Adaptation of dual drainage to control flooding and enhance combined sewer systems in highly urbanized areas

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Abstract: Combined sewer surcharges in densely urbanized areas have become more frequent due to the expansion of impervious surfaces and intensified precipitation caused by climate change. These surcharges can generate system overflows, causing urban flooding and pollution of urban areas. This paper presents a novel methodology to mitigate sewer system surcharges and control surface water. In this methodology, flow control devices and urban landscape retrofitting are proposed as strategies to reduce water inflow into the sewer network and manage excess water on the surface during extreme rainfall events. For this purpose, a 1D/2D dual drainage model was developed for two case studies located in Montreal, Canada. Applying the proposed methodology to these two sites led to a reduction of the volume of wastewater overflows by 100% and 86%, and a decrease in the number of surface overflows by 100% and 71%, respectively, at the two sites for a 100-year return period 3-h Chicago design rainfall. It also controlled the extent of flooding, reduced the volume of uncontrolled surface floods by 78% and 80% and decreased flooded areas by 68% and 42%, respectively, at the two sites for the same design rainfall.

Keywords: Dual drainage, Flooding, Low impact development, Flow control devices, Urban landscape retrofitting

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1 Introduction

Rapid urbanization has been accompanied by a sharp increase in sewer system surcharges in densely urbanized areas with limited space (Zhang et al., 2021). These more frequent sewer system surcharges can be caused by the expansion of impervious areas and increased rainfall intensities due to climate change (IPCC, 2022; Mailhot & Duchesne, 2009; Qin, 2020). These sewer overloads generate numerous problems in urban environments, such as basement flooding, manhole overflows, and pluvial flooding (van Duin et al., 2021; Sandink & Binns, 2021; Gómez et al., 2019). Overflows of combined sewer systems, which transport wastewater and stormwater through the same pipe network, could have severe impacts due to the pollution load they carry. In addition, overloads in the sewerage network cause social, economic, and health problems for the city and the affected communities (Mobini et al., 2021; Piadeh et al., 2022). Such problems have become more frequent in recent years due to the structural degradation of sewerage networks, their aging, and the alteration of land uses and rainfall patterns (Barreiro et al., 2023; Nasrin et al., 2017).

Sewer network overloading in urban areas can be addressed through urban drainage and stormwater management by applying different source control solutions called low impact development (LID) practices (Zhang et al., 2021; Ortega Sandoval et al., 2023; Knight et al., 2021). These solutions, also known as green infrastructures, include bioretention cells, permeable pavements, green roofs, rain gardens, stormwater curb extensions, and bioswales (Fletcher et al., 2015). Such infrastructures seek to mimic natural processes and reduce the runoff volume, promoting water infiltration into the ground and slowing runoff flow to allow using a smaller proportion of the hydraulic capacity of the stormwater conveyance network during rainfall events (Martin-Mikle, 2015; Barbaro et al., 2021; van Duin et al., 2021; Qi et al., 2021). In addition, stormwater management has been addressed through urban landscape retrofitting, in which existing built environments are sought to be transformed into more functional, sustainable, and resilient spaces (Wang et al., 2023; Wang, 2021; Shafique et al., 2017).

Dual drainage, combined with LIDs, can also help reduce pluvial flooding since it integrates and accounts for water behavior both in the sewer network (minor system) and on urban surfaces (major system) (Djordjevic et al., 1999; Schmitt et al., 2004; Smith, 2006 Jahanbazi & Egger, 2014; Wisner & Kassem, 1980; Wisner et al., 1981). Dual drainage is widely applied in hydraulic and hydrologic modeling, for which coupled one-dimensional to one-dimensional (1D/1D) and one-dimensional to two-dimensional (1D/2D) or integrated models were developed (Leandro et al., 2011). These dual drainage models allow for the assessment of flooding and sewer networks in the same model, improving the reliability and performance of existing urban drainage assessment (Djordjevic et al., 2013; Fraga et al., 2017; Guo et al., 2021). This improvement can be realized by analyzing the behavior of surface water overflowing from the sewerage network. As well, dual drainage modeling helps to better represent the spatial distribution of runoff and thus can help increasing the resilience of cities to flood risk (Djordjevic et al., 2005; Mark et al., 2004; Simoes et al., 2010).

Different engineering approaches have been developed to adapt dual drainage in urban environments to increase the resilience of stormwater management in cities (van Duin et al., 2021; Walesh et al., 2000). Among these approaches are creating depressions in localized areas, designing urban structures to convey water to specific locations and adding/modifying geometric elements in the street (e.g., speed bumps, increased sidewalks levels, and raised access ramps) (Balsells et al., 2013; Burda & Nyka, 2023; Langeveld et al., 2022; Palla et al., 2018).

Various stormwater management programs have been implemented around the world to prevent flooding from extreme rainfall events by combining urban landscape retrofitting and LID practices as, for example, the cloudburst management plans by the city of Copenhagen (City of

Copenhagen, 2012) and New York City (Balci et al., 2022). However, conventional stormwater management strategies (e.g., grey infrastructure) are not always able to prevent all sewer overflows during heavy rainfall events (Huang et al., 2020; Schmitt & Scheid, 2020; Van Duin et al., 2021; Xu et al., 2022).

The objective of this paper is to develop and assess a methodology to improve the performance of urban drainage systems by combining flow control devices, stormwater management practices such as LIDs, and urban surface retrofitting strategies (described later in Table 4). In particular, this research focuses on applying dual drainage in densely urbanized areas, specifically examining how its implementation aids in reducing sewer system surcharges and flooding extent. The criteria for assessing the minor system involve reducing the number of overloaded pipes and manholes and decreasing the number and volume of wastewater overflows. Similarly, the major system is evaluated based on the reduction in uncontrolled flood volume and area. These criteria were used to compare the performance of the drainage system for extreme rainfall events before and after the implementation of the proposed methodology. For this purpose, 1D/2D coupled dual drainage hydrodynamic models for two case studies in Montreal, Canada, were developed and analyzed, applying the proposed methodology. The scientific contribution of this work lies in the in-depth evaluation of the maximal performance of the tested strategies in an urban context which had not initially incorporated them and is, therefore, particularly vulnerable to problems such as sewer systems surcharges and flooding. More specifically, its novelty is related to the following aspects: i) evaluating the potential effectiveness of integrating flow control measures, LID practices, and urban surface adaptation for two case studies; and ii) developing a methodology to improve the performance of sewer networks while retaining and controlling excess water on the surface.

2 Material and methods

2.1 Case studies

The two case study areas are located respectively in the boroughs of Rosemont-La Petite-Patrie and St. Leonard in Montreal, Canada. The city receives an average annual precipitation of 1,000 mm with an average of 209 cm of snow in the winter. Meanwhile, 785 mm of rainfall is relatively uniformly distributed during the non-freezing months (May to November) (Environment Canada, 2022). The area's climatology is characterized as a humid, continental climate with warm summer conditions (Dfb in the Köppen classification; Kottek et al., 2006). The two areas are highly urbanized, with residential, commercial, and industrial buildings (with flat roofs connected directly to the sewer system), parking lots, and public spaces. The first area covers 117 ha and has an imperviousness of 74%, while the second area covers 69 ha and has an imperviousness of 65%. The study areas' location and land use are portrayed in Figure 1. While these two areas share many similarities, some distinctions exist. In the second area, for example, there are no alleys, fewer green spaces, limited space for locating surface water management solutions, and there are many garages and houses entrances below the street level. Additionally, there are hydraulic differences in the sewage systems of these two areas. The second area is positioned midstream of the main collector of the city's sewer system, which is usually overloaded, leading to backflows in the sewer system of this area. In contrast, the first area is situated at the upstream end of the main collector within the network.

Both areas are drained by a combined sewer system built in the late 1920s and designed to collect stormwater from events with a 5 to 10-year return period. These areas face multiple problems linked to the sewer system during rainfall events, such as surcharges, manhole overflows, and sewer backups, causing urban floods and flooding into basements (Sandink & Binns, 2021; Jahanbazi & Egger, 2014).

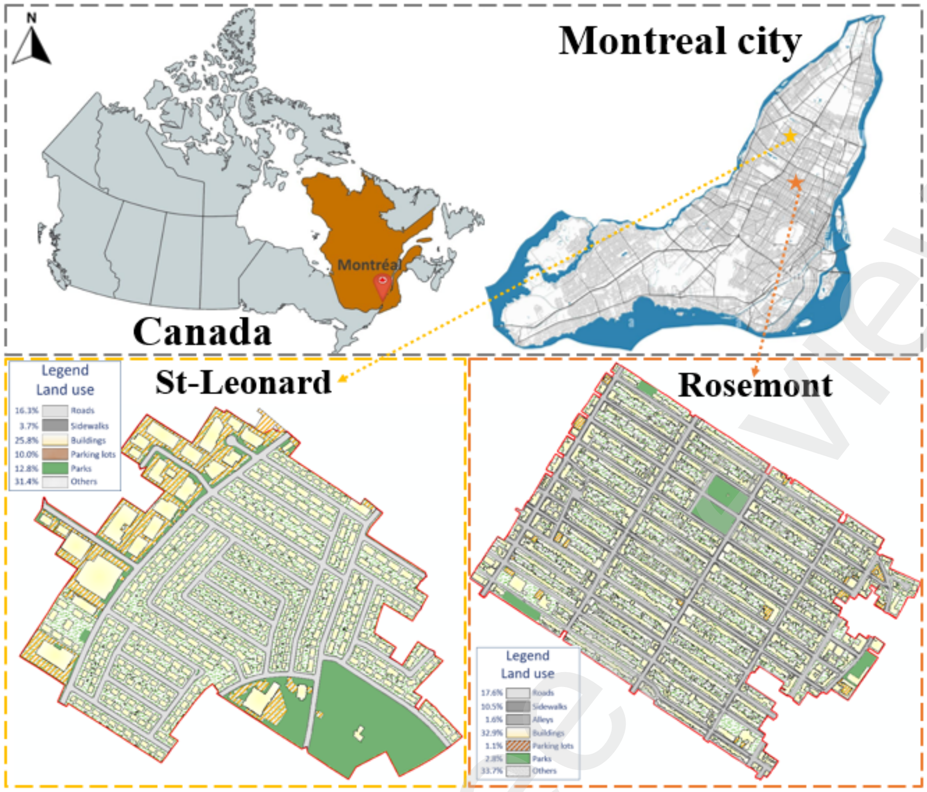


Figure 1. Location and land use maps of the first (Rosemont) and second (St. Leonard) case studies in Montreal, Canada

2.2 Developed methodology

The proposed methodology uses the principles of dual drainage to improve the performance of sewer networks in highly urbanized areas while controlling pluvial flooding by temporarily storing water on the surface. Each aspect of the planning scheme is based on regulating the inflow of stormwater runoff in the sewer system and then collecting and controlling the excess runoff on the surface. Stated briefly, the methodology aims at:

1. Restricting and regulating the inflow of stormwater into the sewer network by implementing flow control devices in the catch basins and rooftops, preventing excess water in the network and sewer overflows.
2. Reducing, retaining, storing, and controlling stormwater on the surface by applying green infrastructure that mimics natural processes.

