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Nature-based solutions for flood mitigation in Canadian urban centers: A review of the state of research and practice

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A R T I C L E I N F O

Keywords:
Blue-green infrastructure
Flood-resilience
Nature-based solutions
Urban flooding
Urban land use planning

A B S T R A C T

Study region: Canadian urban regions.
Study focus: This paper examines nature-based solutions (NBS) for urban flood mitigation, assessing various practices such as bioretention cells, green roofs, permeable pavements, and rainwater harvesting in the context of Canadian cities.
New hydrological insights for the region: The findings reveal that NBS are increasingly recognized as effective tools for managing urban stormwater and improving flood resilience. However, there is a significant gap between research and practice, with many municipalities still in the pilot project phase. Challenges include lack of region-specific design guidelines, especially for cold climates, and insufficient long-term performance and monitoring data. The paper highlights the need for more studies on assessing NBS effectiveness in northern regions, which remain under-researched. Additionally, the integration of NBS with traditional grey infrastructure is critical to maximizing flood mitigation benefits. The review also identifies the importance of developing cost-effective strategies and improved modeling tools to support the broader implementation of NBS. Future research should focus on evaluating NBS combinations, understanding their adaptive capacity in a warming climate, and addressing data gaps to bridge the divide between academic findings and practical applications of NBS.

1. Introduction

Over the past century, rapid urbanization and ongoing expansion of urban areas (Jha et al., 2012; Seto et al., 2010) have led to significant changes in land use patterns, a notable increase in impervious surfaces and surface runoff, and reduced stormwater infiltration (Bell et al., 2016; Chen et al., 2017; Czemiel Berndtsson, 2010; Du et al., 2012; Guan et al., 2015; Valtanen et al., 2014; Yang et al., 2011; Yao et al., 2016). Furthermore, the frequency and intensity of extreme rainfall events are projected to increase under a warmer climate in the future, notably for short duration storms which are mostly responsible for urban flooding (Bush and Lemmen, 2019; Cannon et al., 2020; IPCC, 2023; Martel et al., 2020, 2021; Oh and Sushama, 2020; Silva et al., 2021). A potential consequence of

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these changes is the increase in the frequency and magnitude of urban flood events. The findings of Canadian studies by Teufel et al. (2017, 2019) and Martel et al. (2020, 2021) support this assertion.

Climate change and urbanization not only have the potential to alter surface flooding but also impact the planning and design of drainage systems (Arnone et al., 2018; Semadeni-Davies et al., 2008; Willems, 2013; Zhou et al., 2019). For instance, persistent alterations in hydrologic patterns, particularly the routes and features of surface flooding, may necessitate the transformation of urban drainage systems (Mahmood et al., 2017). The aging drainage systems were not designed to accommodate these changes, posing substantial risks and hazards to local communities (Binns, 2020). Stormwater systems are traditionally engineered using past rainfall data, grounded in the stationarity assumption (Hathaway et al., 2024; Karamouz et al., 2022). However, this foundational assumption has become questionable, creating a knowledge gap concerning reliability of these systems and adequacy of existing design methodologies. Incidents related to intense rainfall, resulting in extensive surface and basement flooding, occurred in Ottawa-Gatineau region in 2017, 2019 (Olthof and Svacina, 2020) and 2023 (Global News, 2023), Vancouver, British Columbia, in 2018 (Pallathadka, 2023), Burlington, Ontario, in 2014, Thunder Bay, Ontario, in 2012 (Sandink, 2016), Windsor, Ontario, in 2011 (Ganguli and Coulibaly, 2019), and Toronto, Ontario, in 2013. These events highlight the need for innovative solutions than being solely dependent on conventional drainage systems.

Nature-based solutions (NBS) have proved to be an ecologically harmonious approach to address urban flooding challenges (Dorst et al., 2019). These solutions encompass a wide range of decentralized, vegetative and some non-vegetated techniques designed to mimic natural hydrologic processes such as infiltration and evapotranspiration (Ferreira et al., 2022). Techniques such as temporary detention and rainwater harvesting and reuse can also be considered as NBS. The NBS term serves as an umbrella term, encompassing

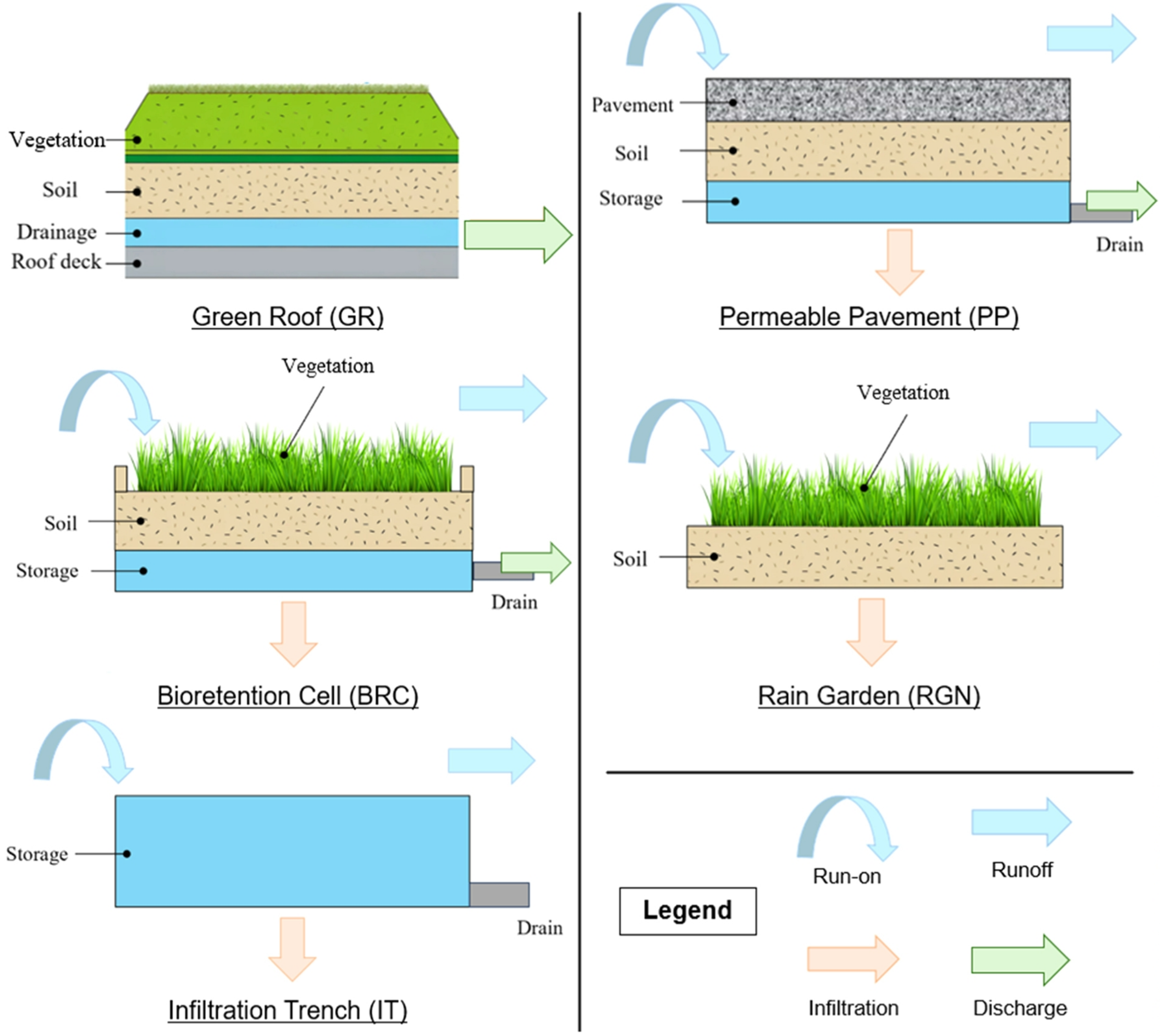

Fig. 1. Schematic illustration of some of the NBS, namely GR, BRC, RGN, RB, IT, and PP, inspired by various illustrations of the Stormwater Management Model (US EPA 2022).

various terminologies such as blue-green infrastructures (BGI), best management practices (BMP), green infrastructures (GI), integrated urban water management (IUWM), low-impact-development (LID), sponge city (SC), sustainable urban drainage systems (SUDS), and water-sensitive urban design (WSUD), all of which refer to a wide range of urban flood risk management and mitigation solutions inspired by nature. These practices include bioretention cells (BRCs), blue or green roofs (GRs), infiltration basins or trenches (ITs), permeable pavements (PPs), rainwater harvesting (RWH), rain gardens (RGNs), rainwater-receiving trees (RRTs), vegetative swales (VSs), among other solutions (Eckart et al., 2017). Fig. 1 gives a schematic illustration of some of these practices. The above-mentioned abbreviations are used throughout the paper and are listed in Table 1 for clarity. By adopting NBS, stormwater runoff can more effectively be reduced from urban areas, alleviating the strain on conventional stormwater systems (Ahiablame et al., 2013; Dhakal and Chevalier, 2017; Li et al., 2019; Vogel et al., 2015). Furthermore, NBS provide numerous additional co-benefits, including enhanced urban aesthetics, increased biodiversity, improved air quality, and a reduction in the urban heat island effect (Raymond et al., 2017).

Numerous studies have provided compelling evidence of the effectiveness of NBS in managing stormwater and improving surface water quality. These findings were derived from a wide range of sources, including laboratory experiments, in situ assessments, and modeling studies (Autixier et al., 2014; Czemiel Berndtsson, 2010; Li et al., 2019; Qin et al., 2013; Zhuang et al., 2016). Canada is also active in both researching and implementing NBS for various purposes, including flood mitigation (Rahman et al., 2022). This review paper aims to consolidate the current state of research and implementation of NBS in Canada in an effort to bridge the gap between research and practice, which will be an ingenious contribution to the broader literature on urban flood management and flood resilience. The outcomes of this paper are expected to advance research on NBS and invigorate discussions on adapting these solutions at local and regional scales. In addition, the outcomes will also help promote nature-inspired sustainable solutions to applied problems in urban settings both in Canada and internationally.

Rest of the paper is organized as follows. Approaches to the identification of technical documents, including published papers and professional reports/manuals, are described in Section 2. A synthesize of the current state of research is provided in Section 3, followed by a review of implementations of NBS, Canadian federal and provincial government initiatives on flood mitigation, and targeted modeling studies from select municipalities in Section 4. Recommendations and obstacles concerning translation of research progress into practical implementations of NBS are discussed in Section 5. Finally, the main conclusions, perspectives on the future of NBS for urban flood mitigation, and relevance of the findings to other regions of the world are provided in Section 6, which also concludes the paper. In order to carefully manage the available literature on NBS and to retain the focus on the above-mentioned objectives of this review, supporting information is organized into three supplementary documents, which are referred to as SM-1, SM-2, and SM-3 in the remainder of the paper; SM stands for "supplementary material".

2. Methods, scope, and outline

2.1. Approach to literature identification

A systematic approach, inspired by online search facilities, schematically shown in Fig. 2, was employed to identify and select relevant literature. The search aimed to encompass a diverse range of sources, including peer-reviewed academic journals, conference articles, theses, scientific reports, municipal documents, books, book chapters, and grey literature. To ensure a broad coverage of the topic, various keywords were included into the search terms encompassing different terms associated with NBS listed in Table 1. To tailor the search for the Canadian context, these search terms were combined with "Canada" and the names of various provinces. Additionally, notable Canadian cities, such as Calgary, Halifax, Montreal, Ottawa, Toronto, and Vancouver were also included as part of the search criteria. This focused approach aimed to identify literature specifically pertinent to NBS for flood mitigation in Canadian urban settings.

The search encompassed three scientific databases: Web of Science, Scopus, and Google Scholar. No restrictions were imposed on document type, language, or time period to ensure identification of a comprehensive range of documents. Both Canada's official languages (French and English) were used to identify all relevant literature. A snowballing procedure (Garousi et al., 2016; Wohlin, 2014; Zhang et al., 2011) was also employed to identify additional studies. In the forward snowballing process, ten gathered articles (five in English and five in French) were randomly selected and checked for references that may have been overlooked in the data gathering process. Simultaneously, in the backward snowballing process, the references cited within these five selected articles were explored to identify additional sources. The documents found through this process were then evaluated based on predefined criteria

Table 1
The list of various abbreviations used in relation to NBS.

	NBS alternative terminology		NBS practice
BGI	Blue-green infrastructures	BRC	Bioretention cell
BMP	Best management practices	GR	Green roof
GI	Green infrastructures	IT	Infiltration trench
IUWM	Integrated urban water management	PP	Permeable pavement
LID	Low-impact development	RB	Rain barrel
SC	Sponge city	RGN	Rain garden
SUDS	Sustainable urban drainage systems	RRT	Rainwater-receiving tree
WSUD	Water-sensitive urban design	VS	Vegetative swale

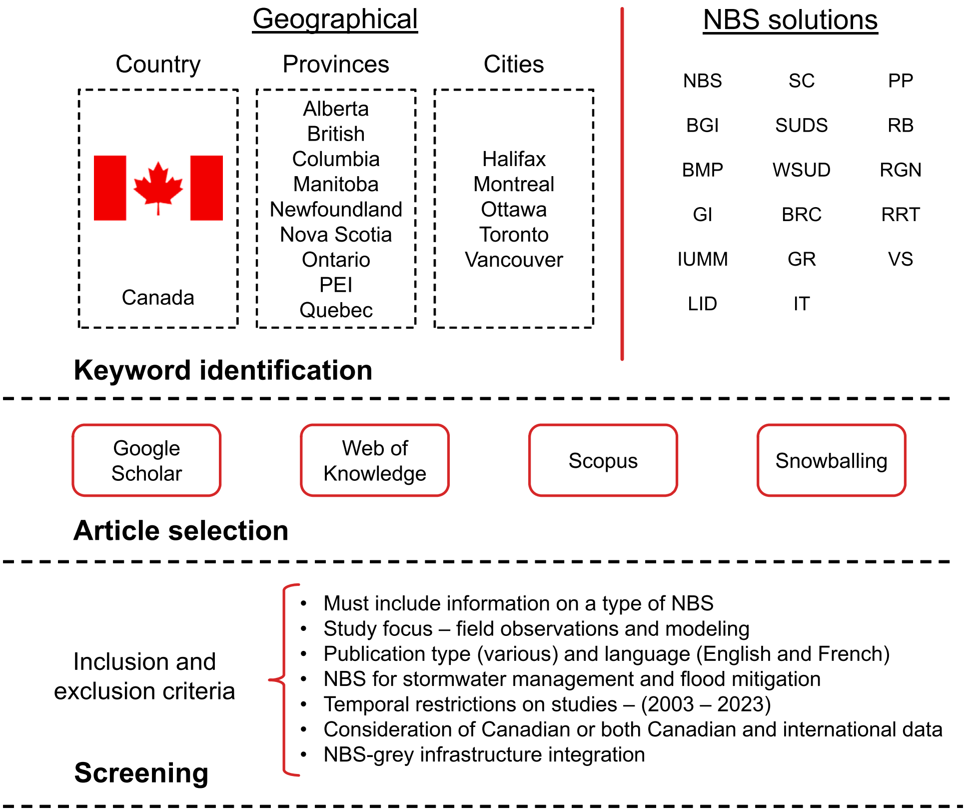

Fig. 2. Schematic diagram showing the three-step procedure used to identify various documents related to NBS and urban flood mitigation in Canada. Description of the inclusion and exclusion criteria is provided in Table 2.

