

Evaluating the Hydrological Performance of a Water Square with 2D Modeling and In Situ Monitoring

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ABSTRACT

In situ monitoring and numerical modeling tools are essential to quantify the advantages of stormwater management infrastructures and to improve their future designs. Such infrastructures offer effective solutions for decreasing runoff volume and mitigating surface sewer overflow issues in urban environments. This paper assesses the hydraulic and hydrologic performance of a stormwater management infrastructure using numerical modeling and in situ monitoring for a water square called Place des Fleurs-de-Macadam, located in a dense urban area in Montreal, Canada. This floodable park comprises a detention pond and bioretention cells that redirect and accumulate surface water from adjacent streets, enabling water infiltration and preventing excess water from surcharging the sewer system. The performance of the water square was evaluated with a coupled 1D/2D model in PCSWMM, as well as in situ monitoring, which was carried out by a flood test on site. The associated rainfall event was a three-hour rainfall of 62 mm, equivalent to a 100-year event for this area. Results obtained by numerical modeling and in situ monitoring indicated that urban stormwater runoff can be effectively mitigated. For the tested rainfall event, simulation and in situ monitoring results showed that the water square reduced the runoff volume by 98% and delayed outflows by two hours.

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1. INTRODUCTION

The increase in impervious surfaces and the effects of climate change on the intensity and frequency of rainfall have altered hydrological processes, generating an increase in surface runoff in urban environments (Chang et al. 2015; Schmitt and Scheid 2020). Consequently, large volumes of surface runoff must be conveyed through the drainage system. This runoff can lead to pluvial flooding, which may occur on the surface (major system) and can be due to the surcharge of the underground sewer networks (minor system). The surface flooding is usually due to insufficient interception capacity between the major and minor systems, while the sewer surcharge occurs when the amount of water intercepted by the minor system exceeds its capacity (van Duin et al. 2021). The surcharge of the sewer system reduces its level of service and increases the vulnerability of urban areas to heavy rainfall events (van Duin et al. 2021; Sandink and Binns 2021).

Urban flooding, resulting from the limited capacity of drainage systems to manage current and future runoff volumes, can lead to damage to public and private property including buildings, human casualties, and service disruptions (Sandink and Binns 2021; Schmitt and Scheid 2020). Street flooding can impede or entirely obstruct traffic operations and cause pedestrian safety problems (Evans et al. 2024). Additionally, consequences may extend to social and public health, such as the psychological distress among disaster victims and mold growth in flooded homes (Mobini et al. 2021; Piadeh et al. 2022). These impacts often have repercussions that involve economic losses, including loss of business opportunities and reduction of economic activities (Piadeh et al. 2022).

The significant costs and losses caused by inadequate capacity of combined sewer systems have led to an increasing interest in source control infrastructures as opposed to traditional infrastructures. Source control infrastructures are designed to capture, infiltrate, store, evaporate, retain, and slowly release stormwater, reducing the risk of flooding and sewer surcharge in densely developed areas (Zellner et al. 2016). A key objective of these structures is to increase the municipality's capacity to adapt to climate change, to manage surface runoff, and to reduce pressure on sewer networks. In addition, these source control infrastructures create public green spaces and promote a water and vegetation conservation culture. Among these infrastructures are floodable parks, which enhance water management through natural processes by integrating various techniques (Muñoz et al. 2024). These include temporary runoff storage in ponds or across the entire park surface during heavy rainfall, as well as infiltration systems like bioretention cells. The Place des Fleurs-de-Macadam water square is an example of a floodable park. Although a relatively novel approach, research by Muñoz et al. (2024), has shown that the surrounding vegetation and biodiversity of floodable parks can improve performance and even support future water reuse. Thus, it helps to create more sustainable urban environments that are resilient to climate change.

Understanding the performance of stormwater management infrastructure is crucial for quantifying its benefits and improving overall design and functionality. In this context, the objectives of this work are to:

1. Evaluate and validate the hydrologic and hydraulic performance of the water square Place des Fleurs-de-Macadam, in Montreal, focusing on:
 - a. Assessing its capacity to reduce the runoff directed to the sewer system,

- b. Investigating its effectiveness in managing stormwater from adjacent areas, in terms of reducing peak flows and total flow volume within the drainage system, and
 - c. Examining key stormwater management outcomes such as runoff volume reduction, surface ponding, and infiltration performance.
2. Demonstrate how two-dimensional (2D) hydrodynamic models can help in assessing the hydrologic and hydraulic performance of stormwater management infrastructure.

2. METHODOLOGY

2.1 Case study

The studied site is in a densely populated urban area of Montreal, Canada. The city receives 1,000 mm of precipitation annually, with 209 cm of snow in winter and 785 mm of rainfall mostly during non-freezing months (May to November) (Environment and Climate Change Canada n.d.). The site comprises a water square featuring stormwater management infrastructure to manage runoff from approximately 1,848.8 square meters of permeable and impervious surfaces. This catchment area is surrounded primarily by residential and commercial buildings, as well as streets and sidewalks, served by a combined sewer system.

The water square was designed to capture, infiltrate, store, and slowly release stormwater from adjacent areas, reducing sewer overload in the area. The water square comprises two low-impact development (LID) systems, including a detention pond and bioretention cells. The detention pond is a surface storage area that receives the rainfall that falls on the impervious surfaces inside the site and redirects the water to the bioretention cells. The water is detained in the detention pond by a vortex flow regulator located in the catch basins that connect the detention pond to the bioretention cells. The bioretention cells receive runoff from the adjacent streets and from the detention pond. These bioretention cells simulate some natural hydrologic processes such as infiltration, evapotranspiration, and water storage. Water must reach a height of 15 cm (catch basin overflow level) in the bioretention cells to overflow and be conveyed to the municipal combined sewer system. The inflow to the municipal sewer system is controlled by a vortex flow regulator. The main functions of the water square are to:

1. Capture stormwater from the site drainage basin (including adjacent streets),
2. Reduce the runoff volume and flow rate toward the municipal sewer system, and
3. Enable infiltration of retained water through the bioretention cells.

