) were adopted to ensure equivalency in both models considering fill media and soil type of A and B as clay and sand respectively. Also, r in APA represents area ratio between sub-catchments A and B in SWMM and S_d in APA is considered as equivalent to S_{dp} in SWMM. A detailed explanation of parameterization and suggested values of both models are given in the study of Zhang and Guo, 2014. All input parameters data used to develop both models are given in Table 3.4.

Table 3.4 *Input Parameters of contributing catchments and BR*

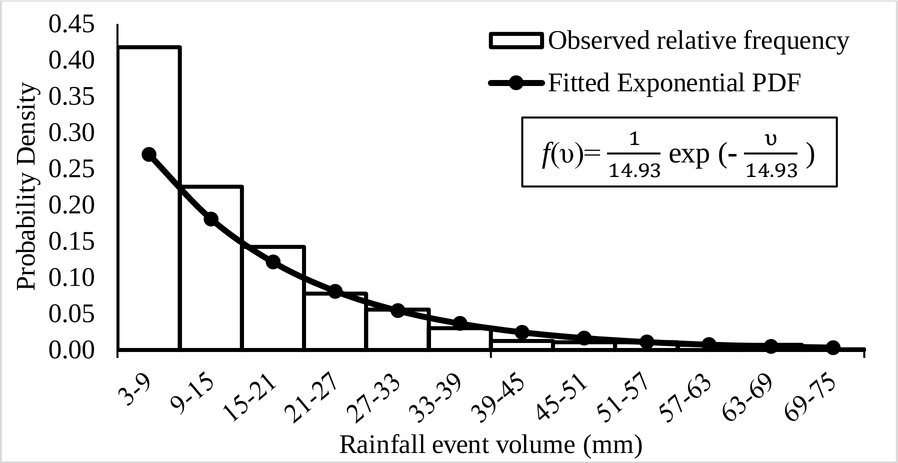
Models	SWMM		APA	
Sub-catchment	A	B	A	B
Fill media/soil Type	Clay	Sand	Clay	Sand
Area ratio of contributing sub-catchment and BR, r (unitless)	x	5-45	x	5-45
Depression storage of BR, S_d (mm)	x	100-600	x	100-600
Evaporation rate, E_a (mm/h)	x	0.11	x	0.11
Maximum infiltration rate, f_m (mm/h)	25.4	127	x	127
Minimum infiltration rate, f_c (mm/h)	0.36	36	x	36
Infiltration capacity decay constant, K(1/h)	6	3	x	3
Drying time, D(day)	12	4	x	x
Depression storage of contributing sub-catchment, S_{dc} (mm)	x	x	2.3	x
Runoff-co-efficient, ϕ (fraction)	x	x	0.912	x
Constant, R (unitless)	x	x	x	0.014
Area of sub-catchments (ha)	1	0.02-0.2	x	x
Sub-catchment width (m)	500	25	x	x
% slope of sub-catchment	3	0.5	x	x
% imperviousness of sub-catchment	70	0	x	x
Manning’s co-efficient for impervious sub-area, N-Imperv	0.013	0.01	x	x
Manning’s co-efficient for pervious sub-area N-perv	0.15	0.15	x	x
Depression storage for impervious sub-area, Dstore-Imperv, S_{di}(mm)	2	0	x	x
Depression storage for pervious sub-area Dstore-Perv, S_{dp} (mm)	3	100	x	x

3.4 Results and Discussion

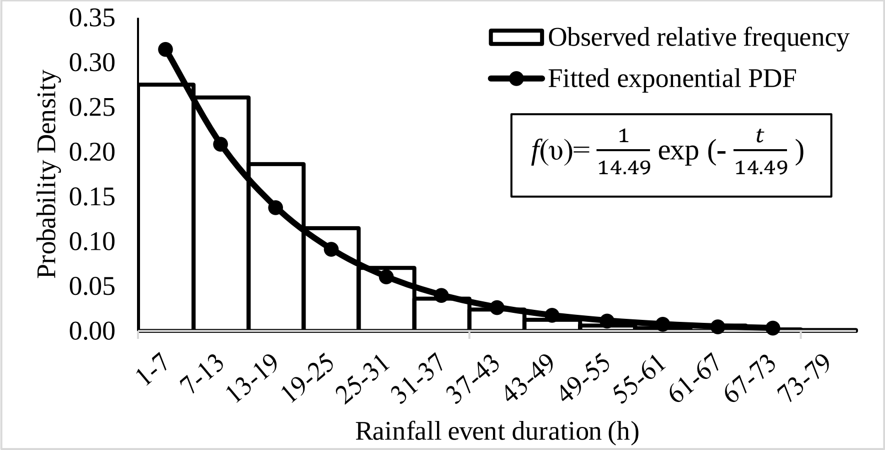
3.4.1 Poisson test results and Estimated Distribution Parameters

A MIET of 12 hr and v_{min} of 3mm has resulted in an acceptance of the hypothesis that the annual number of events follows a Poisson distribution. This selection generates a poisson ratio (r_p) value of 1.08 for the rainfall of Hamilton A, which lies within the range of critical values r_p (0.604-1.476) at a 10% significance level.

