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INTÉGRATION DU CONTRÔLE À LA SOURCE ET DU CONTRÔLE EN TEMPS RÉEL COMME MESURES DE RÉDUCTION DES DÉBORDEMENTS DE RÉSEAUX D’ÉGOUT UNITAIRES

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« L’homme se découvre quand il se mesure avec l’obstacle. » Antoine de Saint-Exupéry

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RÉSUMÉ

L’impact croissant des problèmes environnementaux, économiques et sociaux causés par les débordements de réseaux d'égout unitaires (DRU) requiert l’action des municipalités pour établir une gestion plus durable des eaux pluviales. En réponse à ce besoin, la thèse doctorale a évalué comment l’optimisation intégrée de l’implantation de solutions de contrôle à la source (SCS) à l'échelle du bassin versant et du contrôle en temps réel (CTR) du réseau de drainage est applicable comme solution de contrôle des DRU.

Le processus de recherche a impliqué deux études de cas et le couplage de deux logiciels d'optimisation avec des modèles de simulations hydrologiques et hydrauliques. Dans le premier cas, l'optimisation des SCS est effectuée avec l’*Integrated Planning and Optimization Program* (iPOP), qui permet de minimiser les coûts totaux des solutions en déterminant l'emplacement optimal des SCS, le volume des réservoirs et la définition des règles locales pour l’application du CTR. Dans le second cas, la distribution spatiale des SCS est determinée par le biais d'un processus itératif impliquant le logiciel *Control of sewer overflow SOFTware* (Csoft) et l'application du CTR par modélisation prédictive. Cet outil d'optimisation peut également être appliqué pour réguler les débits en réseau en fonction d’un CTR de type local réactif basé sur des règles ou selon une gestion statique.

Pour les deux études de cas, les SCS ont été distribuées en se basant sur une pluie de conception et les performances des scénarios ont été évaluées par une simulation continue des données pluviométriques. Les résultats ont démontré que les SCS implantées seules peuvent réduire considérablement les volumes des DRU (65 à 89% selon le cas d’étude), mais que leur impact sur la fréquence des DRU est plus limité et que le maintien de leur performance face à une intensification des événements de pluie est également faible. L’intégration optimisée du CTR et de la distribution spatiale des SCS sur le territoire permet de pallier ces lacunes, en plus d’être l’option la moins coûteuse (50% de réduction des coûts par rapport aux solutions qui n’incluent pas de SCS). Toutefois, l’intégration d’ouvrages de rétention (infrastructures grises) en plus du CTR et des SCS s’avère recommandée, car cette combinaison de tous les types de solutions analysées est une option presque aussi rentable que l’alternative sans infrastructure grise, en plus d’être plus performante lorsque les incertitudes sur les coûts et les données de conception sont considérées. De plus, l'application de la stratégie de contrôle prédictive plutôt que le CTR local réactif permet de réduire davantage la fréquence des DRU et d'améliorer le respect des priorités environnementales associées aux ouvrages de débordement, lorsqu'applicable, menant à une fréquence de 5 à 10 fois plus petite en comparaison aux autres modes de contrôle pour les ouvrages dont la priorité environnementale est la plus élevée.

Mots-clés :

Contrôle en temps réel

Solution de contrôle à la source

Infrastructures vertes

Modèle de contrôle prédictif

Contrôle basé sur des règles

Simulation hydrologique et hydraulique

Systèmes de drainage urbain durables

Gestion durable des eaux pluviales

Développement à faible impact

Simulation de précipitations en continu

ABSTRACT

The increasing environmental, economic and social threats caused by combined sewer overflows (CSO) require municipal actions toward a more sustainable stormwater management. As a response, the doctoral thesis evaluated how the integrated optimization of the implementation of source control solutions (SCS) at the catchment scale and real-time control (RTC) of the drainage network is applicable for CSO control.

The research involved two case studies and the coupling of two optimization softwares with a hydrological and hydraulic simulation model. In the first case, the optimization of SCS is performed with the Integrated Planning and Optimization Program (iPOP), which minimizes the total solution costs by determining the optimal location of SCS, storage tank volumes, and local rules definition for RTC. In the second case, SCS spatial distribution is assessed through an iterative process involving the Control of sewer overflow SOFTware (Csoft) and the application of Model Predictive Control (MPC). This optimization tool can also be applied to regulate flows in the network based on RTC local reactive rules or static management.

For both case studies, SCS were distributed based on a design rainfall event and the scenarios' performance were evaluated through continuous simulation of rainfall data. Results demonstrated that SCS alone can considerably reduce CSO volumes (65 to 89% according to the case study), but their impact on CSO frequency is more limited and the maintenance of their performance when facing an intensification of rainfall events is also weak. The optimized integration of the RTC and spatial distribution of SCS on the territory makes it possible to overcome these shortcomings, in addition to being the least expensive option (50% cost reduction as compared to solutions where no SCS is implemented). However, the integration of underground storage (grey infrastructure) in addition to RTC and SCS is recommended, since the combination of all the types of solutions analyzed is an option almost as cost-effective as the alternative without grey infrastructure, in addition to performing better when considering the uncertainties on the costs and design parameters. Moreover, it was found that applying the model predictive control strategy rather than rule-based RTC further lowered the CSO event frequency and improved the fulfilment of outfall environmental priorities, when applicable, conducting to a CSO frequency 5 to 10 times lower compared to other control methods for outfalls with the highest environmental priority.

Keywords :

Real-time control

Source control solution

Green infrastructure

Model predictive control

Rule-based control

Hydrological and hydraulic simulation

Sustainable urban drainage systems

Sustainable stormwater management

Low impact development

Continuous rainfall simulation

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AAM : Attestations d’assainissement municipales

CC : Changements climatiques / Climate Change

CSO: Combined Sewer Overflows

Csoft : Control of sewer overflow SOFTware

CTR : Contrôle en temps réel

DRU : Débordements de réseaux d'égout unitaires

GI : Green Infrastructure

iPOP : Integrated Planning and Optimization Program

IV : Infrastructures verte

LID : Low Impact Development

MPC : Model Predictive Control

PSO-PSO : Parallel Swarm Oriented-Particle Swarm Optimization

RBC : Rules-Based Control

RCP : Representative Concentration Pathways

RTC : Real-Time Control

SCM : Source Control Measures

SCS : Solutions de contrôle à la source / Source Control Solutions

SUDs : Sustainable Urban Drainage Systems

SWMM : Storm Water Management Model

1 INTRODUCTION

1.1 Mise en contexte

Dans de nombreuses villes du monde, les eaux usées sanitaires et les eaux de ruissellement sont interceptées et transportées dans un même réseau de conduites vers une station de traitement des eaux usées (Salvadore et al., 2015). Tels que conçus, la capacité de ces systèmes peut être dépassée lors d'événements de pluie ou de fonte des neiges, entraînant le rejet d'eaux non traitées dans les milieux récepteurs. Les débordements de réseaux d'égout unitaires (DRU) qui en résultent sont l'une des principales causes de dégradation de la qualité de l'eau des cours d'eau urbains (Bi et al., 2015; Passerat et al., 2011). Dans la province de Québec (Canada), par exemple, entre 50 000 à 60 000 DRU se produisent typiquement chaque année. De ce nombre, environ 85% sont causés par la pluie ou la fonte des neiges tandis que le reste s'explique par des défaillances du système ou des travaux (MELCC, 2022), ce qui contribue à la dégradation de la vie aquatique et de l'environnement, à la contamination des sources d'approvisionnement en eau potable et à la restriction des usages récréotouristiques (Madoux-Humery et al., 2015). Alors que les pratiques actuelles pour les nouveaux réseaux consistent à évacuer les eaux pluviales et sanitaires dans des canalisations séparées (c'est-à-dire par la mise en place d'un réseau d'eaux pluviales et d'un réseau sanitaire distinct), de nombreuses villes sont encore confrontées à des problèmes reliés aux DRU, car leur ancien réseau d'égout unitaire ne peut pas ou ne peut être que partiellement séparé en raison de contraintes économiques ou techniques (Lund et al., 2019).

En réponse aux impacts des DRU sur l'environnement, les gouvernements ont mis en place une réglementation pour limiter la fréquence, le volume et/ou la charge polluante des DRU. Au Québec, depuis 2014, tous les projets de prolongement d'égout doivent être accompagnés de mesures compensatoires pour éviter d'augmenter la fréquence saisonnière des DRU (MDDELCC, 2014), conformément à la Stratégie pancanadienne de gestion des effluents d'eaux usées municipales (CCME, 2009). Par ailleurs, depuis 2020, le gouvernement émet des attestations d'assainissement municipales (AAM), qui sanctionnent les dépassements de fréquence des DRU par rapport aux limites définies dans les AAM. Le coût estimé pour la mise aux normes des réseaux d'égout unitaires non conformes à l'échelle de la province est estimé à 6 milliards de dollars (Lavallée, 2016). Atteindre les objectifs de réduction des DRU présente des défis supplémentaires pour les municipalités de petites et moyennes tailles, car leurs ressources techniques et financières sont limitées. De plus, la complexité de cet enjeu est exacerbée par les impacts des changements climatiques (CC) et du développement urbain (Alves et al., 2016; García et al., 2015; Semadeni-Davies et al., 2008; Yazdanfar et al., 2015).

Dans ce contexte, les pratiques traditionnelles de gestion des eaux pluviales doivent s'orienter selon une stratégie plus durable afin de mieux faire face à l'augmentation du ruissellement urbain et des impacts des DRU sur l'environnement, et ce, à un coût minimal. La gestion durable des eaux pluviales consiste à réduire les volumes de ruissellement, à réduire et à retarder les débits de pointe et à diminuer les charges polluantes. Par rapport aux pratiques traditionnelles, qui se concentraient sur la collecte et le transport rapide des eaux de ruissellement à travers des infrastructures souterraines, la gestion durable des eaux pluviales vise à reproduire les conditions hydrologiques qui prévalaient avant l'urbanisation du territoire en essayant de minimiser le ruissellement par la mise en place de mesures localisées le plus près possible de sa source de production (CERIU, 2016). Cette approche est essentielle à la qualité et à la viabilité des ressources en eau, à la rentabilité des infrastructures municipales et au bien-être de la communauté (Boucher, 2010). De plus, l'idée de mettre en œuvre des solutions durables de contrôle des eaux pluviales a été largement promue pour atténuer les perturbations induites dans le cycle hydrologique naturel par l'imperméabilisation accrue des sols en milieu urbain, tout en contribuant à la réalisation des objectifs de développement durable des Nations Unies établis pour l'agenda 2030 (Pennino et al., 2016).

Compte tenu du large éventail de solutions possibles pour le contrôle des eaux pluviales et des DRU (allant des approches plus conventionnelles aux pratiques plus innovantes et durables), déterminer une méthode d'analyse et de conception de solutions permettant de limiter la fréquence annuelle ou le volume des DRU au moindre coût entraîne de nombreux questionnements. Ces questions sont accentuées par la spécificité de chaque réseau de drainage et par la variabilité des événements pluviométriques qui peuvent être pris en considération lors de la conception de solutions. Pour y répondre, cette recherche doctorale vise à réduire le volume et la fréquence des DRU par l'intégration de différents types de solutions basées sur l'optimisation des coûts et des performances.

La suite de cette introduction présente une revue générale de la littérature concernant les approches de contrôle des DRU qui ont été évaluées dans la thèse de doctorat et les lacunes scientifiques liées à leur application. Par la suite, l'objectif principal et les sous-objectifs qui en découlent, définissant le cadre méthodologique du projet de recherche, sont présentés. Finalement, la structure résultante de la thèse est détaillée en fournissant un bref aperçu de chaque article scientifique ayant contribué à la diffusion des résultats obtenus.

1.2 Revue de littérature générale

La revue de littérature s’attarde aux enjeux liés à l’application de deux types de solutions de contrôle des DRU qui ont récemment démontré leur potentiel pour contrôler efficacement les DRU tout en favorisant une gestion durable des eaux pluviales, soit les solutions de contrôle à la source (SCS) et celles impliquant le contrôle en temps réel (CTR) du réseau de drainage (Piro et al., 2019; Quaranta et al., 2022). Les sections suivantes font la description et présentent l’état de l’art sur l’application des SCS et du CTR comme mesures individuelles et complémentaires de réduction des DRU. De plus, comme l’analyse par modélisation des performances attendues de ces solutions demande une attention particulière sur le choix des intrants pluviométriques, une description des données pluviométriques appliquées à l’analyse des DRU est ensuite présentée. Les récentes études sur l’impact des CC et les sources d'incertitudes liées aux études de modélisation appliquées au contrôle des DRU sont aussi détaillées pour mieux comprendre la portée des bénéfices et les limites potentielles de l’application de ces solutions. Enfin, les besoins de recherche identifiés par la revue de littérature sont résumés.

1.2.1 Solutions de contrôle à la source

Parmi les solutions existantes pour contrôler le ruissellement urbain et les impacts des DRU sur l'environnement, les solutions de contrôle à la source (SCS), telles que les infrastructures vertes (IV), contrastent avec les solutions traditionnelles impliquant, par exemple, la construction d’infrastructures grises comme des ouvrages de rétention souterrains (Simard et al., 2022). Diverses terminologies sont ainsi associées aux SCS, notamment les IV, les pratiques de développement à faible impact (*Low Impact Development*), les systèmes de drainage urbain durable (*Sustainable urban drainage systems*), etc., mais tous ces termes signifient généralement que l’eau pluviale est gérée le plus près possible de la source de ruissellement, avec l'objectif de reproduire les conditions hydrologiques qui prévalaient avant l’urbanisation (Fletcher et al., 2015). Ces solutions incluent toute infrastructure favorisant l’infiltration, la rétention temporaire et/ou les pertes par évapotranspiration du ruissellement urbain. La Figure 1.1 illustre ces processus dans le cas d’un système de biorétention typique. Quelques autres exemples de tels systèmes sont les jardins de pluie, les noues végétalisées, les pavés perméables et les toits verts. Les SCS, et les IV en particulier, offrent également de nombreux avantages complémentaires tels que la réduction de l'impact des îlots de chaleur, l'augmentation de la résilience face aux changements climatiques, la diminution de la pollution atmosphérique et le soutien à la biodiversité (Watkin et al., 2019).

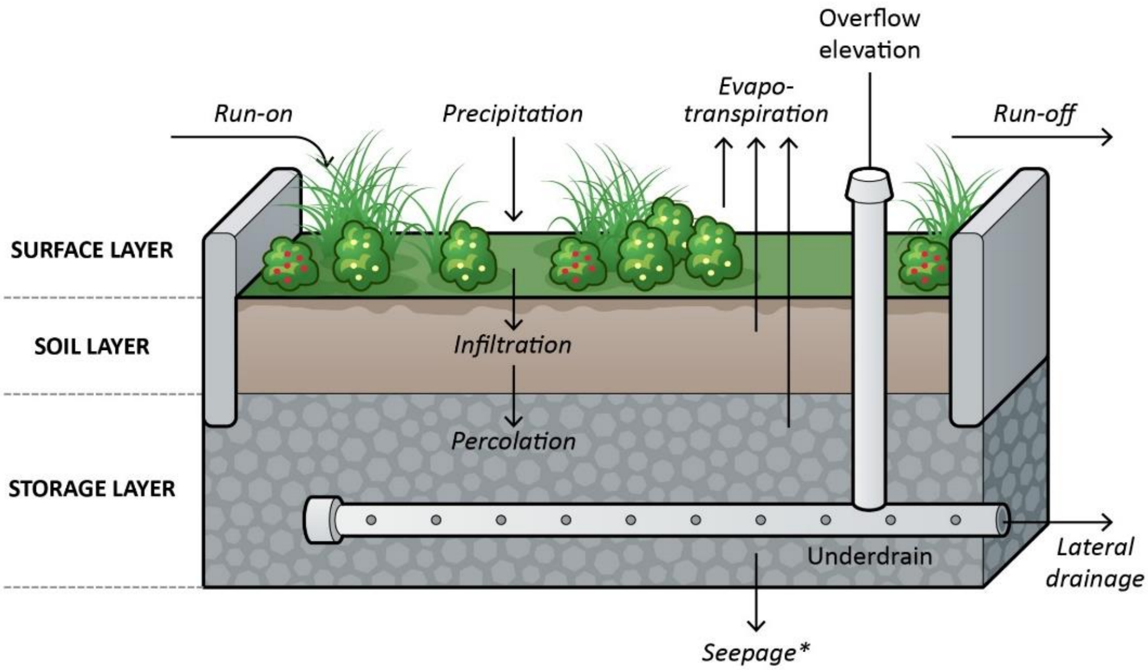

Figure 1.1 Processus hydrologiques dans les systèmes de biorétention (tirée de CHI, 2019)

Différentes études ont évalué le potentiel d'application d'un grand nombre de SCS à l'échelle du bassin versant pour réduire l'impact des DRU. En particulier, de nombreuses recherches ont démontré des réductions de volume de DRU (Autixier et al., 2014; McGarity et al., 2017; Radinja et al., 2018; Smullen et al., 2008; Torres et al., 2018) ou à la fois des réductions de volume et de fréquence des DRU (Lucas et Sample, 2015; Stovin et al., 2013) grâce aux SCS. Alors que les avantages des SCS pour l'atténuation des DRU ont également été détaillés en termes de coût d'implantation par rapport aux solutions de rétention conventionnelles (telles que le stockage souterrain) par plusieurs études (Joshi et al., 2021; Liao et al., 2015; Montalto et al., 2007; Quaranta et al., 2022), certains auteurs ont, au contraire, souligné la nécessité de combiner les SCS avec des solutions de rétention centralisées pour améliorer le rapport coût-efficacité des solutions mises en place (Alves et al., 2016; Dong et al., 2017; Jato-Espino et al. 2022) ou pour atteindre des objectifs de contrôle des DRU spécifiques (Fu et al., 2019; Liao et al., 2015; Tavakol-Davani et al., 2015).