An overview of the functioning of the Place des Fleurs-de-Macadam water square can be found in Figure 1. This figure shows the water flow paths and hydraulic components such as sewer pipes, manholes, and catch basins.

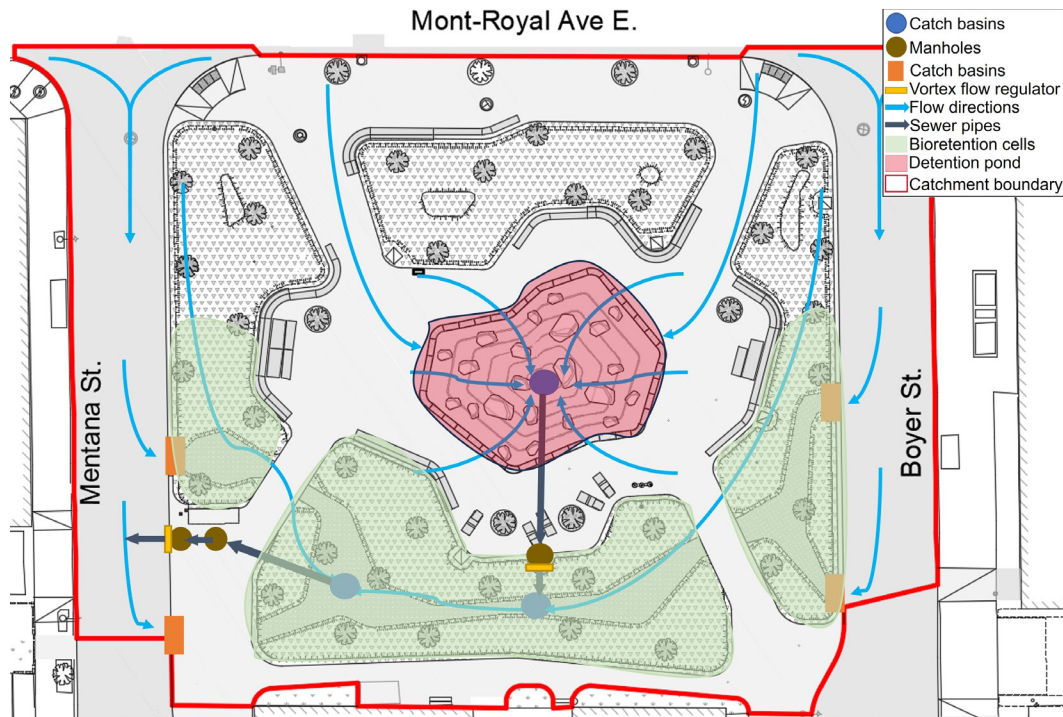


Figure 1 Flow paths and structures of the studied water square.

The surface area of the bioretention cells is 200 m², which corresponds to an impervious drainage area to permeable surface area ratio (I/P ratio) of 10%. Each cell contains a 1.5-meter-deep soil media composed of four layers: mulch, planting soil, granular filter, and fine sand, as shown in Figure 2, illustrating the cross-sectional profile. The bioretention cells are equipped with a 200 mm perforated underdrain that conveys water to the central catch basin that overflow into the bioretention cells, as explained in Section 2.4 and Figure 7. A fixed infiltration rate of 8.0 l/s was set for the whole infiltration surface. Beneath the bioretention cells, the native soil consists primarily of silts, silty sand, and sand filling materials, extending approximately 3 meters below the bottom of the bioretention cells, underlain by a bedrock layer. Based on field tests, the in situ permeability of the native soil measured at a depth of 1.15 m is 8×10^{-3} cm/s. The bottom elevation of the bioretention cells is 46.60 m, which is located between 0.84 m and 1.1 m above the water table (values recorded on different dates).