3. Preventing surface water from causing damage to urban infrastructure by retrofitting urban landscapes and conveying surface water through a continuous flow route to solutions designed for its management.

This methodology is meant to be carried out in two phases. The first phase consists of enhancing the performance of the minor system, i.e., limiting the overloading of pipes and nodes, preventing overflows, and retaining surface runoff water on surfaces. In this study, the scenarios for phase I were analyzed with 1D models due to their faster computational speed. The second phase consists of retrofitting the major system to manage surface water, i.e., preventing uncontrolled flooding, water accumulation in critical areas, and surface water entering the buildings. Phase II scenarios were analyzed using a coupled 1D/2D model because the aim at this point is to understand the behavior of water in the major system. The flow diagram for the developed methodology is presented below in Figure 2.

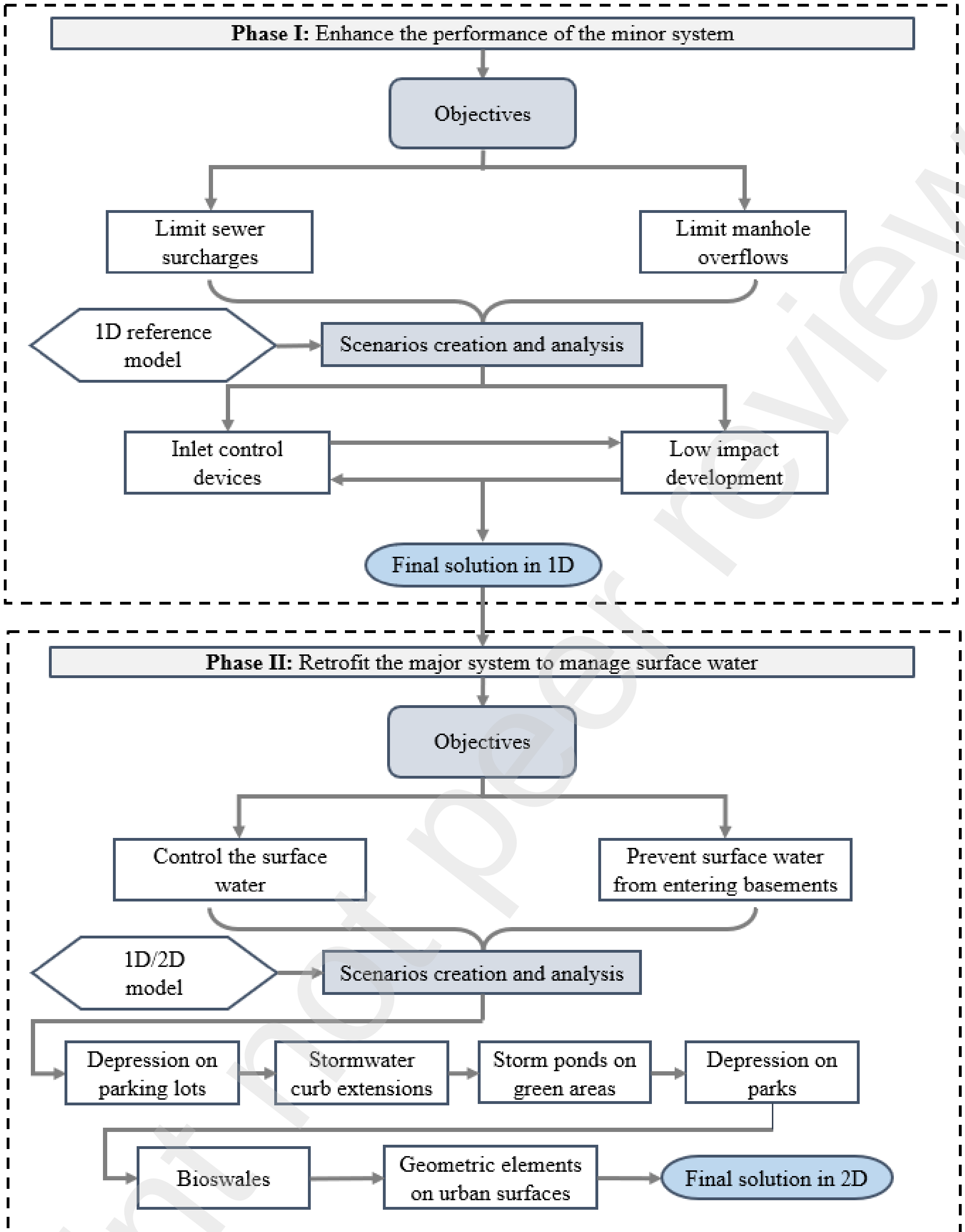


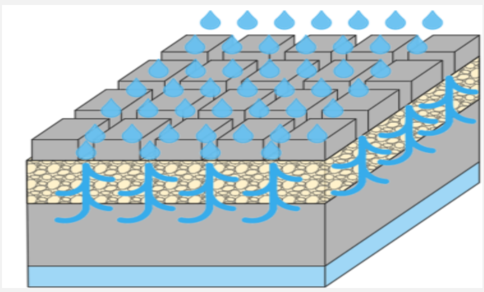
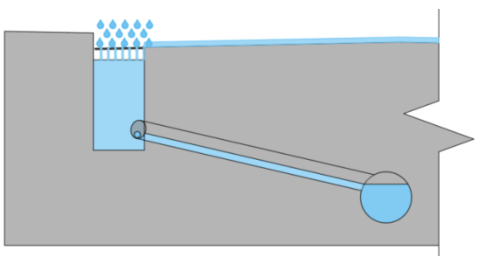
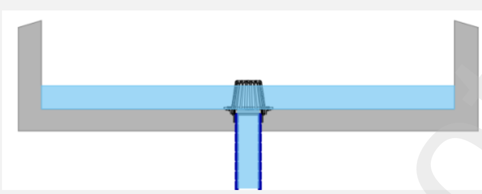
Figure 2. Flowchart of the developed methodology

2.3 Scenarios

2.3.1 Phase I

A total of 19 scenarios were developed by combining the solutions listed in Table 1 to meet the objectives of phase I. These scenarios are described in Table 2; they include LID practices to reduce the amount of stormwater runoff and flow control devices to limit water inflows to the sewer. The solutions implemented were first selected according to their suitability for the study areas and, then, the best-performing strategies were combined to make up the final scenarios.

Table 1. Solutions for stormwater management of phase I

Measure	FEATURES AND FUNCTIONS
	**Permeable pavement:** Allows stormwater to infiltrate into the ground to reduce runoff or into underground storage to slow the release of runoff.
	**Inlet control devices (ICD):** These devices regulate the flowrate of stormwater runoff entering a sewer system by allowing a predetermined flowrate to exit a catch basin or manhole at a specified head. These allow temporarily storing the water and preventing the sewer system from becoming surcharged.
	**Rooftop flow control devices:** These restrict stormwater from entering the sewer system, temporarily storing water on the building roofs, and preventing the sewer system from overflowing.

162 **Table 2. Simulation scenarios of phase I (results for the scenarios in bold are presented in section 3.1)**

Target	Name	Description
Reference model	**Scenario 0 (Reference model)**	**Reference model as described in section 2.4.2**
Reduce stormwater runoff	Scenario 1	Permeable pavement implemented on 100% of all alleys
	Scenario 2	Permeable pavement implemented on 100% of all parking lots
	Scenario 3	Combination of scenarios 1 and 2
Retain water on the surface	Scenario 4	Inlet control device type 1* implemented in 100% of the catch basins
	Scenario 5	**Inlet control device type 2* implemented in 100% of the catch basins**
	Scenario 6	Inlet control device type 3* implemented in 100% of the catch basins
	Scenario 7	Inlet control device type 4* implemented in 100% of the catch basins
Reduce stormwater runoff and retain runoff on the surface	Scenario 8	Scenarios 1 and 4 combined
	Scenario 9	Scenarios 1 and 5 combined
	Scenario 10	Scenarios 1 and 6 combined
	Scenario 11	Scenarios 1 and 7 combined
	Scenario 12	Scenarios 3 and 4 combined
	Scenario 13	Scenarios 3 and 5 combined
	Scenario 14	Scenarios 3 and 6 combined
	Scenario 15	Scenarios 3 and 7 combined
	Scenario 16	**Scenario 13** with strategic location of ICD and LIDs**
	Scenario 17	Scenario 14** with strategic location of ICD and LIDs
Reduce stormwater runoff, retain runoff on the surface and retain stormwater on the rooftops	Scenario 18	Flow control devices implemented on rooftops and combined with scenario 16
	Scenario 19 (Final scenario phase I)	**Flow control devices implemented on rooftops and combined with scenario 17**

163 *The different types of inlet control devices (1, 2, 3, and 4) are described below in section 2.3.1.2

**The strategic location of ICD and LIDs was determined based on the characteristics of the subcatchments, considering factors such as water flow patterns, catchment area and the potential effectiveness of LIDs in specific locations

2.3.1.1 Permeable pavement

The permeable pavement was modelled with the SWMM LID module, using the parameter values listed in Table S-1 in the Supplementary Material; those were taken from Rossman & Huber (2016), CSA (2018), Vaillancourt et al. (2019), and Zhang et al. (2015).