(see Table 2). Following this process, 87 documents with extractable data and information were retained. These documents served as the foundation for synthesizing an overview of the current state of progress on research and implementation of NBS in Canada. A complete list of these studies, including 64 English and 23 French studies, and their objectives, climate context, methodologies, and identified gaps are provided in SM-1. The recommended design specifications and a brief description, the purpose, and key features of selected NBS considered in these studies are provided in Tables SM-2.1 and SM-2.2 in SM-2.

Table 2
Detailed description of the inclusion and exclusion criteria considered for the identification of various documents for this study.

Criteria	Inclusion	Exclusion
Must include information on a type of NBS	Studies that provide information on a type of NBS, encompassing various techniques such as BRCs, GRs, PPs, etc. (Fig. 2).	Studies not providing information on any form of NBS.
Study focus	Studies involving real-world field observations and modeling of stormwater systems.	Studies not involving field observations or modeling of stormwater systems.
Publication type and language	Various publication types, including journal articles, conference papers, guides, scientific reports, theses, books, and book chapters. No restriction was set on the language of the documents.	Publication types not listed in the inclusion criteria.
NBS for stormwater management and flood mitigation	Studies focusing on NBS implementation or modeling stormwater management and flood mitigation in Canada.	Studies not related to stormwater management or flood mitigation aspects of NBS in Canada.
Temporal restrictions	No studies were found before 2003 and hence a timeframe of 2003 to 2023 was considered.	No exclusion criteria were defined.
Consideration of Canadian and international data	Studies containing information from Canada as well as other nations or only encompassing Canadian information.	Studies solely focused on non-Canadian information.
NBS-grey infrastructure integration	Studies on standalone NBS applications or NBS-grey combinations.	Studies solely exploring grey solutions.
Combined sewer overflow (CSO)-related studies	Studies focusing on broader stormwater management systems that may indirectly mention CSO.	Studies primarily focusing on CSO management, impacts, or mitigation.

2.2. Accessing municipal level flood mitigation related documents

In contrast to scientific journals that offer insights into emerging techniques and experimental work, government literature, particularly planning, modeling, and assessment reports, provides a more comprehensive understanding of how Canadian municipalities integrate and implement NBS to address urban flooding. However, despite the recent efforts to improve open access to municipal data and reporting, it is still challenging to obtain such documents. Therefore, additional documents were obtained for this paper through personal communications with public sector collaborators from various regions of Canada.

Initial insights from municipalities were collected through collaborative research conducted by Kim and Khaliq (2022). These insights were subsequently expanded through personal correspondences and information gathering carried out between September 2022 and March 2024. In-depth insights into the state of modeling within the municipalities of Montreal, Ottawa, Thunder Bay, and Vancouver were acquired through in-person engagements with city engineers and officials. Additionally, an examination of all provincial flood mitigation initiatives was conducted to assess the adequacy of funding allocation to identify regions that may exhibit heightened vulnerability to flooding, based on publicly accessible data from provincial websites. Finally, a similar inquiry was undertaken to discern and consolidate information on Canadian federal expenditures and financial allocations related to flood and disaster mitigation programs, including those supporting NBS and ecological restorations.

3. Current state of research

3.1. Breakdown of the reviewed documents

The systematic search, described in the above section, produced 87 documents. Most of these were journal papers (57 %), with the

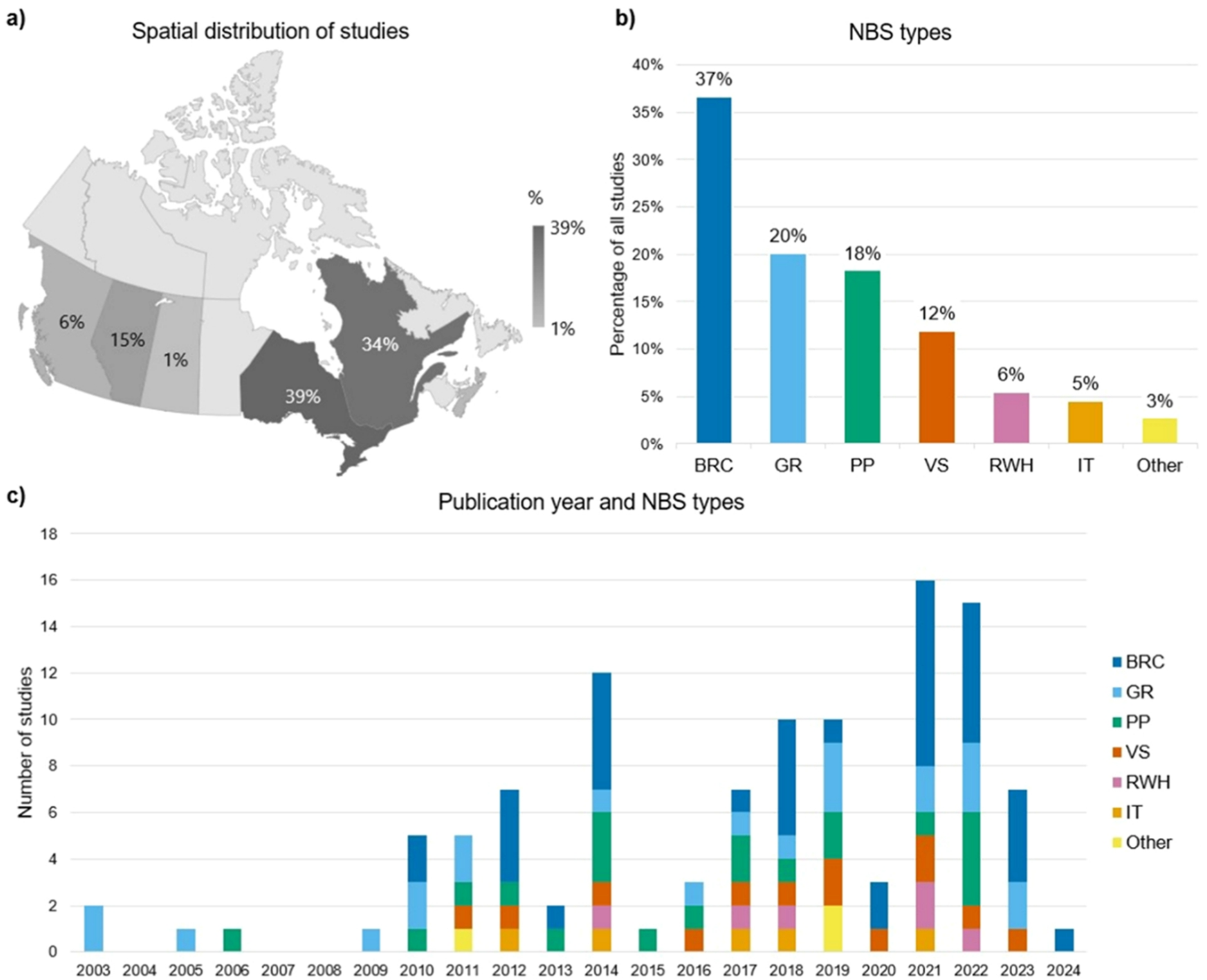

Fig. 3. Spatial (a), typological (b), and temporal (c) analysis of NBS related studies. The information pertaining to BRC includes both bioretention cells and rain gardens.

rest distributed among conference papers (11 %), theses (17 %), and technical reports (13 %). Additionally, one technical note (1 %) was also included in the final pool. The published literature predominantly comprised observational studies (44 %), followed by modeling studies (26 %), and literature reviews (18 %). Approximately 10 % of the studies employed a multifaceted approach, combining research methods such as simulation-observation or simulation-optimization. There was also an editorial note, accounting for approximately 1 % of the total studies. Fig. 3 illustrates the geographical and temporal distribution of these studies, as well as the types of NBS studied. It is worth noting that only 22 % of the reviewed literature, incorporated data from cold winter season or addressed topics relevant to cold winter climatic conditions.

The studies exhibited geographical diversity, with 39 % conducted in Ontario and 34 % in Quebec, reflecting substantial urban population of both provinces, as well as strong presence of academic institutions and research funding. Alberta emerged as the third-largest contributor, making up 15 % of the studies. British Columbia accounted for 6 % of the literature. The remaining literature 5 % originated from the Prairie and Atlantic provinces. Notably, no studies were identified from Newfoundland and Labrador, Prince Edward Island, and Manitoba.

Over the past 15 years, there has been a consistent increase in academic contributions focused on NBS for urban flood mitigation in Canada. Notably, more than half (57 %) of the reviewed literature was published in the last five years (2018 to 2024). This surge in research activity underlines the growing recognition of NBS as a viable strategy for flood mitigation. Remarkably, 2021 and 2022 stand out as the most prolific years in Canadian NBS research, with respectively 16 and 15 publications emerging in these years.

NBS research has evolved, with different types of NBS receiving specific attention. BRC (37 %), GR (20 %), and PP (18 %) have been the primary focus, followed by VS (12 %), RWH (6 %), IT (5 %), and other practices (3 %). BRC and PP gained interest in 2010 and 2006, respectively, as they proved effective in managing both runoff quantity and quality. GRs started gaining attention in 2003 but experienced a significant surge after Toronto implemented its Green Roof Bylaw, in 2009, which officially took effect in 2010. Toronto was the first city worldwide to mandate GRs for buildings over 2000 m^2, with coverage requirements ranging from 20 to 60 % (Mora-Melià et al. 2018). This Green Roof Bylaw mandated green roof construction on new industrial, commercial, and residential buildings (Basu et al., 2021). Literature reviews covering a variety of NBS, constituted 7 % of the reviewed studies, while the remaining 3 % covered other types of NBS, such as green alleys and facades, soakaways, urban forests, and soil tree trenches. IT and RWH emerged as NBS around 2012 and 2014, respectively, further expanding the repertoire of urban flood management approaches.

3.2. Lessons learned through academic research

NBS for urban flood mitigation have received extensive attention in Canada, specific strategies such as BRC, GR, and PP have garnered significant focus, warranting in-depth discussion in this review. It is important to note that this analysis is exclusively centered on instances of urban flooding caused by excessive surface runoffs and does not consider other aspects, such as the environmental co-benefits or water quality improvements associated with NBS and the reduction of combined sewer overflows.

A key insight from the literature is that the effectiveness of NBS depends heavily on climatic and hydrological conditions. For example, studies by Khan et al. (2012), (2013) demonstrate that BRCs are particularly effective in cold climates, where they manage runoff and peak flows even under freeze-thaw conditions. Similarly, research by Talebi et al. (2019) highlights that GRs perform best in drier climates with infrequent rainfall, as they optimize water retention, though their efficiency decreases in wetter regions. PPs and ITs, as noted by Van Seters et al. (2006), excel in regions with low precipitation, focusing on infiltration and groundwater recharge. Conversely, RGNs and detention basins, as explored by Cristiano et al. (2022) and Autixier et al. (2014), are most effective in areas prone to intense, short-duration rainfall, providing effective flood control and runoff volume reduction.

The findings of this study in the Canadian cold climate align closely with those from other cold regions, including New Hampshire, USA (Roseen et al., 2009), Scandinavia (Ahiablame et al., 2012), northeastern China (Xiao et al., 2022), and Norway (Hamouz et al., 2020). These studies show that LID systems, such as BRCs, PPs, and GRs, maintain significant hydrologic performance despite freezing and thawing cycles. For example, BRCs in New Hampshire and Scandinavia demonstrated consistent stormwater retention and peak flow reduction across seasons, while systems in northeastern China effectively regulated snowmelt runoff during winter and spring. These results indicate the relevance of our findings beyond Canada, particularly in regions with similar climatic and geographical conditions, such as heavy snowfall, freeze-thaw cycles, and high impervious surface coverage.

These findings underscore the need to tailor NBS to the specific climatic and geographical context of urban areas to optimize their performance. The following sections will explore in detail the evidence from studies on BRCs, GRs, and PPs, shedding light on their applications and limitations in various environmental settings.

3.2.1. Bioretention

In line with the research focus on NBS internationally, some lessons can be learned from research on BRC in Canada. Khan et al. (2012) assessed BRC effectiveness in Calgary, Alberta, comparing warm and cold conditions. This study defined cold conditions as those occurring during or preceding Chinook. Their findings demonstrated that BRC effectively reduced stormwater runoff volume with capture rates of 96 % and 93 % during warm and cold conditions, respectively. However, hydraulic efficiency decreased in cold weather, prompting the need for further investigations into NBS effectiveness in cold environments. The absence of region-specific design guidelines posed a challenge to bioretention adoption, particularly in cold climates. Addressing this issue, Khan et al. (2013) developed a multiple linear regression model based on experimental data to predict bioretention system performance, focusing on inlet volume and event duration. This led to a new design tool for Calgary-specific BRCs, resulting in an average reduction of 92 % in runoff volume and a 95 % reduction in peak flow. Geheniau (2014) also compared BRC in warm and cold seasons, but in a city near Montreal, Quebec. They showed that the average reduction in retention volume and peak flow in the warm season was 81 % and 60 %, respectively, compared to 75 % and 35 % in the cold season. In the same region, another case study conducted recently by Pineau et al. (2021) in the vicinity of Montreal assessed the effectiveness of a stormwater treatment system comprising a BRC and a retention pond during winter conditions. Their findings confirmed the continued functionality and effectiveness of BRC throughout the winter season, with snow cover maintaining suitable soil temperatures for efficient infiltration.

Bacys et al. (2019) used advanced numerical modeling techniques along with local and global sensitivity analyses to identify key design factors for flood mitigation. They conducted long-term simulations spanning nearly 12 years, with their top-performing scenario proving highly effective, mitigating up to 100 % of runoff, notably during extreme events. Overall, the study emphasized the critical role of comprehensive BRC design in managing stormwater overflow and urban flooding.

In a study conducted by Li et al. (2021), four large BRCs were used to simulate Edmonton's climate for a period of 1.6 years, testing various media types across all seasons. The results revealed that less porous media led to a reduction in peak flows of over 83 % for summer 2-year events, while more porous media maintained high conductivities. All BRC columns effectively managed 2-year events in subsequent summers, with preliminary findings suggesting suitability for 5- and 10-year events.

Nasrollahpour et al. (2021) conducted a study on evapotranspiration in BRC in Okotoks, Alberta, spanning from 2018 to 2020. They utilized 24 vegetated mesocosms with varying design parameters and climate conditions, with a specific focus on moisture levels at depths of 20 and 40 cm. Their findings highlighted the significant impact of design and climate, especially at the surface. Sandy media, lower organic matter content, and the presence of woody vegetation were associated with higher evapotranspiration rates. These findings were corroborated by Spraakman et al. (2022), who investigated the water balance of a bioretention system in Vaughan, Ontario, categorized by event size. Their study revealed that recharge accounted for 88 % of inflow, with evapotranspiration contributing 6 % overall and 19 % for small events. The average daily evapotranspiration rate was 2.3 mm, increasing to 2.9 mm during the growing season. The study revealed an average volume reduction of 97 % for all events. Prior to these studies, Glorieux (2010) studied the integration of trees into BRC. The results of their modeling showed that evaporation and infiltration could retain 45 to 97 % of the rainfall, and that certain trees could intercept between 1.6 and 8 % of the annual rainfall volume.

Recently, Gougeon et al. (2023) used the Storm Water Management Model (SWMM) to model BRC performance, highlighting their effectiveness on industrial road sites during snowmelt. The study emphasized that neglecting snow cover dynamics can lead to increased runoff and poor performance of BRCs. Efficient snow management techniques, such as snow pushing, were shown to enhance the effectiveness of BRCs. In summary, BRCs were found to reduce runoff from both rainfall and snowmelt by 33 to 70 %. To consolidate all the valuable information gathered on various features of BRCs and their efficacy in Canadian urban settings, a summary is provided in Table SM-2.3 (SM-2). This information would be useful for designing and conducting experiments on BRCs in other regions and climatic conditions.