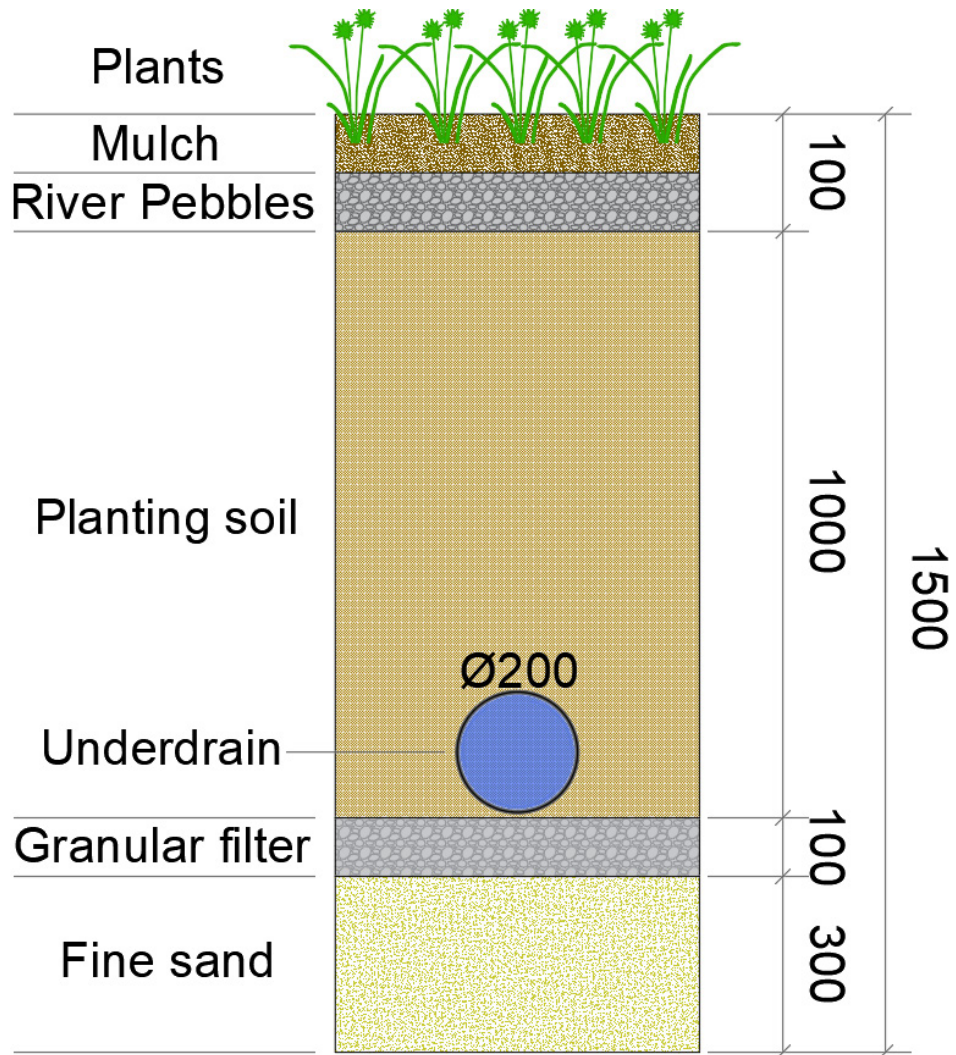


Figure 2 Schematic profile of the bioretention cell structure (units in mm).

2.2 Data collection

The rainfall characteristics of the area were obtained from the site design report (EXP 2021), as depicted in Figure 3, which illustrates the 3-hour Chicago design rainfall for return periods of 100, 50, and 25 years.

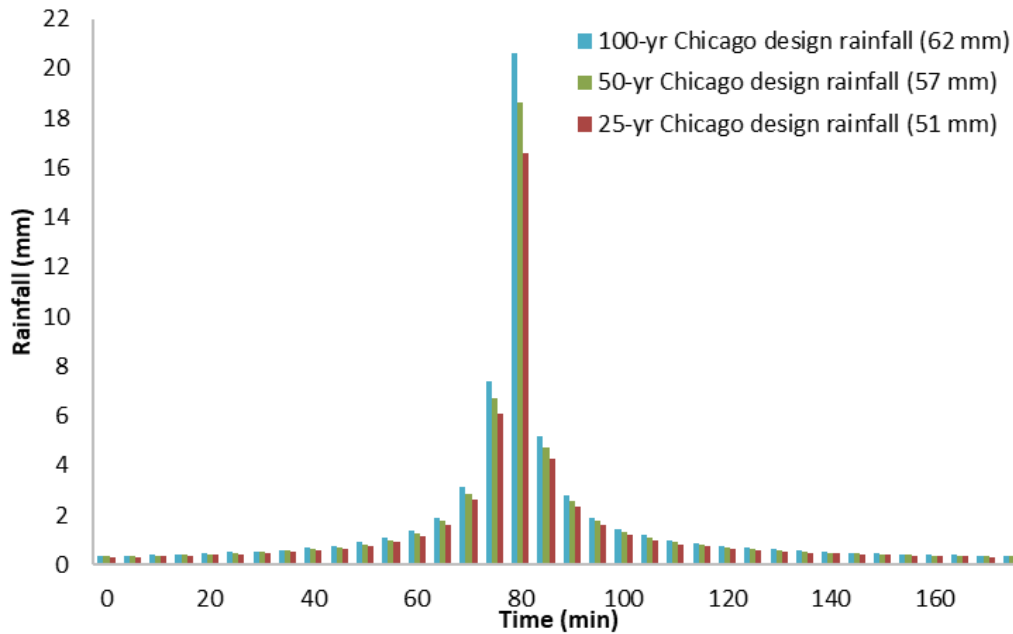


Figure 3 Rainfall hyetographs.

For the 2D hydrodynamic modeling of the site, a digital elevation model (DEM) was generated using light detection and ranging (LIDAR) data, resulting in a planimetric and altimetric accuracy of ± 20 cm. This DEM was then refined using topographical survey data and site design plans, resulting in a final DEM with a horizontal and vertical accuracy of ± 1 cm. Additional data pertinent to surface types, slopes, and soil characteristics were obtained from past studies conducted during the project design phase and information provided by the city (EXP 2021; Vinci Consultants and Les Ateliers Ublo 2019; FNX-INNOV 2020; NIPPAYSAGE and EXP 2020; Montréal 2021).

2.3 In situ monitoring

The flood test was designed to reproduce a 3-hour rainfall event with a 100-year return period, which is 62 mm for the study area. This means that a total water volume of 118 m^3 was discharged onto the site through fire hydrants over a 3-hour period (presented as red points in Figure 4). It should be noted that the reproduction of this rainfall event did not match with its original temporal pattern, due to the complexity involved. Instead, the inflow was discharged at an approximately constant flow rate during the 3 hours, with slight variations to meet on-site operational constraints. These inflows are shown in the results section (Figure 9). During the in situ monitoring, water from two hydrants was conveyed to the water square through three fire hoses. This approach was adopted as the water square collects water coming from three areas: the two adjacent streets (blue and yellow shading in Figure 4) and the site itself (green shading in Figure 4). Therefore, the site was divided into three catchments, depicted in Figure 4. The discharged (constant) flow rate to each area was calculated using Equation 1.