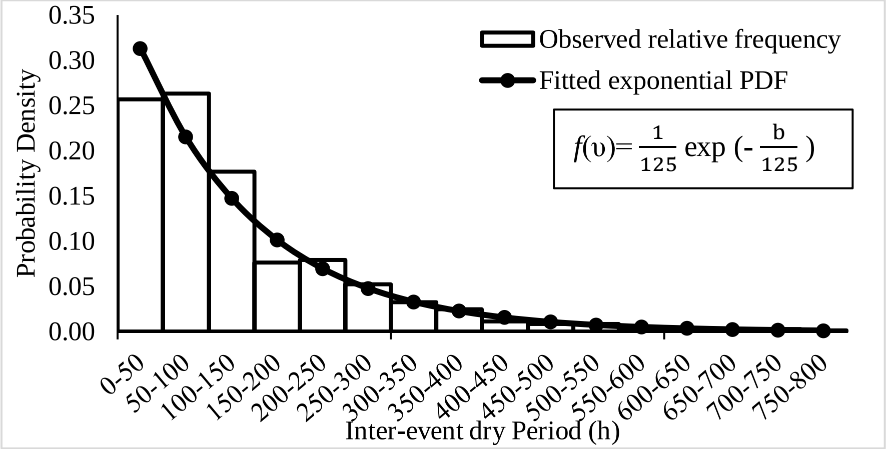
The resulting MIET and v_{min} segregated continuous rainfall series into 1046 individual events (n=1046). The histograms of the rainfall event characteristics such as v, t and b are shown in Figure 3.5.


Observed relative frequency
Fitted Exponential PDF
$f(\upsilon)=\frac{1}{14.93}\exp\left(-\frac{\upsilon}{14.93}\right)$
Probability Density
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
3-9
9-15
15-21
21-27
27-33
33-39
39-45
45-51
51-57
57-63
63-69
69-75
Rainfall event volume (mm)

(a)


Observed relative frequency
Fitted exponential PDF
$f(\upsilon)=\frac{1}{14.49}\exp\left(-\frac{t}{14.49}\right)$
Probability Density
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1-7
7-13
13-19
19-25
25-31
31-37
37-43
43-49
49-55
55-61
61-67
67-73
73-79
Rainfall event duration (h)

(b)


Observed relative frequency
Fitted exponential PDF
$f(\upsilon)=\frac{1}{125}\exp\left(-\frac{b}{125}\right)$
Probability Density
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0-50
50-100
100-150
150-200
200-250
250-300
300-350
350-400
400-450
450-500
500-550
550-600
600-650
650-700
700-750
750-800
Inter-event dry Period (h)

(c)

Figure 3.5: *Frequency distributions of rainfall event characteristics at Hamilton A (IETD=12 hr, v_{min}=3mm): (a) rainfall event volume; (b) rainfall event duration, and (c)inter-event dry period*

The visual examination of the above Figure 3.5 depicted that exponential distribution fit all the histograms very well similar to previous studies (Zhang and Guo, 2014' Hassini and Guo, 2016; Guo and Guo, 2018). The estimated distribution parameters (ζ, λ, ψ) are found from the means of the event characteristics i.e $\overline{v}$ = 14.93mm; $\overline{t}$= 14. 49 h and $\overline{b}$ =125h, which are 1/14.93 mm^{-1}, 1/14.49 $h^{-1,}$ and 1/125 $h^{-1,}$ respectively.

3.4.2 Comparison of Resilience Assessing Indicators between APA and SWMM

3.4.2.1 Robustness

A typical comparison between robustness using both approaches is shown in Figure 3.6 (for clarity and space constraints, not all r ratio cases are included). The figure shows the average robustness variation in both models which is 81.43%- 99.93% (SWMM) and 76.75%- 98.99% (APA), respectively, and the difference in robustness estimation using both approaches is less than 6%.

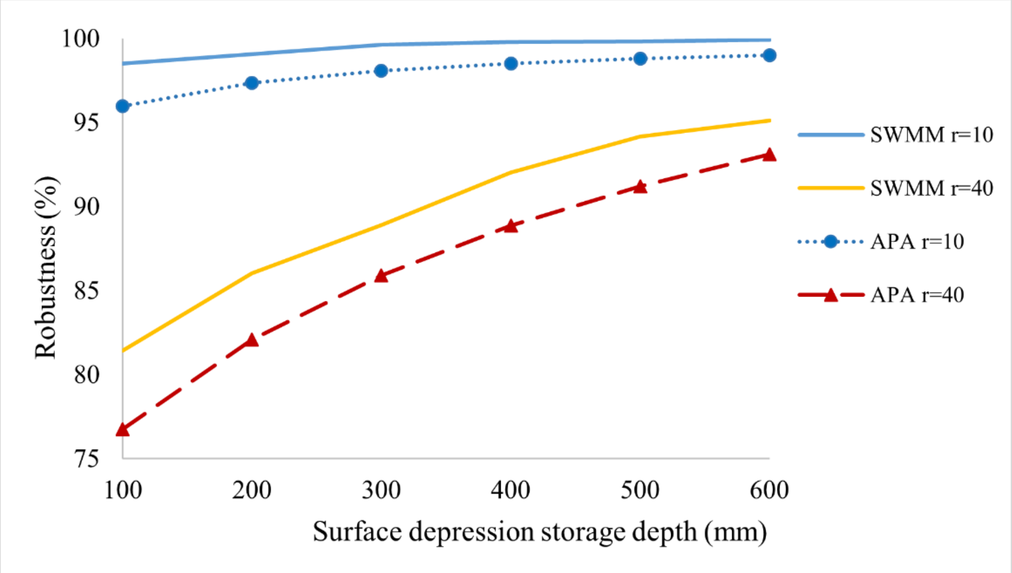


Figure 3.6: *Robustness determination using APA and SWMM*

3.4.2.2 Rapidity

This indicator measures the total time required to recover its full functionality after reaching a minimum value (F_{min}). The rapidity estimated considering using both approaches is depicted in Figure 3.7. The result shows that the average rapidity for all r and S_d values vary between 3.90 and 17.94 h in SWMM whereas in APA they vary between 2.13 and 6.94 h. Amount of infiltration increases proportionally with BR's area. Consequently, all r ratios having same S_d, generates same rapidity. The difference between rapidity calculated using both models is very high (approximately 55%) and the reason behind this discrepancy is mainly attributed to the difference between the APA and SWMM model approaches of estimating functionality.