D'une part, les conditions locales (c'est-à-dire les propriétés du sol, la topographie, le climat, l'élévation de la nappe phréatique, etc.) ainsi que les caractéristiques des précipitations (volume, durée et rapport durée/pointe des événements pluvieux) peuvent grandement affecter les performances des SCS (Eckart et al., 2017). L'étude de Hernes et al. (2020) a toutefois démontré que la réduction des volumes des DRU varie selon le type de SCS mis en œuvre et l'ampleur des événements de pluies; les aires de biorétention sont plus performantes lors d'événements pluvieux générant de grands volumes de ruissellement, tandis que les toits verts et les aires de biorétention présentent des performances similaires lors d'événements pluvieux générant de plus petits volumes de ruissellement. De même, Ma et al. (2022) ont étudié comment la distribution spatiale des SCS et leur interconnectivité influencent les performances du système selon une gamme de critères incluant les débits de pointe et les volumes débordés. D'autre part, le climat continental froid et humide qui caractérise la province de Québec ne devrait pas compromettre la performance des technologies de contrôle à la source, qui permettent une réduction élevée du ruissellement et des polluants, et ce, même durant les périodes les plus froides de l'année (Géhéniau et al., 2014; Khan et al., 2012; Pineau et al., 2021).

Dans le cas de la gestion du ruissellement pour les réseaux séparatifs, divers auteurs ont appliqué des techniques d'optimisation pour quantifier et distribuer les SCS à l'échelle du bassin de drainage. Par exemple, certaines études se sont concentrées sur la minimisation du coût de conception des SCS pour atteindre des objectifs fixes de contrôle du ruissellement et de concentration en polluants (Cheng et al., 2009; Liu et al., 2017a; Seo et al., 2017; Xu et al., 2017) ou bien sur l'analyse du rapport coût-efficacité des SCS selon une conception et une distribution optimale des SCS (Cano et al., 2016; Giacomoni et Joseph, 2017; Jia et al., 2015; Jia et al., 2012; Lee et al., 2012).

En particulier, Cano et al. (2016) ont trouvé que les SCS implantées dans la partie amont et plus pentue du bassin versant étaient plus performantes en termes de réduction des volumes de ruissellement, tandis que, au contraire, les travaux de Giacomoni et Joseph (2017) montrent que les SCS placées à l'aval étaient plus efficaces pour réduire les débits de pointe et le risque d'inondation à l'aval. Ainsi, selon l'objectif visé par l'implantation des SCS, la distribution spatiale optimale de ces ouvrages peut varier.

Dans les cas d'application de technique d'optimisation multiobjectifs, l'étude d'Eckart (2015) a démontré que certains compromis étaient obligatoires entre les différents objectifs tels que la réduction du volume ruissellement et du débit de pointe, car différentes combinaisons de SCS entraînaient différentes réponses hydrologiques. En général, il a été constaté qu'il en coûte plus cher de réduire les volumes globaux de ruissellement que les débits de pointe ou tout autre objectif de contrôle de la qualité de l'eau avec les SCS (Jia et al., 2015, Liu et al., 2016).

Moins fréquentes, certaines études concernaient l'optimisation des SCS dans les réseaux d'égout unitaires afin d'atténuer, au moindre coût possible, soit les débits de pointe (Sebti et al., 2016), soit les volumes de DRU (Fu et al., 2019; Joshi et al., 2021; Torres et al., 2018). Les résultats de ces études montrent généralement que la localisation des SCS sur le territoire peut avoir un impact sur la réduction des DRU.

1.2.2 Solutions de contrôle en temps réel

Le CTR appliqué au système de drainage urbain agit sur le ruissellement une fois qu'il a atteint le réseau d'égout; soit en limitant les débits de pointe sortant d'une portion du réseau jusqu'à ce que la capacité de la station d'épuration devienne disponible, en détournant les débits vers des parties moins sollicitées du réseau d'égout, en contrôlant l'accumulation et la vidange d'ouvrages de rétention, ou en distribuant les débits selon les capacités résiduelles de traitement disponibles dans le cas où il y aurait plus d'une station de traitement (Cheung et al., 2005). De cette manière, le CTR contribue à améliorer les performances des systèmes de drainage, puisqu'il permet d'exploiter au maximum la capacité de transport, de stockage et de traitement du réseau en fonction des conditions hydrauliques changeant dans le temps et l'espace.

La mise en œuvre du CTR implique un contrôle dynamique des infrastructures du réseau basé sur des mesures en temps réel et, parfois, sur des données prévisionnelles, telles que l'intensité des précipitations, les niveaux d'eau ou les débits dans les conduites. Les stratégies de CTR peuvent être développées en s'appuyant sur divers algorithmes de contrôle incluant des méthodes heuristiques comme celles se basant sur l'application de règles de contrôle (comme des règles de type « si alors sinon »). Ce type de règles est souvent défini sur la base de l'expérience et des connaissances disponibles sur le système et son comportement. Le CTR basé sur des règles a été largement utilisé puisqu'il implique un processus de décision simple (Garcia et al., 2015). Par exemple, une stratégie couramment utilisée est l'algorithme de remplissage uniforme des réservoirs distribués dans le réseau, qui permet d'utiliser le volume de stockage disponible de manière uniforme (Kroll et al., 2018). Alternativement, le CTR peut être déployé en se basant sur des approches plus complexes basées sur des algorithmes d'optimisation. Ces derniers impliquent de minimiser une fonction objectif en fonction de divers paramètres du réseau tout en respectant un ensemble des contraintes (García et al., 2015; Lund et al., 2018).

Parmi les algorithmes d’optimisation pouvant s’intégrer au CTR, les algorithmes de programmation linéaire et de programmation quadratique sont applicables pour résoudre des problèmes d’optimisation convexes, linéaires et ayant un optimum global. La résolution de ces problèmes garantit une solution optimale, mais nécessite de simplifier la formulation du problème, ce qui peut entraîner une perte de justesse par rapport à la réalité des systèmes de drainage urbain (Lund et al., 2018).

Alternativement, la complexité des systèmes de drainage urbain, dont les contraintes physiques sont souvent non linéaires, peut requérir l'utilisation d'autres types d’algorithmes d'optimisation qui ne sont pas contraints par les mêmes hypothèses sur le problème d’optimisation à résoudre (Schütze et al., 2001). Par exemple, la programmation quadratique est linéaire dans ses contraintes, mais non linéaire (quadratique) dans sa fonction objectif. La programmation linéaire mixte a des contraintes et fonction objectif linéaires, mais utilise des variables continues et discrètes qui permettent de linéariser par morceaux des fonctions non linéaires. D’autres algorithmes d’optimisation permettent de résoudre des problèmes dont la fonction objectif ou les contraintes sont non linéaires en appliquant des méthodes comme la programmation non linéaire. Toutefois, l’application de ces algorithmes peut converger vers un optimum local plutôt que global et entraîner une augmentation des temps de calculs (Lund et al., 2018)

Les algorithmes d’optimisation globaux tels que les algorithmes évolutionnaires (*evolutionary algortihms* – EA) ou génétiques (*genetic algorithms* – GA) peuvent aussi s’appliquer même dans le cas de fonctions objectif non continues. À chaque itération, ces algorithmes imitent les principes évolutifs en utilisant une population représentant un ensemble de solutions possibles au problème d’optimisation. Cette recherche évolutive permet de trouver plusieurs solutions sous-optimales et de résoudre des problèmes d'optimisation multi-objectifs (Garcia et al., 2015).

D’un point de vue opérationnel, les boucles de contrôle impliquées dans le déploiement du CTR sont schématisées à la Figure 1.2. Les capteurs (‘*sensor’*) comprennent les outils de mesure qui suivent en continu les variables d’état du système, comme les niveaux d'eau, les débits, les paramètres de qualité de l'eau, etc. Les actionneurs (‘*actuator’*) sont des équipements télécommandés qui activent les éléments (‘*process’*) à optimiser, tels que l’opération de pompes, de vannes, de déversoirs, de répartiteurs de débit ou de dispositifs de dosage de produits chimiques et d'aération, dans le cas de l'optimisation du traitement des eaux usées. Les contrôleurs (‘*controller’*) permettent d'ajuster les actionneurs en fonction des consignes optimisées (‘*set point’*) à chaque pas de temps. Les consignes correspondent à la valeur souhaitée pour le processus en cours d'optimisation par la stratégie de CTR. Par exemple, dans le cas d'un réservoir géré pour minimiser les DRU, la consigne pourrait être le niveau d'eau auquel le réservoir doit être maintenu afin de garder de l'espace disponible pour le ruissellement à venir tout en minimisant les risques de débordement en aval. Deux boucles interviennent dans le processus de réglage de l'actionneur commandé par le contrôleur : l'anticipation (mesure de perturbation – '*disturbances* ») et la rétroaction (mesure de l'état du processus – '*process measurement*'). Les perturbations peuvent inclure la pluie, ou tout intrant qui viendra modifier l'état du système. Dans le cas de l'anticipation, l'écart du procédé par rapport à la valeur de consigne est anticipé et, dans le cas de la rétroaction, l'écart réel mesuré est compensé par le contrôleur afin de maintenir la consigne (Schütze et al., 2004).

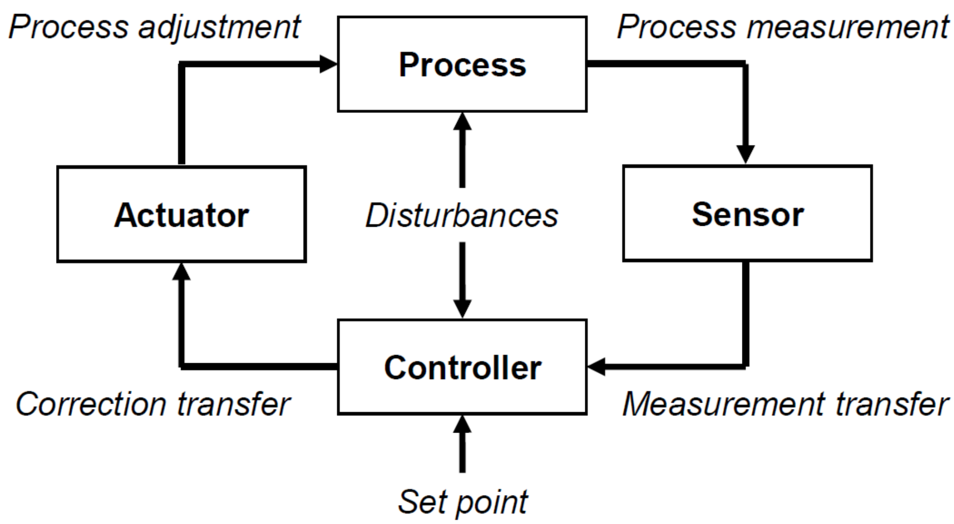

Figure 1.2 Boucle d'application opérationnelle du contrôle en temps réel (adaptée de Creaco et al., 2019)

La stratégie de contrôle peut se déployer pour atteindre des objectifs de performance locaux, lorsque les consignes de contrôle sont déterminées localement pour une seule partie du système sans tenir compte des performances globales du réseau (par exemple, lorsque la consigne d'ouverture d'une vanne dépend du niveau d'eau mesuré à l'aval de cette dernière).

Alternativement, plusieurs points de contrôle opérés en temps réel peuvent être gérés conjointement afin que les consignes qui leurs sont appliquées tiennent compte des performances globales du système.

D'un point de vue théorique, il a aussi été démontré que le CTR pouvait être appliqué pour réaliser un contrôle coordonné de différents sous-systèmes (Kroll, 2019). Le CTR de type intégré permettrait ainsi de coupler la gestion du réseau d'égout, de la station d'épuration et/ou des cours d'eau récepteurs et éventuellement d'autres systèmes comme la station de production d'eau potable.

Le déploiement du CTR peut également être de type réactif, si seules les mesures en temps réel de l'état actuel du système sont considérées comme variables d'entrée, ou prédictif, si des données prévisionnelles sont également incluses comme des données de précipitations, de débits, de niveaux ou encore des variables liées à la qualité (Shishegar et al., 2018). Autant le CTR de type réactif que prédictif peut s’effectuer sur la base d’un contrôle basé sur des règles qu’un contrôle impliquant un algorithme d’optimisation, couplé ou non avec l’utilisation d’un modèle. À titre d’exemple, l’étude de Xu et al. (2020b) a fait la comparaison des performances de la gestion de réservoirs d’eau de pluie selon différentes stratégies de CTR basé sur des règles incluant des prévisions météorologiques.

Le contrôle prédictif par modélisation (*Model predictive control*-MPC) est une forme avancée de CTR qui permet de déterminer la meilleure stratégie de gestion globale du réseau pour chaque contrôleur du système selon des données prédictives en utilisant un modèle orienté pour le contrôle du réseau et un algorithme d’optimisation (Garcia et al., 2015).

En particulier, le MPC tient compte d’un horizon défilant, ce qui signifie que le l'optimisation des consignes est répétée de manière récursive selon un horizon temporel fini. À chaque pas de temps, les actions de contrôle actuelles et futures sont déterminées en résolvant le problème d'optimisation pour cet horizon de temps fini sur la base d'informations prévisionnelles et mesurées ainsi que des résultats simulés selon les conditions actuelles et celles de la période d'évaluation restante. La période d'évaluation peut différer de l'horizon de contrôle (séquence des consignes optimales) et de l’horizon de prédiction (horizon de temps pour laquelle des données prédictives sont estimées), comme illustré à la Figure 1.3. La séquence optimale des réglages (*trajectory of control action*) futurs des actionneurs est déterminée à chaque pas de temps, mais seule la première séquence, associée au pas de temps courant, est appliquée, avant que la boucle ne soit à nouveau répétée. Cependant, dans une analyse hors ligne où l'information prévisionnelle (prévision de précipitations) utilisée serait parfaite, la boucle de simulation-optimisation du contrôle prédictif par modélisation pourrait n’être effectuée qu'une seule fois si la taille du problème d’optimisation le permettait, car la séquence optimale des réglages actuels et futurs des actionneurs de contrôle peut être théoriquement déterminée à partir d'une seule résolution du problème d’optimisation. En termes de durée, l'horizon de contrôle doit être plus long que le temps de concentration du bassin versant contrôlé afin d'assurer l'optimalité de la stratégie de CTR.