3.2.2. Green roofs

GRs are broadly categorized as either intensive or extensive. An intensive GR involves a thicker substrate and supports a wider variety of vegetation, including shrubs and trees, requiring more maintenance. Compared to this, an extensive GR has a shallower substrate, supports low-growing vegetation, and requires less maintenance. In Canada, the research on GRs has been almost exclusively on extensive systems. Bass et al. (2003) demonstrated the benefits of GRs, particularly their capacity to reduce runoff. In a three-year study conducted by Van Seters et al. (2006), an extensive GR in Toronto was compared to a neighbouring conventional roof. The GR demonstrated a 63 % reduction in runoff, except during the winter months. Notably, GR runoff was 42 % lower on average in April and November, with significantly greater reductions ranging from 70 to 93 %, observed during the summer months.

Roehr and Kong (2010) conducted a study on the reduction effects of runoff when using GRs in Vancouver and Kelowna in Canada, as well as in Shanghai in China. This study compared how different climates influence the effectiveness of GR in reducing runoff. The study employed the Soil Conservation Service Curve Number (USACE 2024a) and Hargreaves-Samani methods (USACE 2024b). Their assessment covered aspects such as water gains and losses, soil water balance, and irrigation requirements for GRs. The results of this study revealed that GRs reduced annual rooftop runoff by 29 % in Vancouver and 100 % in Kelowna. Factors such as soil properties, depth, and plant selection played significant roles in promoting plant growth and reducing the need for irrigation.

Lundholm et al. (2010) conducted a study in Halifax, where they implemented a modular extensive GR system with a shallow growing medium. They planted various combinations of monocultures or mixtures containing one, three, or five different life-forms to assess the water retention benefits over a four-month period. The results of the study demonstrated that strategic combinations of life-forms on GRs can enhance ecosystem services. In a recent study by Saade et al. (2022), eight extensive GRs in urban Toronto were examined throughout the 2021 growing season. Some of these testbeds featured a biochar-enriched substrate derived from sugar-maple sawdust pyrolysis. The research involved the measurement of discharge, along with monthly vegetation assessments conducted using a pin-frame technique.

Sims et al. (2016) conducted a GR related study, considering three Canadian cities (i.e., Calgary, London, and Halifax), representing different regional climates. Higher stormwater retention (67 %) was noted for GRs in Calgary, a location with a semi-arid continental climate. However, GRs in London, representing a humid continental climate, retained the greatest depth (598 mm) of stormwater, followed by those in Halifax, representing a humid maritime climate, with 471 mm, and Calgary, with 411 mm. The retention values are based on data collected during the September 2012 to November 2014 period for more than two full monitoring seasons, defined as the March to November period, excluding months with snow cover. The nature of climate significantly impacted medium-sized storms (3–15 mm), with antecedent moisture conditions at the onset affecting retention. Antecedent moisture conditions emerged as a reliable predictor of stormwater retention. For large storms (with amounts $>$ 45 mm), GRs in all cities achieved an average retention ranging from 16 to 29 %. The study highlighted that even in the case of a wetter climate, GRs reasonably reduced stormwater volume.

Talebi et al. (2019) evaluated the performance of GRs in six different Canadian cities. In their study, the type of vegetation had a greater impact on retention than substrate storage. The retention of GRs in Regina depended on substrate moisture, whereas those in Calgary faced moisture limitations. Transitioning from low- to high-water-use plants increased cumulative evapotranspiration. Deeper substrates improved retention but required structural load considerations. Jahanfar et al. (2019) compared the hydrologic performance of two integrated GR photovoltaic systems to a traditional GR during 51 rainfall events. The results indicated that these integrated systems were less effective in reducing stormwater runoff and peak flow compared to standard GR. Similar studies leading to similar results were also conducted by Liu and Minor (2005), and Hill et al. (2017). Fléchais (2011), using SWMM simulations, demonstrated that the peak flow for a 12 mm rainfall could be reduced by 22 %, and by 15 % for a 24 mm rainfall. Their findings also revealed the sensitivity of GR to soil moisture conditions, with performance halved for saturated soil compared to dry soil.

Almaaitah et al. (2022) assessed the performance of green, blue-green, and blue roofs in Toronto. They recorded maximum retention of stormwater, with retention percentages ranging from 47 to 63 %. In another study by Cristiano et al. (2022), GRs, modified bio-based GR (MBGR), and RWH were evaluated in nine different cities around the world, with four located in Canada. The study categorized roofs as either flat or sloped, with flat roofs being deemed suitable for both GR and MBGR installations. The researchers also considered cost-effectiveness evaluations for extensive and intensive GRs. It was found that sloped rooftops, particularly those equipped with RWH systems, exhibited superior runoff reduction capabilities during high-intensity rainfall events. The MBGR and intensive GR performed well at the building scale, with their effectiveness influenced by local climate conditions. The most efficient solutions for reducing flood risk involved a combination of MBGR on flat surfaces and RWH tanks on sloped surfaces, ensuring a minimum 2 % reduction in discharge across all locations, with even greater reductions ranging from 10 to 16 % observed in Airdrie, Alberta, and Montreal, Quebec. The highest potential discharge reduction, ranging from 20 to 25 %, was achieved by pairing RWH systems with intensive GR or MBGR. Observations made and findings of all studies on GRs are summarized in Fig. 4 and can also be found in Table SM-2.4 (SM-2) to facilitate a quick inter-comparison.

3.2.3. Permeable pavements

There have been controversies about the effectiveness of PPs in reducing runoff. Bean et al. (2004) suggested that PPs could reduce runoff volume under specific conditions, such as the presence of sandy or loamy sand soils, the absence of a high-water table, regular maintenance, proper construction, flat pavement surfaces, and no overburdening loads. However, Drake et al. (2014) challenged these

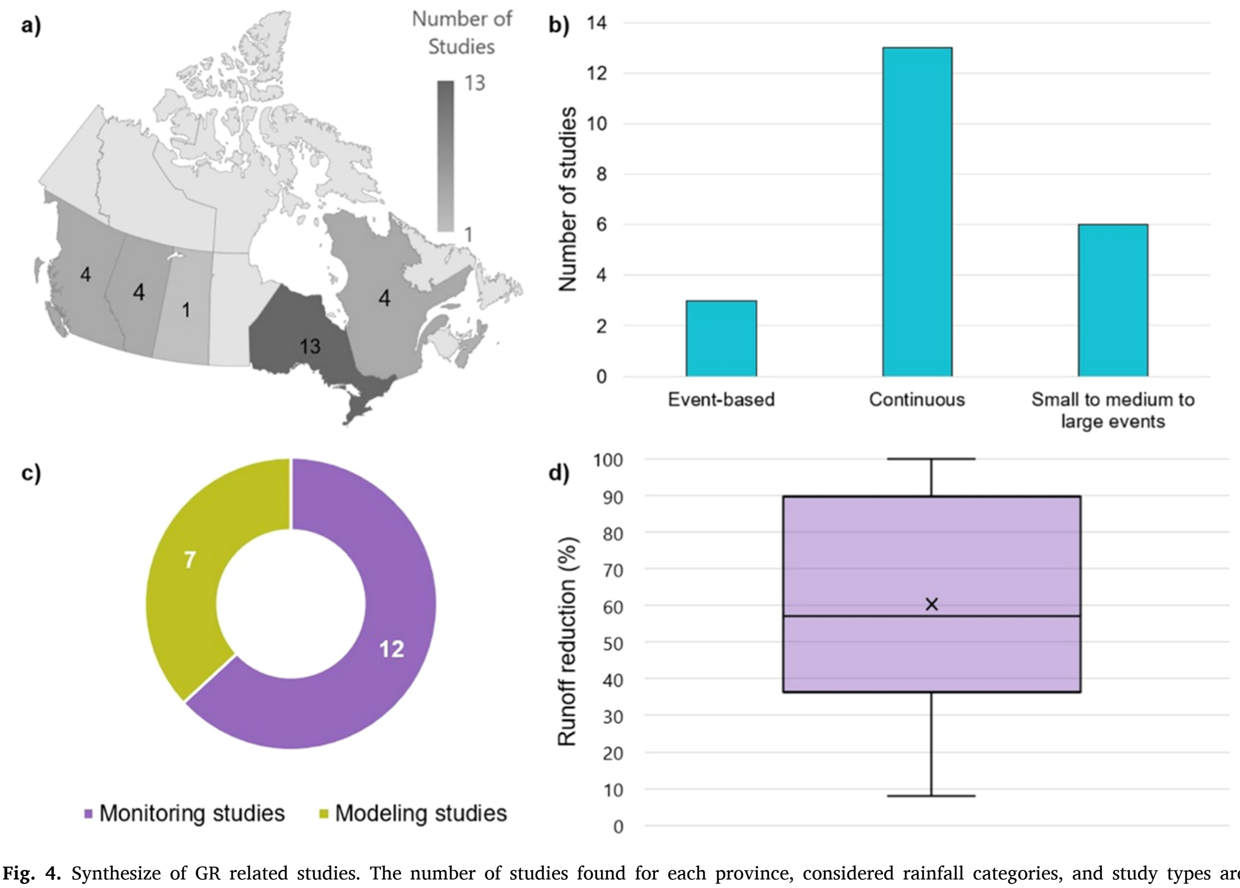

Fig. 4. Synthesize of GR related studies. The number of studies found for each province, considered rainfall categories, and study types are respectively shown in panels (a) to (c). The reported percent runoff reductions are shown in panel (d) in the form of a box and whisker plot. Whiskers correspond to minimum and maximum values, while the box represents the 25th and 75th percentile values. Median value is located inside the box, with the mean value shown using a cross symbol.

notions by demonstrating that volume and peak flow reduction can still be achieved even when the underlying soil is not sandy or loamy sand. In their study, PP systems equipped with underdrains featuring flow-restricting valves achieved a remarkable peak flow reduction exceeding 90 % and reduced runoff volumes by 43 %, even when constructed over clayey soils.

Van Seters et al. (2006) conducted a study on PP and VS at Seneca College's King Campus parking lot. The results showed that PP effectively prevented surface runoff during large storms, while the swale efficiently managed runoff. Huang et al. (2012) examined permeable interlocking pavers (PICP) in Calgary, focusing on their performance during winter conditions, including Chinook thaws. Field runoff tests conducted under varying temperatures showed significant peak flow reductions, particularly during freeze-thaw periods. Surface infiltration rates dropped notably in winter. Despite these performance variations, PCIP effectively reduced surface runoff in urban environments. However, further research is needed, especially concerning the use of sanding materials and the impact of cold temperatures on pavement performance. In another study, Huang et al. (2016) assessed PPs, including porous asphalt (PA), porous concrete (PC), and PICP in Calgary for storm runoff reduction. The study spanned from October 2011 to December 2013, and it was noted that pavement maintenance was needed due to winter sanding. Initial infiltration rates for PA, PC, and PICP met design requirements for handling a 100-year storm event without ponding.

Crookes et al. (2017) examined PP performance in a parking lot consisting of four different cells, including PC and conventional asphalt. The PC section featured a high-density polyethylene liner to isolate each cell, ensuring zero exfiltration. Results indicated a high variability in infiltration capacity across the PC pavement, with lower capacities near the center driving lanes due to clogging by debris from vehicle traffic. However, even with this variability, the infiltration capacity remained significantly higher than typical rainfall intensities. In a prior study, Drake et al. (2010) also revealed varying infiltration capacities of PP, ranging from 460 to 19, 460 mm/h.

Vaillancourt et al. (2019) assessed PICP infiltration capacity across five sites in greater Montreal, Quebec. They observed high surface infiltration rates, even during sub-zero winter temperatures, reaching up to 20,000 mm/h. Over a 12-month monitoring period at one site, they noted various benefits, including peak flow delays and runoff reductions depending on the specific characteristics of rainfall events. The empirical data collected in this study was used to calibrate an SWMM, tailored for PICP. The model was then used to assess the impact of PCIP in four urban watersheds using an eight-year rainfall series. The results highlighted reductions of 65 % in overflow volume, 21 to 48 % in combined sewers overflow duration, peak flow ranging from 6 to 45 %, volume averaging 30 % for separate systems, and surface flooding duration between 24 and 81 %. While SWMM is widely adopted for simulating runoff reduction by PP systems, Zhang and Guo (2015) found that the current NBS module's infiltration calculation for PP layers is inadequate, especially when dealing with shallow pavement depths and long computational time steps. In response to these difficulties, they proposed an alternative method that represents PP systems as equivalent regular sub-catchments by using a case study of rainfall events in Atlanta, USA. This alternative approach enabled more effective modeling in SWMM-based experiments.

Scott et al. (2022) conducted a study in Vaughan, Ontario, focusing on the restoration and maintenance of PICP. Their findings revealed that maintenance technologies specifically designed for PICP outperformed generic street-sweeping methods. Among these technologies, the pressurized-air and vacuum system almost fully restored PICP to its original post-construction baseline condition, whereas other methods achieved varying levels of surface infiltration rate recovery. For further information on the restoration aspects of PPs, the studies of Henderson and Tighe (2012); Huang et al. (2016); James (2004); James et al. (2018); and Marvin et al. (2021) can be consulted. Various features of the specific studies in terms of location, nature of study, PP type, underlying soil type, duration of the study, maximum rainfall, maximum SIR, and reduction in peak runoff volume or flooding duration are summarized in Table SM-2.5 (SM-2).

3.3. Other approaches

In addition to the previously discussed NBS types, Canadian studies have also examined the effectiveness of VS and IT. It is worth noting that, except for a study on IT conducted by Rowe et al. (2021), most of these investigations considered both IT and VS within a broader simulation, optimization, or comparative modes. Rowe et al. (2021) evaluated IT in Ontario considering storm depths ranging from 5 to 50 mm, compared to the commonly used 90th percentile criterion of approximately 25 mm. Their results revealed cost inefficiencies associated with this criterion and recommended a more cost-effective design criterion in the range of 20 to 22 mm. Additionally, they examined this storm sizing criterion for VS practices and found that designs exceeding 25 mm lacked economic efficiency. The study identified economically efficient design criteria, approximately falling within the range of 18 to 26 mm, which can be adapted to various conditions. This study also highlighted the utility of probabilistic approaches for NBS assessment and suggested extending them to different climates to develop region-specific design criteria and cost-effective policies.

Courchesne et al. (2023), on the other hand, compared the on-site performance of BRC with that of VS and showed that BRC was able to retain 90 % of the volume of 80 % of all rainfall events, compared to 90 % of the volume of 75 % of rainfall events for VS. Furthermore, their results also showed that 90 % of peak flows in BRC were less than 1 L/s, compared to 80 % for VS. They also evaluated a critical event of 63.5 mm of rainfall. For this event, the retention capacity of BRC ranged between 69 and 76 %, while that of VS was 58 %.

3.4. Combinations of NBS

Exploring individual attributes of various NBS is valuable, but combining these elements synergistically presents significant opportunities, particularly in addressing the future flood-related challenges linked to climate change. Modeling studies that compared different forms of NBS for urban catchments have focused on optimizing flood control benefits, while considering life cycle costs. In a study by Joksimovic and Alam (2014), cost efficiency of NBS was examined in a greenfield site located in London, Ontario. This site was designated for mixed-use sustainable development, aiming to preserve the base flow of a nearby creek while managing stormwater. The researchers considered seven land use classes and various NBS types, simulating them using Personal Computer SWMM (PCSWMM; CHI, 2019). They assessed 11 combinations of NBS practices, including VS, GR, PP, among others. The study revealed that ITs were the most cost-effective option, with 85 % runoff reduction. In contrast, the combination of PPs and GRs emerged as the least cost-effective, achieving a reduction of runoff by less than 30 %.