2.3.1.2 Inlet control devices (ICD)

Surface runoff water retention was simulated by adding inlet control devices in the catch basins. Four types of inlet control devices were considered; their rating curves, obtained from the technical guidelines provided by the manufacturers (IPEX, 2019), are illustrated in Figure 3. The inlet control devices number 1 and 2 are classified as low to moderate flow rates (LMF), featuring orifices of 77 mm and 94 mm, respectively, and characterized by vortex flow action. Inlet control devices number 3 and 4, on the other hand, use an orifice and plug plate style, both with a 70 mm orifice.

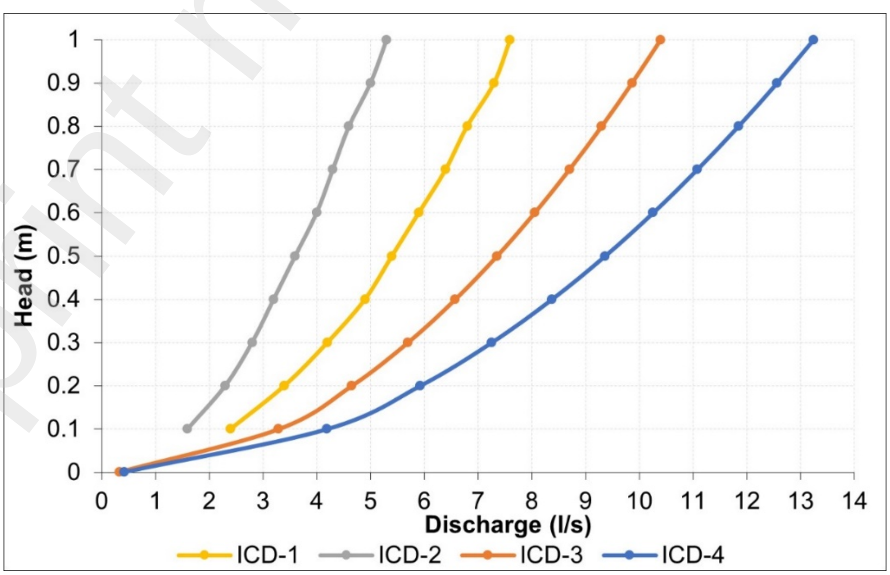


Figure 3. Flow control rate curves for different inlet control devices

2.3.1.3 Rooftop flow control devices

Rooftop detention was modelled by adding flow control devices at building sub-catchments outlets. The characteristics of these flow control devices, presented in Table 3, were selected from Jandaghian et al. (2022), the National Plumbing Code of Canada 2020 (Canadian Commission on Building & Fire Codes, 2022), and the Quebec Construction Code (National Research Council of Canada, 2022).

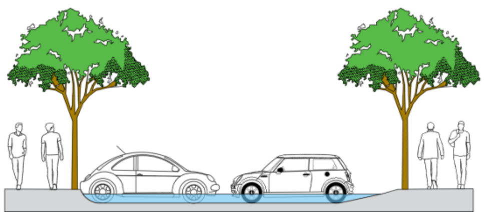
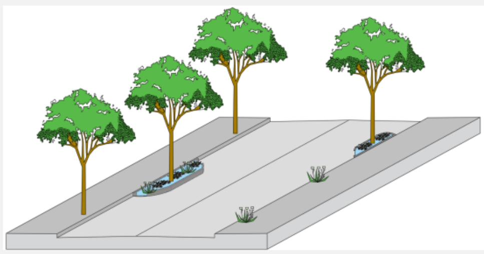
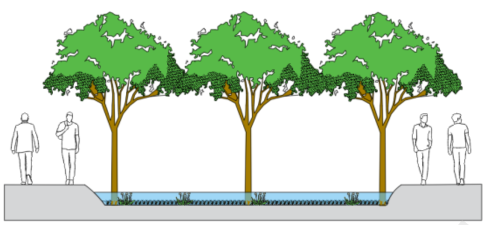
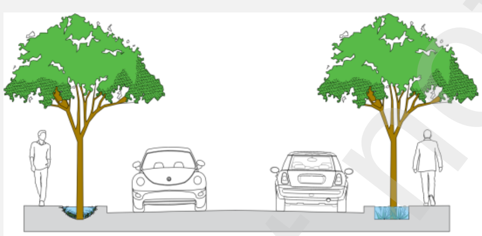
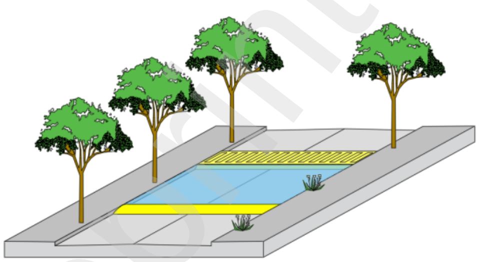
Table 2. Design parameters for rooftop detention in Canada

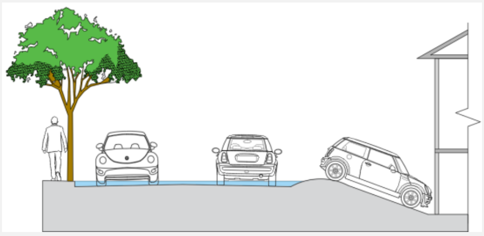
Max. drain down time	Max. ponding depth	Number of drains	Design rainfall
24 h	150 mm	1 for each 900 m^2 area of roof	25-year rainfall of maximum 15 min duration

2.3.2 Phase II

Seven scenarios were constructed in phase II applying the solutions presented in Table 4; these scenarios are listed in Table 5. The scenarios for phase II consisted of retrofitting urban surface areas, by modifying the digital elevation model (DEM), to control the water on the surface and to prevent surface water from entering critical areas. The implemented solutions were applied in sequence until the surface water was mainly under control, i.e., until the vast majority of surface flooding and flooded houses and garages were eliminated. The spatial distribution of the strategies listed in Table 4 was defined based on a spatial analysis and specific land suitability criteria (soil type, slope, critical areas, water accumulation areas, and space availability) of the case studies using the ArcGIS geographic information system (GIS) software and data from orthophotos, urban landscape, and soil characterization maps. In addition, for the first case study, the 82 current stormwater curb extensions in the area were added to the model, and 348 more of these (new stormwater curb extensions) were added at other street intersections. Based on this analysis, the DEM was modified to represent the location and characteristics (e.g., depth and size of the depression) of the tested solutions.

Table 3. Solutions for retrofitting urban surface for stormwater management of phase II

Measure	Features and functions
	**Depression in parking lots:** This is a shallow depression, usually dry, where water is captured during heavy rainfall and slows the flow of runoff into the sewer system, allowing water to be temporarily stored.
	**Stormwater curb extensions:** These are depressions in streets or intersections that capture and detain stormwater runoff, allowing the water to be temporarily stored and to infiltrate into the ground.
	**Depression in parks:** This depression can be flooded in the event of heavy rains, allowing water from the surrounding areas to be stored and infiltrated, thus reducing the amount of runoff that is directed to the sewer system. During dry weather conditions, it can be used as a playground.
	**Depressions in channels:** These depressions are shallow ditches in the sidewalks covered with grass to capture runoff and allow it to infiltrate into the ground or slow down the flow of runoff into the sewer system, as well as convey water to other solutions.
	**Speed bumps:** These can be used as strategies to retain water in specific areas of the street, to allow water to flow to other solutions, or to prevent water from entering critical areas due to below-grade building entrances.



Raised ramps: This is a strategy to prevent runoff water from entering the garages of buildings with below-grade driveways.

Table 4. Simulation scenarios of phase II (scenario results in bold are presented in section 3.2)

Target	Name	Description
Control surface water	Scenario 20	Depression on parking lots implemented in combination with scenario 18
	Scenario 21	Current stormwater curb extension depressions in combination with scenario 20
	Scenario 22	New stormwater curb extension depressions in combination with scenario 21
	Scenario 23	Depression on parks in combination with scenario 22
	Scenario 24	Depression on channels alongside sidewalks in combination with scenario 23
Prevent surface water from entering basements	Scenario 25	Speed bumps in combination with scenario 24
	Scenario 26 (Final scenario phase II)	**Raised ramps of basements with below-grade driveways in combination with scenario 25**

2.4 Stormwater model and data collection

2.4.1 Hydrological and hydraulic modeling software

For the applications presented in this paper, a 1D drainage model and a coupled 1D/2D dual drainage model were developed employing the PCSWMM (Personalized Computer Storm Water Management Model) software (CHI, 2023). PCSWMM builds upon the hydrological and hydraulic engine of EPA SWMM 5.1 (Rossman, 2015) and incorporates group-decision support tools, including Geographic Information System (GIS) technology (James et al., 2010).

For the coupled 1D/2D models, this software possesses the capacity to simulate the routing of overland floods and the corresponding flood depth, duration, and extent in two dimensions (Shrestha et al., 2022). In the context of the 1D/2D dual drainage model, this approach discretizes the overland surface into a mesh, representing each 2D cell with a 2D node or a junction. The catch basin and manhole nodes are coupled with 2D mesh cells, allowing the volume of water exiting during sewer surcharges to be routed over the 2D mesh cells. This excess flow can accumulate on the overland grid cells and re-enter the sewer system when the hydraulic capacity of the system allows it (Finney et al., 2012; James et al., 2012; Shrestha et al., 2022).

2.4.2 One-dimensional reference model setup

The 1D model was used to evaluate the current conditions in the case studies and as a basis for creating the scenarios in phase I. The 1D base model for each case study area, provided by the city, represents the current hydraulic and hydrological conditions. Previously calibrated and validated, these models contained most information relevant to the sewer system, i.e., hydraulic structures such as pipes, nodes, sub-catchments, and their parameters. The catch basins with their characteristics (type, elevation, and connections to the sewer system) were added to the models based on information taken from the open data site of the city of Montreal (https://donnees.montreal.ca/) and verified through field visits. The rating flow curves for the catch basins grates, shown in Figure 4, were also added to the model based on information from Poirier and Provan (2021 and 2023).