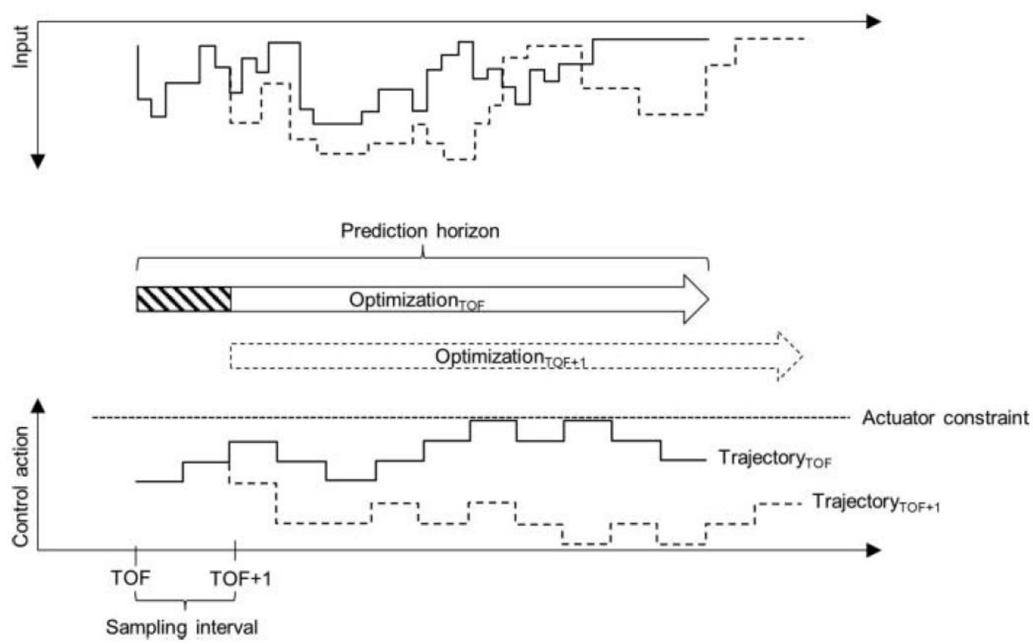

Figure 1.3 Séquence de consignes optimales selon un horizon de contrôle défilant associé au contrôle en temps réel prédictif par modélisation (tirée de Lund et al., 2018)

Note: TOF = *Time of forecast* (temps de la prédiction)

Plusieurs études ont montré que le CTR appliqué aux réseaux d'égout unitaires est une solution rentable pour la réduction des volumes et de la fréquence des DRU (van Daal et al., 2017), tant du point de vue des applications dans des réseaux réels (Entem et al., 1998; Fuchs et Beeneken, 2005; Pleau et al., 2005; Seggelke et al., 2013) que des applications théoriques (Dirckx et al., 2011; Joseph-Duran et al., 2018; Kroll, 2019; Nielsen et al., 2010; Wang et al., 2021). Le CTR peut, en effet, améliorer la gestion des DRU, en particulier dans les systèmes complexes où la capacité de stockage et la vulnérabilité aux débordements varient spatialement (Schütze et al., 2008). Entre autres, les réductions de volume de DRU rapportées dans la revue de la littérature récemment menée par van der Werf et al. (2022) varient entre 13 % et 91 % selon des stratégies d'application de CTR qui incluent des règles heuristiques locales simples et l'application de MPC plus complexe.

Dans le cas de systèmes urbains complexes couvrant un grand territoire avec plusieurs ouvrages de débordement et une variété de points de contrôle et de bassins de stockage pouvant être soumis à des pluies spatialement hétérogènes, une stratégie de type MPC conduit théoriquement à de meilleures performances en termes de réduction de volumes de DRU par rapport au contrôle heuristique, car le MPC permet une plus grande adaptabilité à des contraintes et à des objectifs d'optimisation multiples (Lund et al., 2018; Meneses et al., 2018).

Il a également été constaté que les caractéristiques des événements pluvieux (Lund et al., 2018, van Daal et al., 2017), la précision des données pluviométriques utilisées dans l'analyse des performances du CTR (Löwe et al., 2016, Lund et al., 2018; van Daal et al., 2017), les différents algorithmes d'optimisation employés pour résoudre le problème d'optimisation (Zimmer et al., 2015) et la sélection des points de contrôle pour l'implantation du CTR (Eulogi et al., 2022; Maiolo et al., 2020; Meneses et al., 2018) ont tous un impact direct sur les performances du CTR en matière d'atténuation des DRU.

Enfin, en plus des avantages rapportés du CTR pour l'atténuation des DRU, il a été constaté que des économies potentielles en termes de coût d'investissement et d'atténuation du débit de pointe sont possibles en optimisant l'emplacement des différentes infrastructures grises liées à l'implantation du CTR (comme les stations de pompage et les bassins de rétention) (Shishegar et al., 2018, Yeh et Labadie, 1997).

1.2.3 Intégration des solutions de contrôle de source et du contrôle en temps réel

Les travaux de recherche mentionnés précédemment soutiennent que les SCS sont des solutions complémentaires aux infrastructures grises, permettant de réduire le ruissellement urbain et les DRU, en particulier lors d'événements pluvieux fréquents. Cependant, seulement quelques rares exemples existent concernant l'option prometteuse de combiner les SCS au CTR (avec ou sans infrastructures grises traditionnelles), et il en existe encore moins sur l'intégration de ces différentes solutions lors de la conception pour améliorer les performances des réseaux de drainage à moindre coût tout en améliorant la gestion durable des eaux pluviales.

En effet, les performances des SCS ont été évaluées dans un contexte d'intégration du CTR, lorsque celui-ci : 1) est appliqué de façon locale et décentralisée permettant de contrôler dynamiquement les SCS (par exemple, les débits sortant des SCS) directement sur le site d'implantation (Xu et al., 2020a) à partir de mesures en temps réel (comme les niveaux d'eau, les hauteurs de précipitations, etc.) ; 2) prend la forme d'un contrôle des infrastructures du système d'égout (c'est-à-dire par application du CTR aux stations de pompage, aux vannes ou aux régulateurs) afin d'augmenter la capacité de rétention du réseau (Garcia et al., 2015).

D'une part, l'application du CTR pour le contrôle des SCS sur un site permet d'améliorer les performances des SCS en termes de réduction des volumes et de la fréquence des DRU (Lucas et Sample, 2015; Lund et al., 2019; Oberascher et al., 2021a), même lors d'événements pluvieux consécutifs (Lewellyn et al., 2018). Certains auteurs ont également comparé les performances de différentes stratégies de contrôle locales et globales, parfois combinées à des prévisions météorologiques (Oberascher et al., 2021b; Xu et al., 2022; Xu et al., 2020b). Xu et al. (2020a) ont suggéré d'appliquer des stratégies de CTR plus complexes (comme le MPC) pour améliorer le fonctionnement des SCS.

D’autre part, moins d'applications concernant l'intégration des SCS avec l'application traditionnelle du CTR du réseau de drainage sont citées dans la littérature. Ce n'est que récemment que ces deux types de solutions ont été appliqués pour le contrôle des DRU. Par exemple, Altobelli et al. (2020) ont comparé les performances de la combinaison du CTR avec différents types de SCS ainsi qu’en combinaison avec l’implantation de réservoirs de stockage pour réduire les volumes de DRU et les rejets de polluants. Leur étude n’a toutefois pas permis de faire une conception intégrée des différents types de solutions, qui étaient plutôt combinées les unes aux autres sans tenir compte de leur influence mutuelle. Frey et al. (2013) ont développé un outil logiciel d'aide à la décision visant à trouver la combinaison la plus rentable de SCS avec des infrastructures grises et l’application du CTR pour la ville de South Bend (Indiana, États-Unis). Leur méthodologie n’a toutefois pas permis d’optimiser de façon intégrée l’implantation du CTR et des SCS. Suivant l’approche de ces auteurs, les SCS ont d'abord été distribuées de manière optimale à l’échelle du bassin versant en fonction de leur rapport coût-efficacité, puis la taille des infrastructures grises a été optimisée en appliquant une gestion de type CTR. Frehman et al. (2002) ont également étudié l'impact combiné des solutions de CTR et les SCS pour la réduction du volume des DRU et de la charge polluante à Bochum (Allemagne). Ces auteurs n'ont pas optimisé la distribution des SCS, mais ont plutôt comparé l’impact de différents facteurs de réduction de l’imperméabilité des bassins versants. L'étude de Bilodeau (2018) a également mis en évidence le potentiel de combiner l'application de la gestion par CTR avec des SCS. Cette étude n'a toutefois considéré que des réseaux d'égout séparés. Enfin, Lund et al. (2019) ont proposé un concept novateur pour le contrôle des apports d'eaux pluviales à l’amont des réseaux unitaires qui combinait des SCS et la redirection des eaux de ruissellement des événements pluvieux intenses vers des infrastructures vertes multifonctionnelles (c'est-à-dire des parcs et d'autres espaces publics). Ainsi, une rétention temporaire par CTR était réalisée. Les résultats de simulation de leur étude ont montré une réduction du nombre et du volume des événements de DRU, mais n'ont pas permis d’étudier comment l'optimisation de la conception des SCS pourrait s’intégrer à plus grande échelle pour améliorer le contrôle des DRU.

1.2.4 Sélection des données pluviométriques

Les caractéristiques des précipitations ont un impact sur la fréquence, le volume et la durée des DRU (Andrés-Doménech et al., 2010). Par exemple, Mailhot et al. (2015) ont évalué l'applicabilité d'un modèle simple basé sur un seuil de hauteur de précipitation journalière pouvant être associé à l'occurrence de DRU pour un ouvrage donné. Thorndahl et Willems (2008) ont appliqué une méthode semblable, mais qui considère d'autres caractéristiques des événements pluvieux, en plus de la hauteur de précipitation.

Yu et al. (2018) ont poussé l'analyse encore plus loin en estimant le volume de DRU en fonction de la hauteur et de l'intensité maximale des événements de pluie. Cette étude est basée sur les travaux de Yu et al. (2013), qui ont constaté une corrélation entre le volume de DRU et la hauteur totale de précipitation de l'événement pluvieux associé. Ainsi, ces auteurs ont rapporté que les précipitations de faibles hauteurs totales et celles ayant des intensités maximales élevées avaient de fortes corrélations avec le volume total des DRU, tandis que les précipitations ayant des valeurs de hauteurs totales et d'intensités maximales modérées permettaient plus difficilement de prévoir les volumes des DRU. Pour ce dernier cas, leur étude a indiqué que les caractéristiques du réseau et de l'ouvrage de débordement devaient être prises en compte plus spécifiquement pour déterminer les volumes de DRU.

Schroeder et al. (2011) ont, quant à eux, comparé l'applicabilité de ces trois mêmes caractéristiques des événements pluviométriques (hauteur totale, durée et intensité maximale horaire de la pluie) afin de déterminer quelle était la caractéristique la mieux corrélée avec les volumes totaux et la fréquence des DRU. Bien que la hauteur totale de pluie donnait les meilleurs résultats en termes d'estimation des volumes débordés, aucune caractéristique ne permettait de déterminer la fréquence des DRU.

L'étude menée par Verwom et al. (2001) a traité de l'impact de la variabilité spatiale des précipitations sur les volumes de DRU et a montré que l'utilisation d'une pluie uniforme sur de grands territoires couverts par plusieurs stations pluviométriques menait à une surestimation des volumes de débordement comparativement à l'utilisation d'une pluie distribuée de manière non uniforme et représentative de la variabilité spatiale des précipitations.

Montalto et al. (2007) ont essayé de faire le pont entre la combinaison de la durée et de la hauteur de pluie seuil provoquant un débordement et la façon dont ces valeurs pouvaient être liées au coefficient de ruissellement composite du bassin de drainage. Les auteurs ont ensuite estimé comment l'implantation de solutions de contrôle du ruissellement pouvait se traduire par une diminution du coefficient de ruissellement à l'amont des ouvrages de débordement; une réduction du ruissellement par l'ajout de SCS permet au système de ne pas déborder lors de certaines pluies qui auraient pu causer un DRU avant l'ajout de SCS sur le territoire. Ainsi, ils ont pu établir une relation entre le niveau d'implantation de divers types de SCS et la réduction escomptée des CSO par l'effet de ces SCS sur le ruissellement.

Gooré Bi et al. (2015a) ont plutôt étudié la corrélation entre les caractéristiques des pluies (durée, intensité maximale sur 5 minutes, hauteur totale tombée et temps sec antécédent) et certains paramètres de qualité de l'eau associés aux DRU (comme la concentration moyenne de divers polluants par événement de débordement); ils ont constaté que le temps sec antécédent et la hauteur totale des précipitations étaient les paramètres les mieux corrélés avec ces caractéristiques.

En complément à ces études, différents auteurs se sont penchés sur le type de données pluviométriques à utiliser dans des modèles hydrauliques et hydrologiques pour simuler les DRU. Dans le cas d'événements synthétiques, Vaes et al. (2002a) ont montré que la prise en compte de la relation entre l'intensité, la durée et la fréquence pour toutes les durées de l'événement synthétique (comme dans le cas de la pluie de type Chicago) (Keifer et Chu, 1957) permet de ne pas sous-estimer les volumes de DRU. Similairement, Calabrò (2004) a comparé l'impact des DRU sur les cours d'eau récepteurs, en termes de quantité et de qualité de l'eau (masse totale de matières en suspension rejetée, concentration massique maximale de matières en suspension et débit de pointe) pour différentes pluies synthétiques. Ces travaux ont permis de déterminer que les pluies synthétiques ayant une durée similaire au temps de concentration du bassin versant et ayant une distribution temporelle de type triangulaire ou de Chicago sont celles causant le plus d'impact au milieu récepteur par rapport aux pluies d'autres durées ou de forme rectangulaire.

Certaines études ont comparé les performances de différentes pluies synthétiques (Fontanazza et al., 2011; Vaes et al., 2001) ou une sélection de pluies historiques (Shütze et al., 2004) pour estimer les caractéristiques d'événements historiques des DRU en vue de déterminer quelles simplifications permettaient une meilleure estimation. Selon Vaes et al. (2002b), dans le cas des grands bassins de drainage où les événements pluviométriques peuvent se déplacer dans la même direction que l'écoulement principal du réseau de drainage, la détermination des événements pluviométriques synthétiques de conception doit aussi tenir compte d'une analyse statistique des pluies historiques et de différents mouvements des fronts de précipitation.

Plusieurs auteurs ont aussi noté l'importance d'utiliser la simulation en continu pour représenter plus adéquatement les impacts cumulatifs des événements pluvieux successifs en termes d'humidité du sol, de charge polluante, de niveaux de stockage, de capacité restante des infrastructures de contrôle des eaux pluviales et d'autres variables ayant un impact sur les DRU (Abdellatif et al., 2014; Hvitved-Jacobsen et al., 1988; Mailhot et al., 2015; Vaes et al., 2001).

Malgré ces avancées, peu d'information s'avère disponible sur le type de données pluviométriques qui devrait être utilisé dans l'analyse des DRU pour une sélection et une conception optimale des solutions de contrôle des DRU.

1.2.5 Impact potentiel des changements climatiques

L'impact des CC sur le réchauffement planétaire global et sur d'autres variables climatiques est un enjeu incontestable auquel doivent faire face les sociétés d'aujourd'hui si elles veulent pouvoir continuer à assurer un niveau de performance et de risque acceptable de leurs infrastructures urbaines (Mailhot et al., 2008). Dans ce contexte, l'impact potentiel des CC sur les caractéristiques des précipitations présente un intérêt particulier dans l'analyse des performances attendues pour les ouvrages de débordements et pour le développement de critères de conception des solutions de contrôle des DRU.

La littérature montre que les modèles climatiques mondiaux actuels ont une capacité limitée à simuler correctement les précipitations extrêmes à une échelle locale et intra-journalière (par exemple, les précipitations horaires). Les modèles présentent encore des limitations quant à la prise en compte des processus convectifs qui sont normalement associés aux orages de forte intensité et de courte durée (Westra et al., 2014; Fowler et al., 2021). Il devient ainsi difficile de faire des projections fiables sur les changements des précipitations extrêmes locales et intra-journalières dérivées de ces modèles, alors que c'est à cette échelle temporelle et spatiale que l'impact des CC s'avère pertinent aux applications urbaines (temps de réponse très court et phénomène très localisé spatialement). Les avancées informatiques et les améliorations récentes des modèles simulant la convection suggèrent que les incertitudes actuelles sont sur la voie d'être résolues (Fowler et al., 2021).

La complexité des phénomènes météorologiques associés aux CC est aussi accentuée par l'effet des rétroactions climatiques qui peuvent avoir un effet soit stabilisateur ou amplificateur de certaines causes du réchauffement climatique. Ainsi, compte tenu de l'incertitude attachée aux prévisions des émissions futures de gaz à effet de serre, les impacts des CC doivent être examinés à la lumière de différents scénarios.