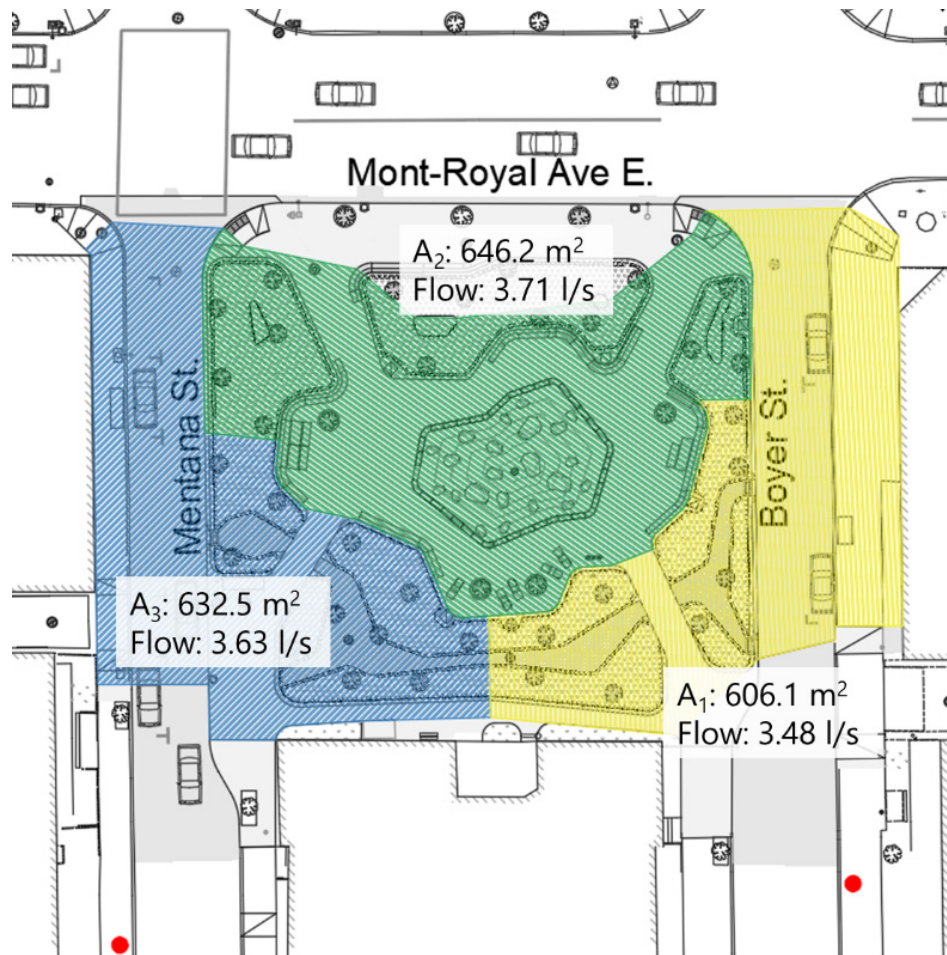


Figure 4 Catchments of the water square for the flood test.

$$Flow\left(\frac{l}{s}\right) = \frac{Precipitation(mm) \times Area(m^2)}{Duration(s)} \quad (1)$$

During the test, four flowmeters were used to measure the inlet and outlet flows. The location of these flowmeters is shown in Figure 5a in red and purple circles. Figure 5b shows that two flowmeters (1 and 2) were installed on the fire hydrants supplying water for the test, and Figure 5c shows that two flowmeters (3 and 4) were placed in the outlet pipes from the center of the site and from the bioretention cells. Flowmeters 1 and 2 measured the water entering the site, while Flowmeter 3 measured the water leaving the detention pond and entering the bioretention cells, and Flowmeter 4 measured the water leaving the site to the municipal sewer system. Specifically, a Hose Monster flow meter with an accuracy of 0.3% was used at Point 1, and an Octave Ultrasonic flow meter with an accuracy of $\pm 1.5\%$ was used at Point 2. For Points 3 and 4, the Teledyne ISCO 2150 Area Velocity flow modules were used, with a level measurement accuracy of ± 0.003 m and a velocity accuracy of ± 0.03 m/s.