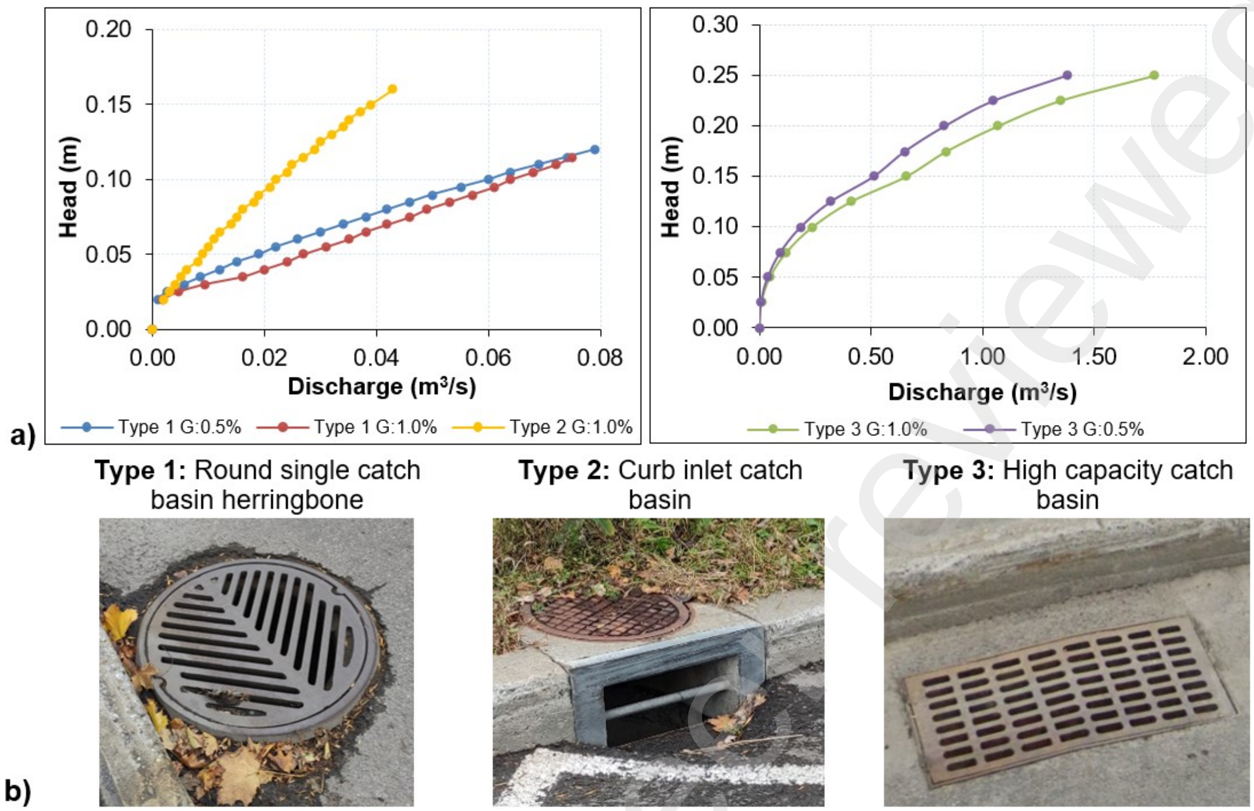


Figure 4. a) Rating curves for various grate inlet types and street grades (G); b) catch basin configurations at the study sites

The sub-catchments for each catch basin were delineated using a digital surface model (DSM), a DEM, street profiles, and shapefile layers taken from the open data site of the city of Montreal. The DSM was created from preprocessed LIDAR (light detection and ranging) data to obtain a model resolution of $\pm$ 20 cm. These discretized sub-catchments were divided into categories which are alleys, backyards, buildings, parks, and streets (including sidewalks and parking lots). Hydrologic and hydraulic parameters for each category of sub-catchment were taken from city sources and are shown in Table S-2 of the Supplementary Material. Furthermore, the sub-catchments representing flat roofs of residential and commercial buildings were simulated as LIDs of the rain barrel type, as suggested by the city of Montreal, using the parameters shown in Table S-3 of the Supplementary Material. These LIDs occupy 70% of the total surface area of each roof, and the other 30% is modelled as a non-LID area. Also, all nodes representing manholes were assigned a ponded area of 1000 m^2.

2.4.3 Coupled one-dimensional to two-dimensional model setup

The 1D/2D model served as the basis for evaluating scenarios in phase II. The creation of the 1D/2D coupled models was based on the 1D reference models, to which the following layers were added:

- The bounding layer, which delimits the study zones, i.e., streets, sidewalks, lots, and alleys, and allows setting the values of the mesh parameters for the different delimited zones, which are presented in Table 6.
- The DEM layer, which allows for fixing the elevation of the mesh nodes and, therefore, the elevation of the cells.
- The 2D nodes layer, created from the DEM.
- The obstruction layer, which delimits all buildings and obstructions in the area (no mesh is created in these obstruction zones, saving computational time).
- The downstream layer, which delimits the study area's boundaries and creates the outlets.

The mesh representing the major system is connected with the catch basins and manholes of the minor system, facilitating direct interaction between the two systems. This allows water to overflow from the minor to the major system through the 2D mesh cells. This design enables the transportation or temporary storage of excess water within the mesh cells until it can re-enter the sewer system when this one is not overloaded anymore (Djordjevic et al., 1999; Shrestha et al., 2022).

Table 5. Mesh parameters for each type of area

Surface type	Mesh style	Resolution (m)	Roughness of the surface (Manning's n)	Seepage rate (mm/h)*
Streets	Rectangular	2	0.011	n/a
Alleys	Rectangular	3	0.010	n/a
Pervious	Hexagonal	5	0.15	1 mm/h
Obstructions	n/a	n/a	n/a	n/a

*The seepage rate parameter represents the infiltration of water into the soil

2.5 Rainfall events

The proposed methodology was applied to three 3 h-duration rainfall events illustrated in Figure 5: i) the 100-year return period Chicago-type design rainfall for the case studies region, ii) the same design rainfall increased by 21.5% to simulate the effects of climate change, and iii) an historical rainfall event that happened on July 13th, 2023, which has been one of the most intense rainfall events of the last two decades in Montreal and caused sewer system overloading and uncontrolled floods.

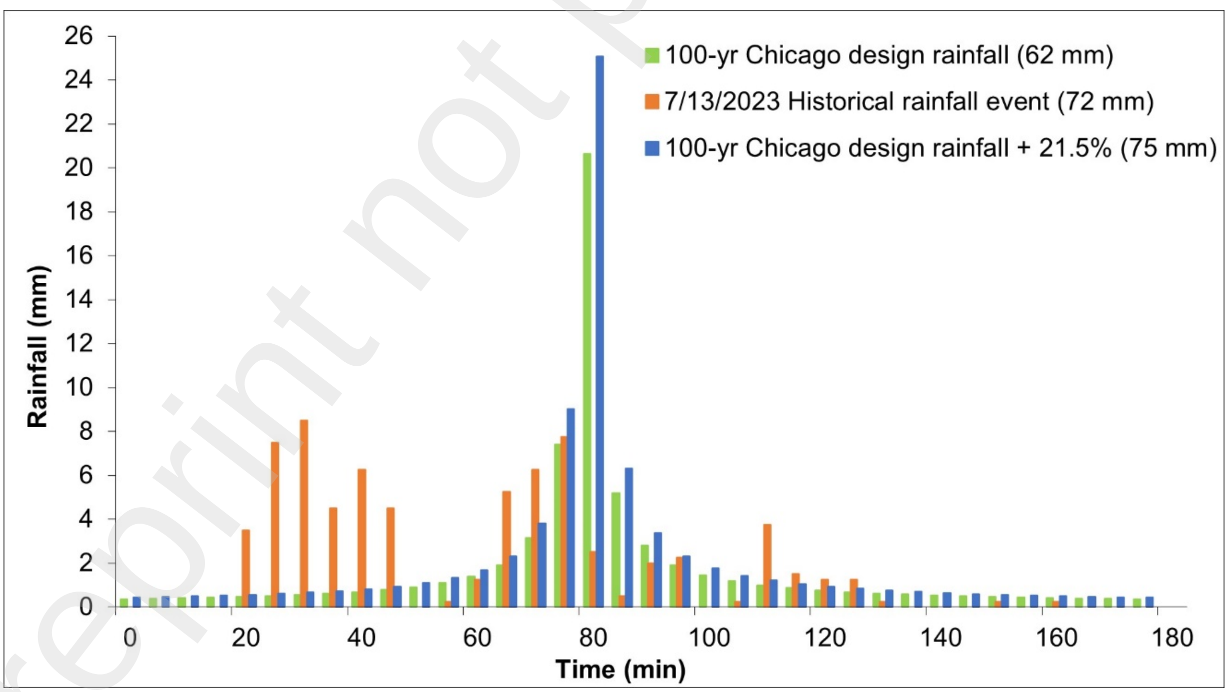


Figure 5. Rainfall hyetographs

2.6 Analysis of the scenarios

2.6.1 Phase I performance analysis

The scenarios in phase I were analyzed based on the number of surcharged pipes, of surcharged manholes, and of overflows from nodes, as well as on the volume of overflows from nodes. These results were compared with the results of the reference model, which represents the current conditions of the system.

The number of nodes experiencing overflows, including manholes and catch basins, was determined by identifying nodes where there were overflows and for which sewer backflow occurred through the outlets representing the ICD.

In the case of catch basins, the calculation of the overflow volume included the overflowing water volume and the stormwater volume retained on the surface (i.e., water that could not enter the sewer network).

2.6.2 Phase II performance analysis

The scenarios in phase II were analyzed based on the area and volume of uncontrolled flooding zones, as compared to the reference scenario. It is worth mentioning that the uncontrolled flooding zones do not include areas where runoff management and storage solutions exist (e.g., stormwater curb extensions).

