Real-time model predictive and rule-based control with green infrastructures to reduce combined sewer overflows

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Real-time model predictive and rule-based control with green infrastructures to reduce combined sewer overflows

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ABSTRACT

The impact of integrating large-scale distribution of green infrastructures (GIs) with different real-time control strategies on combined sewer overflows (CSOs) is assessed for the southern area of the City of Montreal's combined sewer system (Canada). An iterative process involving a synthetic design rainfall event and model predictive control (MPC) of the sewer system is developed to distribute GIs according to cost-efficiency and spatial analysis criteria. The distributed GIs are alternatively integrated with static, rule-based control (RBC) and MPC, for which model simulations are performed for a two-month period. The performance of the three strategies is compared in terms of CSO volume and frequency reductions, fulfillment of the outfall environmental priorities and transfer of runoff capture to CSO volume reduction. A gradual increase in GI implementation levels and an alternative scenario of GIs distribution are also considered to assess the performance of the two real-time control (RTC) strategies. By comparing the scenarios where GIs are uniformly distributed with those where no GIs are implemented and omitting the most extreme rainfall event, average CSO volume reduction is about 65%, 82% and 92%, respectively, for static control, RBC and MPC. Moreover, the scenario integrating GIs with MPC is the only one permitting to avoid almost all CSO events and the fulfilment of the outfall environmental priorities. GIs efficiency performance (the transferability between global runoff capture and CSO volume reduction) is also the highest under MPC, even when considering varying GI implementation levels and spatial distribution schemes.

1. Introduction

In urbanized areas, combined sewer overflows (CSOs) remain a major cause of water pollution (Botturi et al., 2021; Rizzo et al., 2020; Van der werf et al., 2021), impeding first contact activities, altering drinkable water source quality and threatening receiving waters viability (Gooré Bi et al., 2015 Madoux-Humery et al., 2015; Passerat et al., 2011). CSO occurs in combined sewer systems which were designed to drain both wastewater and stormwater in one network. During rainfall or thawing periods, the sewer inflows can be increased tenfold by urban runoff and thus exceed the system capacity. During those events, CSO helps relieve the network to avoid local urban flooding and pipe surcharges. Many cities in the world are still facing CSO problems as their former combined sewer network cannot or can only be partially separated due to economic or technical constraints (Lund et al. 2019). In addition, climate change, combined to population growth and land development are putting additional threats on the sustainability of stormwater infrastructures (Alves et al., 2016; Zhang et al., 2021; Semadeni-Davies et al., 2008, Yazdanfar and Sharma, 2015), while some urban centers must recover from decades of deficiency in assets management (Lund et al., 2019).

The scientific literature shows a growing interest in green infrastructures (GIs) applications for CSO abatement. For instance, previous studies assessed large-scale implementation of GIs for CSO volume and frequency reduction (Autixier et al., 2014; Hernes et al., 2020; Joshi et al., 2021; McGarity et al., 2017; Patwardhan et al., 2005; Torres et al., 2018). Whereas GI benefits for CSO mitigation were demonstrated both in terms of CSO reduction performance and implementation cost, when compared to conventional retention solutions (such as underground storage) (Joshi et al., 2021; Liao et al., 2015; Montalto et al., 2007), some authors highlighted the need for combining GIs with centralized retention to improve their cost effectiveness (Alves et al., 2016; Dong et al., 2017) or to meet specific CSO control targets (Fu et al., 2019; Liao et al., 2015; Tavakol-Davani et al., 2015). Moreover, a few studies applied optimization tools to distribute GIs for CSO control at a lower cost (Fu et al., 2019; Torres et al., 2018) or decision support systems to facil-

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itate GI sites selection based on hydrological needs or space availability (Kuller et al., 2017).

Alternatively, improvement of GI performance has also been studied through the integration of real-time control (RTC) technologies. This could be realized in a decentralized manner when real-time measurements (i.e. water levels, rainfall depths, etc.) allow to dynamically controlled GI processes on-site, such as GI outflow rates (Xu et al., 2020a), or through the application of an intelligent control of the sewer infrastructures (i.e. pumping stations or regulators) in order to increase the actual retention capacity of the underground network (Garcia et al., 2015). In both cases, RTC techniques can involve heuristic or optimization-based algorithms. A heuristic strategy often implies the application of rule-based control (RBC) which defines a set of control actions based on the state of the system. In the case of the application of an optimization-based algorithm, a single or multiple objective(s) define the desired behavior of the system and are transposed mathematically in a set of constraints and a cost function to be minimized or maximized. Different optimization tools can be applied to solve the optimization problem. Model predictive control (MPC) is a complex form of optimization-based RTC scheme which allows to determine the best global management strategy for each controller of the system and involves a control-oriented model of the network as well as predicted data (Garcia et al., 2015, Shishegar et al., 2018).

Previous applications of RTC technologies with GIs demonstrated increased GI performance in terms of CSO volume reduction (Lucas and sample, 2015; Lund et al. 2019; Oberascher et al., 2021a), as well as under a single rainfall event or multiple consecutive rainfall events (Lewellyn et al., 2018). Some authors also compared the performance of various RBC strategies representative of different control objectives with more complex MPC scheme (Oberascher et al., 2021b) or forecast lead-times (Xu et al., 2020b). It was thus suggested that future research work should be oriented in applying more complex RTC schemes (such as MPC) to improve GIs control (i.e., filling and emptying processes) with a global strategy (Xu et al., 2020a). Fewer applications are found in the literature on the integration of GIs with the traditional application of RTC at the sewer system scale. It is only recently that this solution has been integrated to GIs for CSO control. For instance, Altobelli et al. (2020) compared the performance of combining RTC with different types of GIs as well as storage tanks to reduce CSO volume and pollutant discharges. Frey et al. (2013) applied an optimization tool to determine the best combination and quantity of GIs that should be implemented with gray infrastructures managed by RTC technology which reduced the cost as compared to the base-case scenario without GI. Similarly, the study of Jean et al. (2021) demonstrated that the CSO volume, frequency and cost can be reduced when the spatial distribution of GIs is optimized over the watershed area in integration with gray infrastructures design as well as RTC rules parametrization. In comparison, applications of various RTC strategies in combination with gray infrastructure for CSO management have been highlighted in both empirical and modeling studies (van Daal et al., 2017; Lund et al., 2018)..

Whereas previous above-mentioned works did assess the impact of combining RTC with various types of GIs or compared the performance of different RTC strategies without considering GIs impact, there is still a need to compare the performance obtained from the application of different types of RTC management in combination with GIs. The main objective of this paper was thus to understand how two different types of RTC strategies (i.e., RBC and MPC) influence the performance of large-scale implementation of GIs for CSO abatement and how these control strategies compare to static control. The evaluated performance criteria comprised CSO volume and frequency reductions, fulfillment of environmental priorities (established to avoid overflows primarily where the receiving water is most vulnerable to water pollution), and GIs efficiency (i.e., the fraction of runoff volume captured by GIs that is converted into CSO volume reduction). The main objective can be divided in two sub-objectives to analyze how the performance of the different control strategies combined with GIs differs for: i) a series of rainfall events; and ii) under different GIs implementation strategies (GIs gradual implementation and GIs distribution based on environmental priorities for avoiding CSO).

2. Material and methods

Simulation and optimisation tools were applied to simulate large-scale distribution of GIs in a highly urbanized area with different control strategies. A spatial analysis of the case study area was conducted to determined GIs space availability and an iterative design process was then applied to distribute GIs according to their efficiency and estimated costs. Different scenarios integrating GIs with different types of RTC strategies were developed to better analyse the combined impact of these solutions for CSO control. The following section provides details on the applied method and models.

