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► To cite this version:

Marie-Ève Jean, Camille Morin, Juan Esteban Ossa Ossa, Sophie Duchesne, Geneviève Pelletier, et al.. Intégration de la gestion en temps réel et des infrastructures vertes comme mesures d'adaptation aux changements climatiques. Novatech 2023, Jul 2023, Lyon, France. hal-04176836

HAL Id: hal-04176836

<https://hal.science/hal-04176836v1>

Submitted on 3 Aug 2023

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Integration of real-time control and green infrastructure as climate change adaptation measures

Intégration du contrôle en temps réel et des infrastructures vertes comme mesures d'adaptation aux changements climatiques

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RÉSUMÉ

La distribution spatiale des infrastructures vertes (IV) a été optimisée pour réduire la fréquence des débordements d'égouts unitaires (DRU) d'un réseau d'égout situé dans la province de Québec (Canada). La performance de quatre alternatives de contrôle des DRU a ensuite été évaluée pour une période de simulation de neuf ans de données pluviométriques historiques. Cette performance a également été évaluée pour une série de précipitations augmentée de 20 %, représentative de l'impact potentiel du changement climatique (CC). Les quatre solutions de contrôle qui ont été analysées et comparées au scénario de base sont les IV: 1) seules, 2) avec des réservoirs de stockage, 3) avec le contrôle en temps réel (CTR) des vannes du réseau d'égout et 4) avec des réservoirs de stockage et du CTR. Les résultats ont aussi que l'intégration des IV avec le CTR (avec ou sans réservoirs) était la meilleure option pour atteindre l'objectif de fréquence des DRU et pour faire face aux impacts potentiels du CC. Ces scénarios ont permis de réduire le volume total des DRU de 95 % à 99 % pour la série de précipitations historiques et de 93 % à 96 % pour la série avec CC, par rapport au scénario de référence pour lequel aucune solution n'était implantée.

ABSTRACT

The spatial distribution of green infrastructures (GIs) was optimized to reduce the seasonal frequency of combined sewer overflows (CSOs) from a sewer system located in the Province of Quebec, Canada. The performance of four CSOs control alternatives was then evaluated for a nine-year simulation period of historical rainfall data. This performance was also evaluated for a 20%-increased rainfall series representative of potential climate change (CC) impact. The four control solutions that were analyzed and compared to the base case scenario were GIs: 1) alone, 2) with storage tanks, 3) with real time control (RTC) of the sewer network gates, and 4) with both storage tanks and RTC. The simulation results showed that the optimization of GI's spatial distribution alone: i) was insufficient to reach the CSO frequency target and ii) had a limited capacity to reduce the potential impact of CC on total CSO volumes. The 20%-increased rainfall intensities conditions increased considerably the CSO frequencies for all scenarios, but the scenario integrating RTC and GIs was the least impacted. The integration of GIs with RTC (with or without storage tanks) is considered the best option to achieve the CSO frequency target and to cope with potential CC impacts. These scenarios lowered total CSO volume by 95% to 99% under historical rainfall data and by 93% to 96% under increased rainfall intensities when compared to the reference scenario.

KEYWORDS

Genetic algorithm, Rule-based control, Source control measure, Sustainable urban drainage systems, Low impact development

1 INTRODUCTION

Climate change (CC) could increase the frequency of combined sewer overflows (CSOs) (Kilic et al. 2022; Mailhot et al. 2014), their volume (Gooré Bi et al., 2015, Kim et al., 2022), or both their volume and frequency (Dirckx et al., 2018) in many regions. Various studies have assessed the impact of applying different types of green infrastructures (GIs) on CSO volume, frequency, and sometimes water quality (Kim et al. 2022; Riechel et al., 2020). To improve CSO volume or frequency control, some studies suggested that a large number of GIs should be implemented (Jean et al., 2022). Many authors recommended that GIs should be implemented in combination with conventional grey infrastructures (i.e. storage tanks) (Bakhshipour et al., 2019; Fu et al. 2019) and/or real-time control (RTC) technologies at the GI site scale (Brasil et al., 2021; Xu et al., 2022) or RTC within the network (Jean et al., 2022; Jean et al., 2021). In this context, this research aims at evaluating how the individual or integrated implementation of distributed GIs, with RTC and grey infrastructure, can help reducing the impact of climate change on the volume and frequency of CSOs.