Les résultats les plus récents pour le Québec projettent de fortes augmentations des précipitations extrêmes, notamment pour les durées les plus courtes et pour les périodes de retour les plus longues (c'est-à-dire pour les événements les plus rares et extrêmes) (Mailhot et al., 2021).

Plus particulièrement, les résultats de Singh et al. (2022) projettent, pour le Canada, une augmentation moyenne de 3 à 17 % des précipitations annuelles et une augmentation moyenne de 9 % à 36 % des précipitations extrêmes (somme des hauteurs de précipitations quotidiennes au cours desquelles les précipitations dépassent le 99e centile des précipitations quotidiennes de la période de référence). Ces pourcentages varient selon la région et l'augmentation des températures moyennes annuelles depuis la période préindustrielle (augmentation de 1,5°C à 4°C) considérant le scénario des voies de concentration représentatives d'un forçage radiatif de 8,5 W/m^2 (RCP8.5 ; Meinshausen et al., 2011). Similairement, l'étude de Zhang et al. (2019) projette une augmentation médiane de 7,1 à 22,5 % des précipitations annuelles moyennes dans le cas du Québec, selon différents scénarios de forçage radiatif (RCP2.6 et RCP8.5).

L'impact des CC sur les hauteurs de précipitations pour différentes durées et périodes de retour a aussi été largement étudié. En ce qui concerne les maximums annuels des précipitations journalières (c.-à-d. le plus grand total de pluie enregistré une année donnée en une journée), Mailhot et al. (2012) ont estimé qu'ils augmenteront de 9,5 à 18,6 % pour des périodes de retour variant entre 2 et 50 ans pour le Canada selon les scénarios RCP4.5 et RCP8.5. Zhang et al. (2019) estiment, pour leur part, que l'augmentation sera de l'ordre de 6,0 à 26,5 % pour des périodes de retour de 10 à 50 ans pour le Québec. Innocenti et al. (2019), sur la base d'un autre ensemble de simulations climatiques, projettent des augmentations variant de 4,5 à 42,5 % pour les précipitations de durées 1, 2, 6, 12, 24, 48 et 72 h et périodes de retour 2, 25 et 100 ans selon le scénario RCP8.5. Enfin, Mailhot et al. (2018) ont estimé, en combinant les résultats de simulations de plusieurs modèles climatiques, des augmentations de 10 à 26 % pour des durées de 1, 2, 6, 12 et 24 h et des périodes de retour de 2, 5, 10 et 25 ans, toujours selon le scénario RCP8.5.

Concernant l'impact des CC sur les DRU, les auteurs s'attendent généralement à une augmentation de la fréquence des DRU (Kilic et al., 2022; Mailhot et al., 2014), du volume des DRU (Gooré Bi et al., 2015b; Kim et al., 2022), ou du volume et de la fréquence des DRU (Dirckx et al., 2018; Nie et al., 2009; Nilsen et al., 2011; Semadeni-Davies et al., 2008). Alternativement, d'autres travaux suggèrent des variations sur une base mensuelle (Fortier et al., 2014) ou une tendance à la baisse lorsque des stratégies de développement urbain durables sont appliquées (Abdellatif et al., 2015, Mahaut et Adrieu, 2019).

En réponse à la menace climatique, de nombreuses études se sont attardées au potentiel des SCS à fournir au réseau urbain un certain niveau de résilience en termes de contrôle des fréquences et des volumes de DRU (Bolduc et al., 2011; Lucas et Sample, 2015; Semadeni-Davies et al., 2008), de réduction des volumes de ruissellement (Dagenais et al., 2014; Zahmatkesh et al., 2014), de réduction des débits de pointe (Sebti et al., 2016; Wang et al., 2016) et de contrôle des inondations (Karamouz et al., 2013). Il a également été constaté que l'efficacité des SCS était limitée aux événements pluvieux les plus fréquents (Eckart, 2015), qui représentent la plus grande proportion du nombre annuel d'événements pluvieux, alors que les SCS seraient insuffisantes, comme mesures individuelles, pour faire face à l'impact des CC en termes de contrôle des volumes de DRU (Mailhot et al., 2014).

De même, dans le cas du CTR, il a été constaté que cette approche ne permettait pas d'éliminer complètement l'impact potentiel des CC, mais qu'elle pouvait tout de même contribuer à atténuer considérablement les volumes de DRU (Dirckx et al., 2018) ou à réduire les débits de pointe à l'exutoire des bassins de drainage (Bilodeau et al., 2018). Li et Burian (2022) ont tout de même constaté que le CTR avait un plus gros impact sur la performance du système lorsqu'il était soumis à des événements pluvieux de plus grande envergure, comme dans le cas de périodes de retour supérieures à 10 ans.

1.2.6 Incertitudes dans les applications de modélisation

Les études se basant sur une approche par modélisation hydrologique et hydraulique comprennent un certain niveau d'incertitude inhérent au développement et à l'application d'hypothèses simplificatrices associées : 1) aux modèles utilisés pour simuler les bassins versants urbanisés (Fletcher et al., 2013; Salvadore et al., 2015) ainsi que pour la simulation de solutions de contrôle à la source en particulier (Lucas et Sample, 2015) et 2) aux outils d'application du CTR (Kroll, 2019; Shishegar et al., 2018; van Daal et al., 2017).

D'autres sources d'incertitudes sont associées à la quantification tant de la nature que de l'impact des DRU sur les milieux récepteurs, particulièrement en ce qui concerne la caractérisation qualitative des débordements. Ces limitations découlent, entre autres, des biais associés aux modèles hydrodynamiques et des difficultés opérationnelles et financières d'appliquer une surveillance continue à grande échelle (Dirckx et al. 2022).

De plus, plusieurs incertitudes découlent des difficultés à évaluer avec précision la gamme des coûts et des bénéfices des solutions analysées (Ashley et al., 2018) et à bien représenter l'efficacité décroissante des performances due à l'âge des infrastructures et/ou à leur manque d'entretien (Liu et al., 2017b).

En ce qui concerne les incertitudes sur les données d'entrée des modèles, et notamment celles associées aux précipitations, elles peuvent avoir un impact sur le choix des solutions (Damodaram et al., 2010) et sur l'évaluation de leurs performances (Qin et al., 2013; Tavakol-Davani, 2016).

Enfin, le vaste choix des méthodes et des résultats rapportés dans l'évaluation de l'impact des CC sur les caractéristiques des précipitations en milieu urbain conduit à une plus grande variabilité quant aux impacts potentiels que peuvent avoir les CC sur certains paramètres de modélisation (Willems et al., 2012).

Compte tenu de toutes ces sources d'incertitudes, il reste difficile de choisir l'approche la plus rentable pour atteindre les objectifs réglementaires de contrôle des DRU.

1.3 Conclusions de la revue de la littérature

Dans un contexte de développement de solutions plus performantes applicables au contrôle des DRU, les conclusions suivantes peuvent être tirées de la revue de la littérature :

- De nombreuses sources d'incertitude sont liées à l'analyse des DRU et celles-ci doivent être identifiées afin de mieux évaluer les performances des solutions de contrôle des DRU puisque peu d'information existe sur l'impact possible de ces incertitudes sur la performance et la recherche de solutions.
- Les études de modélisation doivent inclure plusieurs sources de données pluviométriques dont, idéalement, des séries temporelles en continu (afin de représenter une variété d'événements pluviométriques), car la performance des solutions évaluées est tributaire de la qualité des données pluviométriques utilisées.
- La robustesse des solutions proposées pour l'atténuation des DRUs doit être évaluée en fonction de divers paramètres d'entrée pour tenir compte de l'impact potentiel des CC et d'autres incertitudes attachées aux performances réelles.
- Il s'avère difficile de généraliser les résultats décrits précédemment, puisque la spécificité de chaque réseau de drainage étudié amène parfois des contradictions entre les conclusions de diverses études.

La revue de la littérature a aussi conduit à l’identification des lacunes scientifiques suivantes :

- L'optimisation de tous les aspects attachés à la conception des SCS a été étudiée (c'est-à-dire le type d’ouvrage, le nombre et l'emplacement sur le territoire), mais il existe encore un nombre limité d'études qui ont inclus ces aspects dans leur schéma d'optimisation avec pour finalité la réduction des DRU.
- Seuls quelques travaux de recherche ont analysé l'impact combiné du CTR et des SCS, et encore moins ont permis d’intégrer ces deux types de solutions au niveau de la conception, alors que de nombreuses études ont mis en évidence le potentiel de combiner les SCS aux infrastructures grises traditionnelles, ainsi que les bénéfices additionnels apportés par le CTR par rapport à une gestion statique du réseau en termes de volume et de fréquence des DRU.
- Peu d’information existe pour orienter la sélection des données pluviométriques (événements de pluie synthétiques, historiques ou simulation en continu) à appliquer comme intrants de simulation pour la conception de solutions de contrôle des DRU.

1.4 Structure de la thèse

Cette section présente les objectifs du projet doctoral ainsi que la façon dont chaque article y répond.

1.4.1 Objectifs de recherche

L'objectif principal de la recherche est d'évaluer le potentiel d'application de l'optimisation intégrée du CTR du réseau de drainage et de l'implantation de SCS à l'échelle du bassin versant comme solution de contrôle des DRU, puis de déterminer les conditions d'application qui maximisent les performances de cette intégration en matière de réduction des DRU. D'une part, l'implantation des SCS permet d'agir sur les débits de ruissellement en amont du réseau de drainage et, d'autre part, les décisions du CTR sont fortement influencées par la distribution temporelle et spatiale des débits drainés vers le réseau d'égout unitaire. Il est donc supposé, comme hypothèse de recherche, qu'une meilleure compréhension des modes d'application et des performances attendues de l'intégration du CTR et des SCS comme mesures de contrôle des DRU permettrait d'améliorer le développement de solutions innovantes, durables et rentables pour le contrôle des DRU. Comme les ouvrages de rétention traditionnels peuvent aussi s'intégrer de manière complémentaire aux SCS ou au CTR, ce type de solution est également pris en compte dans la définition des sous-objectifs de la thèse doctorale. Ainsi, l'objectif principal se traduit par deux objectifs spécifiques, soit :

1. Identifier les données pluviométriques à utiliser comme données d'entrée pour l'optimisation de la conception de solutions de contrôle des DRU.

2. Étudier comment l'intégration de l'optimisation du CTR, des SCS et des ouvrages de rétention à l'échelle du bassin versant a un impact sur la fréquence et les volumes de DRU par rapport à leur application individuelle, en considérant :

    2.1 le coût nécessaire pour atteindre les fréquences cibles de DRU ;

    2.2 diverses stratégies d'application du CTR ;

    2.3 diverses stratégies de distribution spatiale des SCS ;

    2.4 divers apports pluviométriques pour tenir compte de l'impact des CC.

La Figure 1.4 présente comment la conception des SCS, du CTR et des ouvrages de rétention peut être intégrée de manière optimisée.

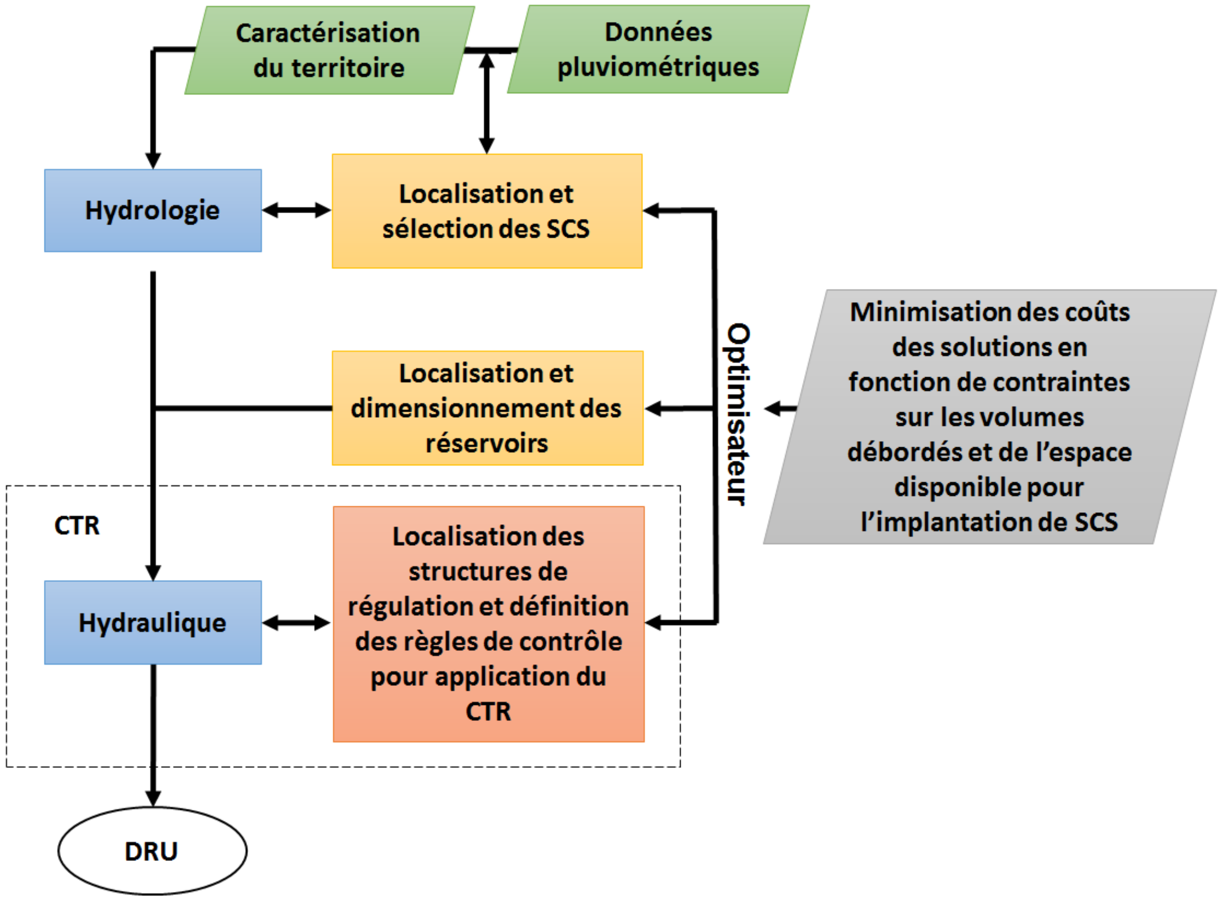

Figure 1.4 Schéma conceptuel de l'intégration optimisée des SCS, du CTR et des ouvrages de rétention

1.4.2 Présentation des articles scientifiques

Les objectifs spécifiques présentés précédemment ont été poursuivis à travers un total de quatre articles scientifiques, décrits sommairement au Tableau 1.1. Pour chaque article, le Tableau 1.1 présente les objectifs, les hypothèses associées et leur réfutabilité, une brève description de l'approche méthodologique employée ainsi que l'originalité de la contribution.

Plus précisément, le premier objectif spécifique, qui s'attarde à la définition des bases méthodologiques pour la sélection des intrants pluviométriques en vue d'atteindre les autres objectifs spécifiques du projet, a conduit au premier article de la thèse intitulé « *Selection of rainfall information as input data for the design of combined sewer overflow solutions* » (Jean et al., 2018). Cet article a permis d'orienter le choix des données pluviométriques à appliquer comme données d'entrée pour la conception ainsi que pour l'évaluation des performances des différents scénarios intégrant le CTR et les SCS élaborés dans les articles suivants. Cet article devait donc être réalisé en amont des autres, car tout le travail subséquent de la thèse se basait sur les résultats qui y sont décrits. En complément à cet article, la présentation orale suivante a été réalisée :

> Jean M-È., Duchesne S., Pelletier G. (2016, novembre) Impact des données de pluie utilisées pour estimer les volumes compensatoires pour réduire les débordements de réseaux d'égout unitaires. Présentation orale au Symposium sur la gestion de l'eau de Réseau Environnement, Montréal, Canada.