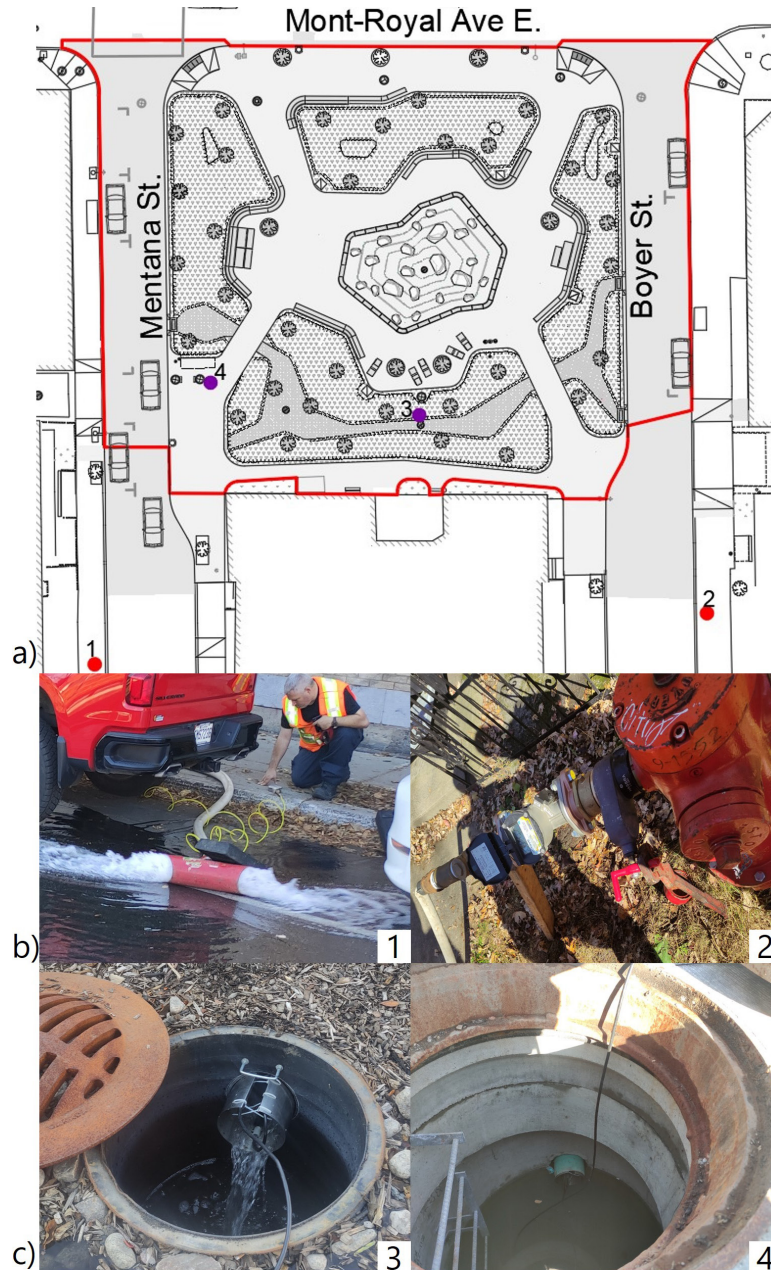


Figure 5 Measurement of flow rates: a) Locations of the flowmeters; b) Flowmeters on fire hydrants (left: Mentana St., right: Boyer St.); and c) Flowmeters on sewer pipes (left: detention pond outlet, right: bioretention cells outlet).

Figure 6 presents the locations of the test inflows and outflows and their volumes. The total inflow volume for each draining area was 19 m³ at the center (17 m³ at the detention pond and 2 m³ at bioretention cells), 68 m³ at Mentana St. and 31 m³ at Boyer St. All these inflows correspond to a volume of 118 m³, which is equivalent to a 100-year rainfall event with a tolerance of +1.4%.

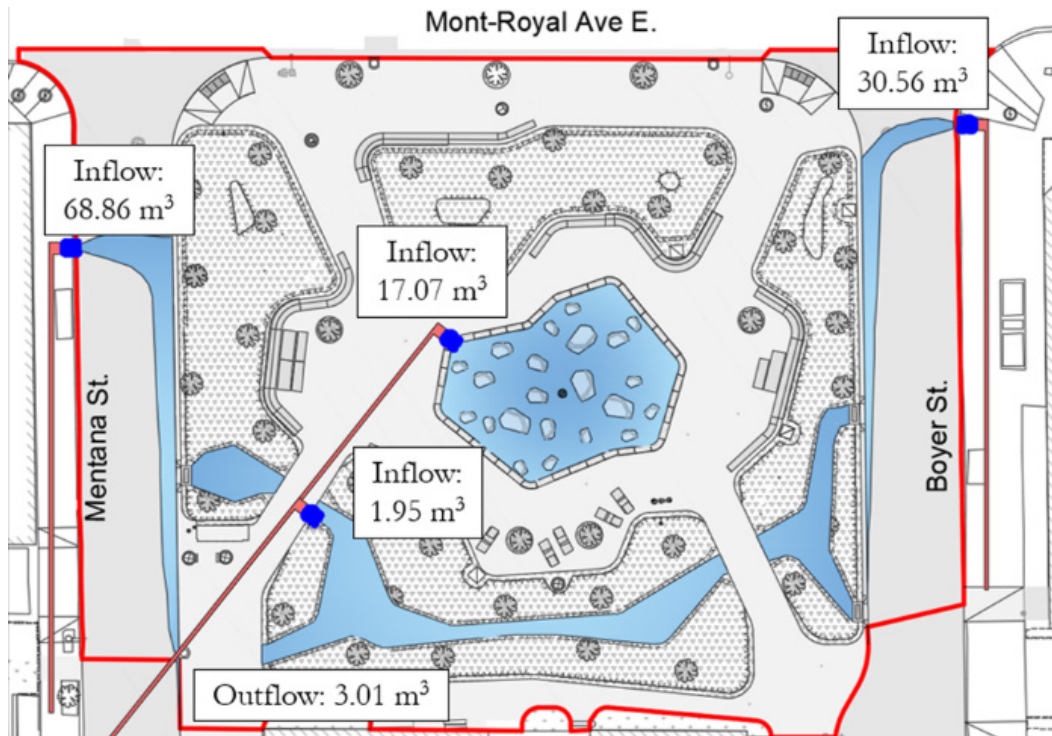


Figure 6 Inflows and outflows during the test.

The incoming water volumes slightly differed (by about 1.4%) from the quantities initially planned. Due to challenges encountered during the installation of the flowmeters on the fire hydrants, it was not easy to precisely regulate the outflow rate of each hydrant. However, these actual inflows were recorded and used as inputs in the model.

During the in situ monitoring, a visual inspection was conducted to examine the water dynamics at the site over a five-hour period: three hours during the flood test and up to two hours after the inflows stopped. This was done to determine whether the site operated in accordance with its design, to verify whether water was entering from the adjacent streets, to assess slope conditions, and to observe flow directions. Photographs were taken during the test and used to record key observations and to support the interpretation of the 2D model results.

The performance indicator for the flooding test was the reduction in runoff volume, which was calculated with Equation 2:

$$R_{test} = \frac{V_{test} - V_{site}}{V_{test}} \times 100 \quad (2)$$

Where:

R_{test} = runoff retention at the site during the test,

V_{test} = test runoff volume, and

V_{site} = runoff volume flowing out of the site.

2.4 Visual inspection

Figure 7 provides schematics illustrating the observations made from visual inspection and from measurements during the flood test. Additionally, Figure 7 illustrates the processes occurring inside the water square. This figure presents transverse and longitudinal cross-sections of the water square. Note that the same bioretention cell is illustrated in both schematics from two different directions. Upon the visual inspection, the stormwater management system was found to be well-constructed, with catch basins allowing runoff from adjacent streets to drain into the bioretention cells. Here, the flow regulator is the hydraulic link between the bioretention cells and the detention pond. This flow regulator controls the magnitude of water flow from the detention pond to the bioretention cell, causing water detention within the pond.