3 Results and discussion

3.1 Phase I - sewer system conditions for the 100-year design rainfall

Figure 6 illustrates the results of the sewer system conditions for the first case study, for the reference model (current conditions) and scenario 19 (Table 2). Figure 6 shows that, in the current conditions, numerous sections of the sewer network are surcharging, and some nodes are overflowing while with scenario 19, there are only a few pipes surcharging and no node overflowing.

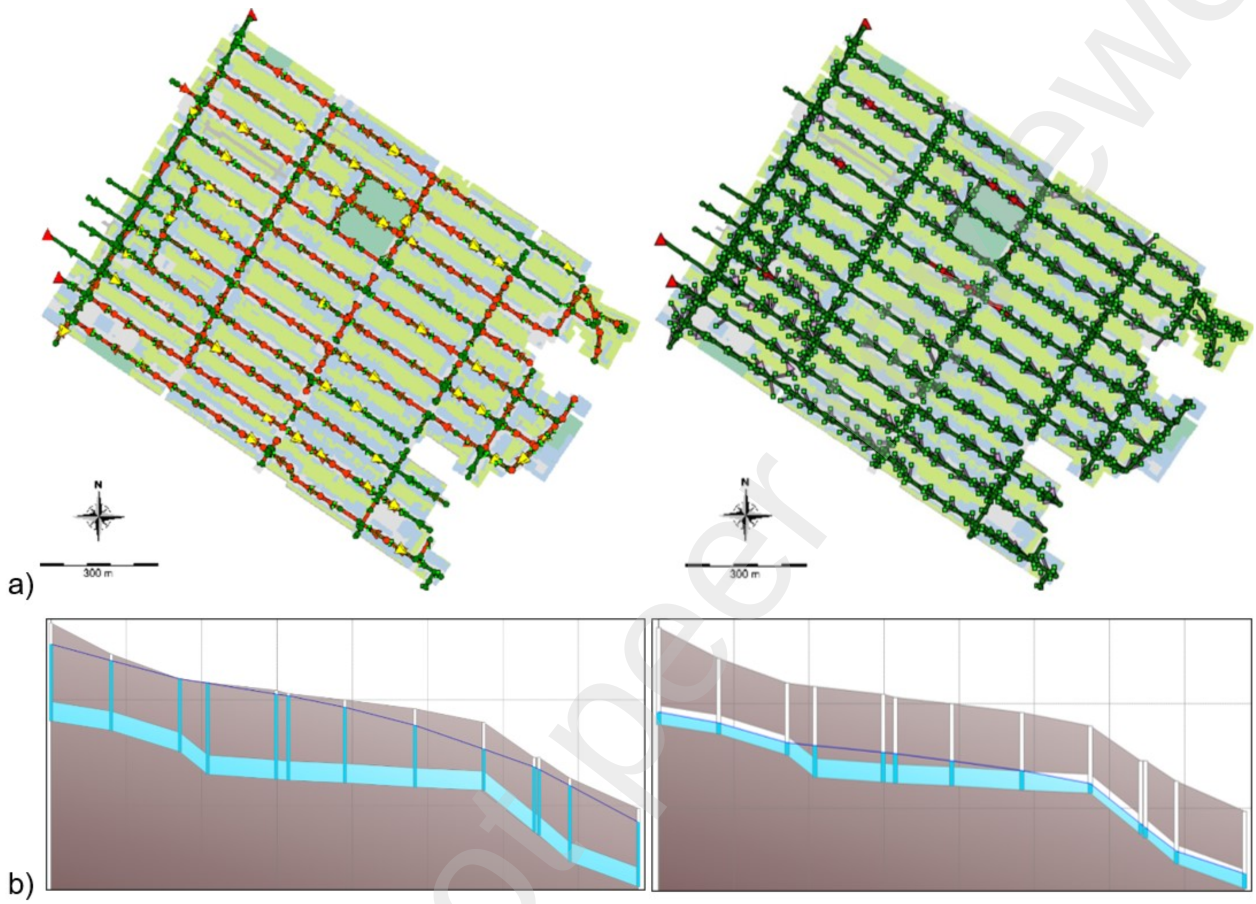


Figure 1. Comparison of current conditions (left) and scenario 19 (right) for the 100-year Chicago design rainfall; a) Sewer system conditions (green pipes: pipes without surcharge; red pipes: surcharged pipes; green nodes: nodes without overflow; red nodes: nodes with overflow); b) hydraulic profile for the time step with the maximum water depth in the minor system for a critical sub-area

Figure 7 shows the number of surcharged pipes, surcharged manholes, and sewer overflows for four scenarios (current conditions, 5, 16 and 19) and the location of the solutions for scenario 19 for the two case studies. This figure shows that, for the first case study, there is a 97% decrease in the number of surcharged pipes, a 99% reduction in the number of surcharged manholes, and a complete elimination (100% reduction) of the number of sewer system overflows for scenario 19, as compared to the current conditions. For the second case study, scenario 19 shows a 33% reduction in the number of surcharged pipes, a 43% reduction in the number of surcharged manholes, and a 71% reduction in the number of overflows when compared to the reference model. Furthermore, it can be observed that the integration of control devices into catch basins (scenario 5), in the first case study, reduces the number of surcharged manholes and pipes by 65%. In contrast, in the second case study, only a slight decrease of 2% in the number of surcharged pipes and manholes is observed when scenario 5 is applied. However, when the control devices are implemented on rooftops (scenario 19), this reduction exceeds 33%.

The lower performances of the scenarios in the second case study can be attributed to its position in the global city sewer catchment, as it is located midstream of a main collector which frequently surcharges during rainfall events. Consequently, the main collector backflows into the sewer system of the study area. Also, these backflows can become more severe when stormwater management solutions are applied in this study area as they allow a greater hydraulic capacity to the collector. Indeed, in this case, the greater hydraulic capacity in the collector allows more water to enter the area as backflow. Consequently, despite the application of various solutions, the network still experiences overloading for the 100-year design rainfall. This suggests that it would be necessary to implement stormwater management solutions, such as those described in Tables 1 and 4, in the drainage areas connected to the main collector and located upstream of the studied area. This strategic expansion of solutions to additional areas could enhance the overall performance of the sewer system in the second case study area.

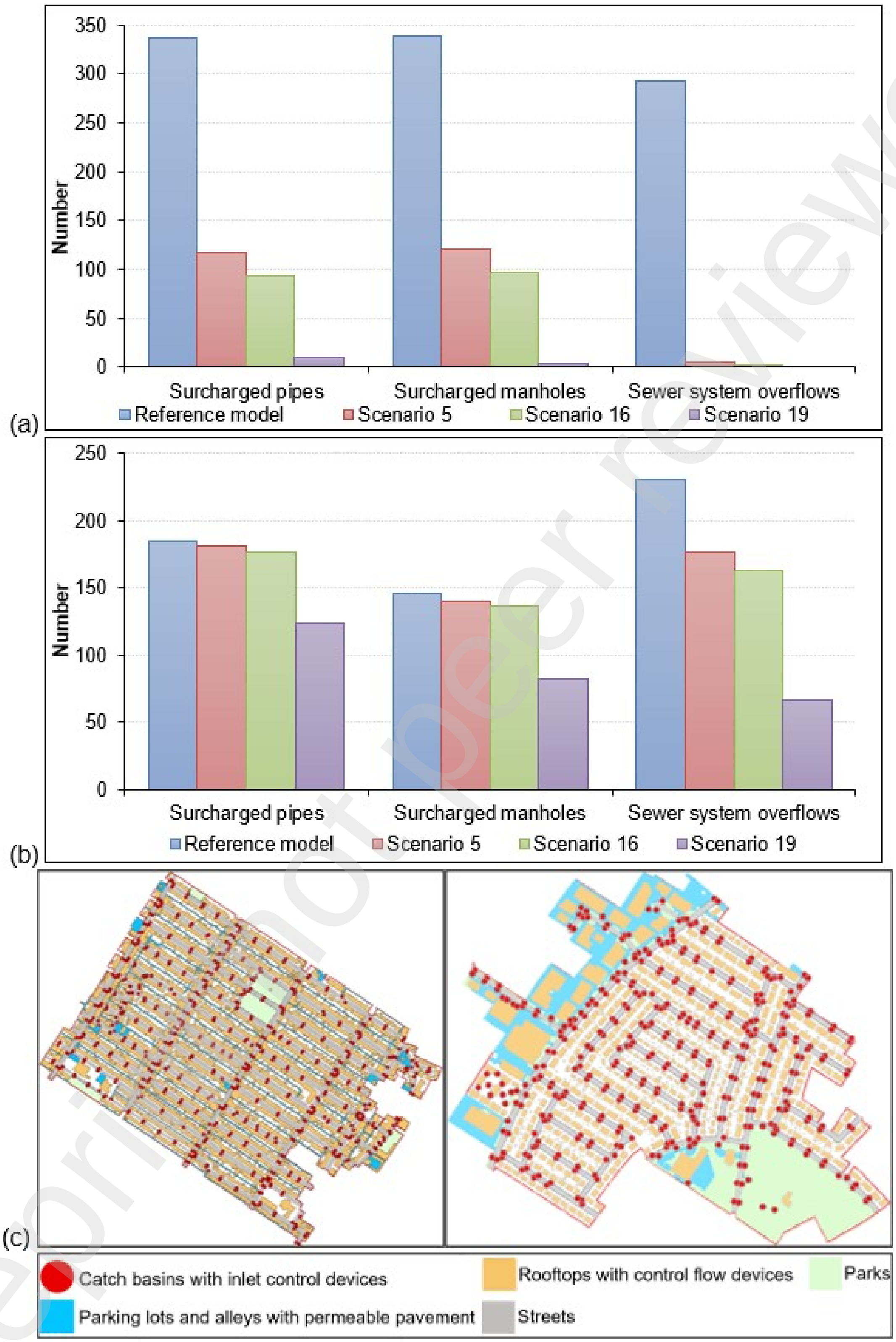


Figure 2. Sewer system conditions improvement in phase I scenarios for the 100-year design rainfall - (a) first case study results, (b) second case study results, (c) location of solutions for the first (left) and second (right) case studies for scenario 19

Since both study areas are drained by a combined sewer system, the overflows from the sewer system in these areas are a mix of stormwater and wastewater. Figure 8 shows the volumes of stormwater and wastewater on the surfaces for the 100-year design rainfall for four scenarios. Figure 8a shows that, under current conditions in the first case study, 56% of the surface flood water is wastewater, and the other 44% is runoff water that has not been able to enter the sewer system. However, when the proposed solutions are implemented, the volume of overflowing wastewater is eliminated for scenarios 16 and 19 and reduced by 99% for scenario 5. It should be noted that implementing these scenarios causes stormwater retention on the surface to increase by 184%, 266% and 549%, respectively, for scenarios 16, 19, and 5. In the first case study, for scenarios 16 and 19, the entire floodwater volume consists of stormwater retained on the surface. In the second case study, sewer system overflows are still present with the implemented solutions. Nonetheless, there is a reduction of 86% in the volume of overflowing wastewater with scenario 19 for the 100-year design rainfall. This implies that this volume would probably be eliminated for less intense rainfall events.