Le deuxième objectif spécifique de la thèse et les sous-objectifs qui en découlent constituent le cœur du projet de recherche et ont été atteints par le développement de différentes approches méthodologiques et l'évaluation de leur performance sur deux cas d'études réels localisés dans la province de Québec (une municipalité de taille moyenne et une municipalité de très grande taille plus densément urbanisée que la première); ces travaux ont fait l'objet de trois articles scientifiques. Parmi ceux-ci, le deuxième article de la thèse intitulé « *Optimization of Real-Time Control with Green and Grey Infrastructure Design for a Cost-Effective Mitigation of Combined Sewer Overflows* » (Jean et al., 2021) permet d'asseoir les bases du cadre conceptuel d'optimisation intégrée des SCS, du CTR et des ouvrages de rétention en se basant sur le premier cas d'étude. Ce deuxième article répond au sous-objectif spécifique 2.1, puisque l'approche développée implique des outils de simulation et d'optimisation minimisant les coûts nécessaires pour atteindre des cibles prédéfinies de fréquence de DRU. En parallèle à la publication de cet article, différentes présentations orales et articles de conférences ont aussi contribué au partage des connaissances :

> Jean M-È, Morin C, Duchesne S & Pelletier G (2021, septembre) Infrastructures vertes et contrôle en temps réel : le duo gagnant pour contrer les débordements d'égouts unitaires. Présentation orale au Congrès annuel de l'Association des ingénieurs municipaux du Québec, virtuel.
>
> Jean M-È, Morin, C, Duchesne S & Pelletier G (2021, juin) Infrastructures vertes et contrôle en temps réel : le duo gagnant pour contrer les débordements d'égouts unitaires. Présentation orale à la Conférence nationale annuelle de l'Association canadienne des ressources hydriques, virtuel.
>
> Jean M-È, Duchesne S, Pelletier G & Pleau M (2018) Conceptual Framework for Integrating Real-Time Control and Source Control Solutions for CSO Frequency Control. International Conference on Urban Drainage Modelling. Cham : Springer, 2018.
>
> Jean M-È., Duchesne S., Pelletier G. (2018, mars) Intégration du contrôle à la source et du contrôle en temps réel comme mesures de réduction des débordements de réseaux d'égout unitaires. Présentation orale à la Journée québécoise des étudiants CentrEau, Longueuil, Canada.

Le cas d'étude du deuxième article (municipalité de moyenne taille) ainsi que la méthodologie qui y est présentée pour optimiser la conception de solutions de contrôle des DRU ont aussi été appliqués dans le troisième article, intitulé « *Optimal Distribution of Green and Grey Infrastructures with Real Time Control for Combined Sewer Overflows Control as an Adaptation Measure to Climate Change* » (en cours de rédaction), pour réaliser des analyses supplémentaires. Ce troisième article permet d'approfondir la compréhension des performances de certains scénarios de contrôle des DRU. Il répond aux sous-objectifs spécifiques 2.3 et 2.4, soit l'évaluation de diverses stratégies de distribution spatiale des SCS et de la performance de différentes solutions faces à l'augmentation des précipitations due aux CC.

Le cadre méthodologique développé pour la réalisation du deuxième article, subséquemment transposé au troisième article de la thèse, a servi de guide pour le développement de la méthodologie du quatrième article, intitulé « *Real-time model predictive and rule-based control with green infrastructures to reduce combined sewer overflows* » (Jean et al. 2022). Cette fois, la méthode d'optimisation intégrée des SCS, du CTR et des ouvrages de rétention a été adaptée afin de permettre d'évaluer comment les performances de deux stratégies de CTR (CTR par modélisation prédictive et CTR basé sur des règles) influencent les performances de la mise en place des SCS pour le contrôle des DRU tout en considérant, encore une fois, diverses stratégies de distribution spatiale des SCS. Dans cet article, les performances des diverses solutions ont été évaluées sur le deuxième cas d'étude (municipalité de très grande taille densément peuplée). Cet article a permis de répondre directement au sous-objectif 2.2 et de contribuer au sous-objectif 2.3. Les résultats de cet article ont fait l'objet de quelques conférences :

> Jean M-È, Morin C, Duchesne S, Pelletier G & Pleau M (2021, novembre) Infrastructures vertes et contrôle en temps réel: un changement local pour un impact global. Présentation orale au 27^{e} congrès annuel INFRA, Centre d'expertise et de recherche en infrastructure urbaine (CERIU), virtuel.

> Jean M-È, Morin C, Duchesne S, Pelletier G & Pleau M (2021, octobre) Green infrastructure and real-time control: local change for global impact. Présentation orale à la « *International Conference on Urban Drainage* 2021 (ICUD 2021) », virtuel.

De manière plus globale, deux présentations orales ont aussi été réalisées dans l'optique de faire un retour sur les résultats obtenus par la mise en application des différents cas d'études et des approches méthodologiques développées pour la réalisation des quatre articles scientifiques inclus dans la thèse :

> Jean M-È, Morin C, Duchesne S, Pelletier G & Pleau M (2022, mars) Integration of green infrastructure and real time control to reduce combined sewer overflows, Présentation orale pour le *Waterway Ecosystem Research Group*, Melbourne, Australie.

Jean M-È, Morin C, Duchesne S, Pelletier G & Pleau M (2021, novembre) Intégration des infrastructures vertes et du contrôle en temps réel pour réduire les débordements de réseaux d'égout unitaires. Présentation orale pour les webinaires mensuels CentrEau, virtuel.

La contribution innovante du projet de recherche réside principalement dans l'intégration du CTR et des SCS via l'optimisation intégrée des paramètres d'application de ces deux types de solutions, dès leur conception. Comme détaillé dans la revue de littérature (section 1.2), alors que l'impact sur les DRU d'une conception optimisée des SCS et des stratégies de CTR a été démontré individuellement pour une variété d'études de cas trouvées dans la littérature, seul un petit nombre d'auteurs ont combiné ces deux types de solutions et aucun n'a étudié les avantages d'optimiser l'intégration du CTR et des SCS lors de la conception. La recherche permet ainsi d'explorer l'impact du CTR sur la conception optimale des SCS en termes de nombre et de localisation des sites d'implantation de SCS ainsi que de coûts d'investissement nécessaires pour une performance cible. Une optimisation intégrée du CTR et des SCS permet de tirer profit de la flexibilité du CTR afin de réduire le nombre de SCS nécessaire pour atteindre le même résultat en matière de contrôle de DRU ou alternativement afin d'améliorer les performances de contrôle de DRU pour un nombre donné de SCS. Par conséquent, cette recherche doctorale contribue à fournir de nouveaux outils d'analyse et de conception pour l'évaluation et le développement de solutions durables de réduction des DRU.

Tableau 1.1 Description des articles scientifiques associés à la thèse doctorale

1. "*Selection of rainfall information as input data for the design of combined sewer overflow solutions*" (Sélection des informations pluviométriques à utiliser comme données d'entrée pour la conception de solutions de contrôle des débordements de réseaux d'égout unitaires)	
Objectifs principal et spécifique(s) de l'article:	Étudier l'impact des données pluviométriques sur l'estimation des volumes de rétention nécessaires à l'atteinte d'une fréquence de DRU annuelle maximale spécifique - Effectuer une revue de littérature des types de données pluviométriques d'entrées disponibles pour la modélisation des DRU - Évaluer comment l'application de trois méthodes de sélection des données pluviométriques (simulation en continu, pluie historique sélectionnée en fonction de la hauteur totale tombée ou de l'intensité maximale de l'événement et pluies synthétiques dérivées de courbes IDF) à appliquer dans un modèle de simulation affecte la conception des volumes à retenir pour le contrôle des DRU.
Hypothèse:	Il existe une méthode spécifique de sélection des données pluviométriques qui peut conduire à une meilleure estimation des volumes à retenir pour la conception de solutions de contrôle des DRU, car la fréquence, le volume et la durée des DRU sont étroitement liés aux caractéristiques des précipitations.
Réfutabilité:	L'hypothèse serait réfutable si les différentes méthodes de sélection des données pluviométriques évaluées ne conduisaient pas à une estimation appropriée des volumes à retenir pour le contrôle des DRU ou si les résultats obtenus selon les différentes méthodes produisaient des résultats trop similaires pour que l'application d'une méthode en particulier soit recommandée.
Approche méthodologique:	- Validation d'un modèle hydrologique/hydraulique d'un bassin versant urbain réel de la province de Québec (Canada) pour sa capacité à reproduire les DRU historiques répertoriés pour différents ouvrages de débordement distribués sur son territoire. - Réalisation d'une analyse fréquentielle des séries chronologiques de DRU simulées afin de déterminer le volume maximal de DRU correspondant à la fréquence cible de DRU à atteindre pour chaque ouvrage de débordement et pour chaque année simulée. - Évaluation de la sensibilité des résultats au nombre d'années prises en compte dans l'analyse. - Séparation des séries pluviométriques historiques en événements distincts afin de sélectionner, parmi ces événements, ceux ayant une récurrence équivalente à la fréquence cible de DRU à atteindre selon: a) la hauteur totale tombée ; et b) l'intensité maximale de l'événement sur diverses durées; détermination par simulation des volumes de DRU associés à ces événements pour chaque ouvrage de débordement. - Détermination des valeurs d'intensité maximale des précipitations sur des durées variées et selon une récurrence équivalente à la fréquence cible de DRU à atteindre pour les séries pluviométriques historiques afin de dériver une courbe de régression IDF permettant de développer des pluies synthétiques selon différents patrons temporels dérivés des hyétogrammes de Chicago et d'autres hyétogrammes standards utilisés en conception hydraulique; détermination par simulation des volumes de DRU associés à ces événements pour chaque ouvrage de débordement.
Originalité:	Amélioration des procédures de modélisation pour concevoir des solutions de contrôle des DRU permettant d'atteindre une fréquence saisonnière maximale de DRU, puisqu'il existe peu de guides sur le type de données pluviométriques qui devraient être appliquées dans les méthodologies de conception des solutions de contrôle des DRU.

2. "***Optimization of Real-Time Control with Green and Grey Infrastructure Design for a Cost-Effective Mitigation of Combined Sewer Overflows***" **(Optimisation du contrôle en temps réel et de la conception d'infrastructures vertes et grises pour une atténuation rentable des débordements de réseaux d'égout unitaires)**	
Objectifs principal et spécifique(s) de l'article:	Intégrer l'optimisation du CTR, de la distribution spatiale des SCS et du dimensionnement d'ouvrages de rétention à l'échelle du bassin versant afin de réduire la fréquence et les volumes des DRU à moindres coûts. - Décrire comment l'optimisation intégrée du CTR basé sur des règles de contrôle (« *rule-based control* »), la distribution spatiale des SCS et le dimensionnement d'ouvrages de rétention a un impact sur la fréquence et la réduction des volumes de DRU par rapport à leur application individuelle. - Évaluer comment le coût nécessaire pour atteindre des cibles de fréquence de DRU spécifiques peut être réduit grâce au cadre d'optimisation intégrée du CTR, des SCS et des ouvrages de rétention.
Hypothèse:	Comme, d'une part, les décisions du CTR sont fortement influencées par la quantité, le moment et la répartition spatiale du ruissellement entrant dans le réseau d'égout unitaire et que, d'autre part, l'impact de l'implantation des SCS et des ouvrages de rétention pourrait être maximisé si les SCS étaient situées là où le ruissellement excédentaire ne peut être géré par le CTR seul, il est supposé que l'optimisation intégrée de ces divers types de solutions permettrait de réduire la fréquence et les volumes de DRU plus efficacement (soit d'atteindre les objectifs de contrôle des DRU à moindres coûts).
Réfutabilité:	L'hypothèse serait réfutable si l'optimisation intégrée de la distribution spatiale des SCS et du dimensionnement d'ouvrages de rétention à l'échelle du bassin versant avec le RTC ne pouvait pas améliorer la réduction des volumes et de la fréquence des DRU ni réduire les coûts globaux de mise en œuvre des solutions proposées par rapport à l'application de ces solutions séparément.

Approche méthodologique:	- Utilisation d'un modèle hydrologique/hydraulique d'un bassin versant urbain réel de la province de Québec (Canada) pour lequel aucune solution de contrôle de DRU n'a été mise en place et dont plusieurs ouvrages de débordements ne respectent pas la fréquence maximale de DRU leur étant imposée.
	- Réalisation d'une analyse spatiale de la zone d'étude pour déterminer l'espace disponible pour l'implantation de SCS.
	- Élaboration d'une routine d'optimisation pour déterminer de manière individuelle ou intégrée le nombre et l'emplacement optimal de SCS, le nombre et les volumes des réservoirs et les règles de CTR à appliquer aux vannes du réseau de drainage pour le contrôle de la fréquence des DRU basée sur :
	    o L'utilisation d'événements pluviométriques de conception dont la récurrence est équivalente à la fréquence de DRU cible et la validation de la conception des solutions par une simulation en continu des données pluviométriques historiques disponibles.
	    o La minimisation d'une fonction objectif qui tient compte de la somme des coûts totaux des infrastructures de SCS et d'ouvrages de rétention ainsi que des pénalités associées aux volumes de DRU, aux surcharges aux nœuds et aux dépassements de la capacité du réseau de drainage en aval à l'aide d'un outil d'optimisation par essaimage de particules.
	- Comparaison des performances en termes de maintien de la fréquence de DRU, de réduction des volumes de DRU et de coûts de mise en œuvre des solutions de contrôle des DRU de différents scénarios intégrant l'optimisation des règles de contrôle de vannes modulantes du réseau par CTR, la distribution spatiale des SCS et le dimensionnement d'ouvrages de rétention de manière individuelle ou combinée.

Originalité:	L'optimisation de la distribution spatiale des SCS et du dimensionnement d'ouvrages de rétention ainsi que le CTR à l'échelle du bassin versant ont été appliqués dans de nombreuses études empiriques et théoriques, mais seules quelques études ont combiné ces différents types de solutions dans le même système de drainage urbain, alors qu'aucune d'entre elles n'a mené une optimisation intégrée pour améliorer les performances de contrôle des DRU et/ou diminuer les coûts de mise en œuvre.

3. “*Optimal Distribution of Green and Grey Infrastructures with Real Time Control for Combined Sewer Overflows Control as an Adaptation Measure to Climate Change”* (Distribution optimale des infrastructures vertes et grises avec le contrôle en temps réel pour le contrôle des débordements de réseaux d'égout unitaires comme mesure d’adaptation aux changements climatiques)	
Objectifs principal et spécifique(s) de l’article:	Évaluer les réductions de volume et de fréquence des DRU suite à l'implémentation individuelle ou intégrée de SCS avec le CTR et des ouvrages de rétention et étudier comment ces réductions peuvent varier selon : - des niveaux d'implémentation variables des SCS ; - des stratégies de distribution des SCS (basées sur l'optimisation ou l'espace disponible) ; - des intensités pluviométriques accrues en raison des CC.
Hypothèse:	Il est supposé que l'optimisation intégrée des SCS et du CTR pourrait améliorer le contrôle de la fréquence et des volumes de DRU pour différents niveaux d’implantation des SCS et conditions de précipitations changeantes, car les deux méthodes ont un impact dynamique sur le ruissellement du système à l'échelle du bassin versant.
Réfutabilité:	L'hypothèse serait réfutable si l'optimisation intégrée de la distribution spatiale des SCS et du dimensionnement d’ouvrages de rétention à l'échelle du bassin versant avec le CTR ne pouvait pas améliorer la réduction des volumes et de la fréquence des DRU par rapport à l'application séparée de ces solutions lorsque différentes stratégies d’implantation des SCS et conditions de précipitations sont prises en compte.
Approche méthodologique:	- Utilisation d’un modèle hydrologique/hydraulique d'un bassin versant urbain réel de la province de Québec (Canada) pour lequel aucune solution de contrôle de DRU n’a été implantée et dont plusieurs ouvrages de débordements ne respectent pas la fréquence maximale de DRU leur étant imposée. - Comparaison des performances en termes de maintien de la fréquence de DRU et de réduction des volumes de DRU des solutions des différents scénarios développés dans l’article précédent et intégrant l’optimisation de la distribution spatiale des SCS de manière individuelle ou en combinaison avec des règles de contrôle de vannes modulantes du réseau par CTR et/ou le dimensionnement d’ouvrages de rétention selon : o l’application d’une série pluviométrique historique; o l’application de la même série pluviométrique historique à laquelle un facteur de majoration constant et uniforme de 20 % est appliqué. - Développement de scénarios complémentaires dans lesquels le nombre total de SCS implanté est limité et augmenté progressivement selon deux stratégies de distribution différentes, soit : o proportionnellement au nombre optimisé de SCS tel qu'obtenu à partir du cadre d'optimisation; o proportionnellement à l'espace disponible pour les SCS dans chaque sous-bassin selon une analyse spatiale.
Originalité:	L'optimisation de la distribution spatiale des SCS et du dimensionnement d’ouvrages de rétention ainsi que le CTR à l'échelle du bassin versant ont été appliqués dans de nombreuses études empiriques et théoriques, mais seules quelques études ont combiné ces différents types de solutions dans le même système de drainage urbain, alors qu’aucune d'entre elles n'a mené une évaluation de leur performance combinée en fonction de différentes stratégies d’implantation des SCS et de conditions de précipitations changeantes.