2 METHODOLOGY

2.1 Case study

The case study is a combined sewer system of about 181 ha located in the central southern region of the Province of Quebec in Canada, where land use is a mix of suburban residences and more dense urban neighbourhoods with industrial and commercial areas, which result in a weighted imperviousness of about 30%. The modelled network is schematized in Figure 1. Runoff is drained toward the

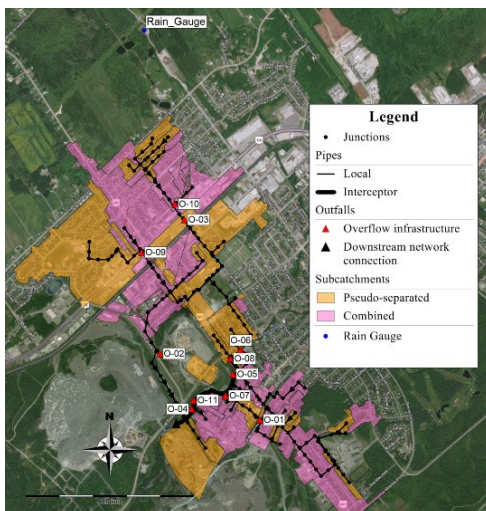


Figure 1. Case study area

interceptor, which is often saturated during rainfall events. To avoid excessive surcharge and flooding along the interceptor, a total of 10 regulators are located downstream of the overflow structures (O-01 to O-10) identified in Figure 1. These regulating devices are restricting flows and any excess water is spilled to nearby streams. As seen in Figure 1, there are three branches of the local pipe network where one or two outfalls are located downstream of another outfall (O-01, O-02, O-03, O-06, O-07, O-09 and O-10), while the remaining outfalls are located along the interceptor. Six outfalls (O-01 to O-06) are exceeding their seasonal (May to November) frequency target of seven spills, as established by the provincial legislation based on the environmental vulnerability of the receiving waters. Additional information on the model calibration and validation process can be found in Jean et al. (2018) whereas more details on the sub-area of the system used as the case study are available in Jean et al. (2021).

2.2 Rainfall data

Rainfall data at a 5-min interval was available at the nearby rain gauge station (located in Figure 1) for a nine-year period (from 2006 to 2015, omitting 2010 due to missing data). Rainfall data were used to define intensity-duration-frequency (IDF) curves and develop a design rainfall event based on the synthetic Chicago rainfall distribution of the same return period as the CSO frequency target of 7 CSOs/season, or a return period of 1/month, as suggested by Jean et al. (2018). The design rainfall event duration is 3 h, which corresponds to the time of concentration of the network. The design rainfall event was used as input to the simulation-optimisation tool in order to optimize the distribution of GIs and design of the other CSO mitigation measures. Subsequently, the developed scenarios were simulated with the nine-year continuous time series in order to compare the scenarios' performance over a range of different rainfall conditions. The CC potential impact on precipitation characteristics for the case study area has been assessed through different studies over the past decade. Based on these studies, a constant and uniform factor of 20% was applied to the entire nine-year period of rainfall data to simulate more extreme rainfall intensities and to compare scenarios performance in the average range of expected CC impact.

2.3 Optimization problem

Details about the optimization problem are given in Jean et al. (2021). It consists in upgrading an existing

combined sewer network for CSO mitigation by adding distributed GIs, implemented either alone or in integration with underground storage and/or rule-based RTC in the sewer network. Optimization variables include: 1) the number of distributed bioretention cells in each sub-catchment (i.e. GI units), 2) the number and volume of underground off-line storage tanks (i.e. grey infrastructure), and 3) the parametrization of RTC rules for dynamic sluice gates control using “if-then-else” rules. The values of these optimization variables are determined by minimizing the total cost associated with the implementation of GIs, storage tanks and RTC rules to achieve zero CSO volume at each outfall for the design rainfall event. The optimization problem was solved by the simulation-optimization tool Integrated Planning and Optimization Program (iPOP). This software allows optimizing the design values of any input parameter used in a hydrological/hydraulic SWMM 5.1 (Rossman, 2015) model representing a given sewer system by the evolutionary algorithm Parallel Swarm Oriented-Particle Swarm Optimization (PSO-PSO) (Gonsalves and Egashira, 2013).