2.1. Case study

The case study is the southern area of the combined sewer system of the City of Montreal (Canada). The total area totalizes about 17 000 ha from which 15 000 ha correspond to the combined sewer area (weighted imperviousness of about 43%). The combined subcatchments are drained toward the interceptor where regulators and overflow infrastructures at each confluence point control water inflows toward the wastewater treatment plant (WWTP). The estimated concentration time is six hours. While the interceptor is gravitational, there is a pumping station with a maximal flow of 42 m^3/s to the WWTP. According to their location along the receiving watercourse, each overflow structure is associated to one of the six environmental priority categories (from A = highest priority to F = lowest priority for avoiding overflows) reflecting receiving water vulnerability to CSO pollution, see Fig. 1). The watercourse vulnerability is assessed by the municipality based on various criteria (such as dilution rate at the overflow location, aquatic life evaluation, presence of primary and secondary water contact activities, etc.). Moreover, underground storage is available at eight sites for a total of 150 000 m^3 of retention capacity.

The network is dynamically controlled through the application of a RTC strategy. A total of 22 regulators are controlled using MPC during the summer season (May to October), whereas a simpler RBC strategy is applied during the other months. Details on the RTC management are included in section 2.4.

2.2. Rainfall data

2.2.1. Continuous simulation

Continuous simulation of an historical rainfall time series was realized to compare the scenario performance over a variety of rainfall events. Historical rainfall data with a five-minute resolution were available from 2010-2019 for the 23 rain gauge stations distributed over the watershed area (see Fig. 1). From these records, the wettest two-month period, namely July-August 2016, was selected for the continuous simulation as those summer months are the ones for which CSO have the greatest impact in terms of water contamination and recreational water use limitation. During the July-August 2016 period, rainfall depth totalized 223 mm and was distributed mainly among 14 rainfall events.

2.2.2. Design rainfall event

A design rainfall event, illustrated in Fig. 2a, was selected to determine the spatial distribution of GIs for CSO abatement. This synthetic rainfall event is currently applied for CSO management projects (Ville de Montréal, 2021a). The event total depth (19 mm) and temporal distribution are based on the analysis of historical rainfall events at three locations over a period of 14 years. The total depth of 19 mm is exceeded for 20% of the historical rainfall events and the event temporal

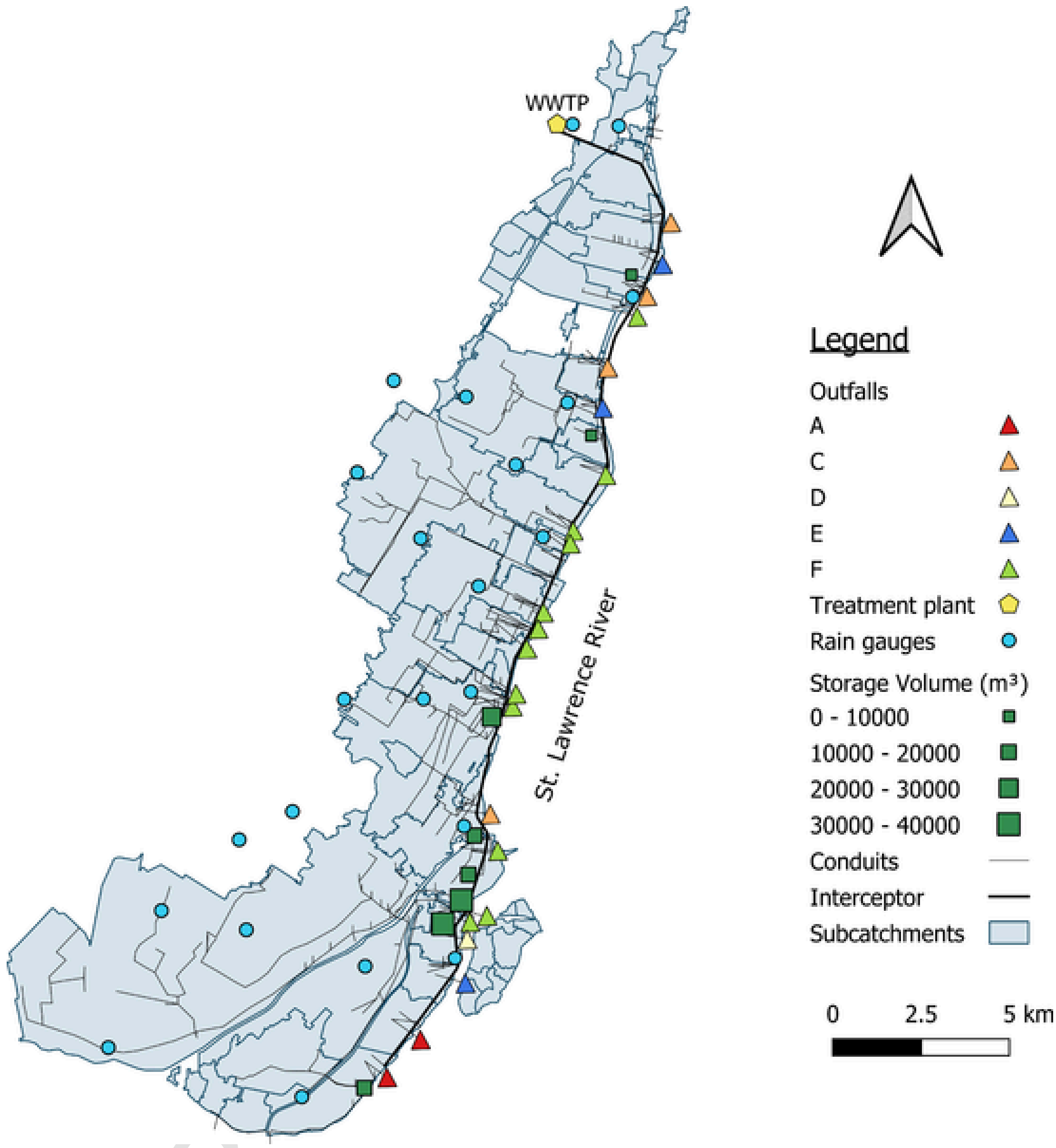

Fig. 1. Case study map

distribution corresponds to the average normalized mass curves (Lasalle NHC, 2019). By eliminating CSO event under this design rainfall event, the assumption was made that the CSO frequency over the study period should be reduced to the same extent as for the design rainfall estimated frequency.

2.2.3. Historical rainfall event

A historical rainfall event was also selected to compare simulated results from the design rainfall event and another more heterogeneous rainfall event. The area-weighted temporal distribution over the case study of the selected rainfall event of August 21, 2016 is presented in Fig. 2b. Both the synthetic and historical rainfall events have similar duration of about 6 hours, total rainfall depths (19 and 21 mm respectively) and average intensity over 5 minutes (3.2 and 3.4 mm/h respectively). In the case of the historical event, the spatial distribution of the rainfall is highly heterogeneous. The maximal rainfall intensity over 5 minutes attains 81 mm/h in some sub-catchments, whereas total rainfall depths vary from 13.5 to 30 mm according to the location.

2.3. Hydrological and hydraulic simulation

The uncontrolled flows of the sewer system, which comprises the surface runoff and the flows in the upstream portions of the network, were modeled using SWMM5 (Rossman, 2015). The controlled flows (i.e., sewer flows and overflows along the interceptor) were simulated (and optimised) through the application of the Control of Sewer Overflow SOFTware (Csoft) (Pleau et al., 2005).

Csoft hydraulic involves five sub-models: 1) flow conveyance model, 2) storage model, 3) flow regulator model (gates, weirs and orifices), 4) pump model, and 5) water elevation model.

The flow conveyance model is a Moving Average (MA) model, where the flowrate at a given pipe outlet varies according to flowrates at the pipe entry points and their associated flow routing coefficients calibrated from simulated flows in SWMM.