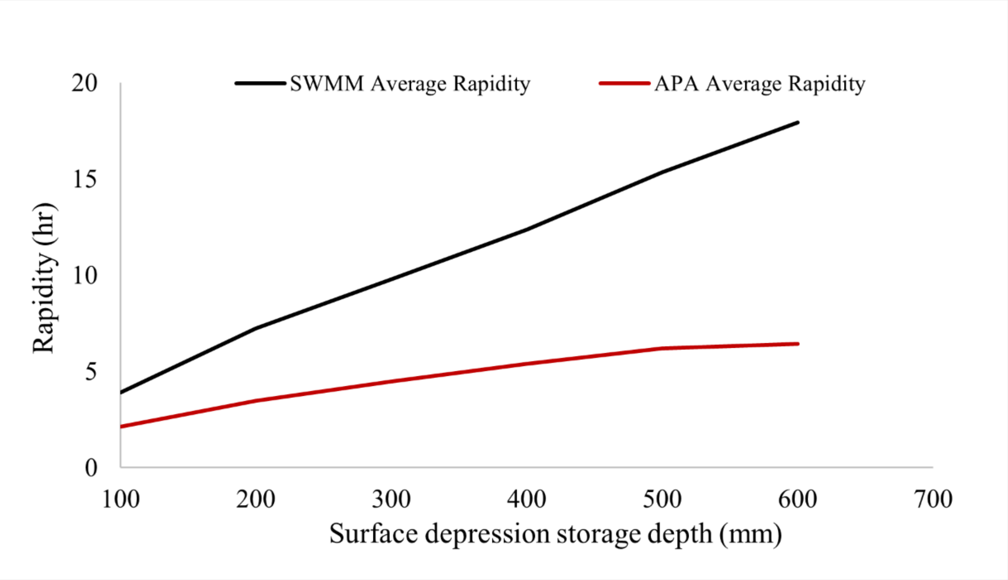


Figure 3.7: *Rapidity estimation using APA and SWMM approach*

3.4.2.3 Functionality loss and Serviceability Index

The second term of Eq. (12) and Eq. (13) estimates the average functionality loss of the BR. This value varies from 1.01%-23.25% in APA and 0.07%-18.57% in SWMM which means that the system is expected to lose 0.07% to 23.25% of its original functionality (both approaches) due to storm events from 1978 till 2015. Figure 3.8 illustrates serviceability index value for the cases (r=10 and r=40) using both models. S_I value ranges from 89.54% to 99.94 % in SWMM whereas in APA this variation ranges from 85.70% to 99.66 % and the difference in S_I estimation using both models is less than 5% if BR implementation area varies from 2.5% to 10% of its contributing drainage area. The higher S_I indicates that the parameters used in the case study of the BR system are sufficient to provide significant serviceability.

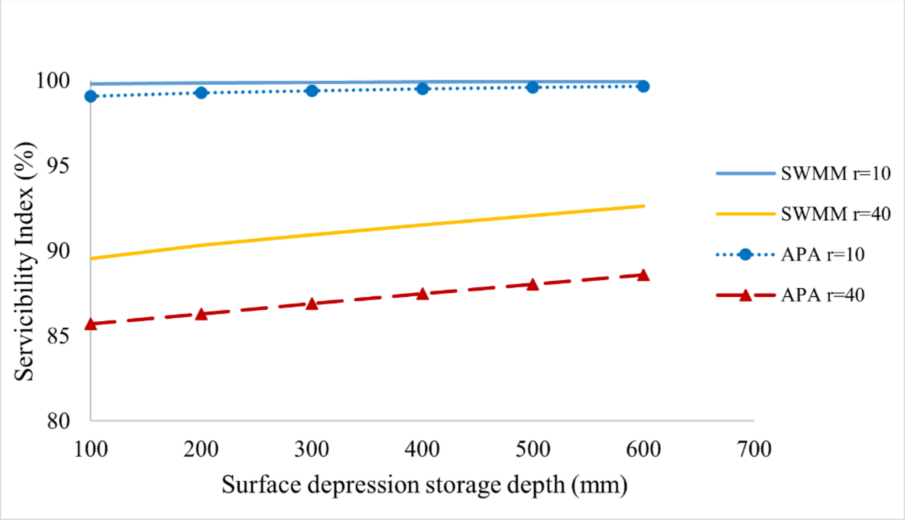


Figure 3.8: *Serviceability Index determination using APA and SWMM*

3.4.2.4 Overall Resilience Index

Figure 3.9. presents overall resilience index (я) value using both approaches. This value varies between 0.73-1.0 in SWMM whereas in APA it ranges from 0.66 to 0.99 for all possible combination of cases shown in Figure 3.9. SWMM generates a slightly larger я value due to having higher robustness (R_d) and S_I value compared to APA.