While the abovementioned study dismissed BRCs and PPs as effective NBS, a study by Jiang and McBean (2021) suggested that these NBS options can be quite effective in reducing runoff volumes. They evaluated the effectiveness of four key NBS practices: BRCs, PPs, RB, and VS. Using lot-level modeling with PCSWMM, they assessed the performance of each NBS in reducing surface runoff volumes and peak runoff rates under historical weather conditions. The study found that PPs outperformed other NBS, achieving a maximum reduction of 58 % for a 2-year storm and 20 % for a 100-year storm. This provided substantial, though not complete, flood risk mitigation for the latter. Additionally, the study examined the resilience of NBS practices under climate change scenarios, highlighting BRC as the most resilient NBS option. While NBS, particularly BRCs, can mitigate surface runoff and urban flooding for smaller storms, it is important to recognize that they are not typically designed to prevent flooding from extreme storms.

Vidil (2012) modeled the Roland-Therrien sector of Longueuil, Quebec, in both current and future climates to assess the impact of adding NBS such as BRC, IT, and VS. The NBS proved effective for events of 2-year return period. Guay et al. (2024) conducted an experimental study considering a combination of BRC, permeable cellular paving (PCP) and PCIP in a parking lot in Boucherville, Quebec. Results showed an average reduction in runoff volume of 91 %, a reduction in peak flow of 98 %, and a delay in peak flow by 6.7 hours. As important as identifying the most efficient and cost-effective NBS is, it is equally essential to examine the integrated effectiveness of various combinations of flood mitigation solutions and operational practices of NBS. In this regard, Joksimovic and Sander (2016) analyzed the hydraulic functionality of GI implementation using SWMM. Their study focused on passive and actively controlled GI in a mixed land-use area in Toronto, considering residential, institutional, and commercial lots. Active monitoring involves direct manipulation of system parameters for real-time analysis, while passive monitoring observes system performance without intervention. The research evaluated GRs, infiltration chambers, and RWH systems, over seven months of continuous simulation. The findings indicated that passive GI significantly reduced runoff volume and average flow in the sewer system. In contrast, active GI showed modest peak flow reduction (0.9 %) and moderate flow reduction, particularly during less intense rainfall events. These results underscore the potential of GI in mitigating urban runoffs and emphasize the importance of considering both passive and actively controlled strategies in GI planning.

For urban stormwater management, the study by Eckart et al. (2018) explored strategies to mitigate runoff and peak flows through NBS combinations. Emphasizing the inherent nonlinear dynamics in runoff generation and infiltration processes, their research underscored the need to identify optimal combinations of NBS to achieve maximal runoff reduction while minimizing associated costs. To that end, the study devised an advanced coupled optimization-simulation model that integrated SWMM with the Borg Multi-objective Evolutionary Algorithm. This model was applied to a 77 ha suburban sewershed in Windsor, Ontario. After calibrating and validating the model for existing conditions, five NBS were evaluated. They found that IT proved to be a more cost-effective stormwater control option than vegetated systems. A summary of the findings on runoff mitigation characteristics of NBS combinations is provided in Table SM-2.6 (SM-2).

4. State of practice in Canada

In this section select municipal level initiatives are discussed first, followed by reviews of select modeling efforts from municipalities of Montreal, Ottawa, Thunder Bay, and Vancouver. Since various levels of financial support from federal and provincial governments are necessary to initiate larger scale flood mitigation programs and inititiaves, including NBS, a review of various programs and breakdown of available funding are reviewed in a separate section to reflect on regional flood risk profiles and financial commitments.

4.1. Municipal level NBS implementation

4.1.1. Select municipal initiatives

The adoption of NBS in Canadian cities encompasses a range of notable approaches and strategies. Many cities are currently introducing NBS through pilot projects. For instance, the City of Vancouver has introduced the RainCity Strategy, aligning itself with the Integrated Rainwater Management Plan mandated by British Columbia in 2016. This long-term strategy introduces various green rainwater infrastructure, including GRs, blue roofs, PPs, VSs, and tree planting. The goal is to capture and purify a significant portion of the annual rainfall. Similar incremental projects are noticed in cities such as Edmonton, Winnipeg, and Halifax, each tailored to address their unique urban challenges through NBS.

An increasing number of cities are taking a proactive stance by conducting city-wide flood risk assessments. Ottawa, for instance, developed a city-wide flood risk profile using risk assessment proxies, categorizing them into maturity levels, with computer models at the highest. This proactive approach aids in understanding urban flood risks for strategic decision-making. Complementing this, Ottawa's Stormwater Management (SWM) Retrofit Program supports runoff retention and volume control, including policy targets, SWM retrofit studies, and NBS pilot projects. Initiatives like the Sunnyside and Hemmingwood Bioretention Retrofits, Stewart Street and Senio Bioretention Cells, and upcoming projects like the Glebe Avenue Stormwater Tree Cell, integrate NBS in road renewal projects, guided by specific design guidelines and tools.

Table 3
Examples of municipal initiatives and policies in select Canadian cities (adapted from Kim and Khaliq, 2022).

City	Initiative/Policy	Key highlights
Vancouver, BC	RainCity Strategy	A comprehensive plan to manage rainwater in response to Vancouver's high annual rainfall and anticipated climate change impacts. Utilizes GI, including green and blue roofs, tree trenches, PPs, bioswales, and wetlands.
Ottawa, ON	Risk Assessment Tool (Proxy)	The city-wide risk profile employs a risk assessment tool called "Proxy" to categorize various factors for risk assessment, facilitating a proactive approach to urban flood risk management.
Toronto, ON	Green Streets Technical Guidelines	The Toronto Green Streets program integrates GI to mitigate urban flooding. The city emphasizes NBS, despite some data availability challenges.
Edmonton, AB	The Way We Green	A comprehensive environmental strategy addressing water quality, water supply, and the impact of increased winter rainfall. Focuses on implementing NBS within individual buildings and maintains an inventory of NBS projects.
Winnipeg, MB	CSO Master Plan	The CSO Master Plan allocates funding for green infrastructure projects to reduce combined sewer overflows. Projects include rain gardens, natural and constructed wetlands, and initiatives to enhance water quality.
Halifax, NS	Halifax Green Network Plan	Endorses ecological open space systems and green infrastructure for urban sustainability and climate resilience. The plan recommends urban forests, wetlands, and riparian areas, and promotes natural stormwater management approaches.
Victoriaville, QC	Plan de diminution des charges et débits cheminés vers les cours d'eau par le contrôle à la source des eaux pluviales	The plan aims to integrate stormwater management facilities such as BRCs and VSs into the annual roadworks planning.
Other Municipalities	Emerging Practices	Many municipalities are in the early stages of integrating NBS practices into their urban planning and infrastructure, highlighting the need for further research, investment, and collaboration to advance environmentally friendly and resilient practices in urban settings.

Additionally, municipalities are providing tools for NBS selection and design standards. In Toronto, the introduction of Green Streets Technical Guidelines reflects the city's commitment to adopting NBS. However, challenges related to data availability for NBS implementation persist, emphasizing the urgent need for comprehensive data sharing and dissemination. Table 3 summarizes the key city-level initiatives and policies, showcasing the varied approaches to urban flood mitigation and NBS implementation.

4.1.2. Select urban flood modeling work

This section examines modeling efforts undertaken by select municipalities across Canada. Urban hydrologic models provide a fundamental tool for implementing NBS in order to enhance flood resilience, manage stormwater effectively, and promote sustainable urban development (Rosenzweig et al., 2021). Noteworthy contributions have been made by various municipalities, each characterized by diverse populations and distinctive attributes. Table 4 summarizes the key information obtained from various modeling examples taken from the cities of Montreal (Benoit et al., 2024), Vancouver (McKee and Sandhu, 2019; City of Vancouver, 2021, 2022; Urban Systems Inc. 2022; Van de Valk et al., 2020), Ottawa (City of Ottawa, 2020; J.L. Richards and Associates Limited, 2018), and

Table 4
Key details and outcomes of the selected modeling examples from select Canadian municipalities.

City	Model name	Calibration & validation strategy	Scenarios	Modeling purpose
Montréal	Pointe-aux-Trembles	Dry and wet weather calibration and validation through flow monitoring at the outfall	2-, 5-, & 10-yr (+18 %) 3-h Chicago storms	Decision-making for adding NBS
Ottawa	Byron & Golden	Validation using recorded flooding photos and information from the downstream end	2-, 5-, & 100-yr 3-h Chicago storms	Management and grey infrastructure upgrade at source stormwater management for new hard surfaces
	Crystal Beach	Event-based validation through flow monitoring at the outfall	2-, 5-, & 100-yr 3-h Chicago storms	Management and grey infrastructure upgrade at source stormwater management for new hard surfaces
City of Thunder Bay	Tupper & Prospect	Event-based validation through flow monitoring at the outfall and also anecdotal information	2-, 5-, 10-, 25-, 50-, & 100-yr 24-h SCS storms; 25 mm event	Management and grey infrastructure upgrade
	InterCity Model	Event-based validation through flow monitoring at the outfall and also anecdotal information	2-, 5- &, 10-yr 3-h Chicago storms; 100-yr 24-h SCS storm	Pipe upsizing and addition of storage facilities
City of Vancouver	Oak-Marple	Dry- and wet-weather event-based calibration and validation through flow monitoring at the outfall	2- & 5-yr 1-h AES & 24-h SCS & Chicago storms	Sewer separation, pipe upsizing, and addition of NBS
	West Point Grey	Event-based calibration and validation through flow monitoring at the outfall	10- & 100-yr 1-, 2-, & 6-h AES; and 24-h SCS storms (+1 m SLR)	Sewer separation, pipe upsizing, and addition of NBS

Thunder Bay (Emmons and Olivier Resources Inc. 2015, 2020, 2022a, 2022b, 2022c; Hatch Mott Macdonald Inc. 2014; The City of Thunder Bay, 2018).

Urban flood modeling in Canada has been predominately completed using SWMM (or PCSWMM) and typically employing 1D representations of the sewer and urban environment. An interesting case is the Broadway Plan Area models based in Vancouver, which deviates from the standard approach using an unusual 1D and 2D configuration. The in-house 1D model, developed by city engineers, focuses on evaluating the sewer system's service level. In contrast, a 2D model, created by an external firm, assesses major system performance during significant storms, presuming a negligible impact from the minor system. In Vancouver, coastal boundary models consider sea-level rise (SLR), while non-coastal models primarily address climate change impacts related to changes in rainfall patterns.

In 2018, the City of Montreal enlisted the expertise of a consulting firm to refine an existing SWMM model of Pointe-aux-Trembles. The upgraded SWMM model features enhanced sub-catchment delineation, which categorizes areas based on their physical characteristics and hydrologic responses, distinguishing between road elements, flat roofs, and other land uses. Road elements are modeled individually, whereas flat roofs are represented as storage nodes controlled by outlet parameters mimicking orifice behavior. The model encompasses various land uses within the study area. Calibration and validation were conducted by comparison against flow measurements in 2016 and 2017.

Calibration and validation methods vary among the models outlined in Table 4, often relying on event-based data primarily sourced from flow monitoring. Unconventional approaches, such as anecdotal information, complaint call logs, and visual evidence, are sometimes used to validate models, with city engineers' expertise playing a pivotal role in addressing these challenges.

Several scenarios, encompassing both current and future situations, were simulated, aligning with specific city's guidelines and specific needs. Notably, some of these models were tailored in special ways, using simplifications or specific modeling approaches, to fulfill the unique municipal needs for understanding hydrologic risks in emerging urban developments. Surprisingly, the majority of models, with a few exceptions featuring simplifications, do not account for or consider NBS implementation. This can be traced to the uncertainty around NBS's performance under less frequent, larger storm events, as opposed to the more common smaller storms for which they are designed. This absence of NBS in reports highlights a critical gap between governmental encouragement and integration of NBS into urban modeling, exacerbated by the conservative approach of sewer design engineers compared to the more progressive stance of planners. For the time being, NBS implementation remains limited to pilot projects, indicating a disconnect between policy support and practical applications in the engineering field. However, efforts are underway to address this gap at the municipal level, aiming to integrate GI effectively and potentially reducing reliance solely on traditional grey infrastructure.

4.2. Federal initiatives for flood mitigation

The Government of Canada continues to allocate financial resources to support initiatives related to flood risk reduction and disaster mitigation across the country, but there is no distinct funding category that is exclusively designated for flood mitigation through NBS. However, the support to promote NBS for flood risk reduction exists as an integral component of larger programs. A detailed description of various available programs is provided in SM-3. This review study focuses on programs which are closely associated with flood mitigation and their relevance to NBS.

In the context of federal spending on flood mitigation, the Flood Hazard Identification and Mapping Program (FHIMP), which is being jointly implemented by Natural Resources Canada and Environment and Climate Change Canada, is expected to play a crucial role in Canada's ongoing efforts to address flooding issues through updating floodplain maps and development of associated guidelines (Government of Canada, 2023). In January 2022, the Government of Canada pledged $164.2 million over five years to enhance FHIMP and collaboratively develop new and updated flood hazard maps. These updated maps empower communities to make informed decisions regarding land use planning, flood mitigation, climate adaptation, and property protection.

In response to impacts of climate change, the Government of Canada initiated the Disaster Mitigation and Adaptation Fund (DMAF) in 2018 with an initial investment of $2 billion over a decade (Government of Canada, 2023). This funding aims to enhance community resilience against climate-induced disasters, including urban flooding, through both structural and natural infrastructure projects. The 2021 budget reaffirmed the commitment to DMAF by allocating an additional $1.375 billion over 12 years. DMAF addresses a range of climate-related risks, including floods, by supporting infrastructure construction and reinforcement.

Considering the collective financial allocation exceeding $7 billion for flood risk reduction and disaster mitigation initiatives (detailed in SM-3), it is notable that only a fraction can be specifically earmarked for flood mitigation using NBS within the DMAF, while a significant portion of the total funding is being invested to address riverine flooding. While acknowledging funding for disaster mitigation, it is vital to emphasize the significant prevalence of floods in many parts of Canada. Further emphasis on integrating NBS into federal budget allocations for flood mitigation is a critical consideration, highlighting the potential benefits and merits of a more concerted and strategic financial commitment to NBS within the broader context of flood mitigation in Canada.

Across Canada, some initiatives are emerging to improve and standardize the design, construction, and operation of NBS, which are directly and indirectly related to urban flood mitigation. These initiatives, for instance, contribute to refining guidelines on the NBS use for commercial roofs (Jandaghian et al., 2022; Jandaghian and Baskaran, 2022), urban flood mitigation through the Climate Resilient Built Environment initiative (Government of Canada, 2022), and water quality control design criteria for BRCs (Rowe et al., 2024), among other applications.

4.3. Provincial flood mitigation programs

At least seven provincial governments across Canada have implemented programs on pluvial flood mitigation (Table SM-2.7 in SM-2). Compared to other provinces, there was no publicly available information for Newfoundland and Labrador, Prince Edward Island, and New Brunswick, regarding pluvial flood mitigation programs. One significant aspect to highlight is the proactive approach taken by provinces that experience a higher frequency of urban flooding, such as Alberta, British Columbia, Nova Scotia, and Quebec. Ontario, where urban flooding is a prevalent issue, leads the way in terms of funding allocation, aligning resources with the region's flood risk profile. Among other flood-prone provinces, Quebec stands out for its substantial funding commitment. It is worth noting that most provincial programs primarily focus on infrastructure development and reinforcement or enhancing community resilience. Notably, British Columbia and Alberta take a unique approach by allocating funds to specific watersheds or regions.