The storage model is based on the continuity equation for determining reservoir and pipe stored volumes. The behavior of the flow regulating structures and pumps are defined using rating and pumping curves. Finally, the water elevations at the nodes are computed using backwater and recession curves. During the optimization process, the nonlinear

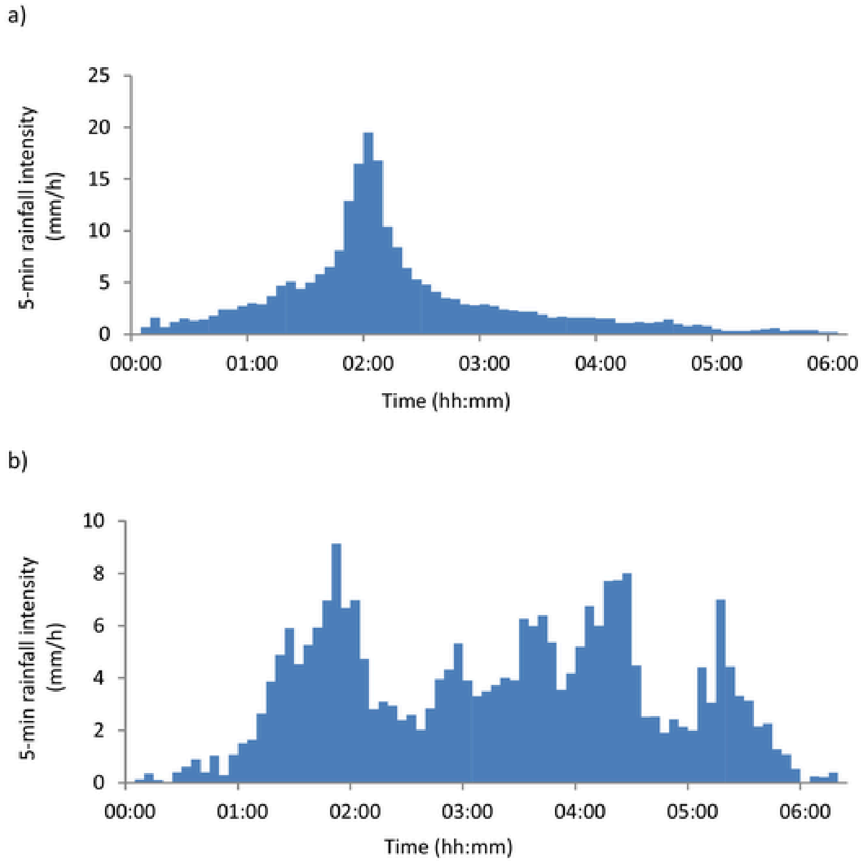

Fig. 2. a) Design rainfall hyetograph b) Historical rainfall event of August 21, 2016 (area-weighted value of the 23-rain gauge stations)

equations related to the flow regulator model, pump model and water elevation model are piecewise linearized to reduce computing time (Lin et al., 2013).

Measured water levels along the interceptor and flowrates at the flow regulating structures were used to calibrate the Manning's n coefficients for the SWMM and Csoft models. SWMM results were further used to calibrate the simplified Csoft model routing coefficients and bathymetric and backwater curves. The overall model performance for hydraulic simulation was validated by comparing simulated flowrates and water levels with observed data. More details about the Csoft submodels and their calibration are provided in the Supplementary Material section.

2.4. *Real-time control scheme*

Fig. 3 details the RTC scheme for the three studied control strategies (MPC, RBC and static). As shown in this Fig., rainfall data and the SWMM model were used to simulate the uncontrolled flows, which were managed based on different optimization tools for the two RTC strategies, or rating curves in the case of static management, all implemented in Csoft. In all cases, the coupling between SWMM and Csoft is a one-way coupling scheme. Details about each control strategy are presented below.

When MPC was considered, the flow set points to be applied at the 22 flow regulators are computed repeatedly every 5 minutes by solving

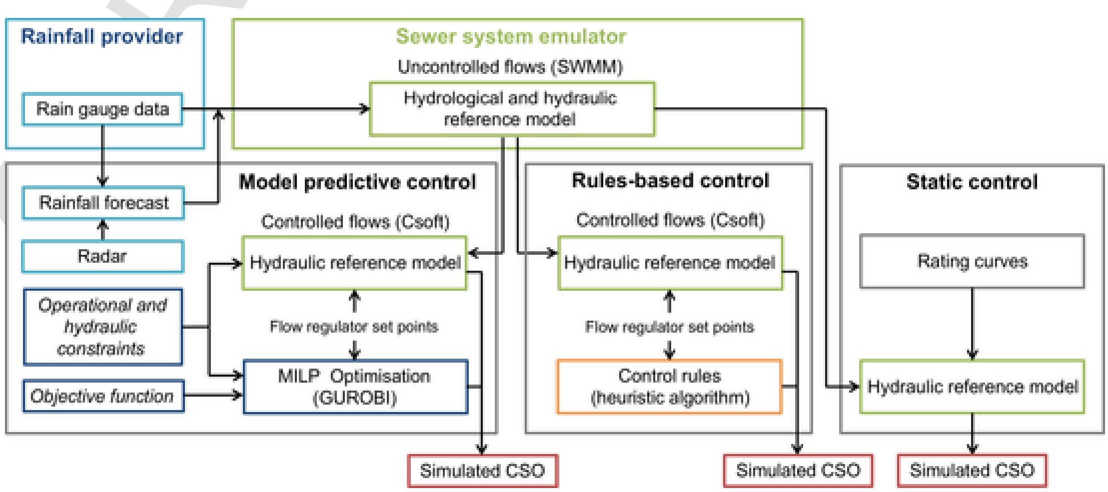

Fig. 3. Real-time control and static control scheme

an optimization problem formulated as a Mix Integer Linear Programming (MILP) problem which included an objective function to be minimized over a 2-hour control horizon and a set of operational and hydraulic constraints. Since repeated optimization runs took into consideration updated measurements for the initial conditions and updated load trajectories for the future conditions, past inaccuracies with respect to the process behaviour (introduced by modelling) and load trajectories (introduced by the rainfall predictions) did not affect the new control decisions.

The objective function of this optimization problem (see Equation 1) was defined to achieve, in order of priority, the following behaviour: 1) avoid flooding volumes; 2) minimize surcharge flows; 3) minimize total CSO volume; 4) prioritize CSO volumes according to the environmental priorities (site specific); 5) minimize the time to empty the storage units; and 6) minimize gate movements. It was defined as a scalar function made of penalty weights multiplying different control and process variables. These variables were all defined in unit of volume to simplify the determination of the penalty weights. The use of penalty values in the objective function ensures that the trade-off between each objective reflect their relative priority (i.e. avoiding flooding volumes within the network will always be more important than avoiding CSOs).

$$\mathrm{F}\,(\mathrm{t}) = \sum_{\mathrm{t}=1}^{\mathrm{n_t}} F_t * \left(W_w * V_{w,t} + \sum_{f=1}^{n_f} W_f * V_{f,t} + \sum_{s=1}^{n_s} W_s * V_{s,t} + \sum_{c=1}^{n_c} W_c * V_{c,t} + \sum_{k=1}^{n_k} W_k * V_{k,t} + \sum_{m=1}^{n_{sp}} W_m * V_{m,t} \right) \quad (1)$$

Where:

n_{sp} = Total number of set points
n_t = Total number of time steps in the control horizon
n_f = Total number of nodes where flooding should be avoided
n_s = Total number of linkswhere surcharges should be avoided
n_c = Total number of CSO outfalls
n_k = Total number of storage facilities
F_t = Temporal attenuation factor
W_w = User defined penalty weight associated to the underuse of the treatment plant capacity
W_f = User defined penalty weight associated to flooded volume at a given node f
W_s = User defined penalty weight associated to surcharge flow at a given link s
W_c = User defined penalty weight associated to CSO volume at a given outfall c
W_k = User defined penalty weight associated to stored volume at a given storage site k
W_m = User defined penalty weight associated to flow set point variations at a given controlled site m
V_w = Difference between treatment capacity and treated flows expressed in volume (m^3)
V_f = Flooded volume at a given node f (m^3)
V_s = Surcharges expressed in volume at a given link s (m^3)
V_c = CSO volume at a given outfall c (m^3)
V_k = Stored volume at a given reservoir site k (m^3)
V_m = Flow set point variations expressed in volume at a given controlled site m (m^3)

The hydraulic constraints were made of the Csoft hydraulic model expressed as a series of linear equality and inequality constraints. They included continuous and binary variables introduced to piecewise linearize the nonlinear hydraulic behaviour of a sewer system. The operational constraints were introduced to limit flows and levels in the collection systems as well as to restrict the number of gates' movements.