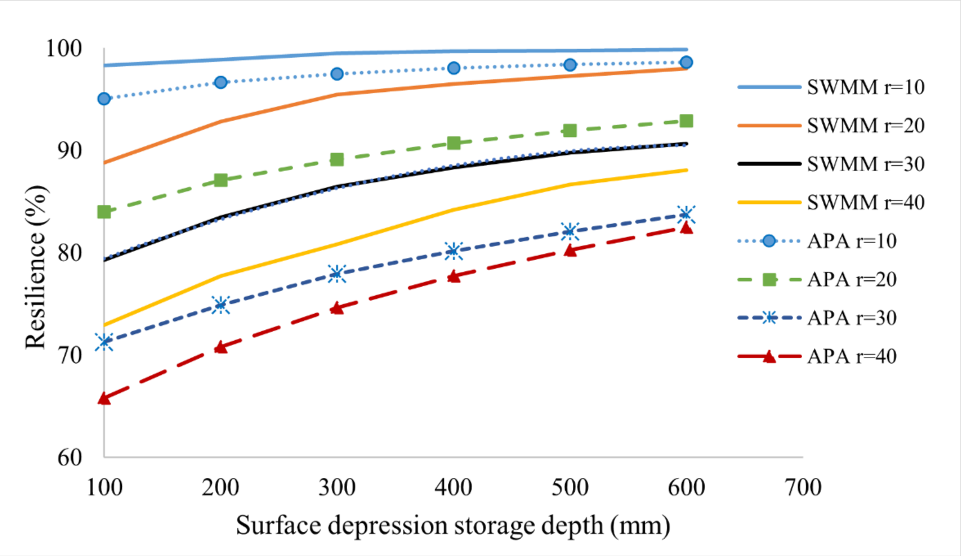


Figure 3.9: *Overall Resilience Index using APA and SWMM*

3.4.2.5 Reliability Index

As the overall reliability index is the product of three indices, each index is separately calculated using Eqs. (25) - (30) and the results of this index using both models are shown in Figure 3.10. Reliability index value ranges from 60.50% to 99.67% in SWMM and 56.67% to 99.99% in APA and the differences in *RI* determined for all cases is not beyond 7%.

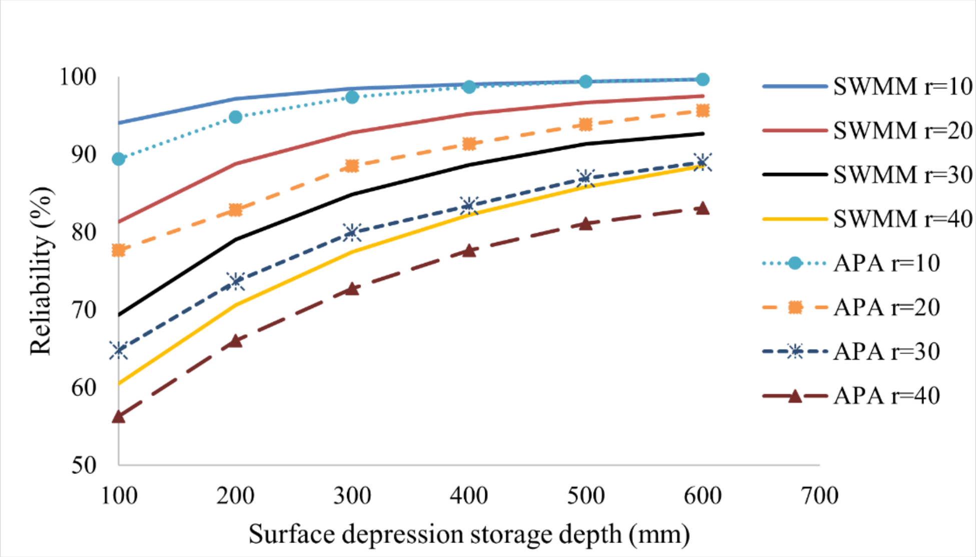


Figure 3.10: *Reliability of BR using APA and SWMM*

3.5 Cost-Effective Design of a Resilient-Reliable BR System

The total capital cost mainly depends on the ratio of contributing catchment area and BR surface area, r and range of S_d values do not affect this expenditure. A decrease in r value or increase in BR area results a larger excavation, materials, installation and inspection costs. Therefore, a rising trend of costs based on area ratios is not shown here. Also, from Figure 3.9 and Figure 3.10, it is clear that resilience and reliability of BR also increases with decrease of r. To ensure cost-effectiveness of a resilient and reliable BR design, a relationship among resilience, reliability and total capital cost for different r values (5,10,20,30,40) is shown in Figure 3.11 and Figure 3.12. Three S_d values (100,300 and 600 mm) are considered to illustrate their relationship due to space limitations and better visualization.