5. Translating knowledge to practice: recommendations and obstacles

NBS have gained significant attention from practitioners and researchers in recent decades. This section explores the challenges of translating academic knowledge into professional practices, particularly through perspectives of Canadian studies.

5.1. NBS implementation for climate resilience

Recent studies indicate that the 20-year and 100-year rainfall events could see a fourfold increase in frequency (i.e., the possibility of the historical 20-year event recurring every 5-year on average by the end of the 21st century) and that short duration storms will see larger relative increases in terms of intensity under a warmer climate (Bush and Lemmen, 2019; Cannon et al., 2020; Masud et al., 2017; Martel et al., 2020, 2021; Oh and Sushama 2020). Considering that most of the existing drainage infrastructure were designed under the hypothesis of climate stationarity, it becomes clear that it will be impacted by future climate change, leading to increases in events of sewer backups and surface flooding.

An exploration of the adequacy of NBS in adapting to a warmer climate using Canadian literature reveals varying levels of performance under diverse rainfall and climatic conditions, as depicted in Tables SM-2.3 to SM-2.6 (SM-2). Additionally, numerous studies indicate that the effectiveness of NBS diminishes, sometimes significantly, with increasing storm intensity (Karamouz et al., 2022; Nasrollahpour et al., 2021). It is crucial to recognize that NBS can play a pivotal role in climate change adaptation strategies, considering the impracticality of completely overhauling every aspect of the existing grey infrastructure. Insights presented in this study highlight NBS as complementary solutions to improve the performance of existing and aging drainage infrastructure (Karamouz et al., 2022). Results from Benoit et al. (2024) suggest that the impact of climate change on peak flow and surface flooding could be mitigated by maximizing the implementation of BRCs, GRs, and PPs. Additional studies using multicriteria analyses to assess the optimal level of implementation from economical, environmental, and social criteria are needed to better understand the potential of NBS for climate change adaptation and mitigation.

5.2. Cost-effective NBS for urban flood mitigation

This study also briefly looked into financial considerations related to urban flood mitigation through NBS based on the published literature, especially the studies by Bacys et al. (2019), Eckart et al. (2017, 2018), Feltmate and Fluder (2018), Joksimovic and Alam (2014), and Li et al. (2019). Among the NBS studied, Eckart et al. (2018) results suggest that ITs emerge as the most cost-effective practice, especially for mitigating peak flows. Their findings emphasize the economic efficiency of prioritizing NBS implementation in areas with high runoff. Eckart et al. (2017) concluded that implementing NBS for stormwater management yields significant cost savings compared to conventional grey infrastructure, reducing flooding costs by 15 to 80 %. Additionally, property values increase in areas with recognized NBS. According to these authors, optimization and life-cycle analysis are crucial for understanding long-term benefits and cost-effectiveness. Prior to the studies of Eckart (2017, 2018), Joksimovic and Alam (2014) endorsed ITs as the most cost-effective NBS, followed by BRCs, PPs, and VSs. Bacys et al. (2019) also identify BRCs as one of the most cost-effective NBS. Li et al. (2019) highlighted financial constraints as a barrier to local adoption of NBS for stormwater management, citing challenges such as increased development costs, limited investments, and a lack of incentives. Jiang and McBean (2021) argue that GRs, due to their high capital costs and the need for frequent professional maintenance, are generally unsuitable for residential properties. Instead, they suggest that PPs, RWH, VSs, and BRCs or RGN are more cost-effective. Despite evidence of NBS cost-effectiveness, initial implementation costs and ongoing maintenance requirements remain significant hurdles. Furthermore, it is likely that political reluctance to support increased fees or taxes can further complicate the situation.

5.3. Transitioning from academic research to practical implementation

Despite the significant academic attention, there remains a noticeable gap between research findings and practical implementations of NBS. While both the federal and provincial levels demonstrate substantial commitment and direct/indirect funding for NBS (as outlined in previous sections and in more detail in SM-2, Table SM-2.7 and SM-3), municipal initiatives mainly consist of scattered pilot projects. In municipal projects, NBS are occasionally integrated; however, this integration often comes with simplifications and constraints that hinder effective implementation.

One of the primary barriers is the lack of comprehensive, region-specific design guidelines for NBS, particularly in cold climate regions like Canada. Many municipalities struggle to implement NBS effectively due to these gaps, leading to inconsistent performance across different implementations (Khan et al., 2012; Rahman et al., 2022). Building on this issue, another critical challenge is the insufficient long-term performance assessment data on NBS. Much of the existing research relies on pilot projects or short-term studies, which are often inadequate to convince policymakers to invest in wider implementations. Without reliable, long-term data on efficacy, financial constraints further complicate the situation, as municipalities remain hesitant to allocate significant initial investments (Feltmate and Fluder, 2018; Li et al., 2019).

Institutional barriers and a lack of coordination between various levels of government create additional hurdles. Resistance to adopting NBS is often linked to perceived challenges in integrating these solutions into existing grey infrastructure systems (Joksimovic and Alam, 2014; Kim and Khaliq, 2022). These institutional constraints limit the scope and ambition of NBS initiatives, even as governmental support and funding increase (Dhakal and Chevalier, 2017; Fletcher et al., 2015). Furthermore, fragmented policies arising from a lack of intergovernmental coordination undermine the effectiveness of NBS in urban settings (Vogel et al., 2015). Policy inertia and competing urban planning priorities further delay widespread implementation, as traditional infrastructure solutions continue to dominate decision-making (Willems, 2013; Rayner et al., 2017).

Despite these barriers, an emerging trend in NBS considerations signals potential for progress, particularly as municipalities begin to address these challenges. Tangible results remain limited, but overcoming obstacles such as gaps in design guidelines, increasing long-term monitoring, securing funding for pilot-to-practice transitions, and fostering intergovernmental coordination will be critical to transitioning academic research into practical implementations.

While addressing technical and performance challenges is vital, it is equally important to consider the role of community involvement and socio-economic factors in the success of NBS. Studies highlight that stakeholder engagement and co-design of solutions are often pivotal. For example, Almaaitah et al. (2021) emphasize the importance of involving local communities in planning and implementing BGI to align environmental goals with community needs. Similarly, Ahiablame et al. (2012) underscore the need to explore socio-economic impacts, including cost-benefit analyses and public perception, when evaluating NBS. Amati and Taylor (2010) discuss how the evolution of green belts and urban public spaces requires strong community engagement to balance environmental sustainability with social needs. Bacys et al. (2019) further stress that integrating socio-economic factors is essential for successfully implementing BRCs in urban environments. While these studies demonstrate the importance of community engagement and socio-economic considerations, this paper primarily focuses on the technical and performance aspects of NBS. Further research is needed to explore these dimensions in greater depth and better understand their role in the successful implementation of NBS.

5.4. *Current knowledge gaps and future directions*

A comprehensive examination of the Canadian literature reveals areas that have received relatively less scholarly attention, particularly in the exploration of NBS combinations, where various approaches are integrated to manage stormwater effectively. Despite the recognized significance of these combinations (Eckart et al., 2017, 2018; Joksimovic and Alam, 2014; Joksimovic and Sander, 2016), there is a noticeable lack of studies that systematically evaluate their collective effectiveness (Cheng et al., 2011; Rosenzweig et al., 2021). Furthermore, optimized approaches involving multicriteria analyses that account for economic, environmental, and social factors remain underdeveloped, marking a critical gap in the academic discourse.

Building on the need for optimized NBS combinations, another notable research gap lies in assessing the adaptive capacity of NBS in a warming climate. Interestingly, municipal studies examined in this paper place greater emphasis on anticipating future conditions using the 2100 intensity-duration-frequency curves (McKee and Sandhu, 2019; City of Vancouver, 2021, 2022; Urban Systems Inc. 2022; Van de Valk et al., 2020) than is evident in broader research articles. This focus underscores the importance of integrating climate change considerations into NBS design.

While climate-specific challenges are critical, geographical disparities in research also highlight significant limitations. Despite Canada's predominantly cold climate, much of the reviewed literature narrowly focuses on months devoid of ice and snow. Although some studies explore NBS performance in winter conditions (Drake et al., 2010, 2014; Henderson and Tighe, 2012; Huang et al., 2016; Khan et al., 2010, 2012; Li et al., 2021; Pineau et al., 2021; Valtanen et al., 2014), addressing aspects like hydrologic performance and snow storage, over 85 % of the literature neglects this dimension. Additionally, research efforts are predominantly concentrated in southern Canada, leaving the Canadian north largely unexplored—a significant geographical gap.

As climate change drives more frequent and intense rainfall, another critical limitation of NBS emerges: their reduced effectiveness during high-intensity storms. Many NBS are designed primarily for smaller, more frequent storms (Dhakal and Chevalier, 2017). Research shows that as storm intensity increases, systems such as BRCs or BRs become overwhelmed, limiting their capacity to manage extreme flow volumes (Joksimovic and Alam, 2014; Eckart et al., 2017). Bacys et al. (2019) and Bouattour (2021) further emphasize that these limitations stem from designs that fail to account for peak flow reductions during extreme weather events. Addressing these challenges requires more robust, dynamic modeling approaches and long-term studies under varying storm conditions (Bali et al., 2023; Spraakman et al., 2020).

In addition to immediate storm resilience, long-term evaluations of NBS effectiveness remain underexplored, particularly beyond four years post-construction (Ahiablame et al., 2012; Dietz, 2007; Drake et al., 2010; Eckart et al., 2017). Enhancing modeling techniques and developing user-friendly decision-support tools are also critical for advancing NBS adoption. Future studies must tackle the challenge of scaling NBS performance from individual lot scales to broader watershed and regional level applications (Ahiablame et al., 2012).

Addressing these gaps—ranging from NBS combinations and climate-specific adaptations to geographical disparities, storm resilience, and long-term performance—is crucial to facilitate the widespread implementation of NBS. Despite substantial progress over the last two decades, continuous research and development efforts are imperative to unlock the full potential of NBS in mitigating urban flood risks effectively.

6. Conclusion

In light of Canada's diverse geography and the persistent threat of natural disasters, urban flooding remains a significant concern. This research delved into the implementation and effectiveness of NBS for mitigating urban flooding across Canada. The findings underscore the commitment of both the federal government and the provinces to enhance urban flood resilience through NBS. The study emphasizes varying levels of NBS performance under diverse rainfall and climatic conditions, indicating the need for nuanced, case-specific analyses. The insights presented in this paper demonstrate that NBS, as standalone solutions, cannot address all circumstances across different regions. This emphasizes the importance of a synergistic combination of grey infrastructure upgrades and NBS.

Financial considerations, as explored within the specific focus of this study, reveal the cost-effectiveness of certain NBS, such as ITs, for urban flood mitigation. However, challenges related to initial implementation costs, maintenance needs, and political reluctance to support increased fees or taxes persist. The literature emphasizes the need for ongoing optimization and life-cycle analysis to ensure the long-term cost-effectiveness of NBS. Despite substantial academic attention, a noticeable gap exists between progress on research and practical implementation of NBS. While federal and provincial levels exhibit substantial commitment and funding plans for NBS, municipal initiatives primarily manifest as scattered pilot projects. However, the emerging trend in considering and experimenting with NBS suggests a prospective increase in municipal projects in the near future, but tangible results are yet to align with societal expectations.

As Canada progresses in fostering climate resilience, including flood resilience, through ongoing governmental and provincial initiatives, the nation's commitment to action should be acknowledged. The existing momentum, coupled with the seamless transition of ongoing research endeavours into practical implementation, suggests that Canada possesses the potential to achieve a commendable level of resilience amid the dynamically changing climate and associated challenges and adaptation needs. Sustained collaboration, heightened public-private partnerships, and the dissemination of successful models and strategies are deemed crucial to fortifying resilience efforts nationwide. However, as mentioned above, the examination of the Canadian literature also reveals significant research gaps. The need for comprehensive assessments of NBS combinations, a focus on the adaptive capacity of NBS in a warming climate, and an exploration of the performance of NBS in cold climates are highlighted in this paper. Moreover, the study identifies geographical research gaps, particularly in the Canadian north, and emphasizes the necessity for long-term performance studies extending beyond four years post-construction. Continuous research and development efforts are deemed imperative to facilitate the global widespread implementation of NBS.

Finally, cost-effectiveness of certain NBS types, such as ITs and BRCs, noted for Canadian conditions bear international relevance. Toronto is the first city worldwide that has mandated GRs for buildings over 2000 m^2. And, in the years since the bylaw was adopted, many cities and regions around the world have followed suit. From the review of Canadian studies on BRCs it was found that region-specific guidance on their design and implementation would be required to enhance their effectiveness. This finding has direct implications for regions with distinct warm and snow-dominated cold seasons. Guidance on designing simulation and monitoring approaches, development of user-friendly decision support tools that seamlessly integrate NBS, and guidance on life cycle assessments are lacking in the Canadian and international literature on NBS. In particular, the development of municipal protocols for the construction, refurbishment, and decommissioning of NBS are areas that deserve attention from both Canadian and international researchers. Large-scale synergistic implementations and evaluations of a range of NBS in existing and new developments need to be explored in future studies. Region-specific review studies, as attempted in this paper, are important for synthesizing existing research on NBS, benchmarking on-the-ground performance of such solutions, and uncovering areas that require improvement. Better urban water management and effective urban flood mitigation demand better tools and meticulous guidance. It is hoped that such review studies will continue to emerge in the future for other regions of the world.

CRediT authorship contribution statement

Martel Jean-Luc: Writing – review & editing, Visualization, Data curation. **Kim Yeowon:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Drake Jennifer:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Zoghi Ali:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Khaliq Muhammad Naveed:** Writing – review & editing, Resources, Funding acquisition. **Bilodeau Émilie:** Writing – review & editing, Writing – original draft, Investigation, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly Pro. and ChatGPT 4o (premium) for editing, sentence phrasing and grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102460.