The solver used to determine the optimal flow set points is Gurobi (Gurobi Optimization Inc., 2021). In the MPC scheme, the future states of the system were predicted based on rainfall forecast and modelling results. An idealized perfect prediction of upcoming rainfall data was considered in this paper. In real-world applications, a certain level of errors is attached to forecast information. Omitting the uncertainties associated with the rainfall predictions permits to evaluate the best performances that can be achieved by MPC.

Based on current and upcoming inflows data, the optimal sequence of control actions for the regulators was determined for a given control horizon. Ideally, the duration of the control horizon must be longer than the concentration time of the controlled catchment area to guaranty the optimality of the RTC strategy. However, to reduce computing time, the control horizon in the MPC applications presented here was shorter than the concentration time of the whole network, namely two hours instead of six, which is equivalent to the travel time in the main stretches of the interceptor. It was verified that this duration was sufficient to avoid a negative impact on the calculated solution.

The optimization problem included approximately 58,278 binary variables, 93,676 continuous variables and 142, 902 constraints, but the exact numbers could vary according to the hydraulic conditions.

The model solution is as close as possible to optimality due to the hydraulic model calibration, repeated optimization calculation every time step and the duration of the applied control horizon.

Under RBC, a heuristic algorithm determined, for the 22 flow regulators, a level set point to be maintained in the interceptor downstream of the regulating structure. These level set points were computed according to the capacity of the pumping station and the measured level in its wet well. They enabled to maximize the pumped flow to the WWTP while maintaining the interceptor under free flow on its entire length. We considered a fixed pumping capacity of 42 m^3/s and a constant wet well level of 6.5 m. Under such conditions, the level set points to be maintained by the flow regulating structures were constant and almost equal to the crown of the interceptor. In the SWMM and Csoft models, flow regulators were operated to maintain the level set points using Proportional, Integral and Derivative (PID) controllers. From the set point definition, the RBC scheme filled the interceptor from the upstream to the downstream sections. Consequently, the RBC scheme maximized the flows conveyed to the pumping station during rainfall events. However, conversely to the MPC scheme, it cannot maximize, for all the rainfall events, the storage volume available for CSO abatement nor prioritize overflows according to the environmental objectives.

Finally, in the case of the static control scheme, rating curves directly defined the regulated flows at each control structures without any dynamic adjustment.

2.5. Green infrastructures spatial distribution

The assessed GI types for CSO control were bioretention swales, bioretention planters (or tree pits) and flat roofs disconnection for diversion toward a GI or a permeable infrastructure (i.e. bioretention cell or infiltration trench), which are the technologies that are most often implemented in the selected case study.

2.5.1. GIs implementation potential

A spatial analysis was conducted to determine the upper GI implementation limit in each sub-catchment and for each type of GIs. The analysis was based on specific land suitability criteria and conducted in ArcGIS (ESRI, 2021) using data about land use and a soil characterization map.

More specifically, the potential maximal number of bioretention swales was determined in each sub-catchment based on previous work conducted by Linard and Charron (2018) and considering that a bioretention swale could be constructed at each local street intersections having at least 10 m² of space available for GIs.

For the maximum number of bioretention planters at the watershed scale, a first estimation was taken from the City's action plan to increase urban canopy for 2030 (Ville de Montréal, 2020). The potential physical constraints limiting bioretention planter's implementation in impervious public street areas were then approximated by applying the same correction factor than the one estimated in a previous study conducted for one central neighborhood of the City (Ville de Montreal, 2021b). As specific data for determining the available space for bioretention planters were not available at the sub-catchment scale, the spatial distribution of bioretention planters was determined by prioritizing the sub-catchments having the highest impervious areas (see eq. 3), as those sub-catchments are considered to be more vulnerable to climate change impacts and would be targeted in priority by the City urban planners for improving urban canopy.

$$BPmax_j = \frac{A_j}{A_{tot}} * \mathrm{Imp}_j * \mathrm{BP}_{tot} \text{ for } j = 1, \ldots, n_{sc} \quad (2)$$

Where:

$BPmax_j =$ maximal number of bioretention planters that could be implemented in sub-catchment *j*
$A_j =$ area of sub-catchment *j* (ha)
$A_{tot} =$ total area of the study area (ha)
$\mathrm{Imp}_j =$ imperviousness of sub-catchment *j* (%)
$BP_{tot} =$ maximal estimated number of bioretention planters that could be implemented in all the study area
$n_{SC} =$ total number of sub-catchments

As for the flat roofs that could be disconnected, they were identified in each sub-catchment by applying criteria based on governmental recommendations, which include a maximum of three floors and a total flat roof area of less than 600 m² (Régie du bâtiment du Québec, 2015).

Data on soil type and soil contamination were lastly used to separate the previously identified maximal number of GIs in each sub-catchment in two categories: 1) GIs of lower efficiency, for GIs implemented in less permeable and/or in contaminated soil areas, and 2) GIs of higher efficiency, for GIs implemented in more permeable and non-contaminated soil areas. The soil permeability was considered low for rock, clay or mixed sediments soil areas and high for sandy soils.

2.5.2. GI design and modeling

The LID module of SWMM was used to simulate GIs impact on surface hydrology using as input, in each sub-catchment, the number and type of GI units and the percentage of impervious area directed toward GIs for treatment. The three types of GI (bioretention swales, planters and flat roof disconnection) were all simulated as bioretention cells of 10 m². Table 1 presents the design parameters. These values were either based on calibrated values (Bilodeau, 2018), recommended values by Canadian design guidelines (CSA, 2018) or SWMM literature (Rossman et al., 2016). As mentioned before, the bioretention cells were divided in moderate and high efficiency types. Consequently, two parameters were adjusted: 1) the seepage rate at the bottom of the infrastructure, and 2) the treated impervious area per bioretention unit. The reduced performance of bioretention cells for less permeable and/or contaminated soil indirectly translated into an increase in construction costs, as a greater number of units need to be implemented to reach the same performance as with the high efficiency bioretention cells. Lastly, all flat roof disconnections were drained toward moderate efficiency bioretention cell. In this way, the GIs distribution process was simplified by considering only bioretention cells as simulated GIs.