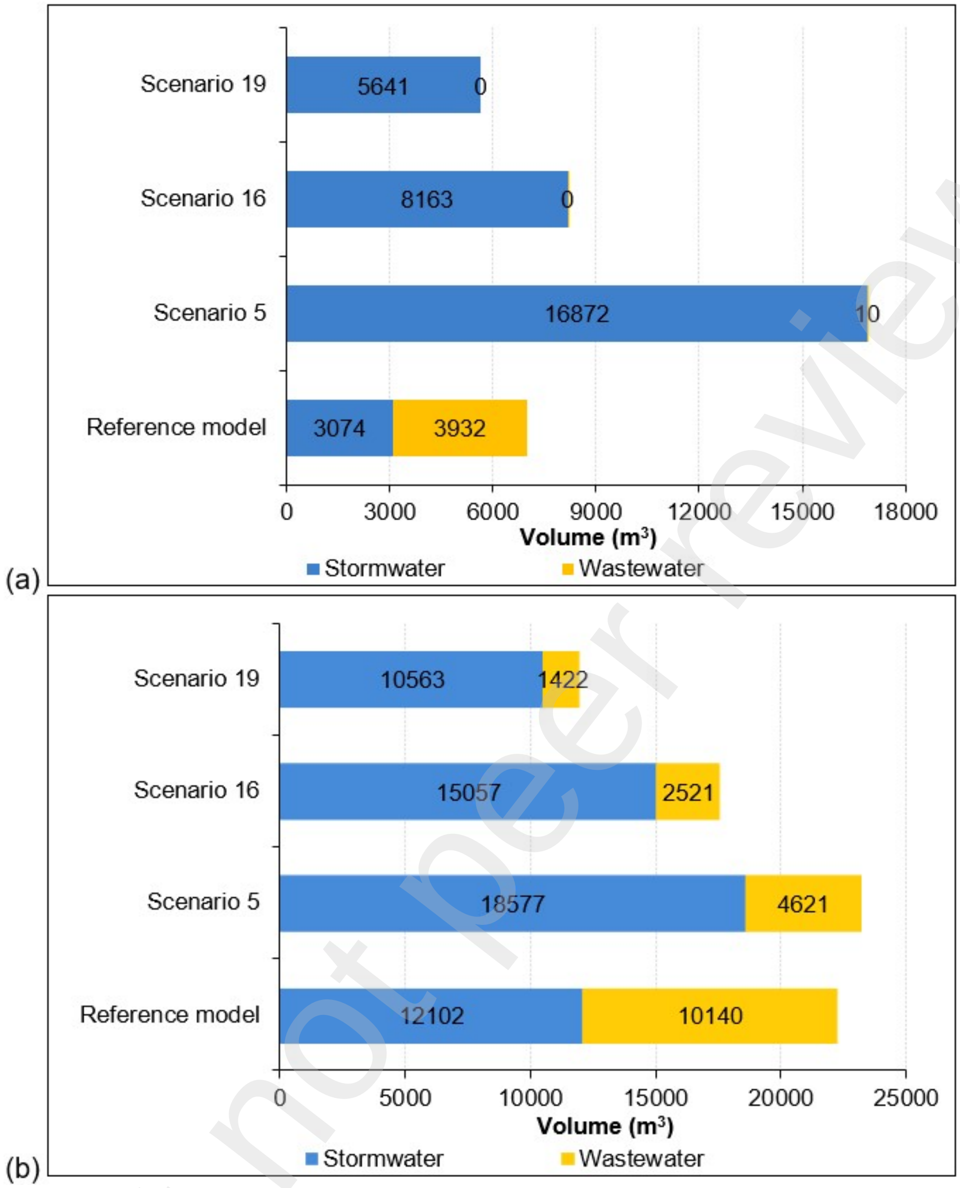


Figure 3. Stormwater and wastewater volumes on urban surfaces in phase I scenarios for the 100-year design rainfall (a) first case study results, (b) second case study results

In previous studies, the implementation of permeable pavements and urban surface retrofitting strategies has shown to reduce surcharges in sewer systems. For example, Ortega Sandoval et al. (2023) found a decrease in the length of overloaded pipes and in the duration of surcharges during a 100-year return period design rainfall event through the implementation of different LIDs typologies. Their study incorporated rainwater harvesting systems (RWHS) on private land, tree pits doubling the number of the current tree distribution in the study sector, green roofs, attenuation storage tanks in residential sectors where RWHS were not suitable, and permeable pavement in corridors, plazas, and other land uses. However, in their study, it was found that these LIDs did not help to reduce the number of surcharged nodes, possibly because they studied a sector with 3 surcharged nodes, unlike the present study, which has a large number of surcharged nodes. Similarly, Bibi et al. (2023) observed a reduction in the number of nodes experiencing overflows in a variety of scenarios by applying bioretention systems and permeable pavements. Their study examined different combinations of LID implementation percentages, future urbanization percentages, and future design rainfall scenarios. Furthermore, Vaillancourt et al. (2019) conducted a research near Montreal, Canada, indicating that permeable pavement could reduce runoff volume by 26% and 98% depending on the rainfall event, as evidenced by a monitoring study. Additionally, numerical modeling results of their study revealed that implementing permeable pavement in a combined sewer system resulted in reductions of 65% in surface overflows volume and 21% to 48% in surface overflow duration.

3.2 Phase II - flooding conditions for the 100-year design rainfall

As noted above, scenario 19 of phase I reduced sewer system surcharges in both studied areas but increased the volume of stormwater retained on the surface. The objective of the second phase is to manage this water in order to prevent it from causing damages to urban infrastructure. Figure 9 shows the reduction in the extent of surface flooding for the final scenarios of each phase (scenario 19 of phase I and scenario 26 of phase II) in comparison with the current conditions; it also presents the location of the solutions for scenario 26. This figure shows that scenario 26 allows controlling 68% of the surface flood area, for the first case study, and 42% for the second case study, implying that this flow is conveyed to areas designed and intended to store and collect it. In these areas, the water can infiltrate, evaporate, or be retained and be released later into the sewerage system in a regulated way. The remaining water on the surface, i.e., 32% and 58% of the flooded area, respectively for the first and second case studies, remain on the streets. The percentages of reduction of the uncontrolled flood volume are 78% and 80% for the first and second case studies, respectively.

The results of phase II are consistent with those of Fonseca Alves et al. (2022). In their study, conducted on a highly urbanized watershed in Brazil, these authors found that for an extreme rainfall event of 60 mm over one hour, the application of various LID measures (including bioretention systems, permeable pavements, infiltration trenches, and rainwater harvesting systems) resulted in a 61% reduction in flood volume in a densely populated area and an 88% reduction in flood volume for a less densely populated area. Similarly, other studies, such as those by Ahiablame and Shakya (2016), Bai et al. (2018), and Ortega Sandoval et al. (2023), have shown that the application of different LID techniques has decreased flood volumes and areas.