Data availability

Some of the used data can be made available upon requst. However, some information has been obtained through data-license agreements and we have not permission to share them

References

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012. Effectiveness of low impact development practices: literature review and suggestions for future research. Water, Air, Soil Pollut. 223 (6), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2.
Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012. Effectiveness of low impact development practices: literature review and suggestions for future research. Water, Air, Soil Pollut. 223 (7), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2.
Ahiablame, L.M., Engel, B.A., Chaubey, I., 2013. Effectiveness of low impact development practices in two urbanized watersheds: retrofitting with rain barrel/cistern and porous pavement. J. Environ. Manag. 119, 151–161. https://doi.org/10.1016/j.jenvman.2013.01.019.
Almaaitah, T., Appleby, M., Rosenblatt, H., Drake, J., Joksimovic, D., 2021. The potential of Blue-Green infrastructure as a climate change adaptation strategy: a systematic literature review. Blue-Green. Syst. 3 (1), 223–236. https://doi.org/10.2166/bgs.2021.016.
Almaaitah, T., Drake, J., Joksimovic, D., 2022. Impact of design variables on hydrologic and thermal performance of green, blue-green and blue roofs. Blue-Green. Syst. 4 (2), 135–155. https://doi.org/10.2166/bgs.2022.016.
Amati, M., Taylor, L., 2010. From green belts to green infrastructure. Plan. Pract. Res. 25 (2), 143–155. https://doi.org/10.1080/02697451003740122.
Arnone, E., Pumo, D., Francipane, A., La Loggia, G., Noto, L.V., 2018. The role of urban growth, climate change, and their interplay in altering runoff extremes. Hydrol. Process. 32 (12), 1755–1770. https://doi.org/10.1002/hyp.13141.
Autixier, L., Galarneau, M., Vanrolleghem, P.A., Pelletier, G., 2014. Evaluating rain gardens as a method to reduce the impact of sewer overflows in urban areas. Sci. Total Environ. 499, 238–247. https://doi.org/10.1016/j.scitotenv.2014.08.030.
Autixier, L., Mailhot, A., Bolduc, S., Madoux-Humery, A.-S., Galarneau, M., Prévost, M., Dorner, S., 2014. Evaluating rain gardens as a method to reduce the impact of sewer overflows in sources of drinking water. Sci. Total Environ. 499, 238–247. https://doi.org/10.1016/j.scitotenv.2014.08.030.
Bacys, M., Khan, U.T., Sharma, J., Bentzen, T.R., 2019. Hydrologic efficacy of Ontario's bioretention cell design recommendations: a case study from North York, Ontario. J. Water Manag. Model. https://doi.org/10.14796/JWMM.C468.
Bali, H., Pelletier, G., & Duchesne, S. 2023 Évaluation de la réponse hydrologique de pratiques de contrôle à la source des eaux pluviales. Novatech 2023 11e Conférence internationale sur l'eau dans la ville, Lyon, France. https://hal.science/hal-04184108 (Accessed 5 December 2024).
Bass, B., Liu, K., Baskaran, B., 2003. Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas. National Research Council Canada, Ottawa, ON, Canada, p. 110. https://doi.org/10.4224/20386110.
Basu, A.S., Pilla, F., Sannigrahi, S., Gengembre, R., Guilland, A., Basu, B., 2021. Theoretical framework to assess green roof performance in mitigating urban flooding as a potential nature-based solution. Sustainability 13 (23), 13231. https://doi.org/10.3390/su132313231.
Bean, E.Z., Hunt, W.F., Bidelspach, D.A., 2004. Study on the surface infiltration rate of permeable pavements. Critical Transitions in Water and Environmental Resources Management. American Society of Civil Engineers, Reston, VA, USA, pp. 1–10. https://doi.org/10.1061/40737(2004)72.
Bell, C.D., McMillan, S.K., Clinton, S.M., Jefferson, A.J., 2016. Hydrologic response to stormwater control measures in urban watersheds. J. Hydrol. 541, 1488–1500. https://doi.org/10.1016/j.jhydrol.2016.08.049.
Benoit, T., Martel, J.-L., Bilodeau, E., Brissette, F., Charron, A., Brulé, D., et al., 2024. Limits of blue and green infrastructures to adapt actual urban drainage systems to the impact of climate change. J. Irrig. Drain. Eng. (Forthcom.).
Binns, A.D., 2020. Flood mitigation measures in an era of evolving flood risk. J. Flood Risk Manag. 13 (3), 1–3. https://doi.org/10.1111/jfr3.12659.
Bouattour, O., 2021. Caractérisation de l'impact de cellules de biorétention sur la qualité et la. Quant. é Des. eaux pluviales à Trois. -RivièRes, Québec [Master'S. Thesis, Polytech. Montr. éal]. PolyPublie. ⟨https://publications.polymtl.ca/9184/⟩. Accessed 5 December 2024.
Bush E. & Lemmen D.S. 2019 Canada's Changing Climate Report (CCCR). Government of Canada, Ottawa, ON. 444 pp.
Cannon, A.J., Jeong, D.I., Zhang, X., Zwiers, F.W., 2020. Climate-Resilient Buildings and. Core Public Infrastructure: An Assessment of the Impact of Climate Change on Climatic Design Data in Canada. Environment and Climate Change Canada, Gatineau, QC, p. 106. ⟨https://publications.gc.ca/site/eng/9.893021/publication.html⟩. Accessed 18 June 2024).
Chen, J., Theller, L., Gitau, M.W., Engel, B.A., Harbor, J.M., 2017. Urbanization impacts on surface runoff of the contiguous United States. J. Environ. Manag. 187, 470–481. https://doi.org/10.1016/j.jenvman.2016.11.017.
Cheng, C.S., Li, G., Li, Q., Auld, H., 2011. A synoptic weather-typing approach to project future daily rainfall and extremes at local scale in Ontario, Canada. J. Clim. 24 (14), 3667–3685. https://doi.org/10.1175/2011JCLI3764.1.
CHI. 2019 PCSWMM User Manual. Computational Hydraulics International. Guelph, ON, Canada. https://www.chiwater.com (Accessed 18 June 2024).
City of Ottawa. 2020 City-Wide Flood Risk Profile. Vol. 2, Ottawa, ON, Canada.
City of Thunder Bay. 2018 2D Stormwater Modeling for Flood Management Intercity Drainage Study. Thunder Bay, ON, Canada.

City of Vancouver. 2021 Broadway Interim Integrated Water Management Plan (Draft). Vancouver, BC, Canada.
City of Vancouver. 2022 Broadway Plan One Water Strategy. Vancouver, BC, Canada.
Courchesne D., Maisonneuve A., Trudel G., & Fuamba M. 2023 Suivi expérimental de performance de cellules végétalisées sur le boulevard Papineau à Montréal. In: Novatech 2023 11e Conférence internationale sur l'eau dans la ville. Lyon. https://hal.science/hal-04167783 (Accessed 18 June 2024).
Cristiano, E., Farris, S., Deidda, R., Viola, F., 2022. How much green roofs and rainwater harvesting systems can contribute to urban flood mitigation? Urban Water J. 20 (2), 140–157. https://doi.org/10.1080/1573062X.2022.2155849.
Crookes, A.J., Drake, J.A.P., Green, M., 2017. Hydrologic and quality control performance of zero-exfiltration pervious concrete pavement in Ontario. J. Sustain. Water Built Environ. 3 (3), 06017001. https://doi.org/10.1061/JSWBAY.0000828.
Czemiel Berndtsson, J., 2010. Green roof performance towards management of runoff water quantity and quality: a review. Ecol. Eng. 36 (4), 351–360. https://doi.org/10.1016/j.ecoleng.2009.12.014.
Dhakal, K.P., Chevalier, L.R., 2017. Managing urban stormwater for urban sustainability: Barriers and policy solutions for green infrastructure application. J. Environ. Manag. 203, 171–181. https://doi.org/10.1016/j.jenvman.2017.07.065.
Dietz, M.E., 2007. Low impact development practices: a review of current research and recommendations for future directions. Water, Air, Soil Pollut. 186 (1–4), 351–363. https://doi.org/10.1007/s11270-007-9484-z.
Dorst, H., van der Jagt, A., Raven, R., Runhaar, H., 2019. Urban greening through nature-based solutions – key characteristics of an emerging concept. Sustain. Cities Soc. 49, 101620. https://doi.org/10.1016/j.scs.2019.101620.
Drake, J., Bradford, A., Van Seters, T., 2010. Performance of permeable pavements in cold climate environments. In: Low Impact Development. American Society of Civil Engineers, Reston, VA, USA, pp. 1369–1378. https://doi.org/10.1061/41099(367)117.
Drake, J., Bradford, A., Van Seters, T., 2014. Hydrologic performance of three partial-infiltration permeable pavements in a cold climate over low permeability soil. J. Hydrol. Eng. 19 (9), 04014016. https://doi.org/10.1061/(asce)he.1943-5584.0000943.
Du, J., Qian, L., Rui, H., Zuo, T., Zheng, D., Xu, Y., 2012. Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. Journal of Hydrology 464–465, 127–139. https://doi.org/10.1016/j.jhydrol.2012.06.057.
Eckart, K., McPhee, Z., Bolisetti, T., 2017. Performance and implementation of low impact development – A review. Sci. Total Environ. 607, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254.
Eckart, K., McPhee, Z., Bolisetti, T., 2018. Multiobjective optimization of low impact development stormwater controls. J. Hydrol. 562, 564–576. https://doi.org/10.1016/j.jhydrol.2018.04.068.
Emmons & Olivier Resources Inc. 2015 Northwood Modeling Memo. City of Thunder Bay, ON, Canada.
Emmons & Olivier Resources Inc. 2020 Tupper Street and Prospect Avenue Stormwater Model Report. City of Thunder Bay, ON, Canada.
Emmons & Olivier Resources Inc. 2022a Lyons Channel Drainage Improvements Draft Report. City of Thunder Bay, ON, Canada.
Emmons & Olivier Resources Inc. 2022b. McBean Street Drainage Improvements Final Report. City of Thunder Bay, ON, Canada.
Emmons & Olivier Resources Inc. 2022c Tupper Street Storm Sewer Assessment – Phase 2 (Pine Street to Duke Street) Final Report. City of Thunder Bay, ON, Canada.
Feltmate B., & Fluder A. 2018 Too Small to Fail: Protecting Canadian Communities from Floods. Intact Center on Climate Adaptation, Waterloo, ON, Canada. https://www.intactcenterclimateadaptation.ca/wp-content/uploads/2018/10/Climate-Change-Adaptation-Projects-FINAL.pdf (Accessed 19 June 2024).
Ferreira C.S., Kalantari Z., Hartmann T., & Pereira P., 2022. Nature-Based Solutions for Flood Mitigation: Environmental and Socio-Economic Aspects (Vol. 107). Springer Nature.
Fléchais S. 2011 Modélisation des effets de la végétalisation en milieu urbain sur les eaux de ruissellement dirigées à l'égout. École de technologie supérieure, Montreal, QC, Canada. https://espace.etsmtl.ca/id/eprint/904/ (Accessed 19 June 2024).
Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., et al., 2015. SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. Urban Water J. 12 (7), 525–542. https://doi.org/10.1080/1573062X.2014.916314.
Ganguli, P., Coulibaly, P., 2019. Assessment of future changes in intensity-duration-frequency curves for Southern Ontario using North American (NA)-CORDEX models with nonstationary methods. J. Hydrol.: Reg. Stud. 22, 100587. https://doi.org/10.1016/j.ejrh.2018.12.007.
Garousi, V., Petersen, K., Ozkan, B., 2016. Challenges and best practices in industry-academia collaborations in software engineering: A systematic literature review. Inf. Softw. Technol. 79, 106–127. https://doi.org/10.1016/j.infsof.2016.07.006.
Geheniau N. 2014 Évaluation expérimentale de la performance d'un jardin de pluie et d'un toit vert en climat froid. Polytechnique Montréal, Montreal, QC, Canada. https://publications.polymtl.ca/1382/ (Accessed 19 June 2024).
Global News. 2023 Heavy rain in Ottawa causes flooding, power outages and road closures. ⟨https://globalnews.ca/news/9889120/flooding-power-outages-ottawa/⟩ (Accessed 26 May 2024).
Glorieux M. 2010 Gestion de l'eau de pluie en milieu urbain: intégration des arbres dans les systèmes de biorétention. École de technologie supérieure, Montreal, QC, Canada. ⟨https://espace.etsmtl.ca/id/eprint/641/⟩ (Accessed 19 June 2024).
Gougeon, G., Bouattour, O., Formankova, E., St-Laurent, J., Doucet, S., Dorner, S., et al., 2023. Impact of bioretention cells in cities with a cold climate: modeling snow management based on a case study. Blue-Green. Syst. 5 (1), 1–17. https://doi.org/10.2166/bgs.2023.032.
Government of Canada. 2022 Climate Resilient Built Environment. ⟨https://www.canada.ca/en/office-infrastructure/news/2022/06/government-of-canada-announces-funds-for-climate-resilient-infrastructure-initiatives.html⟩ (Accessed 10 October 2023).
Government of Canada. 2023 Environmental Funding Programs. ⟨https://www.canada.ca/en/environment-climate-change/services/environmental-funding/programs/nature-smart-climate-solutions-fund.html⟩ (Accessed 10 October 2023).
Guan, M., Sillanpää, N., Koivusalo, H., 2015. Modeling and assessment of hydrologic changes in a developing urban catchment. Hydrol. Process. 29 (13), 2880–2894. https://doi.org/10.1002/hyp.10410.
Guay, V., Binesh, N., Duchesne, S., Pelletier, G., Grégoire, G., 2024. Performance assessment of stormwater management infrastructures in a parking lot near Montreal, Canada. J. Sustain. Water Built Environ. 10 (1), 04023012. https://doi.org/10.1061/JSWBAY.SWENG-528.
Hamouz, V., Møller-Pedersen, P., Muthanna, T.M., 2020. Modelling runoff reduction through implementation of green and grey roofs in urban catchments using PCSWMM. Urban Water J. 17 (9), 813–826. https://doi.org/10.1080/1573062X.2020.1828500.
Hatch Mott Macdonald Inc. 2014 Neighbourhood Master Stormwater Drainage Study Final Report. City of Thunder Bay, ON, Canada.
Hathaway, J. M., E. Z. Bean, J. T. Bernagros, D. P. Christian, H. Davani, A. Ebrahimian, C. M. Fairbaugh, J. S. Gulliver, L. E. McPhillips, G. Palino, E. W. Strecker, R. A. Tirpak, B. van Duin, N. Weinstein, and R. J. Winston. 2024. "A Synthesis of Climate Change Impacts on Stormwater Management Systems: Designing for Resiliency and Future Challenges." J Sustain Water Built Environ, 10 (2). https://doi.org/10.1061/JSWBAY.SWENG-533.
Henderson, V., Tighe, S., 2012. Evaluation of pervious concrete pavement performance in cold weather climates. Int. J. Pavement Eng. 13 (3), 197–208. https://doi.org/10.1080/10298436.2011.572970.
Hill, J., Drake, J., Sleep, B., Margolis, L., 2017. Influences of four extensive green roof design variables on stormwater hydrology. J. Hydrol. Eng. 22 (8), 04017019. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001534.
Huang, J., Valeo, C., He, J., Chu, A., 2012. Winter performance of inter-locking pavers–stormwater quantity and quality. Water 4 (4), 995–1008. https://doi.org/10.3390/w4040995.
Huang, J., Valeo, C., He, J., Chu, A., 2016. Three types of permeable pavements in cold climates: hydraulic and environmental performance. J. Environ. Eng. 142 (6), 04016025. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001085.
Intergovernmental Panel on Climate Change, 2023. Climate Change 2021 – The Physical Science Basis. Cambridge University Press. https://doi.org/10.1017/9781009157896.
J. L. Richards & Associates Limited. 2018 Crystal Beach 2D Dual Drainage Model: Final Report. City of Ottawa, ON, Canada.
Jahanfar, A., Drake, J., Sleep, B., Margolis, L., 2019. Evaluating the shading effect of photovoltaic panels on green roof discharge reduction and plant growth. J. Hydrol. 568, 919–928. https://doi.org/10.1016/j.jhydrol.2018.11.019.

James, W., 2004. Clogging of permeable concrete block pavement by street particulates and rain. J. Water Manag. Model. 220 (29), 603–626. https://doi.org/10.14796/JWMM.R220-29.

James, W., von Langsdorff, H., McIntyre, M., 2018. Permeable pavers designed for rapid renewal by considering sweeper mechanics: initial field tests. J. Water Manag. Model. https://doi.org/10.14796/JWMM.C450.

Jandaghian, Z., Baskaran, B., 2022. Nature-Based Solutions on Commercial Roofs: How They can Mitigate Urban Flooding. National Research Council Canada, Ottawa, ON, Canada. ⟨https://publications-cnrc.canada.ca/eng/view/author/version/?id= 34d6d1b5-59bc-4fd2-80cd-53fdf71bb3da⟩. Accessed 19 June 2024.