Table 1
LID module design parameters applied for the simulations of GIs in SWMM

LID Layer	Parameter	Selected design value
Surface	Berm height (mm)	300
	Vegetation volume (fraction)	0.1
	Surface roughness	0.3
	Surface slope (%)	0.5
Soil	Thickness (mm)	450
	Porosity (fraction)	0.437
	Field capacity (fraction)	0.105
	Wilting point (fraction)	0.047
	Conductivity (mm/h)	140
	Conductivity slope (%)	30
	Suction head (mm)	110
Storage	Thickness (mm)	600
	Void ratio (fraction)	0.5
	Seepage rate (mm/h)	0.5 / 5 [1]
	Clogging factor (fraction)	0
LID control	Treatment ratio (GI area: Treated area)	1:10 / 1:20 [1]

[1] Moderate efficiency / high efficiency

2.5.3. GIs implementation process

The iterative process to determine the location of GIs, for the scenarios integrating a uniform distribution of GIs according to cost-efficiency performance, consisted in uniformly distributing GI units following their implementation ranking priority, given in Table 2, over the whole watershed area until there is no CSO for the MPC strategy applied under the design rainfall event (see section 2.2). Fig. 4 schematizes the applied iterative process. As seen, the MPC optimization was first realized without any GI. GIs were then gradually implemented to capture a volume of simulated runoff in SWMM that is equivalent to the CSO volume previously optimized in Csoft. As the amount of runoff captured did not translate directly into the same amount of avoided CSO, the iterative process needed to be repeated until all CSO volumes were eliminated.

The choice of location and type of GIs to implement at each step of this procedure was based according to GI cost and efficiency. Indeed, GIs were implemented one type at the time (from the most cost-efficient to the least) until no more space is available for a given GI type. More specifically, GI costs were determined on a per-unit basis according to data provided by the City of Montreal. The cost estimations reflected the City will to implement GIs in an opportunistic way. Indeed, as shown in Table 2, some GIs had a net implementation cost of zero or a very low cost, because these categories of GIs were part of the City's action plan for greening the cityscape. The City thus considers that adapting the design of those infrastructures for stormwater capture requires almost no additional investment.

When considering estimated implementation cost and treated area per GI unit, which varies spatially, a cost-efficiency ranking priority for GIs implementation can be associated to each GI as shown in the first

Table 2
GIs implementation priority based on cost and efficiency (ME = Moderate efficiency; HE = High efficiency)

GIs cost-efficiency priority	GI type	GI unitary cost ($/unit)	GI cost per treated area ($/m²)
1	HE City's planned bioretention swales	0	0
2	ME City's planned bioretention swales	0	0
3	HE City's planned bioretention planters	1,000	50
5	ME City's planned bioretention planters	1,000	100
6	HE bioretention swales	16,000	800
7	Flat roofs disconnection	11,000	1,100
8	ME bioretention swales	16,000	1,600

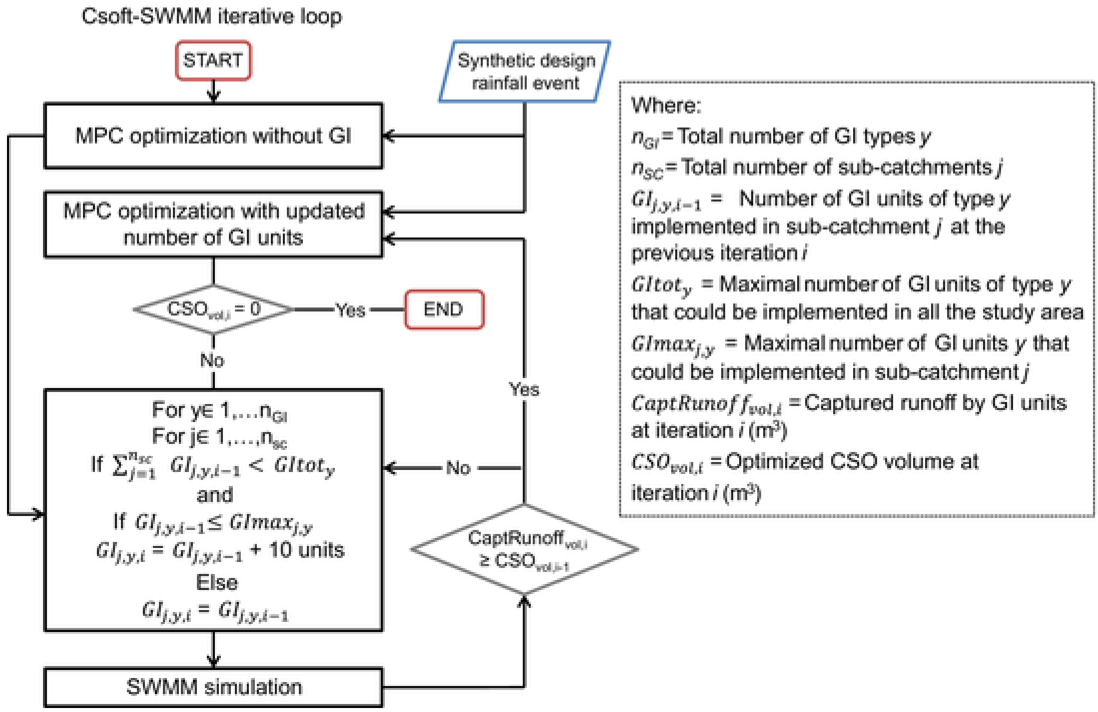

Fig. 4. GIs spatial distribution iterative process

column of Table 2. More specifically, this ranking was based on the GI cost per treated area as indicated in column 4 of Table 2.

2.6. Scenario development

Table 3 summarizes all assessed scenarios. Three reference scenarios (S1, R1 and M1), representing the three types of sewer control (static, RBC and MPC), were first compared for the situation without any GI. Three additional scenarios combining the different types of control with large-scale GIs implementation were developed (S2, R2 and M2). For these scenarios, the design and location of GIs were determined as described previously. A two-month period of continuous rainfall data (July-August 2016) and a synthetic design rainfall event were applied to evaluate the scenarios performance.

In addition, the distributed GI units in scenarios S2, R2 and M2 were reduced gradually to compare the performance of implementing only 25, 50 or 75% of the initial total number of GI units for all the assessed control types (static, RBC and MPC). These gradual implementation levels were simulated for two rainfall events: 1) the synthetic design rainfall event and 2) the historic rainfall event of August 21st 2016.

Lastly, a more heterogeneous distribution of GI units was applied to evaluate how the different control strategies perform when GIs are implemented only in the sub-catchments located upstream of the highest environmental priority outfalls (A to E) as these outfalls are the most vulnerable to CSO impact compared to the outfalls having the environmental priority F. As proposed by Kuller et al. (2017), the GIs distribution strategy should account for both space availability and locations for which GIs are most required for improving CSO reductions, the latter being considered in this last developed scenarios (named S3, R3 and M3 respectively for static control, RPC and MPC). However, for these scenarios, only 50% of the total number of GI units distributed in the previous scenarios (S2, R2 and M2) was implemented as the A to E sub-catchment's total area corresponds to only about one third of the total study area. Again, the performance of these scenarios was assessed for the synthetic and historic rainfall events.

Table 3
Simulated scenarios

Scenario name	GIs implementation %[1]	GIs spatial distribution	Simulated rainfall data
S1. Static - Ref R1. RBC - Ref M1. MPC - Ref	0	N/A	Synthetic design rainfall event, Continuous 2-month period
S2. Static - GI R2. RBC - GI M2. MPC - GI	25, 50, 75, 100	GIs cost-efficiency priority	Synthetic design rainfall event, Historical event (21 August 2016), Continuous 2-month period[2]
S3. Static - GI - ACDE - 50 R3. RBC - GI - ACDE - 50 M3. MPC - GI - ACDE - 50	50	GIs in A, C, D, and E environmental priority sub-catchments	Synthetic design rainfall event, Historical event (21 August 2016)

[1] The GIs implementation percentage was calculated as compared to the distributed GIs scenario to eliminate all CSOs under the synthetic rainfall event and the MPC scheme, as described in the previous section
[2] The continuous 2-month period of rainfall data was only applied for the scenario where 100% of the optimized GIs distribution was implemented

3. Results and discussion

3.1. GIs distribution

For scenarios S2, R2 and M2, only bioretention swales and planters were distributed as their cost-efficiency priority was higher than disconnecting flat roofs and because available space for these types of GI was sufficient in each sub-catchment to meet the design objective. A high number of GIs was necessary to avoid CSO at each outfall as the design rainfall had a high total rainfall depth (19 mm). A total of 198.5 ha (1.3 % of the total case study area) needed to be converted in GIs, which was estimated to cost around 194 million of CAD $. The percentage of impervious area treated by GIs was also very high: 39% on average for all the study area. As a comparison, the City of New York aims to treat 10% of its impervious area by GIs in order to absorb the first 25 mm of rain by 2030, which is an ambitious but yet achievable goal (Wong and Montalto, 2020).