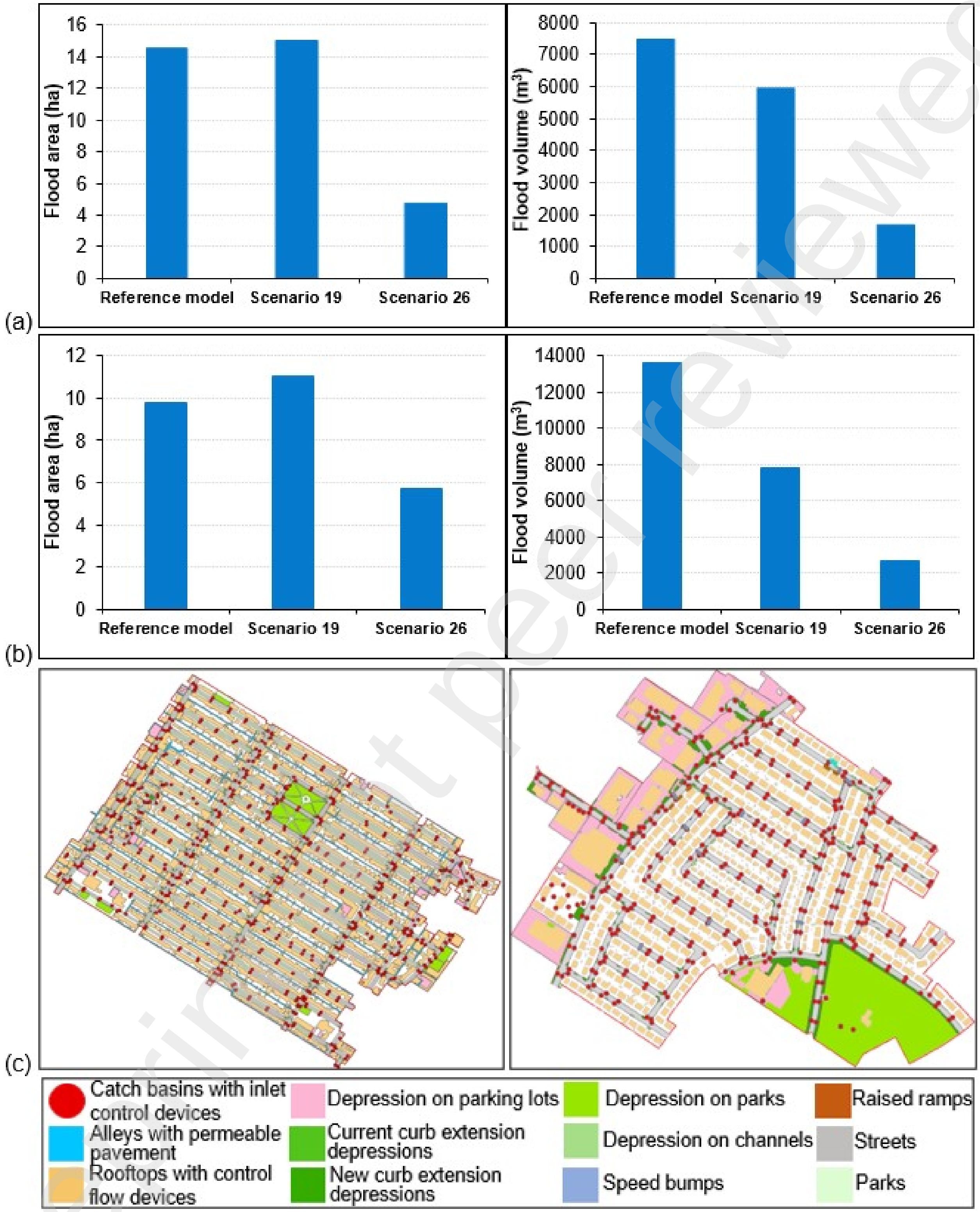


Figure 4. Reduction in uncontrolled surface flood area (left) and volume (right) for the 100-year Chicago design rainfall: (a) First case study results; (b) Second case study results; (c) Location of solutions for the first (left) and second (right) case studies for scenario 26

Figure 10 illustrates the flooded areas for the reference model and scenario 26 in phase II, where, under the current conditions of the system, the overflow water covers the streets, sidewalks, and alleys. In contrast, with the implemented solutions (scenario 26), surface water is being stored and conveyed to specific spots on the public land (in curb extensions and parks in this example). Although the 2D model could not be calibrated and validated due to a lack of measured data of surface water levels during rainfall events, simulation results for current conditions showed that areas where sewer system overflows occur align with places where water enters buildings according to the claims of damage from residents.

Figure 5. Comparison of flooded areas between the reference model and scenario 26 in the first case study

Moreover, the implementation of speed bumps and raised ramps in below-grade building entrances in scenario 26 contributes to a reduction in the number of houses and garages impacted by surface water. In the first case study, under the current conditions, 51 houses would experience flooding for the 100-year design rainfall, while, following the application of the proposed strategies (scenario 26), this number decreases to 13, representing a 75% reduction. In the second case study, 197 houses would be affected by flooding for the 100-year design rainfall in the current conditions and this number could be reduced by 81% following the implementation of the solutions in scenario 26. Houses that experience flooding despite the implemented strategies are typically situated in topographically low points or locations near manholes with overflows, where it is difficult to control water entrances due to the volume of water.

3.3 Results for the 100-year rainfall event under climate change and for the extreme historical rainfall event

Figures 11 and 12 show the results of the final scenarios of phase I (scenario 19) and phase II (scenario 26), respectively, under the Chicago design rainfall with a return period of 100 years increased by 21.5 %, to consider the impact of climate change, and under the rainfall event that happened on 13 July 2023, along with the results for the reference scenario. Figure 11 shows that for the first case study, the number of surcharged pipes is reduced by 82% and 98%, respectively for the design rainfall considering climate change and the historical rainfall event, and that these reductions are 96% and 98% for the surcharged nodes and 100% for the number of overflows for both rainfall events. For the second case study, for the design rainfall considering climate change and the historical rainfall event, there is a respective reduction of 29% and 33% in the number of surcharged pipes, of 52% and 72% in the number of surcharged nodes, and of 86% and 79% in the number of overflows.

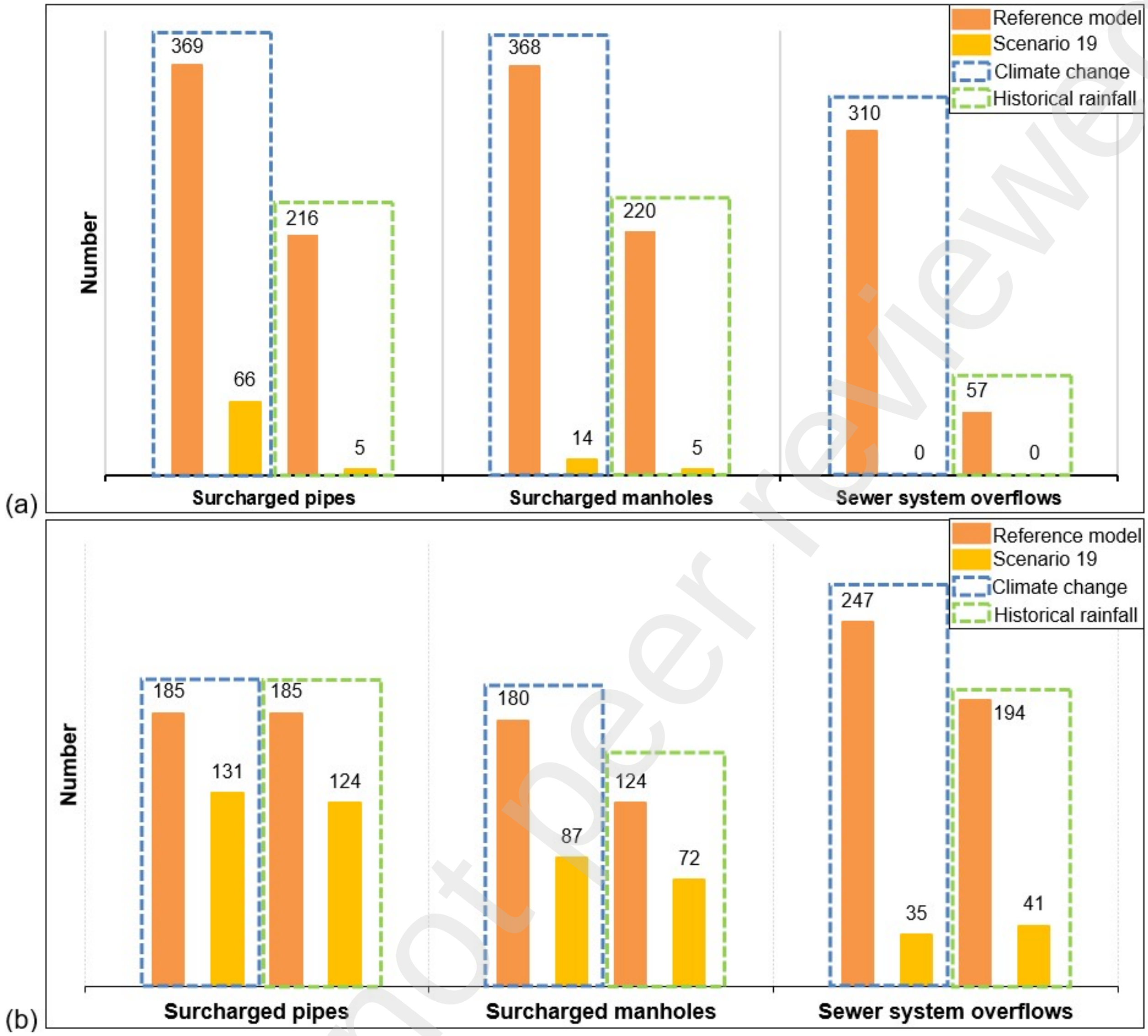


Figure 6. Sewer system conditions during the 100-year rainfall event considering climate change (blue rectangles) and the historical rainfall of 13 July 2023 (green rectangles) for the current conditions (orange bars) and the final scenario of phase I (scenario 19) (yellow bars); (a) First case study results; (b) Second case study results

Figure 12 shows that 63% and 50% of the flood area could be controlled under the design rainfall considering climate change, for the first and second case studies, respectively. Similarly, for the historical rainfall event, scenario 26 allowed controlling 66% of the flood area for the first case study, and 46% for the second case study. These graphs also show that scenario 26 led to the control of 76% and 82% of the flood volume under the design rainfall considering climate change, for the first and second case studies, respectively, and of 75% and 36% of the flood volume under the historical rainfall event.