4. “*Real-time model predictive and rule-based control with green infrastructures to reduce combined sewer overflows*” (Contrôle en temps réel par modélisation prédictive et basé sur des règles avec des infrastructures vertes pour réduire les débordements de réseaux d'égout unitaires)	
Objectif principal et spécifique(s) de l’article:	Étudier comment deux stratégies de CTR (CTR par modélisation prédictive et CTR basé sur des règles) influencent les performances de la mise en œuvre à grande échelle des SCS pour le contrôle des DRU et comment ces stratégies de contrôle se comparent au contrôle statique en termes de réduction des volumes et de fréquence des DRU, de respect des priorités environnementales et d’efficacité des SCS pour convertir le volume de ruissellement capté en réduction du volume de DRU et ce, selon : - une série d'événements pluvieux variables en intensité et en volume ; - différentes stratégies d’implantation des SCS (implantation progressive des SCS et distribution spatiale des SCS en fonction des priorités environnementales).
Hypothèse:	Considérant que le potentiel de réduction de la fréquence et des volumes des DRU est plus élevé pour l’application d’une stratégie de CTR par modélisation prédictive par rapport à une stratégie de CTR basé sur les règles ou à un contrôle statique du réseau de drainage, selon la littérature, il est supposé que les performances des SCS seront également améliorées lorsque celles-ci sont intégrées avec le CTR par modélisation prédictive par rapport à d’autres types de contrôle, et ce, même lors de l’application de différentes stratégies de distribution spatiale des SCS.
Réfutabilité:	L'hypothèse serait réfutable si l’intégration de SCS avec le CTR par modélisation prédictive du réseau ne résultait pas en un gain de performance par rapport à leur intégration avec une stratégie de CTR basé sur les règles ou avec un contrôle statique du réseau de drainage.
Approche méthodologique:	- Utilisation d’un modèle hydrologique/hydraulique d'un bassin versant densément urbanisé réel de la province de Québec (Canada) contenant plusieurs ouvrages de rétention et dont le réseau est contrôlé selon différentes stratégies de CTR (CTR par modélisation prédictive et CTR basé sur des règles) à l’aide d’un outil d’optimisation. - Réalisation d’une analyse spatiale de la zone d'étude pour déterminer l’espace disponible pour l’implantation de SCS. - Élaboration d’un processus de conception itératif basé sur une pluie de conception de grande récurrence permettant de répartir les SCS sur le territoire en fonction de leur efficacité et de leurs coûts estimés ainsi qu’en fonction de la vulnérabilité des émissaires à l’impact des DRU. - Développement d’une série de scénarios intégrant des SCS avec différents types de stratégies de CTR (CTR par modélisation prédictive et CTR basé sur des règles) et un contrôle statique du réseau de drainage, ainsi que différents niveaux d’implantation des SCS et différentes stratégies de distribution spatiale des SCS pour mieux analyser l'impact combiné de ces solutions pour le contrôle des DRU. - Simulation en continu d'une série chronologique de précipitations historiques et selon une pluie historique et une pluie synthétique pour comparer les performances des scénarios sur une variété d'événements pluvieux.
Originalité:	Alors que les travaux précédents ont évalué l'impact de la combinaison du CTR avec différents types de SCS ou ont comparé les performances de différentes stratégies de CTR sans tenir compte de l'impact des SCS, il reste nécessaire de comparer les performances obtenues à partir de l'application de différents types de gestion de CTR en association avec les SCS.

2 SELECTION DES INFORMATIONS PLUVIOMETRIQUES A UTILISER COMME DONNEES D'ENTREE POUR LA CONCEPTION DE SOLUTIONS DE CONTROLE DES DÉBORDEMENTS DE RÉSEAUX D'ÉGOUT UNITAIRES

Selection of rainfall information as input data for the design of combined sewer overflow solutions

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La première auteure, Marie-Ève Jean, a réalisé la revue de la littérature, la validation du modèle de simulation hydraulique et hydrologique, le développement de l'approche méthodologique, le travail de modélisation, l'analyse des résultats et la rédaction du manuscrit. La deuxième auteure, Sophie Duchesne a contribué au développement de l'approche méthodologique, supervisé le travail de modélisation et d'analyse des résultats et a révisé le manuscrit. La troisième auteure et le quatrième auteur, Geneviève Pelletier et Martin Pleau, ont aussi contribué au développement de l'approche méthodologique et ont révisé le manuscrit.

2.1 Highligths

- Available types of rainfall input for CSO modelling were reviewed
- Retention volumes from continuous, historical and IDF-derived storms were compared
- Continuous simulation is advisable for sizing solutions to limit CSO frequency
- Single-rainfall events should be restricted to preliminary design
- Design of CSO solutions is highly sensitive to the number of years simulated

2.2 Abstract

Combined sewer overflows (CSOs) cause environmental problems and health risks, but poor guidance exists on the use of rainfall data for sizing optimal CSO control solutions. This study first reviews available types of rainfall information as input for CSO modelling and, secondly, assesses the impacts of three rainfall data selection methods (continuous simulation, historical rainstorms selected based on rainfall depth or maximum intensity and IDF-derived storms) on the estimation of CSO volume thresholds to control in order to reach specific seasonal CSO frequency targets. The methodology involves hydrological/hydraulic modelling of an urban catchment in the Province of Québec (Canada). Continuous simulation provides the most accurate volume estimations and shows high sensitivity to the number of simulated years. Alternatively, when historical events extracted from rainfall data separated by a minimum inter-event time (MIT) criterion are selected based on their total rainstorm depth, the CSO volumes are underestimated significantly; whereas an analysis based on rainstorm maximum intensities over durations similar to the time of concentration provides more conservative volumes. Finally, synthetic storms constructed from multiple points of an IDF curve tend to underestimate slightly the CSO volumes, but provide acceptable results compared to single point derived storms. It was found that the overflow structures local characteristics had a marginal influence on results obtained from continuous simulation compared to event-based simulation. The use of design rainfall events should thus be restricted to preliminary assessment of CSO volume thresholds, and the final volume estimation for solution sizing should be reviewed under continuous simulation. The innovative contribution lies in the improvement of modelling procedures for solutions design to achieve a maximum CSO frequency, such as specified by many regulating agencies.

Keywords: Combined sewer overflow; Continuous simulation; Hydraulic modelling; IDF curve; Rainfall data; Retention volume design

2.3 Introduction

Sustainable stormwater management in urban areas is essential for water resources quality and viability, municipal infrastructure cost-efficiency and community well-being. Around the world, many urban areas are drained by combined sewer networks that collect and transport both municipal wastewater and stormwater/snowmelt runoff. During wet weather events or thaw periods, the transport capacity of the system and the treatment capacity of the wastewater facility may be exceeded; resulting in the discharge of untreated wastewater into nearby receiving waters. This phenomenon is commonly described as combined sewer overflows (CSO) and is associated with serious environmental problems and health risks (Gooré Bi et al., 2015b; Madoux-Humery et al., 2015; Passerat et al., 2011). CSO impacts are expected to worsen in the near future due to projected climate change as well as urban land development (Alves et al., 2016; Semadeni-Davies et al., 2008; Yazdanfar and Sharma, 2015).

In response to this problem, governments are prescribing regulations to limit the frequency, volume and/or pollutant load of CSOs. For example, since 2014, all sewer extension projects in the Province of Quebec (Canada), such as network densification or the addition of new neighbourhoods in the upstream portions of existing systems, must demonstrate compensatory actions to avoid increasing the annual frequency of sewage overflows (MDDELCC, 2014), according to Canada wide Strategy for the Management of Municipal Wastewater Effluent (CCME, 2009). However, only little guidance exists on CSO analysis methods for optimal selection and design of combined sewer solutions. Because CSO frequency, volume and duration are closely linked to rainfall characteristics (Abdellatif et al., 2014; Andrés-Doménech et al., 2010; Mailhot et al., 2015; Montalto et al., 2007; Schroeder et al., 2011; Thorndahl and Willems, 2008; Yu et al., 2013), the determination of a robust method for the selection of rainfall information as input data for CSO mitigation analysis is of particular importance.

Previous studies analysing the impact of rainfall data on CSO management provide useful information for evaluating possible rainfall input simplifications, estimating flooding risks or comparing scenarios (Calabrò, 2004; Fontanazza et al., 2011; Schütze et al., 2002; Thorndahl and Willems, 2008; Vaes et al., 2002a, 2001), but not for designing CSO mitigation measures in particular. This work aims to improve modelling procedures for sizing CSO solutions by focussing specifically on the impact of rainfall data on simulated CSO volume thresholds. More specifically, in this paper, the term CSO volume threshold defines the CSO volume that has to be controlled by CSO control solutions designed to achieve a specific maximum annual or seasonal CSO frequency. The objective of this paper is thus twofold: first, to complete an exhaustive review on available types of rainfall input for CSO modelling and, second, to evaluate how the application of these different types of rainfall data in a simulation model affects the estimation of CSO volume thresholds for the design of CSO control solutions. To achieve the second objective, the methodology is tested on a real combined sewer network.

2.4 Literature review

In the context of design of CSO control solutions, rainfall data can be divided in two main types: continuous or event-based. Continuous data include chronological wet and dry periods from long-term records whereas event-based data represent individual rainstorm events. Single rainstorm (event-based data) can further be divided into synthetically derived storms or events extracted from historical data. Finally, a fourth type of rainfall data can be derived from a probabilistic modelling approach, in which rainfall data are analysed to identify relationships between a critical rainfall depth threshold and CSO occurrence. The four types of rainfall data, as well as examples of their application for CSO assessment, are subsequently presented.

2.4.1 Continuous and quasi-continuous rainfall data

Continuous simulation of rainfall data consists in using a detailed chronological precipitation record as input to a rainfall-runoff model. A frequency analysis of the resulting runoff output can then be performed to describe the system's response in terms of runoff occurrence and magnitude (Akan and Houghtalen, 2003). Considering that the majority of CSO events occur for small, frequently occurring rainfall events and that antecedent conditions such as the soil moisture or the amount of water already in the network can affect the performance of stormwater retention solutions, several authors recommend the use of long-term continuous hydrologic modelling to analyse the system's response for CSO management (Abdellatif et al., 2015; Nilsen et al., 2011; Shoemaker et al., 2011; USEPA, 1993; Willems, 2011). Quasi-continuous rainfall data described a sequence of seasonal rainfall records when the full annual time series is either not available or when the seasonality in precipitation characteristics impact CSO processes (for example if there is no rain during winter months).

Various modelling studies have applied continuous rainfall data to simulate CSO discharges under baseline and climate change scenarios (Abdellatif et al., 2014; Abdellatif et al., 2015; Dirckx et al., 2018; Nie et al., 2009; Nilsen et al., 2011; Semadeni-Davies et al., 2008); to analyse stormwater control performance for CSO reductions (Dirckx et al., 2011; Lucas and Sample, 2015; Montalto et al., 2007; Tavakol-Davani, 2016); to validate CSO solution designs

(Shoemaker et al., 2011); to address the impact of rainfall spatial variability on CSO volumes (Verwom and Stuecken, 2001); to evaluate combined sewer system performance under dry and wet years (Nasrin et al., 2017); or to assess modelling performances for CSO impact estimations (Ruan, 1999; Vaes et al., 2001). It could be noted that whereas most studies analysed CSO by comparing resulting volume, duration and/or frequency, the study of Ruan (1999) also assessed water quality impacts of CSOs on receiving waters by evaluating model simulation accuracies for estimating total suspended solids loads and concentrations.

2.4.2 Historical rainfall events

As an alternative to complete continuous simulation, some authors based their research work on event-based simulation of historical rainfall events. Simulating independent rainstorm events reduce the validity of the results if no attention is given to antecedent conditions. Indeed, the cumulative impacts of successive rainfall events in terms of soil moisture, pollutant load, storage levels, remaining capacity of existing stormwater control infrastructures and other variables was found to exacerbate CSO impacts (Hvitved-Jacobsen and Yousef, 1988; Mailhot et al., 2015; Vaes et al., 2001).

Nevertheless, in terms of both water quantity (CSO peak flow and volume) and quality analysis (CSO pollutant loads and concentrations), observed rainstorm events were previously used as input to simulation models in order to i) assess the effectiveness of best management practices (BMP) solutions for CSO control (Autixier et al., 2014); ii) assess the impact of climate change by increasing rainfall intensities and comparing the resulting situation with the baseline conditions (Gooré Bi et al., 2015b) also including an analysis of CSO ecotoxicological risks; or iii) investigate relationships between rainfall variables of individual storms and resulting CSOs (Gooré Bi et al., 2015a; Yu et al., 2013).

2.4.3 Synthetic rainfall events

Synthetic rainfall events, or design storms, have been extensively used in the scientific literature as well as in practice for a large spectrum of urban drainage problems. Most commonly used design storms are constructed directly from Intensity-Duration-Frequency (IDF) curves.

The total rainfall depth of a synthetic event can be derived from one point of an IDF curve and an arbitrary temporal profile is then applied to distribute the precipitation volume over time. Simpler profiles include rectangular (uniform intensity over the storm duration), triangular (Yen and Chow, 1980) and double triangular (DGALN-CEREMA, 2014). In the U.S, the Soil

Conservation Service distributions (SCS, 1968) are four types of 24 h-long storms representative of different zones of the country (Types I, IA, II, and III). Other synthetic design storms can also represent all intensity-duration values associated to a specific return period such as the well-known Chicago storm (Keifer and Chu, 1957). For most IDF derived storms, the total duration of the storm has to be defined; which is generally greater than the concentration time of the urban catchment or alternatively specified by regulatory agencies (Rivard, 1996).

Synthetic design storms can be developed by comparing long series of historical storms to define typical temporal distribution of the rainfall. In Canada, common rainstorm profiles are the AES storms of 1 h (convective storm) and 12 h (cyclonic storm) developed by the Atmospheric Environment Service (Rousselle et al., 1990) and the HYDROTEK 1 h linear/exponential hyetographs of Watt et al. (1986), all derived from the same historical rainfall dataset of Hogg (1980). In the U.S, Huff (1967) developed standardised rainstorms from observed data by defining four types of rainfall distribution according to the timing of the rainstorm peak relatively to the total rainstorm duration and their distribution probability. Yen and Chow (1980) also analysed long series of observed storms and defined dimensionless triangular hyetographs.

When the synthetic rainfall is derived from IDF curves, the probability of occurrence of the resulting runoff associated with the synthetic storm is unknown, because IDF relationships are determined from rainfall intensity maxima over a moving time window and does not represent the entire storm event (USEPA, 1993; Rivard, 1996; Watt and Marsalek, 2013). An added uncertainty for the application of synthetic storms is the necessity for the modeller to define some important variables of the rainfall event such as its duration. Finally, the nonlinearity of the resulting CSO volumes with rainfall depth could restrict the interpretation of the model response for synthetic storms, because this interpretation implies some sort of linear response between CSO processes and rainfall statistics (Dirckx et al., 2018; Vaes et al., 2001).

Previous studies have analysed the performances of BMP as potential solutions for CSO control based on modelling work involving standard design storms of different return periods (Chaosakul et al., 2013; Dong et al., 2017; Fuamba et al., 2010; Mailhot et al., 2014; Sebti et al., 2016; Villarreal et al., 2004). Also with the aim of evaluating CSO control measures, other studies developed their own methodology to use available historical rainfall data to construct synthetic rainfall events (Alves et al., 2016; Baek et al., 2015; Shoemaker et al., 2011). Finally, in a more analytical perspective, several authors have simulated various design storms to assess the impact of changing rainfall characteristics on drainage performances in terms of water quantity (Fontanazza et al., 2011; Fu and Butler, 2014; Thorndahl and Willems, 2008; Vaes et al., 2002a), water quality (Calabrò, 2004) or both quantitative and qualitative impacts (Andrés-Doménech et al., 2010).