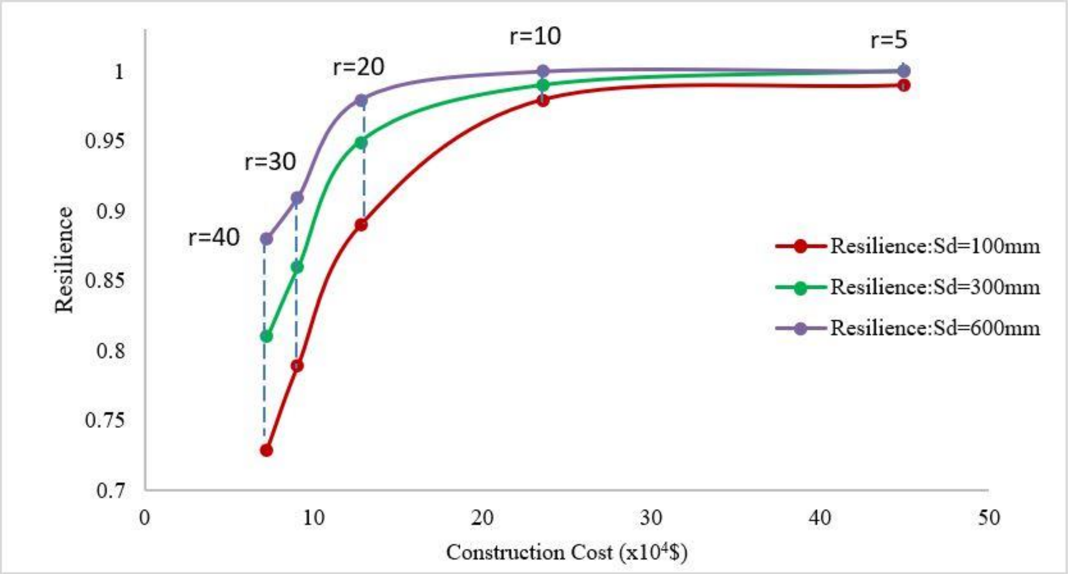


Figure 3.11: *Variation of Resilience with Capital Cost for different area ratios*

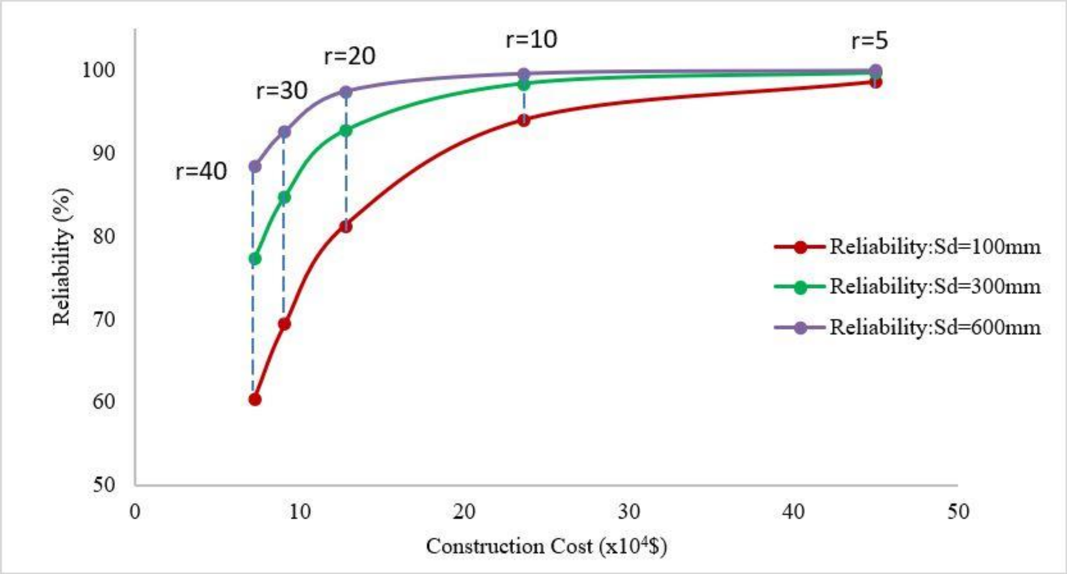


Figure 3.12: *Variation of Reliability with Capital Cost for different area ratios*

Both Figure 3.11 and 3.12 depict that resilience and reliability values tend to plateau after a certain area ratio (*r*=10) however, the cost remains increasing as BR area increases. In order to get 80% resilience and reliability, *r*=40 with S_d ranging from 300 to 400mm is appropriate and 7.23x$10^4$$ will be required for the purpose. However, to achieve 90% performance efficiency (both я and RI), *r*=30 and S_d =500mm is suitable and 9.06 x$10^4$$ will be needed to achieve this target. Almost 95% performance efficacy can be achievable with *r*=20 and S_d ranging from 300-600 mm by spending 12.76x$10^4$$ which is 40% higher than the previous cost. After this point (*r*=20), performance efficiency will increase by only 4% on average but 85% more spending will be required which is costlier in terms of performances. In light of all the results, an area ratio of 30 and 20 with S_d varying from 300-600 mm can be deemed as the most efficient design criteria for BR to get about 90-95% resiliency and reliability and this is achievable by making the length to width ratio (L:W) of BR as 1.875 and 1.25 respectively.