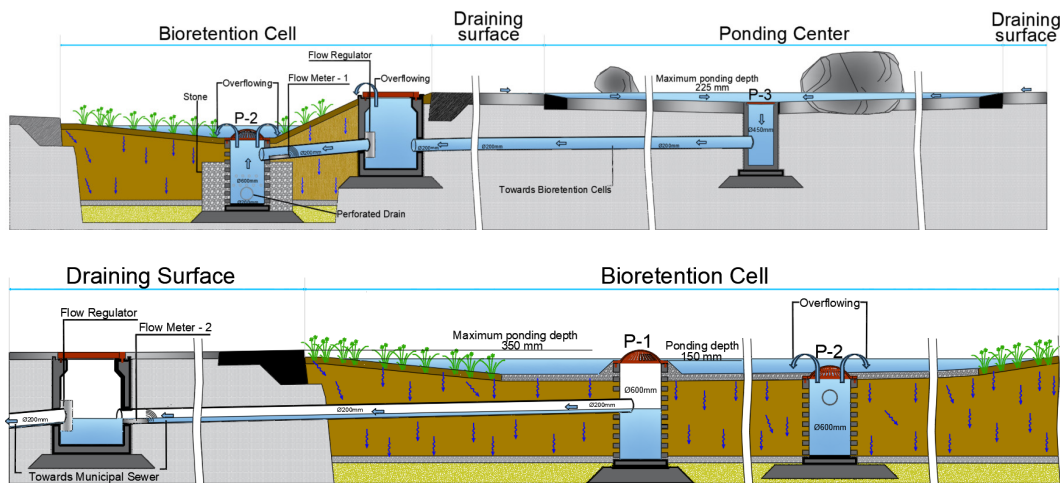


Figure 7 Water behavior inside the water square.

Within the bioretention cells, surface water gradually infiltrates through the soil media, as shown in Figure 2. When the cells reach their maximum infiltration capacity, excess water can accumulate on the surface of the bioretention cells up to a height of 35 cm. However, at a height of 15 cm, the overflow from the water square is discharged through a catch basin and directed to the municipal sewer system via an integrated piping network and a flow regulator. The flow regulator at the sewer connection controls outflow from the water square, allowing water to be retained within the bioretention cells and temporarily detained in the final catch basin.

2.5 Numerical modeling

The numerical model is a two-dimensional dual drainage model developed using PCSWMM 2D software (CHI 2023). This software, based on the hydrological engine of EPA SWMM 5.1 (Rossman 2015), has the capability to simulate both the major and minor drainage systems. These two systems are interconnected through nodes representing inlets within the model.

The 2D dual drainage model of this project was built from the existing 1D model provided by the municipality. This 1D model integrates the hydraulic elements of the sewer system and the subcatchments of the site, for which the parameter values were assigned during the calibration and validation of the model, which was performed by the City of Montreal. The calibration and validation of the 1D SWMM model for the entire watershed of which this site is part, performed

by CIMA+ (2018), was based on flow and rainfall data collected during two measurement campaigns in 2013 and 2014. Key parameters were adjusted for calibration, including Manning's roughness coefficient (n) for pipes and impermeable surfaces, the storage height (or depressions of storage) on impervious surfaces, and the percentage of impervious areas. Seven rainfall events were selected based on specific characteristics, including events ranging from 7 to 48 mm of rainfall and peak intensities between 5 and 46 mm/h. According to the report, the calibration and validation results demonstrate a satisfactory representation of observed flows under dry and wet weather conditions. Dry and wet weather calibration achieved peak flow deviations within $\pm 10\%$ and volume deviations within $\pm 5\%$ for all monitored sites.

The 2D model was developed using input from the calibrated 1D model, ensuring that the sewer network and subcatchments hydrology were represented realistically. Although the 2D model itself was not calibrated due to the lack of surface water data, care was taken to ensure its reliability. The 2D model was created by generating a hexagonal mesh type using the high-resolution DEM. The resolution of the mesh was 0.5 m, and a surface roughness value (Manning's n) of 0.011 was attributed to all its cells. Before the 2D mesh generation, adjustments were made on the DEM based on the field characteristics, as previously described in Section 2.2. For example, the accuracy of the topography was improved with topographic survey data. Specifically, the elevations of the water square and the depression in the detention pond and bioretention cells were defined in detail. The slopes of the surrounding streets were corrected, and the locations of the catch basins through which water entered the place were slightly modified. This last step helped to create the 2D nodes and connect the 2D mesh cells, representing the surface, with the 1D nodes representing the sewer system.

Furthermore, infiltration in the 2D model was represented using the fixed infiltration rate of 8.0 l/s previously described. The soil was assumed to be dry at the start of the simulation, which is consistent with conditions during the actual flood test. Since there was no precipitation in the previous days, only the plants at the site were watered.

The establishment of the 2D model allowed the representation of the hydraulic and hydrological dynamics of the site during the flood test. Figure 8 provides a complete representation of the site with its subcatchments, pipes, and nodes, as well as the 2D mesh. The 2D model was used to simulate the flood test conditions. To ensure consistency between the in situ flood test and the PCSWMM model, the inflows measured during the flood test were added to the model. These inflows, shown in the results section (Figure 9), were assigned to four 2D nodes situated at the same locations as the in situ test inflows in the form of hydrographs. Although the flow rates were approximately constant, slight variations were introduced during the test to accommodate in situ operational constraints. These adjustments were reflected in the model inputs.