Jandaghian, Z., Zhu, Y., Saragosa, J., Doshi, H., Baskaran, B., 2022. Low-sloped rooftop storm-water detention assembly to mitigate urban flooding. Buildings 13 (1), 8. https://doi.org/10.3390/buildings13010008.

Jha A.K., Bloch R., & Lamond J. 2012 Cities and Flooding: a Guide to Integrated Urban Flood Risk Management for the 21st Century. The World Bank, Washington, D. C., USA. file:///C:/Users/user/Downloads/7.CitiesandFloodingGuidebook_Worldbank_2012.pdf (Accessed 19 June 2024).

Jiang, A.Z., McBean, E.A., 2021. Performance of lot-level low impact development technologies under historical and climate change scenarios. J. Hydro-Environ. Res. 38, 4–13. https://doi.org/10.1016/j.jher.2021.07.004.

Joksimovic, D., Alam, Z., 2014. Cost efficiency of low impact development (LID) stormwater management practices. Procedia Eng. 89, 734–741. https://doi.org/10.1016/j.proeng.2014.11.501.

Joksimovic, D., Darko, Sander, M., 2016. Performance modeling of actively controlled green infrastructure options in a mixed use neighborhood retrofit. World Environmental and Water Resources Congress. American Society of Civil Engineers, Reston, VA, pp. 96–105. https://doi.org/10.1061/9780784479889.011.

Karamouz, M., Zoghi, A., Mahmoudi, S., 2022. Flood modeling in coastal cities and flow through vegetated BMPs: Conceptual design. J. Hydrol. Eng. 27 (10), 04022022. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002206.

Khan, U.T., Valeo, C., Chu, A., van Duin, B., 2010. Bioretention cell efficacy in cold climates. Low Impact Development. American Society of Civil Engineers, Reston, VA, pp. 1196–1208. https://doi.org/10.1061/41099(367)104.

Khan, U.T., Valeo, C., Chu, A., van Duin, B., 2012. Bioretention cell efficacy in cold climates: Part 1 – hydrologic performance. Can. J. Civ. Eng. 39 (11), 1210–1221. https://doi.org/10.1139/l2012-110.

Khan, U.T., Valeo, C., Chu, A., He, J., 2013. A data driven approach to bioretention cell performance: Prediction and design. Water 5 (1), 13–28. https://doi.org/10.3390/w5010013.

Kim Y., & Khaliq M.N. 2022 Nature-Based Solutions to Urban Flooding: A Review and Future Directions. NRC Report No. NRC-OCRE-2022-TR-011. National Research Council of Canada, Ottawa, ON, Canada.

Li, Z., Kratky, H., Yu, T., Li, X., Jia, H., 2021. Study on bioretention for stormwater management in cold climate, Part I: Hydraulics. J. Hydro-Environ. Res. 38, 25–34. https://doi.org/10.1016/j.jher.2021.01.007.

Li, C., Peng, C., Chiang, P.C., Cai, Y., Wang, X., Yang, Z., 2019. Mechanisms and applications of green infrastructure practices for stormwater control: a review. J. Hydrol. 568, 626–637. https://doi.org/10.1016/j.jhydrol.2018.10.074.

Liu K., & Minor J. 2005 Performance evaluation of an extensive green roof. Toronto, ON, Canada. ⟨https://nrc-publications.canada.ca/eng/view/object/?id=e10a2c46-5c45-4a9e-8625-d7b0ea46e847⟩ (Accessed 19 June 2024).

Lundholm, J., MacIvor, J.S., MacDougall, Z., Ranalli, M., 2010. Plant species and functional group combinations affect green roof ecosystem functions. PLoS ONE 5 (3), e9677. https://doi.org/10.1371/journal.pone.0009677.

Mahmood, M.I., Elagib, N.A., Horn, F., Saad, S.A.G., 2017. Lessons learned from Khartoum flash flood impacts: an integrated assessment. Sci. Total Environ. 601–602, 1031–1045. https://doi.org/10.1016/j.scitotenv.2017.05.260.

Martel, J.-L., Brissette, F.P., Lucas-Picher, P., Troin, M., Arsenault, R., 2021. Climate change and rainfall intensity–duration–frequency curves: overview of science and guidelines for adaptation. J. Hydrol. Eng. 26 (10), 03121001. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002122.

Martel, J.-L., Mailhot, A., Brissette, F., 2020. Global and regional projected changes in 100-yr subdaily, daily, and multiday precipitation extremes estimated from three large ensembles of climate simulations. J. Clim. 33 (3), 1089–1103. https://doi.org/10.1175/JCLI-D-18-0764.1.

Marvin, J.T., Scott, J., Van Seters, T., Bowers, R., Drake, J.A., 2021. Winter maintenance of permeable interlocking concrete pavement: evaluating opportunities to reduce road salt pollution and improve winter safety. J. Transp. Res. Board 2675 (2), 174–186. https://doi.org/10.1177/0361198120957320.

Masud, M.B., Khaliq, M.N., Wheater, H.S., 2017. Projected changes to short-and long-duration precipitation extremes over the Canadian Prairie Provinces. Clim. Dyn. 49, 1597–1616. https://doi.org/10.1007/s00382-016-3404-0.

McKee, J., Sandhu, N., 2019. Technical Memorandum #2 - Broadway Overland Flow Analysis and Results. McElhanney Inc, Vancouver, BC, Canada.

Mora-Melià, D., López-Aburto, C.S., Ballesteros-Pérez, P., Muñoz-Velasco, P., 2018. Viability of green roofs as a flood mitigation element in the central region of Chile. Sustainability 10 (4), 1130. https://doi.org/10.3390/su10041130.

Nasrollahpour R., Skorobogatov A., He J., Valeo C., Chu A., & van Duin B. 2021 The Effects of Climatic and Design Variables on Evapotranspiration in Bioretention Systems. In: Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021, S. Walbridge, M. Nik-Bakht, K. T. Wai, M. Shome, M. S. Alam, A. El Damatty, & G. Lovegrve (eds.), pp. 57–62. https://doi.org/10.1007/978-981-19-1065-4_5.

Oh, S.-G., Sushama, L., 2020. Short-duration precipitation extremes over Canada in a warmer climate. Climate Dynamics 54, 2493–2509. https://doi.org/10.1007/s00382-020-05126-4.

Olthof, I., Svacina, N., 2020. Testing urban flood mapping approaches from satellite and in-situ data collected during 2017 and 2019 events in eastern Canada. Remote Sens. 12 (19), 3141. https://doi.org/10.3390/rs12193141.

Pallathadka, A., 2023. Urban flooding in Vancouver, Canada. Integr. J. Res. Arts Humanit. 3 (2), 63–69. https://doi.org/10.55544/ijrah.3.2.11.

Pineau, B., Brodeur-Doucet, C., Corrivault-Gascon, J., Arjoon, D., Lessard, P., Pelletier, G., Duchesne, S., 2021. Performance of green infrastructure for storm water treatment in cold climate (Canada). J. Environ. Eng. Sci. 16 (4), 185–194. https://doi.org/10.1680/jenes.20.00041.

Qin, H., Li, Z., Fu, G., 2013. The effects of low impact development on urban flooding under different rainfall characteristics. J. Environ. Manag. 129, 577–585. https://doi.org/10.1016/j.jenvman.2013.08.026.

Rahman, M.A., Alim, M.A., Jahan, S., Rahman, A., 2022. Vegetated roofs as a means of sustainable urban development: a scoping review. Water 114 (19), 3188. https://doi.org/10.3390/w14193188.

Raymond, C.M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M.R., et al., 2017. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environ. Sci. Policy 77, 15–24. https://doi.org/10.1016/j.envsci.2017.07.008.

Rayner, J., Howlett, M., Wellstead, A., 2017. Policy Mixes and their Alignment over Time: Patching and stretching in the oil sands reclamation regime in Alberta, Canada. Environ. Policy Gov. 27 (5), 472–483. https://doi.org/10.1002/eet.1773.

Roehr, D., Kong, Y., 2010. Runoff reduction effects of green roofs in Vancouver, BC, Kelowna, BC, and Shanghai, P.R. China. Can. Water Resour. J. 35 (1), 53–68. https://doi.org/10.4296/cwrj3501053.

Roseen, R.M., Ballestero, T.P., Houle, J., Avellaneda, P., Briggs, J., Fowler, G., Wildey, R., 2009. Seasonal performance variations for storm-water management systems in cold climate conditions. J. Environ. Eng. 135 (3), 128–137. https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(128).

Rosenzweig, B.R., Herreros Cantis, P., Kim, Y., Cohn, A., Grove, K., Brock, J., et al., 2021. The value of urban flood modeling. Earth'S. Future 9 (1). https://doi.org/10.1029/2020EF001739.

Rowe, E., Guo, Y., Li, Z., 2021. Seeking more cost-efficient design criteria for infiltration trenches. J. Sustain. Water Built Environ. 7 (3), 04021009. https://doi.org/10.1061/JSWBAY.0000951.

Rowe, E., Guo, Y., Li, Z., 2024. A closer look at Toronto's water quality control design criteria for bioretention cells. Can. J. Civ. Eng. 51 (1), 1–10. https://doi.org/10.1139/cjce-2023-0148.

Saade J., Cazares S.P., Liao W., Frizzi G., Sidhu V., Margolis L., et al. 2022 Influence of Biochar Amendment on Runoff Retention and Vegetation Cover for Extensive Green Roofs. Proceedings of the Canadian Society of Civil Engineering Annual Conference, pp. 1117–1132. https://doi.org/10.1007/978-3-031-34593-7_71.

Sandink, D., 2016. Urban flooding and ground-related homes in Canada: an overview. J. Flood Risk Manag. 9 (3), 208–223. https://doi.org/10.1111/jfr3.12168.

Scott, J., Sarabian, T., Bowers, R., Drake, J., 2022. Testing restorative maintenance technologies for permeable interlocking concrete pavements. Urban Water J. 19 (3), 221–232. https://doi.org/10.1080/1573062X.2021.1992454.
Semadeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L.-G., 2008. The impacts of climate change and urbanization on drainage in Helsingborg, Sweden: suburban stormwater. J. Hydrol. 350 (1–2), 114–125. https://doi.org/10.1016/j.jhydrol.2007.11.006.
Seto, K.C., Sánchez-Rodríguez, R., Fragkias, M., 2010. The new geography of contemporary urbanization and the environment. Annu. Rev. Environ. Resour. 35, 167–194. https://doi.org/10.1146/annurev-environ-100809-125336.
Silva, D.F., Simonovic, S.P., Schardong, A., Goldenfum, J.A., 2021. Assessment of non-stationary IDF curves under a changing climate: Case study of different climatic zones in Canada. J. Hydrol.: Reg. Stud. 36, 100870. https://doi.org/10.1016/j.ejrh.2021.100870.
Sims, A.W., Robinson, C.E., Smart, C.C., Voogt, J.A., Hay, G.J., Lundholm, J.T., et al., 2016. Retention performance of green roofs in three different climate regions. J. Hydrol. 542, 115–124. https://doi.org/10.1016/j.jhydrol.2016.08.055.
Spraakman, S., Martel, J.-L., Drake, J., 2022. How much water can bioretention retain, and where does it go? Blue-Green. Syst. 4 (2), 89–107. https://doi.org/10.2166/bgs.2022.002.
Spraakman, S., Van Seters, T., Drake, J., Passeport, E., 2020. How has it changed? A comparative field evaluation of bioretention infiltration and treatment performance post-construction and at maturity. Ecol. Eng. 158, 106036. https://doi.org/10.1016/j.ecoleng.2020.106036.
Talebi, A., Bagg, S., Sleep, B.E., O'Carroll, D.M., 2019. Water retention performance of green roof technology: a comparison of Canadian climates. Ecol. Eng. 126, 1–15. https://doi.org/10.1016/j.ecoleng.2018.10.006.
Teufel, B., Diro, G.T., Whan, K., Milrad, S.M., Jeong, D.I., Ganji, A., et al., 2017. Investigation of the 2013 Alberta flood from weather and climate perspectives. Clim. Dyn. 48, 2881–2899. https://doi.org/10.1007/s00382-016-3239-8.
Teufel, B., Sushama, L., Huziy, O., Diro, G.T., Jeong, D.I., Winger, K., et al., 2019. Investigation of the mechanisms leading to the 2017 Montreal flood. Clim. Dyn. 52, 4193–4206. https://doi.org/10.1007/s00382-018-4375-0.
Urban Systems Inc. 2022 Charleson Catchment Integrated Rainwater Study. City of Vancouver, BC, Canada.
Vaillancourt, C., Duchesne, S., Pelletier, G., 2019. Hydrologic performance of permeable pavement as an adaptive measure in urban areas: case studies near Montreal, Canada. J. Hydrol. Eng. 24 (8), 05019020. https://doi.org/10.1061/(asce)he.1943-5584.0001812.
Valtanen, M., Sillanpää, N., Setälä, H., 2014. Effects of land use intensity on stormwater runoff and its temporal occurrence in cold climates. Hydrol. Process. 28 (4), 2639–2650. https://doi.org/10.1002/hyp.9819.
Van de Valk, J., Drake C., Cueto Benger A., Martel J.-L., Costa-Cabral M., & Wang E. 2020 Locarno-Jericho Flood Mitigation Study Appendix C: Hydrologic and Hydraulic Modeling Report. Northwest Hydraulic Consultants Ltd., Vancouver, BC, Canada.
Van Seters T., Smith D., & MacMillan G. 2006. Performance Evaluation of Permeable Pavement and a Bioretention Swale. In: 8th International Conference on Concrete Block Paving. San Francisco, CA, USA. ⟨http://www.sept.org/techpapers/1304.pdf⟩ (Accessed 19 June 2024).
Vidil C. 2012 Gestion des eaux pluviales et changements climatiques: Étude de deux secteurs urbains. Université Laval, Laval, QC, Canada. https://corpus.ulaval.ca/bitstreams/5476f84c-6395-4b17-a00e-82908c3db834/download (Accessed 19 June 2024).
Vogel, J.R., Moore, T.L., Coffman, R.R., Rodie, S.N., Hutchinson, S.L., McDonough, K.R., et al., 2015. Critical review of technical questions facing low impact development and green infrastructure: a perspective from the Great Plains. Water Environ. Res. 87 (9), 849–862. https://doi.org/10.2175/106143015X14362865226392.
Willems, P., 2013. Revision of urban drainage design rules after assessment of climate change impacts on precipitation extremes at Uccle, Belgium. J. Hydrol. 496, 166–177. https://doi.org/10.1016/j.jhydrol.2013.05.037.
Wohlin C. 2014 Guidelines for snowballing in systematic literature studies and a replication in software engineering. In: Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering. New York, NY, USA, pp. 1–10. https://doi.org/10.1145/2601248.2601268.
Xiao, S., Feng, Y., Xue, L., Ma, Z., Tian, L., Sun, H., 2022. Hydrologic performance of low impact developments in a cold climate. Water 14 (22), 3610. https://doi.org/10.3390/w14223610.
Yang, G., Bowling, L.C., Cherkauer, K.A., Pijanowski, B.C., 2011. The impact of urban development on hydrologic regime from catchment to basin scales. Landsc. Urban Plan. 103 (2), 237–247. https://doi.org/10.1016/j.landurbplan.2011.08.003.
Yao, L., Chen, L., Wei, W., 2016. Assessing the effectiveness of imperviousness on stormwater runoff in micro urban catchments by model simulation. Hydrol. Process. 30 (12), 1836–1848. https://doi.org/10.1002/hyp.10758.
Zhang, H., Babar, M.A., Tell, P., 2011. Identifying relevant studies in software engineering. Inf. Softw. Technol. 53 (6), 625–637. https://doi.org/10.1016/j.infsof.2010.12.010.
Zhang, S., Guo, Y., 2015. SWMM simulation of the storm water volume control performance of permeable pavement systems. J. Hydrol. Eng. 20 (8), 06014010. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001092.
Zhou, Q., Leng, G., Su, J., Ren, Y., 2019. Comparison of urbanization and climate change impacts on urban flood volumes: importance of urban planning and drainage adaptation. Sci. Total Environ. 658, 24–33. https://doi.org/10.1016/j.scitotenv.2018.12.184.
Zhuang, Y., Zhang, L., Du, Y., Chen, G., 2016. Current patterns and future perspectives of best management practices research: a bibliometric analysis. J. Soil Water Conserv. 71 (4), 98A–104A. https://doi.org/10.2489/jswc.71.4.98A.