3.6 Discussion

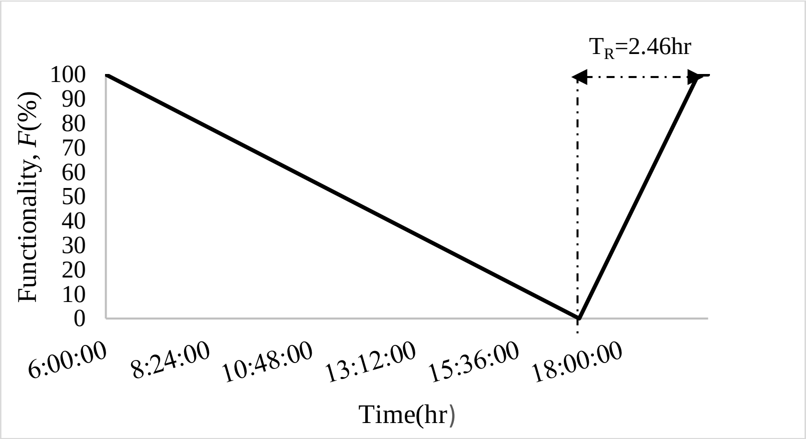
3.6.1 Assessment of resilience and reliability indices of BR system

The APA models are only applicable where rainfall-event characteristics (i.e., volume, duration and inter-event time) are exponentially distributed. For the rainfall data of Hamilton, A, Canada, the results of the Poisson test indicate that the number of rainfall events follow a Poisson distribution. This implies that the interevent time (i.e., dry time between events) is exponentially distributed. Figure 4 shows that the rainfall-event volume and duration follow exponential distributions. Therefore, the selected rainfall data can be used for the resilience analysis, along with the APA model.

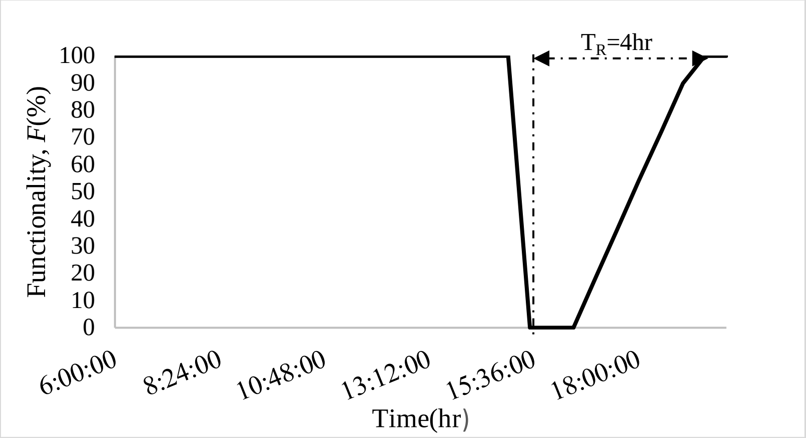
For robustness, SWMM also generates a higher value compared to APA. Figure 3.6 shows the variation between both approaches to be less than 6%, where SWMM generates higher robustness as it considers all small rainfall events (i.e., rainfall depth< 3mm). Attributed to the small rainfall depth and the large BR's capacity, throughout the event duration, functionality did not drastically change from $\mathrm{F_i}$ (i.e 100%)—resulting in a comparatively higher robustness value. However, using APA, such small events are ignored, and functionality was thus not estimated for these cases. As the average robustness is calculated based on the cumulative robustness of all events, APA generates a lower robustness value.

Among all resilience indices rapidity is one of the major indicators. Figure 3.7 depicts that approximately 55% difference lies in rapidity estimation using both models. This is attributed to the fact that the SWMM simulation provides functionality at every time-step and therefore parameters such as i) the exact timing of F_{min} occurrence; ii) the time interval within which BR remains in this $\mathrm{F_{min}}$ state and iii) the exact time of recovery initiation. These parameters enable the model to estimate exact rapidity. However, the APA simulation provides functionality per event specially at the start and end of the event. In this approach, functionality is always 100% at the beginning of an event due to the existence of large MIET between two rainfall events and at the end, this value can vary from 0%-100%. Therefore, rapidity estimation starts from the event's end time assuming that F_{min} can only occur at this instant; however, this may not be the case considering SWMM. Because of the nature of the APA simulation, exact F_{min} occurrence time during a single event and the duration of BR remaining in this state cannot be evaluated, thus limiting the ability of APA to estimate the rapidity time compared to SWMM.

Figure 3.13 illustrates the difference between the rapidity estimation using APA and SWMM. A storm event that occurred on 28th June 2013 is used here for demonstration. The storm occurred at 6:00 am and continued to 5:00 PM. F reaches its minimum value (0%) at 5:00 PM in APA and at 3:30 PM in SWMM. Rapidity is calculated from this time using both simulations which result in 2.46hr (APA) and 4hr (SWMM). SWMM's estimated value is larger than APA as the former is capable of estimating the exact time of F_{min} occurrence and duration at which LID stays in this non-functional state unlike APA.



(a)



(b)

Figure 3.13: *An illustration of rapidity estimation using (a) APA and (b) SWMM approach*

The variation in S_I calculation using both simulation approaches is very small (less than 5%) which means that the parameters used in the case study of the BR system are sufficient to keep the system mostly functional in its overall simulation period indicating a resilient system. The outcomes of these indices are key for the decision-making pertaining to LID systems and to quantify the LID's vulnerability and post-storm event consequences.

The estimated overall resilience index (я) value is higher (closer to 1) considering both simulation approaches when the BR implementation area is large, and it shows an upward trend with increase in surface depression storage value (Figure 3.9). However, SWMM generates slightly larger я value due to its higher robustness (R_d) and S_I value compared to those of the APA. The resulting value reveals that, to achieve high resilience, each of the indices must exhibit values above 90% to 95%, otherwise due to the multiplication nature of calculating the index, the overall system resilience might be severely impacted.