Fig. 5 presents the GI units distribution defined according to the uniform GIs distribution and the outfall environmental priority-based distribution scenarios (S2 and S3; R2 and R3; and M2 and M3). For the uniform GIs distribution based on cost-efficiency priority, the GI units were generally found in the largest sub-catchments as more space for GIs implementation was available at these locations.

3.2. CSO volume and frequency

The two-month period of rainfall data was used as input data in the simulation-optimisation model to assess the performance for 14 rainfall events. Fig. 6 presents total simulated CSO volume per rainfall event for the two RTC management strategies and the static control, alone or in combination with GIs distributed uniformly according to cost-efficiency priority. No CSO was simulated for the seventh smallest rainfall events

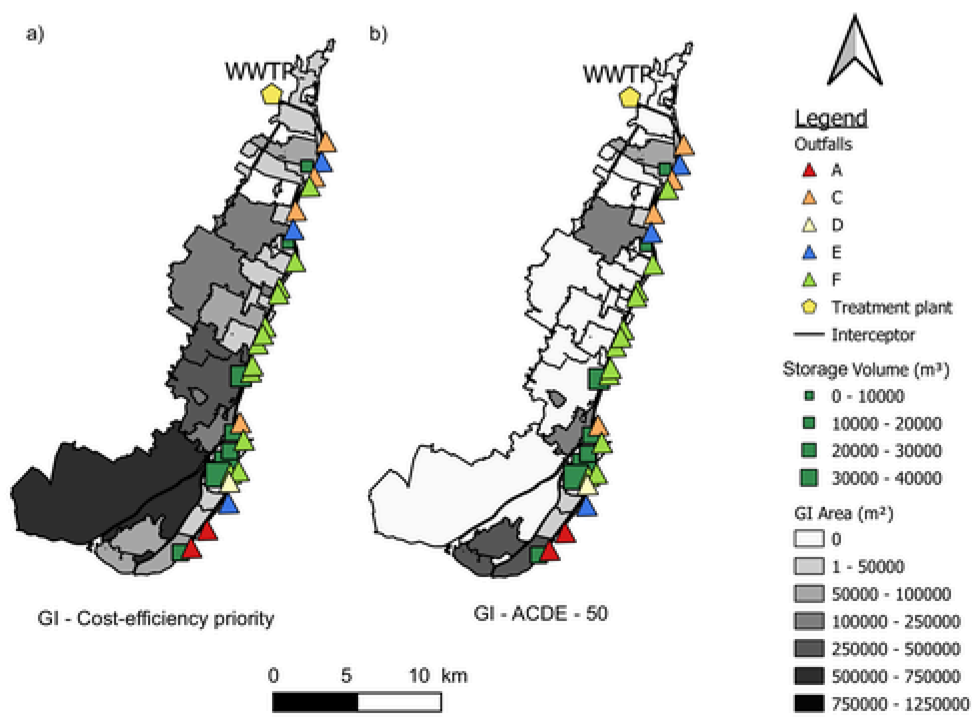

Fig. 5. GIs distribution maps according to a) cost-efficiency priority, b) environmental priority in ACDE sub-catchments for 50% of the total GI units distributed according to cost-efficiency priority

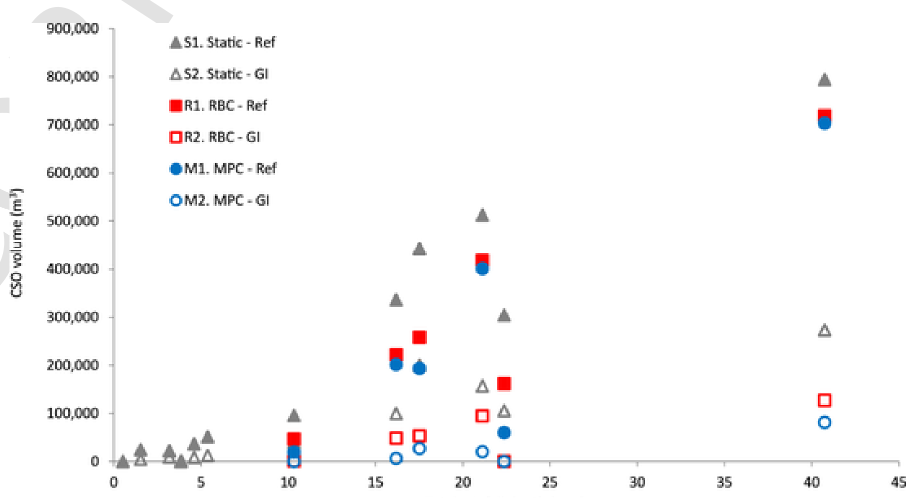

Fig. 6. Total CSO volume per rainfall event for the July-August 2016 period, omitting the August 16th event, for GIs distributed uniformly according to cost-efficiency priority

for both the MPC and RBC. The greatest rainfall event, which occurred on August 16th (duration of 12 hrs, 80-mm and estimated return period of 50 years), was not included in the graph to avoid distortion of the data. For this particular event, the simulated CSO volumes for the three types of control (static, RBC and MPC) were almost identical as the network was highly solicited. For this event, the implemented GI units provided a similar reduction in CSO volume of about 40% for all three types of control. This result agrees with Meneses et al. (2018) which also revealed no improvement due to RTC for CSO control when the network storage capacity was reached as opposed to rainfall events for which the available storage can be optimized.

For the remaining events, GIs reduced CSO volumes considerably, particularly for the MPC strategy. In fact, the average reduction in CSO volumes due to GIs varied from 65% for the static control case, to 82% in the case of RBC application and up to 92% for the MPC strategy. Hernes et al. (2020) also found that large-scale implementation of GIs permitted to avoid CSO events for almost all rainfall events.

Fig. 7 shows the total captured rate for all CSO events; this value was calculated as the ratio between the treated amount of water at the WWTP and the total sewer inflows (sum of runoff and dry weather flows). The presented values include all the simulated rainfall events during the July-August 2016 period except the August 16th event. As expected, the captured rate increased with the addition of GIs and as a more complex RTC scheme was applied. However, the variability followed an opposite trend, as the combination of GIs and RTC tended to improve the consistency of the percentage of total water inflow conveyed toward the WWTP. Captured rates for the RBC and MPC scenarios were similar, with total values of respectively 76 and 79% for the scenarios where no GIs were implemented, while the static case reached 67%. These total captured rates were increased to 96 and 98% for the scenarios where GIs were distributed over the study areas with RBC and MPC respectively, and it was 88% for the statically controlled case.