2.4.4 Rainfall depth threshold

Other research work has analysed long-term sequences of rainfall data to develop statistical relationships between CSOs and rainfall event characteristics without hydrologic and hydraulic modelling tools. Their methodology is based on the hypothesis that there is a critical rainfall depth from which a CSO event has a higher probability of occurring than not occurring (Mailhot et al., 2015). For example, Schroeder et al. (2011) evaluated the effectiveness of certain CSO control measures, whereas Andrés-Doménech et al. (2011) and Fortier and Mailhot (2014) assessed the impact of climate change on combined system performances using this type of methodology.

2.5 Material and methods

This section presents the methodology that was applied to achieve the second objective of this study, namely evaluating how the use of different types of rainfall data impacts CSO volume threshold estimations for CSO frequency reduction.

2.5.1 Study area

The case study is the combined sewer catchment of Thetford Mines, a medium-sized municipality located in the southern part of the Province of Québec, Canada. The drainage network, schematised in Figure 2.1, has a catchment area of 401 ha and a concentration time of about 3 h. Almost all the water entering the sewage system is carried by gravity with only one pumping station connecting a small downstream sub-catchment to the rest of the network. The capacity of the main interceptor is highly restricted by its small diameter and the maximum capacity of the wastewater treatment plant (WWTP). There are a total of 30 overflow structures discharging wastewater to either one of the two receiving rivers of the area. For this municipality, the provincial legislation recommends a maximum of seven CSO spills per year under wet weather conditions between May to November, considering that overflows are recorded on a daily basis. The analysis was carried out for 10 of these 30 overflow structures (identified in Figure 2.1), because they often exceed the permitted occurrence and runoff control solutions have not yet been implemented at these structures, as is the case for the remaining structures.

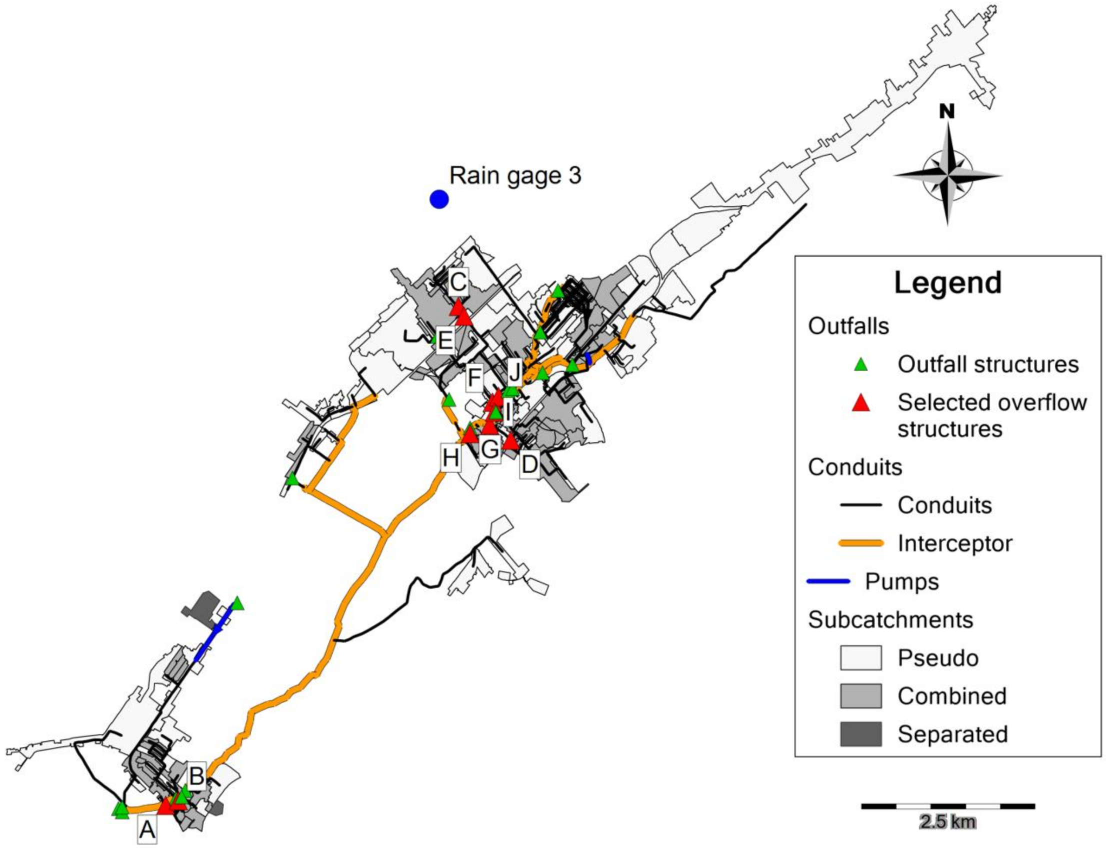

Figure 2.1 **Combined sewer network and selected CSO structures**

2.5.2 Historical CSO data

In the Province of Québec, CSO frequency and sometimes duration data are reported annually to the Ministry of Municipal Affairs and Occupation of the Territory (MAMOT) for each CSO overflow structures and WWTP stations. High uncertainty is attached to observed CSO data. For the majority of the overflow structures monitored from 2006 to 2015, the occurrence of CSOs is determined approximately on a weekly basis. A municipal employee visits the overflows structures and indicates that at least one overflow has occurred since the last visit if a visual floating device has been moved by the water from the manhole to the overflow pipe.

Among all the CSO structures in the study catchment, only the one at the WWTP has been historically recorded on a daily basis by automated devices. All the others have been recorded by intermittent weekly visits. The total volume of CSOs is not monitored on this network.

2.5.3 Hydrologic/hydraulic model

The research methodology is based on the modelling of hydrologic and hydraulic processes using PCSWMM software (CHI, 2016) derived from EPASWMM (Rossman and Huber, 2016a). The case-study network has about 1 360 links and 1 310 nodes, totalizing 78 000m of conduits length. The sub-catchments average slope is 2.8% and total impervious area is about 32%. The low imperviousness is due to the success of a municipality wide gutter disconnection campaign and the number of pseudo and separated sub-catchment areas. The model was developed and calibrated for wet weather and dry weather events measured in 2006 and 2009 by the consulting engineering firm Tetra Tech (formally BPR CSO) based in Québec City, Canada (Marcoux et al., 2011). For wet weather flows calibration, the directly connected impervious areas of the combined sewer sub-catchments, as well as the characteristic width of overland flow, the sub-catchment superficies and initial rainfall abstraction depths for both combined and separate sewer sub-catchments were adjusted using three to four distinct rainfall events. Calibration criteria were based on James (2003): 1) ± 20% for runoff volumes, 2) ± 15% for peak flows, 3) ± 10 min for peak flow synchronism, and 4) ± 0.10m for measured water levels. The RDII unit hydrograph method (Rossman and Huber, 2016a) was utilized to account for rainfall dependent inflow and infiltration into the combined sewers. In the case of dry weather inflows, a constant infiltration flow was added upstream of each overflow structure (Marcoux et al., 2011). Similarly, domestic wastewater flows were simulated based on hourly fluctuation patterns determined at each measurement point during the calibration campaigns.

To estimate the volume of CSO per event, the simulated overflow volume time series for each structure was extracted from the modelling outputs. If an event started earlier than midnight and extended over the following day, it was compiled as two CSO events to mimic historical CSO recording procedure.

2.5.4 Rainfall data

Three rain gauge stations have been operated by the municipality since 2004. At these stations, the rainfall data measured by a tipping bucket are recorded every 5 min and were validated by comparing the records with those of a station operated by Environment Canada and located about 4 km from the studied catchment. Years 2004, 2005 and 2010 were rejected from the analysis due to missing data or invalidated total seasonal rainfall depth, which leads to a total of nine years of rainfall data (2006–2009 and 2011–2015). For each of these years, the analyses were performed from May to November, since winter months are excluded from Quebec legislation limiting CSO occurrence. Therefore, the available precipitation data are considered as a quasi-continuous rainfall record, which should permit to represent with enough accuracy historical conditions leading to CSOs in the study catchment.

The model validation for CSO frequency estimations was done using the quasi-continuously recorded data from the three rain gauges for more accurate spatial representation of historical rainfall conditions. However, the following study results are based on only one rain gauge, namely the one closest to most of the studied sub-catchments (see Figure 2.1 for location), because the impact of changing the rainfall data input on CSO volume estimations for CSO control is better isolated by assuming that the rain is uniformly distributed over the whole study area. Over the study period, seasonal (May to November) rainfall depths at this location ranged from 730 to 960 mm.

2.5.5 Rainfall data selection methods compared for retention volume design

The impact of applying different rainfall inputs on CSO volume thresholds determination for CSO control was evaluated to achieve a specific maximum number of CSOs per year. This frequency performance goal is selected rather than water quality objectives or percentage of capture in order to be consistent with the current legislation applicable in the Province of Québec. The following paragraphs describe three rainfall data selection methods, one of which has two variants.

2.5.1.1 First method: Quasi-continuous simulation

The first method analysed consisted of applying quasi-continuous simulation of available sequence of seasonal rainfall data. A frequency analysis of simulated CSO time series permitted to determine the seventh maximum CSO volume from each simulated year separately. Subsequently, the maximum value among all years was selected in order to obtain the CSO volume threshold for the design of retention solutions to ensure a maximum of seven spills per year.

An assessment of the sensitivity of the results to the number of years taken into account in the analysis was also realized. The aim was to evaluate how the inter-annual variability of rainfall conditions could influence CSO volume thresholds for CSO management, when only a few years of data are available for the analysis. All combinations of years were tested for all the possible simulation lengths ranging from one to nine years (corresponding to the whole available data for this case study).

2.5.1.2 Second method: Historical rainstorm events based on a) total depth and b) maximum intensity

The second method assessed the impact of applying event-based simulation by extracting particular rainstorms from the historical rainfall records. This type of rainfall data analysis was performed, because some engineers use this method or an equivalent as it requires less computational effort than complete continuous simulation.

The method consists in separating the available rainfall record into distinct events. Several event separation methods exist based on rainfall intensity, statistical properties, duration percentage or set dry period criteria in order to extract from the continuous rainfall data individual rainstorm events (Powell et al., 2007). The most common and simple one consists in determining each event bounded by fixed rain-free intervals of minimal duration, usually referred to as the minimum inter-event time (MIT). The selected MIT criterion requires to be identified according to the simulation objective as it has been proved to have a large impact on the resulting rainstorm event characteristics (Dunkerley, 2008). The Quebec government suggests a MIT of 6 h to separate meteorological events from one another (MELCC, 2010) but recommend an emptying time for retention structures of 24 h. Therefore, to cover a broad range of design criteria, the impact of selecting 3, 6, 12 and 24 h MIT values on rainstorm event separation and CSO volume assessment was analysed. Table 2.1 presents the main characteristics of the rainfall events for each MIT criterion.

Table 2.1 **Mean rainfall event characteristics for MIT=3, 6, 12 and 24 h**

Minimum inter-event time (MIT) (h)	Mean number of rainfall events per year [May-November]	Mean rainfall event depth (mm)	Mean rainfall event intensity (mm/h)	Mean maximum rainfall intensity during 5 min (mm/h)	Mean rainfall duration (h)	Mean dry inter-event duration (h)
3	142	6	2.5	9.9	3.9	32.1
6	105	8	2.2	11.8	6.8	41.5
12	75	11	1.7	14.0	13.0	54.8
24	53	16	1.3	16.9	25.4	70.5

The design rainstorms were then selected among the MIT-separated series by frequency analysis based on two event selection criteria: a) the total rainstorm depth; and b) rainfall maximum intensities over various durations as described below.

For historical rainstorms selected based on total rainfall depth, a frequency analysis was conducted on the four MIT-separated rainfall time series to determine the seventh largest rainstorms, in terms of total precipitation depth, for every year. Among the selected events, the rainstorm having the maximum total depth was considered as the design rainfall event to achieve the CSO frequency target. The hypothesis was that CSO events behave linearly with rainfall depth. Other authors also linked rainfall depth with CSO volume based on linear regression analysis of simulated CSO and rainfall data (Alves et al., 2016; Baek et al., 2015). Moreover, similarly to this assessed rainfall selection method, Shoemaker et al. (2011) identified a design storm for CSO solutions sizing by determining from a one-year rainfall record the two-month return period historical storm based on total rainfall depth separated by a 12 h inter-event spacing. Their study was applied to quantify the storage capacity required to achieve a maximum number of six CSO events per year in a combined sewer network of Kansas City (USA).

For historical rainstorms selected on maximum intensity, a frequency analysis was done on the same four MIT-separated rainfall series to identify the rainstorms having the maximum rainfall intensity (Imax) over durations of 30, 60, 120 and 180 min. Several duration values were analysed to evaluate how the CSO volumes varied according to a range of rainfall intensities. The aim is to compare historical rainstorms not only in terms of rainfall depth (as it was done previously) but in terms of sustained intensities. The added value of this method is to avoid selecting a rainfall event having a large total rainfall depth over a long duration, which would result in low average rainfall intensity and might not have the same impact on CSO as a more compact rainfall event. The rainfall event series was ordered to determine the maximum annual seventh rainstorms in terms of Imax for each duration. Among those seventh rainstorms for all years in the analysis, the one having the maximum Imax was selected as the design rainstorm, for each duration. As a comparison, Mailhot et al. (2015) used daily maximum rainfall values of 5 min to 12 h durations to establish a predictive threshold model associating observed rainfall depth over these durations and CSO occurrence probability. However, because their model describes the CSO probability for the actual conditions of the system, it does not permit to further determine CSO volume thresholds for reducing CSO frequency to specified targets. Sandoval et al. (2013)'s empirical study also analysed the link between CSO and rainfall maximum intensities and found that it was the most influential driver of CSO quantity at the main CSO outlet of the city of Berlin (Germany).

2.5.1.3 Third method: IDF derived storms

Finally, the third method is based on IDF relationships, which is representative of current practice in the industry. The method consists in determining rainfall intensity values for frequent events over various durations, as opposed to mostly available IDF curves developed for long return periods (2–100 years). The intensity values are identified by selecting the maximum rainfall intensity that has occurred for various windows of time (5, 10, 15, 30, 60, 120, 360, 720 and 1440 min) for each day of the rainfall record such as suggested by (MDDELCC, 2017). A frequency analysis is then performed for each duration to determine the rainfall intensities having a return period of seven times per season from May to November (or once a month) by selecting the 63th value of the ordered series (7 times/season × 9 seasons).

The identified rainfall intensities for the nine assessed durations (5–1440 min) are used to derive an IDF regression curve of a return period of seven times per season. Based on the fitted IDF parameters, Chicago hyetographs are developed with a symmetrical centred peak and for three storm durations: 1 h, 3 h and 6 h. Symmetrical Chicago storms were applied rather than unsymmetrical storms as the goal of this study is to assess conceptually how various types of widely applied design storms impact the simulated results in a solution design perspective. A time step of 10 min is considered as suggested by the literature to avoid excessive rainfall intensity (Rivard, 2005).

In addition to the Chicago storms, other 1 h and 3 h-synthetic hyetographs were further applied to a single IDF value as currently done in urban infrastructure design. For these synthetic hyetographs, the total rainfall depth was determined by using the rainfall intensity associated with a duration of one hour and a return period of seven times per season. The total rainfall depth is then distributed according to standard hyetograph shapes available in the literature for the case study location: 1) Hydrotek (Rousselle et al., 1990), 2) AES type 2 (Rousselle et al., 1990), and 3) uniform distribution (rectangular). It could be noted that the Hydrotek and AES storms are unsymmetrical. The aim was to assess the impact on retention volumes of using synthetic storms constructed from multiple IDF points (Chicago storms) and single IDF point (synthetic hyetographs).