The results obtained from Figure 3.10 depicts that both the APA and SWMM simulation produce similar reliability index value which ranges from 56%-99.99%. Among all reliability indices, the volumetric reliability (87% on average) is comparatively smaller than the occurrence-and the temporal reliability (98% on average) for all possible combinations listed in Table 2. This fact implies that BR absorbed 87% (on average) of stormwater from past events. The higher occurrence and temporal reliability values mean that BR remains mostly in satisfactory states. This in turn indicates that the system was reliable throughout the simulation period and thereby provides enough retention capacity for any unprecedented events to capture the stormwater. Having enough retention capacity suggests that the LID's storage was not completely full throughout the events, which might be due to i) low inflow volume compared to BR's storage capacity and ii) high infiltration rate of BR's soil.

STEP tool simulation results (Figure 3.11 and 3.12) show that decreasing the area ratio beyond 20 will increase the cost and no improved performance efficacy is achievable. One of the major design input parameters of LID costing tool is L:W ratio and the proposed L:W ratio is considered effective for this case study only; however, it will change based on the actual catchment area and surface area of BR or other LID practices. The case study also discovered that if the length of the BR is greater than the width, the construction cost is lower, however the reverse situation (W>L) raises the cost. This occurs because an overflow or bypass is required in any BR design in order to safely pass large storm volumes to the inlet, and to accomplish this, an overflow pipe drain is built along the width of the BR, with the required length for this pipe being width of BR +1m. If the width of BR's surface area is greater than the length of the BR, the cost of trenching the pipe, pipe fitting material, and labour rises as the width expands. As a result, this research proposes that the BR's breadth be kept less than its length.

3.6.2 Limitations

Despite using both APA and SWMM models for assessing resilience and reliability of BR system, there are still some limitations. First, calibration and validation are critical components of numerical model acceptance. However, the SWMM simulation employed herein was not calibrated using field data as the analysis was performed on a hypothetical catchment, and the focus was on comparing the APA simulation results with those of the SWMM simulation when similar input parameter values are used (Zhang and Guo, 2013, Zhang and Guo, 2014; Zhang and Guo, 2015). Future research can thus use this approach in a real case scenario using real life field data as they become available. Second, since the APA model does not provide exact rapidity estimation (due to its nature), the SWMM simulation is preferred for calculating this indicator. As such, future studies can estimate the rapidity using the APA approach and the variation percentage between both models (i.e., Figure 3.7) can then be applied to determine the exact recovery time. Finally, with time, wastes can accumulate on BR's surface which can cause clogging and subsequently vegetation may be affected which will ultimately disrupts stormwater capturing by the system. In this respect, performance, reliability and the overall LID system's resilience may be impacted. As a first step in introducing the concept of resilience to stormwater management, this study assumes that the LID performs as designed, which can be maintained through routine inspection and maintenance such as removal of wastes, debris and sediments, and plant trimming and maintenance. However, in future studies, more complex resilience models can be improved by including practical aspects and the possibility that the LID may not perform as designed.

3.6.3 Recommendations:

The developed resilience quantification approach and study findings will benefit: 1) policymakers (e.g., to create plans and budgets for LID inspection and maintenance); 2) LID practicing engineers and researchers (e.g., to implement the approach in a decision support tool and choose the best option); and 3) designers (to ensure resilient optimal LID design). The developed approach can be used in different weather conditions and for different LIDs.

Functionality estimation technique using the LID control editor of SWMM is a generic one that can be applied to any LID practices thus facilitates estimation of resilience and reliability indices. The indices considered in this study can be further developed and additional new indices can be proposed and included as a part of the overall resilience index and for optimal LID design. Moreover, future studies can consider climate change scenarios and determine the indices both at the baseline and changing climate condition which may help in determining the adaptability and improvability of LID system, thus fostering additional knowledge in the resilience assessment.

3.7 Conclusion

LIDs have been implemented as an adaptive strategy to counteract the adverse impacts of urbanization and climate change. These practices are expected to withstand the immediate turmoil to its functionality due to perturbations and restore its pre functionality by mitigating the extended-term consequences such as recoverability or repair time. In such case, enhancing LID's resilience will eventually help the UDS to absorb such disturbances and transform efficiently. For the first time, this study establishes a linkage between LID's (BR) storage capacity and engineering resilience based on BR's functionality and three performance indices: rapidity robustness and serviceability index. Apart from rapidity, the other two indices are multiplied to develop a new overall resilience index to quantify LID's resilience. In addition, reliability of the whole BR system is assessed using three reliability indices: volumetric, occurrence and temporal to keep the system operational. Sustainable Technologies Evaluation Program's (STEP's) LID Life Cycle Costing Tool is also used to estimate capital costs of BR under various area ratios and a design guideline through graphical approach is proposed to identify the most cost-effective design parameters of the BR.

Two hydrological modeling approaches: Previously developed APA and continuous simulation using SWMM is adopted to carry out the study. Previously developed equations and a set of new equations are developed in both models to calculate the indicators of resilience and reliability for a wide range of area ratios (5-45) and surface depression storage depths (100-600mm). A close agreement between APA and SWMM results (except rapidity) depicts the accuracy of APA in determining the indices of the BR system. The estimated average robustness index from APA (92.48%) and SWMM (95.84%) is paradigmatic of an acceptable robustness level of the BR system for all possible combination of area ratios (r) and surface depression depths (S_d). However, 55% higher average rapidity value is observed in SWMM compared to APA due to SWMM’s intrinsic capacity of simulating exact functionality at small time increments. The serviceability index value ranges from 89.54%-100% and 82.96-99.96% in SWMM and APA respectively. Using the product of the two indices (except rapidity), a similarity is observed in the overall resilience index value from APA and SWMM which is 0.66-1.0 and 0.73-1.0 respectively. Overall reliability index value ranges from 60.50% to 100% in SWMM and 56.67% to 99.99% in APA, demonstrating that the system operated efficiently throughout the period. The analysis from the STEP tool reveals that an area ratio of 20 and 30 with S_d ranging from 300-600 mm is the most cost-effective design criteria to obtain approximately 90-95% resilient and reliable BR system.