3.3. CSO environmental priority

The simulated CSO frequency classified according to the outfalls environmental priority categories is compiled in Fig. 8 for the 14 rainfall. The frequency value was increased by one unit when at least one outfall attached to a given environmental priority experienced a spill during a given rainfall event; however, if multiple CSO events occured at different outfalls having the same environmental priority, the frequency was

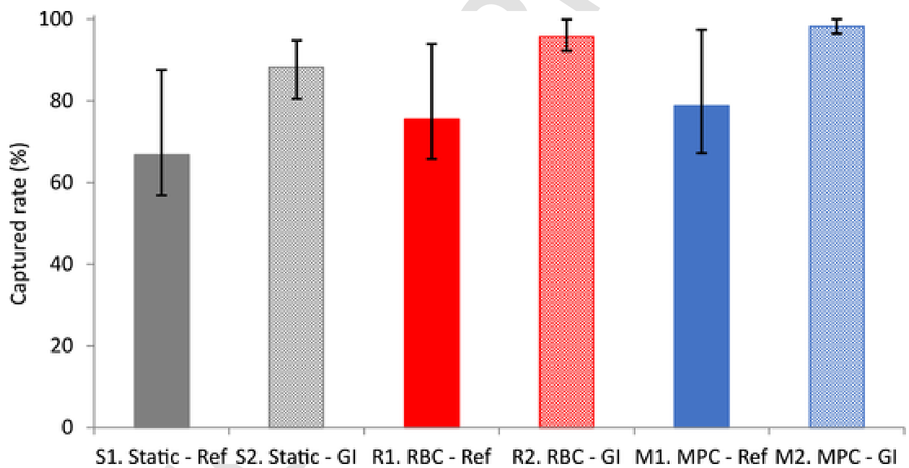

Fig. 7. Total captured rate percentage for the July-August 2016 period, omitting the August-16th event. Note: the error bars show the variability among the simulated events.

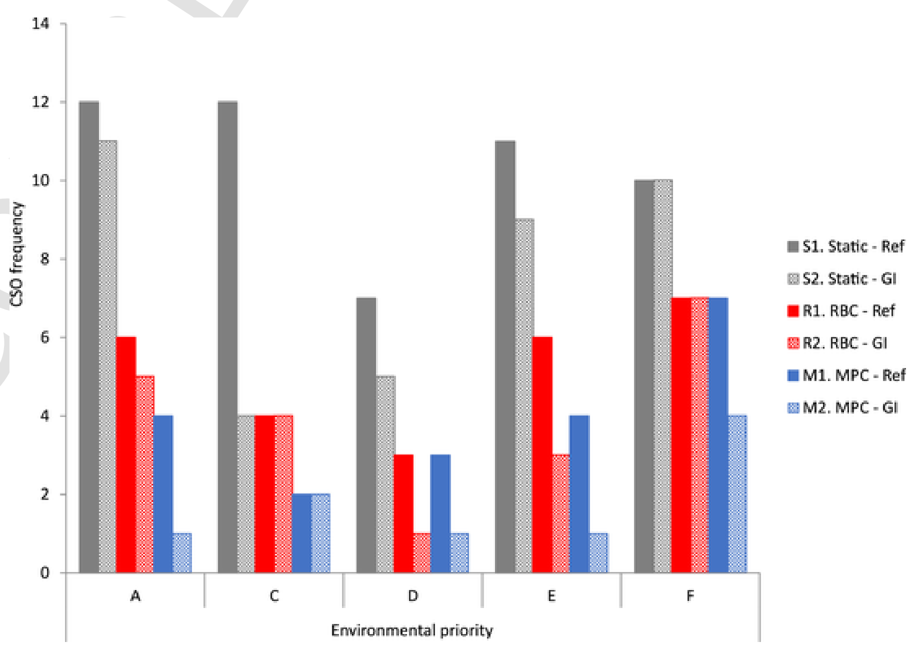

Fig. 8. Simulated CSO frequency per category of environmental priority for July-August 2016

still increased only by one unit. In this way, the overall respect of the environmental priority hierarchy can be compared on an event basis.

As expected, under a static control of the system, each category of environmental priority experienced more frequent CSO events, as compared to the RTC scenarios, and particularly for the outfalls having the highest environmental priorities (categories A and C). The addition of GIs lowered the CSO frequency considerably for the environmental priority C in the case of static control but, for the remaining categories, the impact of GIs was marginal or null. In the case of RBC, the addition of GIs reduced the CSO frequency slightly more than with the static control for about half of the environmental priority categories. In the case of MPC, GIs implementation clearly lowered CSO frequency in almost all categories.

It was not possible to reach a zero CSO frequency for the study period as the rainfall event of August 16^{th} generated important runoff volumes. However, under the MPC-GI scenario, the CSO frequency remained particularly low for all categories (varying from one to four). Meneses et al. (2018) also found that a more complex MPC strategy improved CSO control performance when considering environmental impacts as compared to RBC. However, it might be possible to improve the performance of RBC as suggested by Kroll (2019).

3.4. GIs gradual impact

The captured rates estimated for the various scenarios combining gradual GIs implementation levels and sewer control strategies under the two rainfall events are presented in Fig. 9a and 9b. Fig. 9c and 9d illustrate the GIs efficiency calculated as the ratio between reduced amount of CSO volume and runoff volume captured by GIs.

Captured rate and GIs efficiency had opposite trends as the number of GI units increased. While adding more GI units permitted to reduce a greater volume of CSO overall, runoff captured by the first GI units implemented translated more directly into CSO volume reduction. As the number of GI units increased, some of those units captured runoff that would not have necessarily overflowed, which explains a decreasing GIs efficiency. This phenomenon is even more accentuated in the case of the RBC scenario, as this type of management was less flexible than MPC for transferring the impact of GIs from one sub-catchment to another. In the case of static control, the sewer system was more easily saturated, and therefore, the GI units implemented can help reduce CSO more often as they reduced the inflows of water into the system. McGarity et al. (2017) also noticed a decreasing trend in GIs efficiency as the difference between CSO threshold and the hydrograph peak was gradually reduced due to increased GIs impact on runoff.

3.5. RTC performance for varying spatial distributions of GIs

GIs efficiency for reducing CSO volume was lastly evaluated for the heterogeneous distribution of GI units based on the outfall environmental priority and compared to the initial uniform distribution of GIs. Fig. 10 presents the results obtained for the two GIs distribution scenarios under the two rainfall events (synthetic design storm and historical event of August 16^{th} 2016) and considering a GIs implementation level of 50%.

As expected, distributing GIs according to the outfall environmental priority-based distribution rather than more uniformly over the study area reduced considerably the GIs efficiency under static control (up to 50% for the historical rainfall event), but has a more limited impact for the RTC-based strategies. When GIs are located in a limited number of sub-catchments, the number of GIs implemented in some areas could exceed the number required to mitigate CSO volumes at these locations, while GIs are lacking in the remaining sub-catchments. As opposed to the MPC strategy, static control and RBC do not permit to spatially adapt the use of storage. The RBC scenario still performed well compared to the static control case as most of the GIs are located in the upstream portion and its control strategy is to fill the interceptor from upstream to downstream. Nevertheless, GIs efficiency under the MPC strategy remains the highest for both GIs distribution scenarios.

3.6. Model limitations

The methodological framework implied simulation and optimisation model assumptions and limitations which can impact the modelling results. Limitations of the research work include:

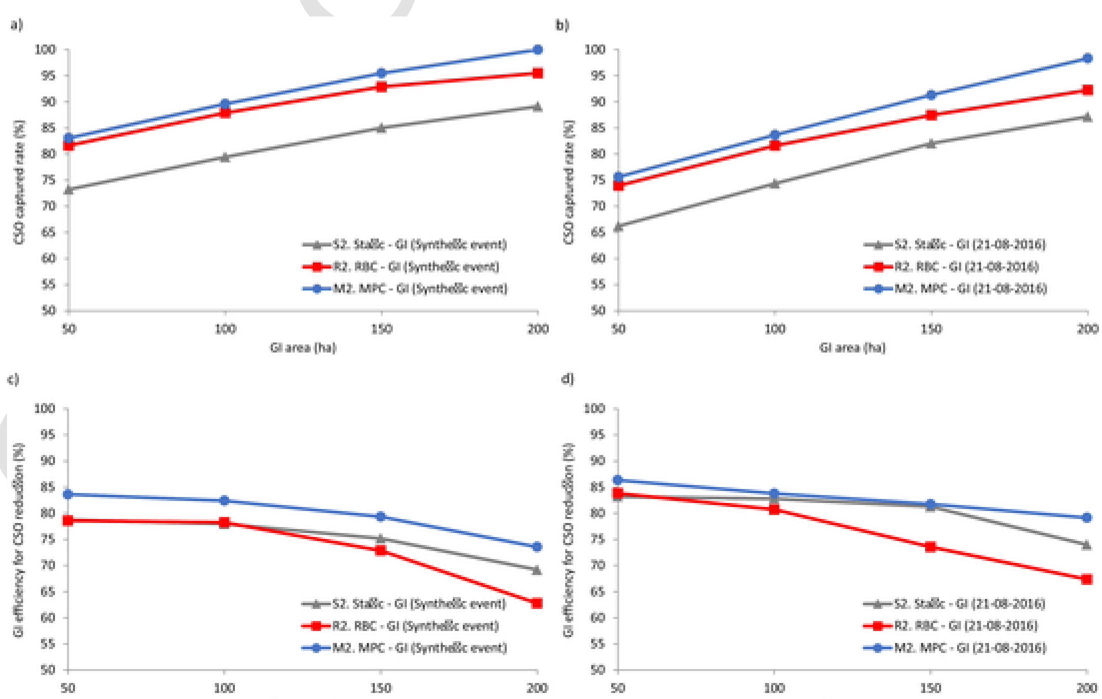

Fig. 9. Resulting captured rates for a) the design rainfall event, b) the historical rainfall event of August 21^{st} 2016, and the GIs efficiency for CSO volume reduction for c) the design rainfall event, and d) the historical rainfall event of August 21^{st} 2016 under varying GIs implementation levels and sewer system control types

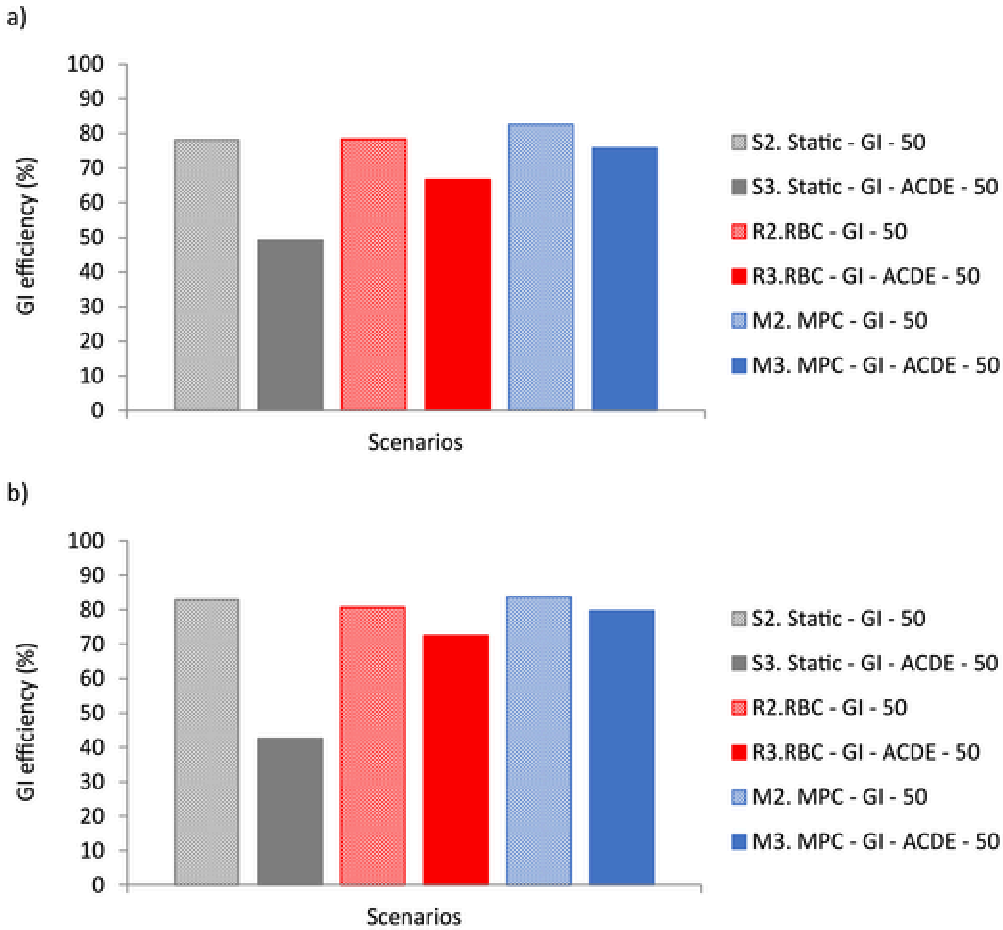

Fig. 10. GIs efficiency for CSO volume reduction according to GIs distribution and sewer system control type under the a) synthetic design storm of 19 mm, and b) historical rainfall event of August 16th 2016.

- MPC is applied with a perfect forecast of rainfall data while in real-world applications the uncertainty attached to the future state of the system could decrease the performance of MPC;
- The rules involved in the RBC application could be optimized for improving the performance of this RTC strategy and avoiding potential MPC efficacy overestimations;
- The spatial analysis for determining GI maximal implementation level in each sub-catchment could lead to an overestimation of available space for GIs. More restrictive and site-specific criteria could be applied for improving the spatial analysis accuracy (i.e. differentiate public vs. non-public area, determining potential treated surface based on topography rather than applying a treatment ratio per surface of implemented GI, etc.);
- The RTC scheme, which involved a one-way loop between SWMM and Csoft, could reduce the modelling result accuracy as compared to a two-way coupling strategy if the method is applied to more complex networks;
- The GIs distribution over the study area could be optimized based on CSO control performance instead of uniformly distributing GIs according to an implementation priority ranking.

4. Conclusion

This research aimed at evaluating the integrated impact of GIs and RTC for reducing CSO volume and frequency according to environmental priorities in the densely urbanized southern portion of the City of Montreal (Canada). More particularly, the study assessed the integration of GIs large-scale implementation with two RTC strategies (RBC and MPC) and static control, as well as according to various GIs distribution scenarios. Results showed that:

- When green infrastructures are distributed uniformly over the study area according to cost-efficiency criteria and spatial constraints, volumes of combined sewer overflows are considerably reduced, even under static control and even considering rainfall events of various magnitudes.
- Integration of model predictive control with green infrastructures leads to greater reduction of combined sewer overflows, both in terms of volume and frequency, while respecting the environmental priorities and leading to higher rates of runoff capture.
- Distributing green infrastructures only in specific sub-catchments instead than uniformly across the case study: i) restrain CSO volume reductions by half under static control; and ii) have only a slight impact on CSO volume reductions for both RTC strategies.

Results of this study demonstrated that GIs can have a considerable impact on CSO mitigation for all types of control, but that this impact can be improved with MPC, particularly for networks favorable to RTC. For instance, combined sewer systems which include an important number of control sites and where the receiving water course vulnerability to CSOs varies spatially, offer leeway to maximize the use of both gray and green infrastructures through RTC.

Future work should continue to apply MPC and other RTC strategies in integration with GIs to better understand how the two technologies can complement each other. The methodological framework could be improved by reviewing the GI simulation assumptions to be more site specific and to include a greater variety of GIs types. Assessment of the MPC performance could also consider the uncertainty in the input parameters (i.e. the impact of broken pumps, gate malfunctions or errors in weather forecasts). Finally, GIs spatial distribution could be optimized in a closed-loop simulation with MPC for improving the integration of both technologies.

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Uncited references

Joshi et al., 2021,

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

The data that has been used is confidential.

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Supplementary materials

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