2.4 Solution design

Bioretention cells were used to represent GI implementation over the case study area through the SWMM LID control module (Rossman and Huber, 2016). Bioretention cell’ area was fixed to 10 m² and the loading ratio was also constant and equal to 1:10. A spatial analysis was conducted on available land use data to establish the upper limit on the number of GI units which can be implemented. The choice of bioretention cell design parameter values was based on previous monitoring work, Canadian design guidelines (CSA 2018) and SWMM literature (Rossman and Huber 2016). Storage tanks were implemented downstream of each regulator to partially capture the diverted water and reduce CSO volumes. If the storage capacity of the storage tanks is overpassed, CSOs occur. Water stored in the tanks is pumped back to the sewer system when the capacity is restored. Storage tanks are simulated downstream of the six regulators where CSO frequency exceeds the prescribed frequency limit (O-01 to O-06). Even if six storage units were included in the SWMM model, the simulation-optimization tool can associate a volume of zero for a given storage tank, which indicates that the optimal solution would not require a storage tank for this specific location. RTC was implemented for nine regulators of the case-study area. RTC regulators are located upstream of the outfalls O-01 to O-09 in Figure 4.1. The RTC scheme simply applies a dynamic control of the regulator’s outflows through “if-then-else” rules using the control rule module of SWMM (Rossman, 2015), which triggers gate opening or closing based on water depth in the interceptor

2.5 Scenarios

Table 1 describes the 10 assessed scenarios. The base scenario is compared to four CSO mitigation measure strategies (scenarios 2 to 5) involving GIs alone or in integration with grey infrastructure and/or RTC. In these scenarios, the CSO mitigation measures were optimized using the design rainfall event with no overflow as a goal, which corresponds to the CSO control target of 7 CSOs/season. All these scenarios, in addition to the base situation, were then submitted to a 20%-increased rainfall time series (scenarios 6 to 10) to evaluate the resiliency of the developed CSO mitigation measures to more extreme rainfall conditions induced by CC.

Table 1. Description of the assessed scenarios

Scenario	Optimized distribution of GIs	Storage tanks	Rule-based control of network gates	Rainfall time series
1. Base				9 yrs. historical
2. Static-Grey-Green	X	X		9 yrs. historical
3. RTC-Grey-Green	X	X	X	9 yrs. historical
4. Static-Green	X			9 yrs. historical
5. RTC-Green	X		X	9 yrs. historical
6. Base+20				9 yrs.+20%
7. Static-Grey-Green+20	X	X		9 yrs.+20%
8. RTC-Grey-Green+20	X	X	X	9 yrs.+20%
9. Static-Green+20	X			9 yrs.+20%
10. RTC-Green+20	X		X	9 yrs.+20%

3 RESULTS

Figure 2 presents the number of outfalls for which the maximal simulated number of CSO events is above the prescribed limit of 7 CSOs/season for at least one season during the simulation period. As seen, with increased rainfall intensities, all scenarios have at least two or more outfalls for which the targeted CSO frequency is exceeded. Scenarios 3 and 5 involving RTC remain the ones with the lowest

number of outfalls exceeding the limit under both rainfall time series.

Table 2 presents the CSO volumes as simulated under the historical and the 20%-increased time series. All the CSOs control strategies provided considerable total CSO volume reductions. Scenarios “Static-Green” have the lowest total CSO

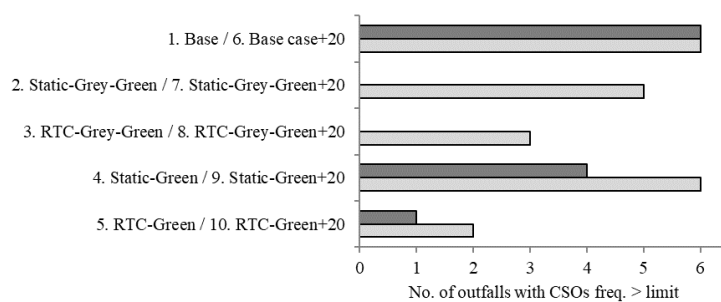


Figure 2. Number of outfalls for which the CSOs frequency is above 7 CSOs/season for at least one year (no bars = 0)

volume reductions as compared to the base case, particularly when considering the potential impact of CC. The scenarios combining RTC and GIs (“RTC-Green”) show the best performance in terms of total CSO volume reduction, even with increased precipitation due to CC, closely followed by the scenarios integrating RTC, GIs and storage (RTC-Grey-Green).

Table 2. Total CSO volume reduction per outfall

	Base case	Static-Grey-Green	RTC-Grey-Green	Static-Green	RTC-Green
	Total CSO volume	Total CSO volume reduction as compared to the base case			
Historical rainfall data series	1,632,662 m ³	93%	95%	89%	98%
20% increase in rainfall	1,921,004 m ³	88%	93%	77%	96%

4 CONCLUSION

This study showed that the integration of GIs with RTC (with or without storage tanks) is a robust solution to achieve CSO frequency targets and to cope with potential rainfall intensification due to CC.

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