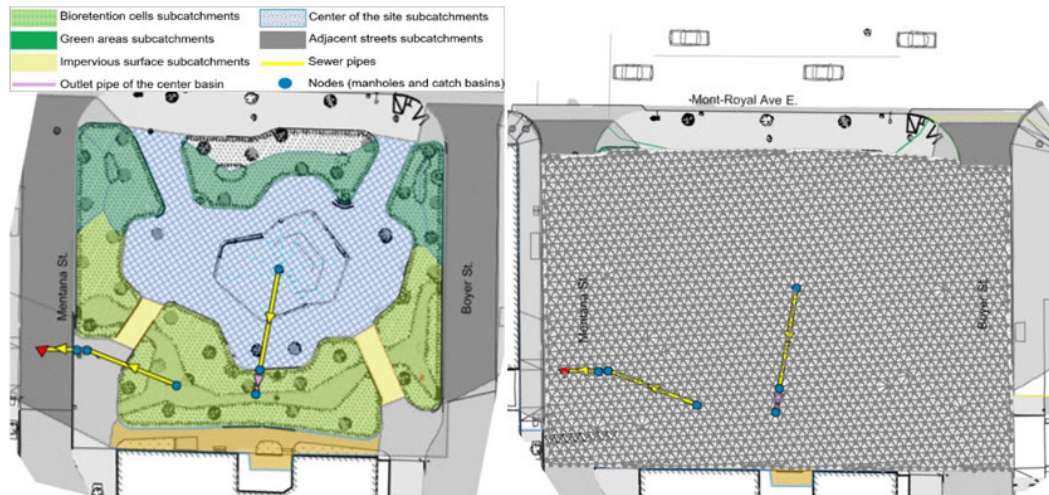


Figure 8 Subcatchments and elements of the 1D model (left), and mesh of the 2D model (right).

3. RESULTS AND DISCUSSION

3.1 In situ monitoring

Table 1 shows the total volume of inflows and outflows, and the retention/infiltration performance of the water square. As shown, only 3 m³ out of the total inflow volume of 118 m³ was discharged as an outflow to the municipal sewer system during the five-hour monitoring period. At the end of the monitoring period, the detention pond was completely drained, and the soil in the bioretention cells was wet, with the presence of a few small puddles with a negligible amount of water.

Table 1 Inflow and outflow volumes.

Inflows		Outflows	
Description	Volume (m ³)	Description	Volume (m ³)
Center	17	Sewer system	3
Bioretention	2		
Mentana St.	68		
Boyer St.	31	V_{site}	3
V_{test}	118		
Retention/infiltration volume (m ³)	115	R_{test} (%)	97.5%

As shown in Table 1, the retention/infiltration volume was 115 m³. This means that the water square demonstrated a retention/infiltration capacity of 97.5% during the simulation of a uniform rainfall event with the same total rainfall depth as a 3-hour rainfall event with a 100-year return period.

Figure 9 depicts the inflow and outflow hydrographs during the flood test. During the first few minutes of the test, water was accumulated, retained, and absorbed in the detention pond and bioretention cells. Thus, no overflow into the municipal sewer was generated. The outflow from the detention pond to the bioretention cells began at approximately 13:00 (67 minutes after the start of the test), controlled by the vortex flow regulator. According to the inflow hydrograph, the detention pond had stored an accumulated volume of 10.9 m³ by that time. From 13:00 onward, water continuously drained into the bioretention cells until the end of the monitoring period, even though no visible water remained in the center of the pond. This ongoing drainage was attributed to water detained within the catch basin and manholes.

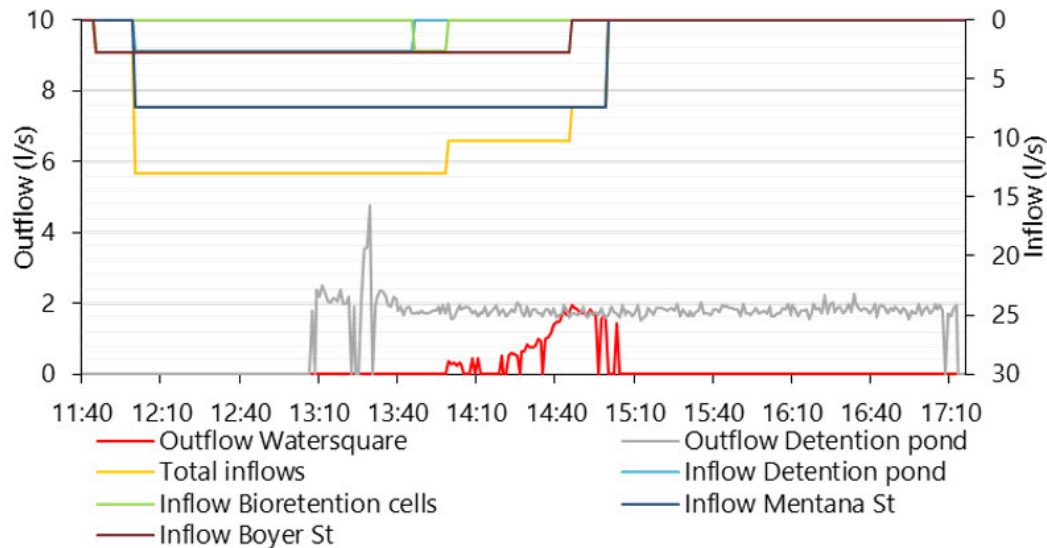


Figure 9 Inflows and outflows during the flood test.

Figure 9 shows that outflow from the water square center began at approximately 13:53 (two hours after the start of the test), with an estimated volume of 3 m³. This indicates that, once the retained water in the bioretention cells reached the overflow level, the excess was discharged into the municipal sewer system. As the flood test progressed, water infiltrated into the bioretention cells and outflowed through the municipal sewer. At the end of the test, the water level in the bioretention cells took five minutes to drop below the overflow level of the water square. This extra time is attributed to the dynamic accumulation of water in the bioretention cells because of the vortex flow regulator in the catch basin located just upstream of the municipal sewer pipe. Furthermore, surface flooding in the bioretention cells continued approximately 100 minutes after the end of the test, after which only small puddles of water remained, according to visual inspection.

It is worth mentioning that even though the flood test simulated a 100-year return period rainfall event, there was no surface overflow onto the adjacent streets.

3.2 Numerical modeling

Figure 10 presents the maximum water levels simulated using PCSWMM during the flood test. The modeled water levels reached 16 cm in the bioretention cells and 15 cm in the detention pond, closely matching the observed values recorded on site. This agreement confirms the

model's ability to accurately reproduce the hydrologic behavior of the site observed during the flood test.