4. Conclusion

This thesis aims to conduct a systematic and bibliometric literature review in the context of LIDs optimization and resilience to identify gaps and prospective research opportunities in LID's optimal design. In addition, this research investigates whether any resilience quantifiable approach to LID still exists. Based on co-citation analysis, this study has identified four research clusters, with the clusters' themes discovered using text mining techniques. The cluster themes are as follows: (1) LID type and size optimization, (2) LIDs location optimization considering uncertainty in climate and land-use change impacts and hydrological parameters (3) utilization of multicriteria analysis and hydraulic parameter optimization, and (4) experimental studies on BR for quantitative and qualitative performance assessment. Climate change, uncertainty, and resilience are identified as the most cutting-edge study topics in this field. Previous studies referred to a LID as a resilient infrastructure if it provides satisfactory performance under changing climate and land use conditions and assess resilience for the entire urban drainage system, not for the LID itself. Since no quantifiable resilience evaluation technique based on resilience goals is identified for LID systems, maximizing LIDs resilience has never been considered as a part of optimization objectives in the past.

Based on this finding and in order to improve future optimal LID design, this study proposes a new resilience quantification method by developing set of equations using both Analytical Probabilistic Approach (APA) and continuous simulation using SWMM. SWMM is used here to ensure that the assumptions employed in APA are admissible and to validate APA results. The equations have established a linkage between engineering resilience and LID's storage capacity by determining LID's functionality. Three performance metrics are considered to assess resilience: rapidity, robustness, and serviceability. Apart from rapidity, the multiplied product of the other two metrics yielded a new overall resilience index, which quantifies LID’s resilience. Furthermore, the whole BR system's reliability is evaluated using three reliability indices: volumetric, occurrence, and temporal to keep the system functioning. The LID Life Cycle Costing Tool of the Sustainable Technologies Evaluation Program (STEP) is also employed to determine the capital costs of BR under various area ratios, and a design guideline based on a graphical approach is proposed to determine the most cost-effective design parameters of the LID to ensure satisfactory resilience and reliability.

A contributing catchment of 1ha with 70% imperviousness, bioretention (BR) as a LID and historical rainfall (1978-2015) of Hamilton A are used in this study as a demonstration purpose. Different area ratios (r) varying from 5-45 and surface depression storage depths (S_d) ranging from 100-600 mm are considered to evaluate the abovementioned performance metrics and the overall capital cost. The accuracy of APA in calculating the indices of the BR system is shown by the close agreement between APA and SWMM results (excluding rapidity). For all possible combinations of r and S_d , the estimated average robustness index from APA (92.48%) and SWMM (95.84%) is representative of an acceptable BR’s robustness level. In APA and SWMM, the serviceability index value varies from 82.96%- to 99.96% and 89.54%-100%. 55% lower average rapidity value is found from APA than SWMM due to APA's inability to measure functionality in small time increments. The overall resilience index values are estimated as 0.66-1.0 and 0.73-1.0 from APA and SWMM respectively. The overall reliability index in SWMM varies from 60.50%-100%, whereas in APA it ranges from 56.67 %- 99.99%, indicating that the system performed competently throughout time. The STEP tool's analysis shows that a r value of 20 and 30 with S_d ranging from 300 to 600 mm provides the most cost-effective solution for an approximately 90-95% resilient and reliable BR system.

In closing, the developed equations of resilience quantification and procedure of selecting a cost-effective design criterion can be adopted for any LID practices and can also be integrated into a decision support tool that enables stakeholders and decision-makers to better plan and design LID systems under different storm event magnitudes and durations.

5. Future Recommendations

The presented study is the first phase of a larger research program. Additional investigation planned include several subsequent phases including the following.

- The newly developed resilience quantifiable approach can be applied to other LIDs such as green roof, permeable pavement, infiltration trenches etc. in the future. To do so, previously developed APA equations of these LIDs must be employed to determine functionality and resilience evaluation indicators in the same way as outlined in this work. In the instance of SWMM, LIDs functionality estimation using the LID control editor is a generic method that may be applicable to any LID practice enabling the estimation of resilience indices easier.
- It might be worthwhile to evaluate the indices (rapidity, reliability, serviceability, reliability) in sites other than Hamilton under severe weather conditions.
- The proposed indices can be integrated into a decision support framework to facilitate the planning and decision-making process of LID system.
- Further development of the proposed indices may be undertaken in future. Furthermore, the overall resilience index can also be expanded with the addition of new indices.
- Existing, modified, or newly proposed indices can be employed as part of the optimization objectives for any LID system during its optimal design.
- Finally, future studies may consider climate and land use change scenarios and evaluate the abovementioned indices at both baseline and changing climate conditions, which could aid in determining the LID system's adaptability and improvability, thereby adding to the resilience assessment knowledge base.

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