Further reading

Aglida K. 2022 Évaluations environnementale, hydrologique et hydraulique d'un enrobé drainant jumelé à une chaussée réservoir en guise d'ouvrage de gestion des eaux pluviales en milieu urbain. Institut National de la Recherche Scientifique (INRS), Montreal, QC, Canada. https://espace.inrs.ca/id/eprint/13176/1/T1041.pdf (Accessed 7 Novermber 2023).
Investment Agriculture Foundation of British Columbia. 2023 Fraser Valley Flood Mitigation Program. https://iafbc.ca/fraser-valley-flood/ (Accessed 7 November 2023).
Auger, S., David, Y., Ho, W., Sani, S., Singh, A., Van Seters, T., Davidson, C., Kennedy, M., & MacKenzie, K. 2016 Development of a low impact development and urban water balance modeling tool. In: International Low Impact Development Conference, Toronto and Region Conservation Authority, Lake Simcoe Region Conservation Authority, Credit Valley Conservation Authority. https://ascelibrary.org/doi/abs/10.1061/9780784480540.005 (Accessed 2 December 2024).
Bond, J. 2020 Quantification of the Hydrologic Performance and Modelling in SWMM of a Bioretention Basin and Vegetated Swale with a Trapezoidal Cross-section. Polytechnique Montréal. Montreal, QC, Canada. https://publications.polymtl.ca/5258/ (Accessed 5 December 2024).
Brodeur-Doucet C. 2018 Évaluation de la performance de pratiques de gestion optimales installées en série: le cas du marché public de Longueuil. Mémoire de maîtrise, Université de Sherbrooke, Sherbrooke, QC, Canada.
Brodeur-Doucet, C., Pineau, B., Corrivault-Gascon, J., Arjoon, D., Lessard, P., Pelletier, G., Duchesne, S., 2021. Seasonal hydrological and water quality performance of individual and in-series stormwater infrastructures as treatment trains in cold climate. Water Qual. Res. J. 56 (4), 205–218. https://doi.org/10.2166/wqrj.2021.026.
Buttle, J.M., Allen, D.M., Caissie, D., Davison, B., Hayashi, M., Peters, D.L., Pomeroy, J.W., Simonovic, S., St-Hilaire, A., Whitfield, P.H., 2016. Flood processes in Canada: Regional and special aspects. Can. Water Resour. J. / Rev. Can. Des. Ressour. Hydr. 41 (1-2), 7–30. https://doi.org/10.1080/07011784.2015.1131629.
Canadian Standards Association, 2018. CSA W200: Design for Bioretention Systems (CSA). CSA Group, Toronto, ON, Canada. ⟨https://www.csagroup.org⟩. Accessed 2 December 2024).
Canadian Standards Association, 2018. CSA W201: Design for Permeable Pavements and Infiltration Trenches (CSA). CSA Group, Toronto, ON, Canada. ⟨https://www.csagroup.org⟩. Accessed 2 December 2024).
Credit Valley Conservation Authority. 2010 Low Impact Development Stormwater Management Planning and Design Guide. Credit Valley Conservation Authority, Mississauga, ON, Canada. https://cvc.ca (Accessed 2 December 2024).

Cristiano, E., Farris, S., Deidda, R., Viola, F., 2021. Comparison of blue-green solutions for urban flood mitigation: A multi-city large-scale analysis. PLoS ONE 16 (1), e0246429. https://doi.org/10.1371/journal.pone.0246429.

Crookes A., Drake J., & Lofty A. 2015 Performance of Hydromedia Pervious Concrete Pavement in Ontario Subjected to Urban Traffic Loads. In: International Low Impact Development Conference. American Society of Civil Engineers.

Dagenais, D., Paquette, S., Thomas, I., & Fuamba, M. 2014 Implantation en milieu urbain de systèmes végétalisés de contrôle à la source des eaux pluviales dans un contexte d'adaptation aux changements climatiques: balisage des pratiques québécoises, canadiennes et internationales et développement d'un cadre d'implantation pour les municipalités du Sud du Québec. Rapport final projet # 551004-XXI, Chaire en paysage et environnement (CPEUM), Université de Montréal. Montreal, QC, Canada. https://www.imaginonsnotredelson.ca/wp-content/uploads/2016/01/Dagenais_systemes_vegetalises_2014.pdf (Accessed 5 December 2024).

Dagenais, D., Dorner, S., & Brisson, J. 2022 Performances des infrastructures vertes de gestion des eaux pluviales (IVGEP) pour la réduction du ruissellement urbain et pour la protection des sources d'eau potable en climat actuel et futur. Rapport de recherche, Ouranos. Montréal, QC, Canada.

De Boer, P. 2019 Assessing the performance of low impact development (LID) measures during large rainfall events in the Humber River watershed, Ontario, Canada. University of Guelph, Guelph, Ontario. https://atrium.lib.uoguelph.ca/items/9e2a4257-62dc-4ed1-b1ac-44c5a92251fe (Accessed 2 December 2024).

Demard, E. 2022 Sélection et évaluation de solutions intégrées en réseau unitaire – cas du bassin d'Argenson à Repentigny. Mémoire présenté pour l'obtention du grade de Maître ès sciences (M.Sc.) en sciences de l'eau, Université du Québec, Institut National de la Recherche Scientifique, Centre Eau Terre Environnement. Montréal, QC, Canada. https://espace.inrs.ca/id/eprint/12586/ (Accessed 5 December 2024).

Desjardins J., Dubuc M., Dugué M., Jelloul A.L., Lajeunesse S., & Michaud A. 2015 Rapport final. Essai sur le terrain du comportement des cellules de biorétention. Projet Stationnement écologique de la MRC Brome-Missisquoi. Cowansville, QC, Canada. 105 pp. https://www.researchgate.net/publication/301201797 (Accessed 5 December 2024).

Ferreira, C.S.S., Mourato, S., Kasanin-Grubin, M., Ferreira, A.J.D., Destouni, G., Kalantari, Z., 2020. Effectiveness of nature-based solutions in mitigating flood hazard in a Mediterranean peri-urban catchment. Water 12 (10), 2893. https://doi.org/10.3390/w12102893.

Foster, J., Lowe, A., & Winkelman, S. 2011 The Value of Green Infrastructure for Urban Climate Adaptation. Center for Clean Air Policy, Washington, D.C., USA. ⟨https://www.ccap.org⟩ (Accessed 5 December 2024).

Frizzi, G., & Drake, J. 2023 Impacts hydrologiques des couches de rétention dans les vastes toits végétalisés. Novatech 2023 11e Conférence internationale sur l'eau dans la ville, Lyon, France. https://hal.science/hal-04167829 (Accessed 5 December 2024).

Fuamba M. 2022 Mandat d'étude pour un suivi expérimental de performance et de surveillance technique de cellules végétalisées (Rapport No. 04 5568). City of Montreal. Montreal, QC, Canada.

Gougeon, G., Bouattour, O., Formankova, E., St-Laurent, J., Doucet, S., Dorner, S., et al., 2023. Impact of bioretention cells in cities with a cold climate: modeling snow management based on a case study. Blue-Green. Syst. 5 (1), 1–17. https://doi.org/10.2166/bgs.2023.032.

Gouvernement du Québec. 2023 Programme de résilience et d'adaptation face aux inondations (PRAFI) – Volet Aménagements résilients. ⟨https://www.quebec.ca/gouvernement/politiques-orientations/plan-de-protection-du-territoire-face-aux-inondations/programme-resilience-adaptation-inondations⟩ (Accessed 7 November 2023).

Government of Alberta. 2023a Alberta Community Resilience Program. ⟨https://www.alberta.ca/alberta-community-resilience-program⟩ (accessed 7 November 2023).

Government of Alberta. 2023b Watershed Resiliency and Restoration Program. ⟨https://www.alberta.ca/watershed-resiliency-and-restoration-program⟩ (Accessed 7 November 2023).

Government of Manitoba. 2022 2022 Spring Flood Residential Flood Protection Subsidy. https://www.gov.mb.ca/emo/pdfs/2022_dfa_subsidy.pdf (Accessed 7 November 2023).

Government of Manitoba. 2023a Mitigation and Preparedness Program. ⟨https://www.gov.mb.ca/emo/mitigation/mpp.html⟩ (Accessed 7 November 2023).

Government of Manitoba. 2023b Mitigation Funding. ⟨https://www.gov.mb.ca/emo/mitigation/funding.html#:~:text=Provincial%20Mitigation%20Programs&text=Maximum%20funding%20for%20projects%20will,cent%20of%20eligible%20project%20costs⟩ (Accessed 7 November 2023).

Government of Nova Scotia. 2023 Nova Scotia Flood Mitigation Framework. ⟨https://novascotia.ca/nse/climate-change/nsfaf-flood-mitigation-framework.asp⟩ (Accessed 7 November 2023).

Government of Ontario. 2023a Guidelines to apply for Municipal Disaster Recovery Assistance (MDRA). ⟨https://www.ontario.ca/page/guidelines-apply-municipal-disaster-recovery-assistance-mdra#:~:text=Related-,Overview,repair%20public%20infrastructure%20or%20property⟩ (Accessed 7 November 2023).

Government of Ontario. 2023b Ontario Community Infrastructure Fund. ⟨https://www.ontario.ca/page/ontario-community-infrastructure-fund#section-8⟩ (Accessed 7 November 2023).

Government of Saskatchewan. 2023 Communities Can Now Apply for a Flood Damage Reduction Program. ⟨https://www.saskatchewan.ca/government/news-and-media/2023/august/14/communities-can-now-apply-for-a-flood-damage-reduction-program⟩ (Accessed 7 November 2023).

Hadi Pour, S., Abd Wahab, A.K., Shahid, S., Asaduzzaman, M., Dewan, A., 2020. Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues, and challenges. Sustain. Cities Soc. 62, 102373. https://doi.org/10.1016/j.scs.2020.102373.

Khalid R. 2021 On the Use of Surrogate Model Ensembles for Bioretention Cell Design Optimization Under Current and Future Climate Conditions. York University, Toronto, ON, Canada. https://yorkspace.library.yorku.ca/server/api/core/bitstreams/05c5678a-5fed-4225-88f6-61a163158cd7/content (Accessed 19 June 2024).

Kokas, T., 2017. Effect of Land Use and Low Impact Development Measures on Urban Flood Hazard: A Case Study in the Black Creek Watershed. The University of Western Ontario, London, ON, Canada. ⟨https://ir.lib.uwo.ca/etd/4397⟩. Accessed 5 December 2024.

Levasseur, M., 2024. Suivi de la performance de saillies drainantes végétalisées, Ville de Montréal – Arrondissement de Rosemont. Rapport préparé pour l'obtention du grade de stagiaire de 1er cycle en recherche, Université du Québec. Centre Eau Terre Environnement. Montréal, QC, Canada.

Martins, R., Leandro, J., Djordjević, S., 2018. Influence of sewer network models on urban flood damage assessment based on coupled 1D/2D models. J. Flood Risk Manag. 11 (S2), S717–S728. https://doi.org/10.1111/jfr3.12244.

Pierre, A., Amoroso, N., Kelly, S., 2019. Geodesign application for bio-swale design: rule-based approach stormwater management for Ottawa Street North in Hamilton, Ontario. Landsc. Res. 44 (5), 642–658. https://doi.org/10.1080/01426397.2018.1498071.

Randall, M., & Perera, N. 2016 Single event and continuous hydrologic modeling for sizing and evaluation of LID systems. Proceedings of the 2016 International Low Impact Development China Conference. University of Copenhagen, Copenhagen, Denmark. ⟨https://researchprofiles.ku.dk/en/publications/single-event-and-continuous-hydrologic-modeling-for-sizing-and-ev⟩ (Accessed 5 December 2024).

Rochette Deslauriers, D. 2018 Performances hydraulique et microclimatique des saillies de trottoir végétalisées conçues pour la rétention des eaux pluviales. Mémoire de maîtrise, École Polytechnique de Montréal. Montreal, QC, Canada. ⟨https://publications.polymtl.ca/3299/⟩.

Saade, J., Pelayo Cazares, S., Liao, W., Frizzi, G., Sidhu, V., Margolis, L., Thomas, S., & Drake, J. 2022 Influence of biochar amendment on runoff retention and vegetation cover for extensive green roofs. Proceedings of the Canadian Society of Civil Engineering Annual Conference. Springer. https://doi.org/10.1007/978-3-031-34593-7_71.

Senior, M., Scheckenberger, R., Smith, N., & Stahl, J. 2017 Low impact development practices for stormwater management for road reconstruction projects in Southern Ontario. In: Leadership in Sustainable Infrastructure, Canadian Society for Civil Engineering. ⟨https://legacy.csce.ca/elf/apps/CONFERENCEVIEWER/conferences/2017/pdfs/GEN/FinalPaper_69.pdf⟩ (Accessed 2 December 2024).

Senosiain, J.L., 2019. Urban Regeneration: Green Urban Infrastructure as a Response to Climate Change Mitigation and Adaptation. Int. J. Des. Nat. Ecodynamics 15 (1), 33–38. https://doi.org/10.18280/ijdne.150105.

Tree Canada. 2023 Canadian Urban Forest Compendium. Tree Canada, Ottawa, ON, Canada. ⟨https://treecanada.ca⟩ (Accessed 2 December 2024).

Vega, O.M. 2019 Green Infrastructure in the City of Vancouver: Performance Monitoring of Stormwater Tree Trenches and Bioswales. The University of British Columbia, Vancouver, BC, Canada. https://doi.org/10.14288/1.0376974.

Venkataramanan, V., Lopez, D., McCuskey, D.J., Kiefus, D., McDonald, R.I., Miller, W.M., Packman, A.I., Young, S.L., 2020. Knowledge, attitudes, intentions, and behavior related to green infrastructure for flood management: A systematic literature review. Sci. Total Environ. 720, 137606. https://doi.org/10.1016/j.scitotenv.2020.137606.
Vijayaraghavan, K., Biswal, B.K., Adam, M.G., Soh, S.H., Tsen-Tieng, D.L., Davis, A.P., Chew, S.H., Tan, P.Y., Babovic, V., Balasubramanian, R., 2021. Bioretention systems for stormwater management: Recent advances and future prospects. J. Environ. Manag. 292, 112766. https://doi.org/10.1016/j.jenvman.2021.112766.
Weiss, P.T., Kayhanian, M., Gulliver, J.S., Khazanovich, L., 2019. Permeable pavement in northern North American urban areas: research review and knowledge gaps. Int. J. Pavement Eng. 20 (2), 143–162. https://doi.org/10.1080/10298436.2017.1279482.