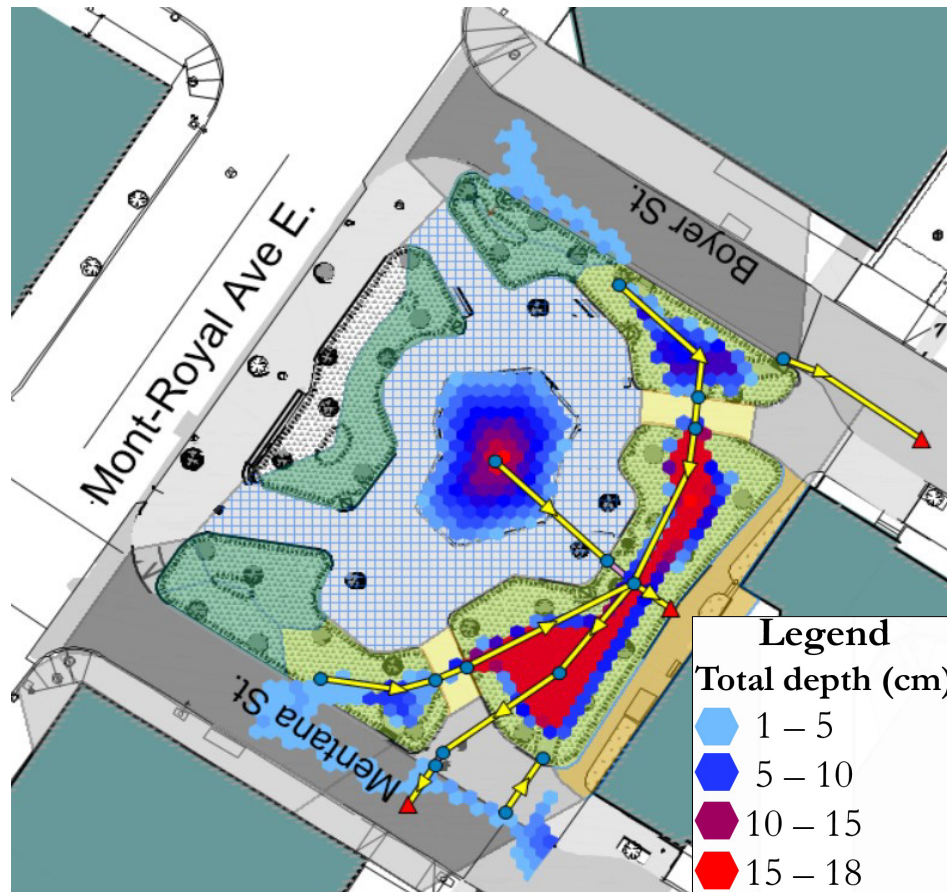


Figure 10 Maximal water level during the flood test according to numerical modeling.

4. CONCLUSIONS

In situ monitoring and numerical modeling tools were used to analyze the hydrological behavior of the water square Place des Fleurs-de-Macadam, situated in a densely urbanized sector of Montreal, Canada, during intense rainfall events. Results showed that numerical modeling is an effective way of assessing the performance of stormwater management structures when based on a calibrated model, developed using high-resolution topographic data, and supporting field tests. This approach reduces the cost and preparation time of an in situ monitoring experiment and can provide decision-makers with valuable insights when designing stormwater management infrastructure. The conducted simulations showcased the efficiency and adaptability of numerical modeling in assessing the maximum water levels and flood extent within the water square, thereby facilitating system evaluation. However, the flood test provided valuable insights into details that the model could not capture (e.g., very small-scale topography and flow paths, inlet channel erosion, debris accumulation, etc.).

The flood test demonstrated that the system could significantly reduce the runoff volume of a 100-year 3-hour rainfall with a 62 mm depth. The water square and bioretention cells effectively captured and stored 97.5% of the incoming stormwater during the flood test. This improvement

implies that the stormwater management strategies could be effective in reducing the risk of flooding and surcharge in the area. While the site catchment represents a small fraction of the combined sewer system catchment and has no impact on combined sewer overflows (CSOs) reduction and has a low impact on overload reduction, it contributes to reduce runoff volumes and pressure on the network. This highlights how decentralized stormwater management facilities can locally reduce peak flows and serve as scalable pilot solutions for wider application in urban areas. Adding many of these solutions can have a major impact on the sewer system by reducing CSOs and the risk of urban flooding.

However, since the temporal pattern of the rainfall reproduced on-site did not reflect the temporal pattern of the real event, the results may differ slightly from those that could be obtained during a real event. This discrepancy arises from the non-uniform nature of rainfall, which could lead to higher peak flow rates in short periods, which are likely to induce alterations in water dynamics within the structures and potentially cause overflows and reduce infiltration, compared to the constant steady inflow used in the simulated test.

Although the 2D model itself was not calibrated, it used parameters from the calibrated 1D model and produced results that closely matched both observed flood test data and the 1D model's outflow. In addition to this consistency, the 2D model improved spatial representation, capturing flow paths, water depths, flood extents, and surface dynamics, details the 1D model could not provide, such as internal water levels and flow trajectories within the water square.

In conclusion, the results of the flood test and numerical modeling demonstrated the effectiveness of the water square system in managing stormwater runoff and reducing the risk of flooding in densely developed areas. This capacity is especially beneficial during heavy rainfall events, as the site stores and manages significant volumes of runoff water from its surroundings. In doing so, it attenuates the immediate entry of large volumes of water into the sewer system, mitigating the overloading of the sewer system. Taken together, these findings highlight the significant impact of integrated stormwater strategies to enhance the urban environment and to elevate the overall quality of life. However, these results should be used with caution. Indeed, performance results depend highly on construction methods and physical characteristics of the site, such as drainage area and soil conditions.

Further research is needed on the long-term performance of the water square to provide better data on the required frequency of maintenance of the bioretention cells, as well as on its performance in different seasons of the year, and in response to continuous rainfall events.

ACKNOWLEDGMENTS

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