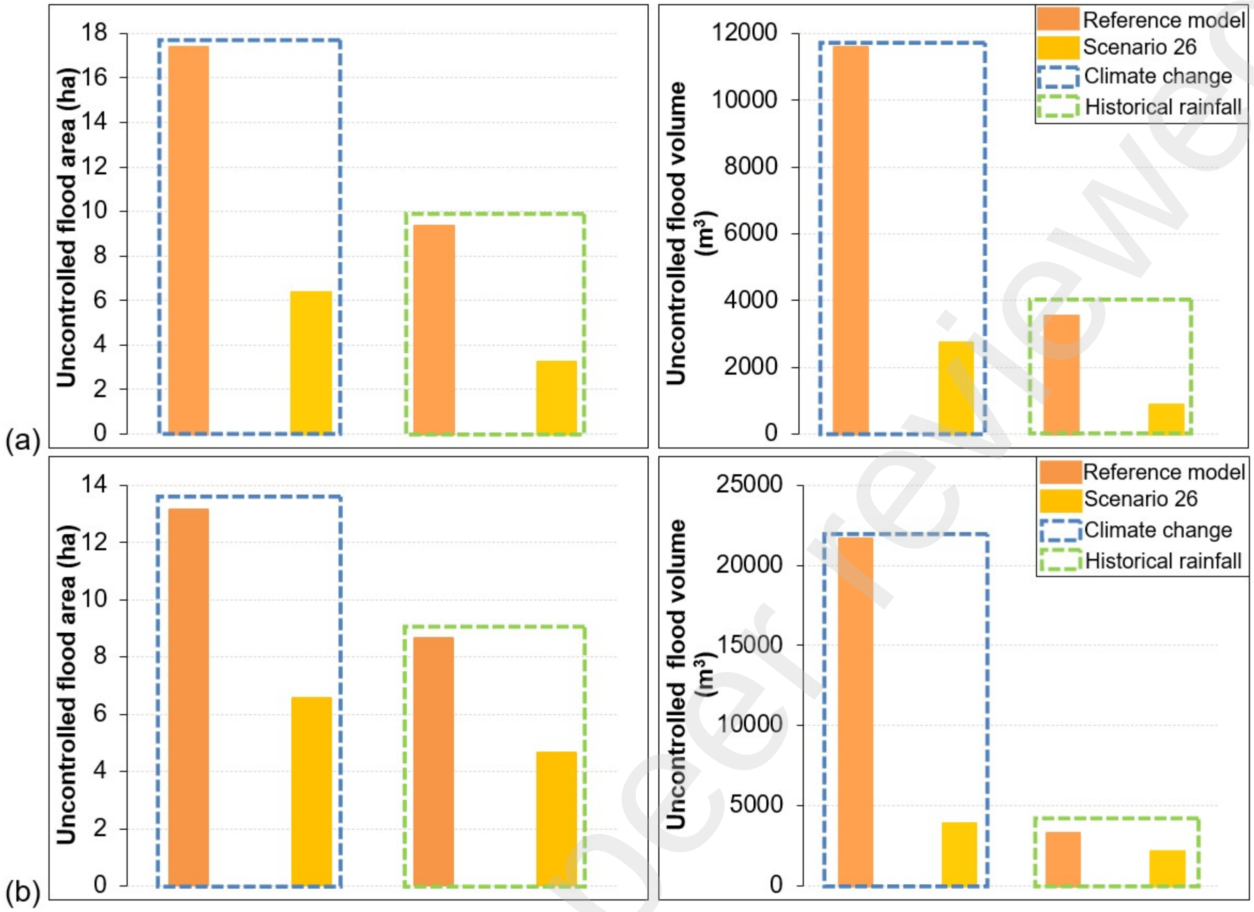


Figure 7. Uncontrolled surface flood area (left) and volume (right) during the 100-year event under climate change and the historical rainfall of 13 July 2023 (blue rectangles: 100-year event under climate change; green rectangles: historical rainfall event; gray bars: current conditions; red bars: final scenario of phase II (scenario 26)); (a) First case study results; (b) Second case study results

4 Conclusion

The methodology developed to reduce sewer surcharges and flooding in urban areas, based on dual drainage, integrates: 1) surface runoff water retention by restricting water from entering the sewer system during extreme events, to improve the performance of the minor system, and 2) surface water management infrastructure to control urban flooding and, thus, to enforce the efficient use of the major system.

Analysis of two case studies showed that the proposed methodology could reduce sewer system overflows and surcharges as well as the uncontrolled flood extent during extreme rainfall events. However, by restricting the runoff water entering the sewer system, the amount of water on the surface will increase. Therefore, solutions to manage this surface water must be implemented simultaneously.

Previous studies have focused on studying either sewer systems or urban flooding individually to improve function of major and minor systems (Knight et al., 2021; Ortega Sandoval et al., 2023). However, the methodology that is proposed here aims to address sewer system enhancements while controlling urban flooding. The obtained results suggest that the risk of uncontrolled flooding and sewer overflows during extreme precipitation events can be effectively reduced by integrating stormwater retention at the source. At the same time, application of the proposed methodology promotes the greening of the landscape and coexistence with water in densely urbanized areas.

The application of this methodology needs coupled 1D/2D models. These models can effectively represent the location of flooding, surface flow directions and how water accumulates in the proposed solution. Furthermore, these models can be used to evaluate the buildings susceptible to be affected by pluvial flooding problems. Accordingly, these models allow to effectively determine the placement of control structures and geometric elements that help prevent water from entering buildings.

The novelty of this research consisted of an in-depth evaluation of implementing flow control devices, such as inlet control devices (ICDs) in catch basins and control flow devices on rooftops, in combination with LID practices and the retrofitting of urban surfaces for surface water management. The proposed methodology encompasses practical solutions for water quantity control by integrating green and grey infrastructure into existing drainage systems within an urban context that had not initially incorporated these solutions and are, therefore, particularly vulnerable to problems of sewer system surcharges. These strategies were chosen based on their ease of implementation and because they are commonly implemented in other parts of the urban drainage systems of the studied city. Therefore, the proposed methodology offers practical solutions to address the growing challenges associated with combined sewer surcharges in densely populated and space-constrained urban environments, as well as the effects of climate change.

Future work could integrate a cost-benefit analysis of the proposed solutions and develop and test methodologies that assess the feasibility and viability of implementing the suggested measures over time. Such methodologies should take into account a number of variables, such as financial constraints, infrastructure restrictions, and community acceptability. In addition, the methodology should be evaluated for different rainfall durations and return periods, as well as using continuous historical series of precipitation data. This would help ensure effective and sustainable implementation of stormwater management strategies. Indeed, it is important to recognize that the scenarios presented in the current study are optimistic due to the 100% implementation of some measures, like permeable paving in all alleys and retention on all flat roofs. While the results obtained from the application of these scenarios provide valuable information on the potential benefits of such measures, it should be recognized that achieving full implementation of these measures may be impractical or economically prohibitive in the real-world context.

Furthermore, it is essential to underline the importance of validating and calibrating the models. In this work, this process could only be executed for the 1D model but not for the 2D model, due to a lack of measured data of surface water levels during rainfall events.

CRediT authorship contribution statement

Juan Esteban Ossa Ossa: Conceptualization, Formal analysis, Methodology, Writing – original draft, Visualization, Software. **Sophie Duchesne:** Conceptualization, Methodology, Supervision, Writing – review & editing, Funding acquisition. **Geneviève Pelletier:** Supervision, Writing – review & editing, Funding acquisition.

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.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author, J.E. Ossa. The data are not publicly available due to a confidentiality agreement with the city where the case study sewer is located.

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Supplementary Material

Table S-1 **Permeable pavement parameters for the SWMM LID control module**

Permeable pavement		Alleys	Parking lots
Layer	**Parameter**	**Value**	**Value**
Surface	Berm height (mm)	1.5	1.5
	Vegetation volume (fraction)	0	0
	Surface roughness (Manning's n)	0.015	0.015
	Surface slope (percent)	1.0	1.0
Pavement	Thickness (mm)	100	150
	Void ratio (voids/solids)	0.16	0.16
	Impervious surface (fraction)	0	0
	Permeability (mm/h)	254	254
	Clogging factor	0	0
	Regeneration interval (days)	0	0
	Regeneration fraction	0	0
Soil	Thickness (mm)	100	100
	Porosity (volume fraction)	0.5	0.5
	Field capacity (volume fraction)	0.2	0.2
	Wilting point (volume fraction)	0.1	0.1
	Conductivity (mm/h)	3.3	3.3
	Conductivity slope	10	10
	Suction head (mm)	88.9	88.9
Storage	Thickness (mm)	450	450
	Void ratio (voids/solids)	0.63	0.63
	Seepage rate (mm/h)	3.3	3.3
	Clogging factor	0	0
Underdrain	**Drain coefficient (mm/h)** The drain exponent determines the flow rate through a drain as a function of the height of stored water above the drain's offset.	0	0
	Drain exponent The drain coefficient determines the flow rate through a drain as a function of the height of stored water above the drain's offset.	0.5	0.5
	Drain offset height (mm) The height from the base of the cell to the drain discharge.	0	6

Table S-2 Hydrological parameters of the sub-catchments by category

Parameter	Alleys	Backyards	Buildings	Parks	Streets
Number of subcatchments (Rosemont area)	61	171	485	5	598
Number of subcatchments (St. Leonard)	-	288	189	15	407
Area (ha) Area of subcatchments	0.008 - 0.015	0.001 - 0.446	0.284 – 0.001	1.033 - 0.225	0.008 – 0.799
Width (m) Width of the overland flow path	5.5	Area/FlowLength	Area/FlowLength	--	14
Flow length (m) Length of overland sheet flow	Area/Width	15	14	--	Area/Width
Slope (%) Average surface slope	1	1	1	1	1.15
Imperv. (%) Percent of impervious areas	70	25	0*	8	72
N Imperv Manning's n value for impervious areas	0.024	0.024	0.016	0.014	0.016
N Perv Manning's n value for pervious areas	0.2	0.2	0.2	0.2	0.2
Dstore imperv (mm) Depth of depression storage on impervious areas	4	4	1.5	1.5	1.5
Dstore Perv (mm) Depth of depression	6.5	6.5	6.5	6.5	6.5

Parameter	Alleys	Backyards	Buildings	Parks	Streets
storage on pervious areas					
Zero imperv (%) Percent of impervious areas with no depression storage	25	25	25	25	25
Max. infil. rate (mm/h) Maximum rate on the Horton infiltration curve	75				
Min. infil. rate (mm/h) Minimum rate on the Horton infiltration curve	7.5				
Decay Constant (h^{-1}) Decay constant for the Horton infiltration curve	4				
Drying time (days) Time for a fully saturated soil to completely dry	7				

* In this case, the rooftop of buildings has an imperviousness of 0 because they are modeled as LID (the explanation is in the text)

Table S-3 Representation of flat roofs as rain barrels

Layer	Parameter	Residential roofs	Industrial, commercial, or institutional roofs
Storage	**Barrel height (mm)**	150	150
Underdrain	**Drain coefficient (mm/h)** Determines the flow rate through a drain as a function of the height of stored water above the drain's offset	13.8	19.2
	Drain exponent Determines the flow rate through a drain as a function of the height of stored water above the drain's offset	0.5	0.5
	Drain offset height (mm) Height of the drain line above the bottom of the rain barrel	0	0
	Drain delay (h) Number of dry weather hours that must elapse before the drain line in a rain barrel is opened	0*	0*
	Open level (mm) Height in the drain's storage layer that causes the drain to open when the water level rises above it	0.01	0.01
	Closed level (mm) Height in the drain's storage layer that that causes the drain to close when the water level falls below	0**	0**

* A value of 0 means that the barrel's drain line is always open and drains continuously

** Default value