2.6 Result and discussion

2.6.1 Simulated versus observed data

Simulated CSO events were compared to observed data in order to assess the model accuracy. As proposed by Jolliffe and Stephenson (2012), the proportion of correct estimation of a binary event is evaluated (occurrence or non-occurrence of a CSO). This type of analysis permits to highlight false positives (number of weeks/days for which a CSO event is simulated when no CSO was recorded) and false negatives (number of weeks/days for which no CSO is simulated when a CSO event has been observed) from true estimations (number of weeks/days for which simulated results correspond to observed ones). Figure 2.2 presents the results, where true overflow estimations are summed up for each structure and each year to compare the proportion of correct values. Lower proportions of correct estimation values are usually associated with observed data having a high standard deviation, which means that the inter-annual variability might be a result of other causes than rainfall variation such as CSO monitoring deficiencies. For example, the years 2007 and 2011 present similar rainfall characteristics in terms of rainfall events frequency and magnitude, but historical recorded CSO events per overflow structure reach 25 on average for the year 2007 and only 11 for the year 2011. As a consequence, the proportion of correct estimations for the years 2011 is much lower, but should probably be associated to data recording deficiencies rather than modelling inaccuracy. The best correlation between observed and simulated values were obtained for the overflow structure associated with the WWTP which is the structure having the best historical data available for comparison. It is believed that with more accurate observed data for the other overflow structures (CSO event monitored at a daily basis rather than every week), a better estimation of CSO frequency might also be obtained. The recent report of Cliche and Saladzius (2018) denoted a drastic increase in CSO frequencies in 2016 compared to the years 2014 and 2015 for the same municipality as our case study. The installation of daily monitoring equipment in 2015 (Personal communication with municipal engineer, 2016) probably explains the increase in overflow events reported by Cliche and Saladzius (2018) and could lead to a better comparison of historical and simulated CSO in the future. Therefore, considering the high uncertainty attached to observed data and the hydrological and hydraulic calibration performed for wet and dry periods (see Section 2.5.3), the model is considered adequate to simulate CSO events.

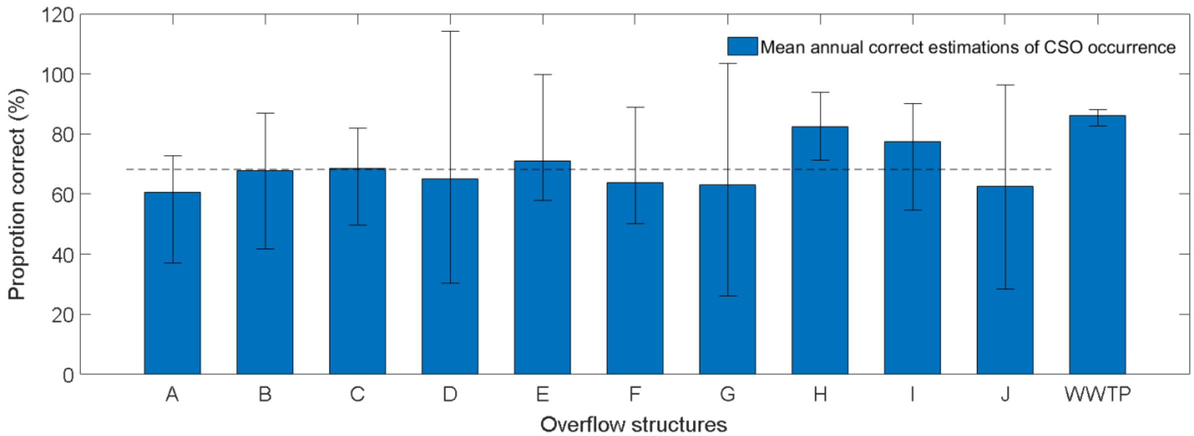

Figure 2.2 Mean of correctly simulated CSO events for selected overflow structures and the WWTP

Note: The error bars show the annual maximum and minimum percentage of correct estimations. The dashed line shows the average annual proportion of correct estimations for the 10 selected overflow structures

2.6.2 Quasi-continuous simulation

Time series of CSO events based on simulation of a sequence of continuous seasonal rainfall data capture the spatial heterogeneity of the system under various rainfall conditions. Table 2.2 presents the average number of CSO spills per year and their associated maximum CSO volumes and average seasonal percentage of rainfall overflowing, which vary considerably from one structure to another. As shown, there is a high gap between simulated numbers of CSOs and the target value of seven CSOs per year as prescribed by the regulations applicable for the case study. Indeed, this network is highly restricted in the volume of wet weather flow that could be effectively transported in the main interceptor. Applying quasi-continuous simulation allows determining a specific CSO volume threshold for each sub-section of the catchment, because the CSO frequency analysis is conducted separately for each structure. Indeed, most of the time the causing rainfall event of the determined CSO volume threshold for each overflow structure is not the same rainfall event. The calculated CSO volume thresholds determined for a maximum number of seven CSO spills per year per overflow structure are presented in Table 2.2 and are considered as reference values for comparison with the following rainfall selection methods.

The application of a longer dataset would better account for extreme values. However, considering that continuous simulation of seasonal rainfall records includes a broad variety of antecedent conditions and rainstorm characteristics, it is believed that this method provides adequate CSO volume estimations for the design of solutions achieving specific CSO control targets. Similarly, Vaes et al. (2001) found that most adequate results for CSO assessment were obtained from simplified conceptual models in combination with continuous long term simulations.

Table 2.2 CSO modelling results under quasi-continuous simulation

Outfall structure	Average number of CSO spills per year	Maximum CSO volume from all years (m^3)	Average annual median CSO volume (m^3)	CSO volume threshold for 7 spills/year maximum (m^3)
A	25	518	33	102
B	62	1,758	114	505
C	35	542	29	125
D	65	8,535	518	2,574
E	54	4,671	298	1,297
F	13	190	26	38
G	58	1,079	83	336
H	63	3,336	235	1,064
I	60	2,413	152	650
J	57	2,786	183	807
Total	494	25,827	1,671	7,498

The impact of using a few years for the analysis of CSO under quasi-continuous simulation was assessed by simulating all possible combination of years among the available nine years of seasonal data for one to nine years-long simulation length. Figure 2.3 shows the median values of the total CSO volume thresholds estimated for the ten structures to achieve the CSO control objective (i.e. maximum of 7 spills per season). Logically, with a larger sample of years used as input data, the rainfall inter-seasonal variability is greater. As a consequence, the determined volume should be greater by accounting for more extreme CSO events. Median values can vary from about 6500 to 7500m^3. Data dispersion is illustrated through error bars which decrease according to the number of years simulated. More specifically, if only one year is simulated among the nine years available, the volume design could be considerably underestimated as the smallest CSO volume threshold could equal 4900m^3, a difference of 35% with the largest value obtained from the simulation of all the available years.

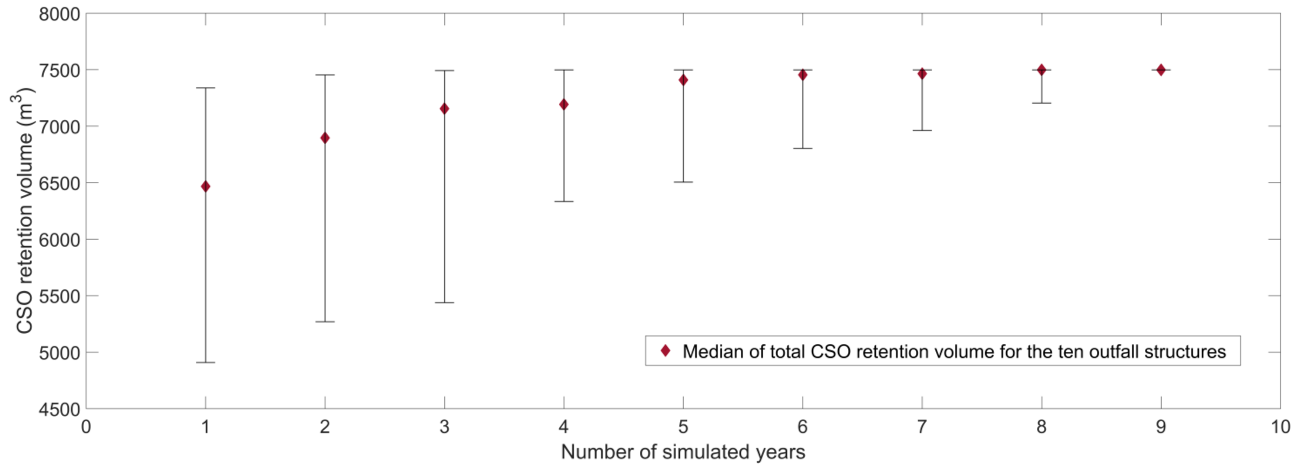

Figure 2.3 Sensitivity to the number of years simulated of the total CSO retention volumes estimated for the ten outfall structures

Another important point raised by this sensitivity analysis, is the difficulty to determine which year(s) should be simulated among the available data. For example, two selection criteria were applied to the available series to determine which year would most likely produce the greatest CSO volumes. Figure 2.4 presents CSO volume thresholds for each structure based on the simulation of the wettest year (2011), as well as the year having the most frequent large (≥30 mm) rainfall events (2015). In Figure 2.4, the CSO volumes obtained are also compared with the results from continuous simulation of seasonal rainfall records and other rainfall selection methods. As shown, the selection of the year having the most frequent large rainfall events provide a more conservative estimation of CSO volume threshold for solution design, because those events are more likely to produce important overflow volumes. Nevertheless, the added value of continuous simulation can only be fully considered when all available data are taken into account rather than reducing the analysis to a single year, because it guaranties obtaining the critical CSO volume for each overflow structure individually among the simulated years.

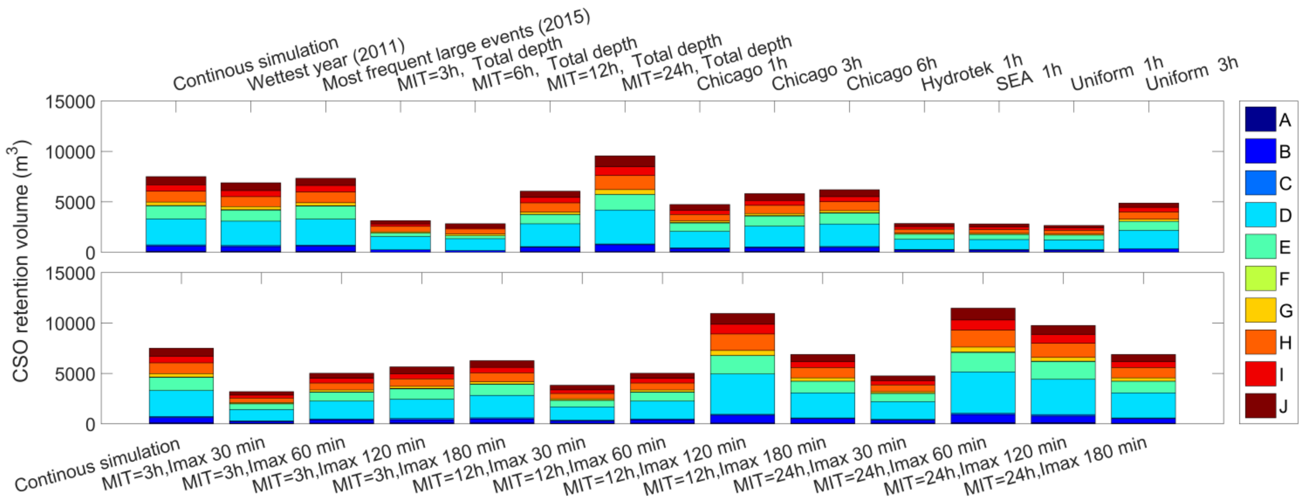

Figure 2.4 Comparison of rainfall data selection methods for determining CSO retention volumes from simulation

2.6.3 Historical rainstorm events

Simulation of specific historical rainfall events was performed using the total rainfall depth per event, and then the Imax over 30, 60, 120 and 180 min from the MIT-separated rainfall series.

2.6.3.1 Historical rainstorms selected based on total rainfall depth

Since four MIT criteria were applied (3, 6, 12 and 24 h) to the rainfall record in order to extract individual rainstorm events, four rainfalls were identified as design storms. Figure 2.4 presents the simulated CSO volumes for each structure under the four rainfall events, along with a comparison with quasi-continuous simulation results and other rainfall selection methods. Except for the value of 24 h, simulation of the maximum annual seventh greatest rainstorm in terms of total rainfall depth underestimated the CSO volumes as compared to quasi-continuous simulation. Even if the simulated rainstorms are characterized by a high total rainfall depth, their extended duration resulted in much lower average rainfall intensities and CSO spilled volumes. For a better assessment of resulting CSO volumes, Figure 2.5 presents the rainfall depth and total CSO volumes for the seventh greatest events determined for each year separately. All these rainstorms are characterized by a large total rainfall depth but have varying durations and average rainfall intensities. As illustrated, similar rainstorms in terms of total rainfall depth led to highly variable CSO volumes. Results showed no linear relationship between total rainfall depths and CSO volumes, explaining partly why results presented in Figure 2.4 are considerably below the ones estimated from quasi-continuous simulation.

Yu et al. (2013) also found that moderate rainstorms, in terms of rainfall total depth, have poor correlation with CSO occurrence. According to these authors, rainstorms of high and low depths better correlate with CSO occurrence or non-occurrence, respectively, based on the analysis of 117 rainfall events extracted from a one year long record in Tokyo (Japan). Similarly, Gooré Bi et al. (2015a) observed high correlations between rainstorm total depth and CSO event pollutant load by analysing the correlation between rainfall variables and water quality indicators monitored during CSO events.

2.6.3.2 Historical rainstorms selected based on rainfall maximum intensity

The four MIT-separated rainstorms series were then used for design rainfall event selection based on Imax over 30, 60, 120 and 180 min. Figure 2.4 presents the simulated CSO volumes for all the seventh greatest rainstorms for various Imax durations and MIT values. However, because the same critical events were identified for both MIT=3 h and 6 h, only the results obtained from the MIT=3 h series are presented in order to avoid redundancy. As shown, estimated CSO threshold volumes are either higher or lower than the volumes determined by continuous simulation of seasonal rainfall records. Schütze et al. (2002) indicated that information on CSO frequency from event-based simulation may be highly inaccurate for non-linear systems, which seems to be the case here.

As a consequence of the disputable linearity between CSO volume and rainstorm total depth or intensity, CSO volume threshold calculations based solely on the total depth or intensity of rainfall events would not guarantee adequate volume estimations for design.

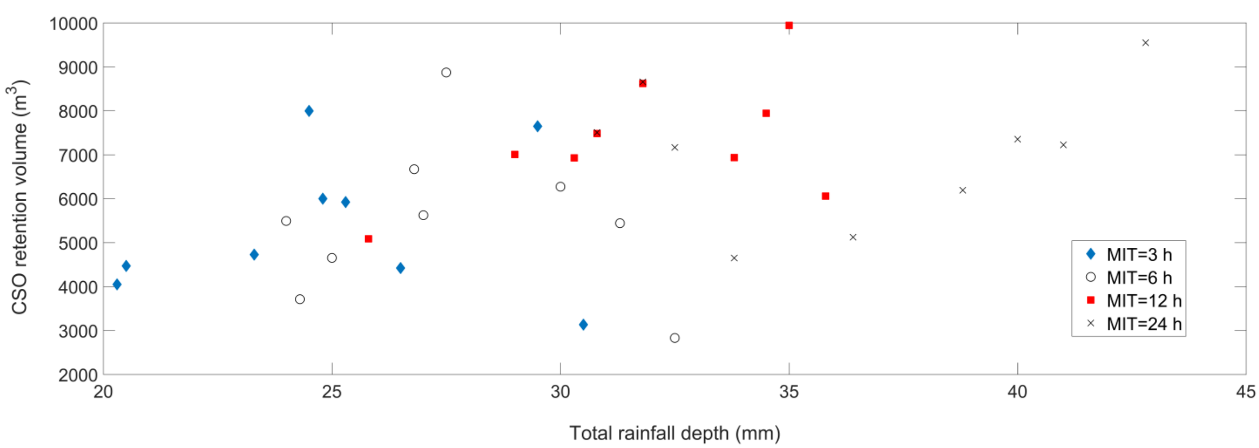

Figure 2.5 **Total CSO retention volumes for the ten outfall structures based on the annual 7th greatest rainstorms in terms of total rainfall depth and MIT=3, 6, 12, and 24 h**

2.6.4 IDF derived storms

The last assessed method focussed on event-based simulation of synthetic design storms. The analysis of daily maximum rainfall intensities record permitted to characterise IDF relationships having an estimated recurrence of seven times per year. Cumulative rainfall depths for the three Chicago storms are respectively 15.6, 20.1 and 23.5 mm. For the other tested standardised hyetographs, a cumulative rainfall depth of 10.5mm was applied for the 1 h-duration and 19.0mm for the 3 h-duration, both determined by frequency analysis for a return period of 1/month.

Figure 2.4 presents the resulting CSO volumes, compared to those obtained from other rainfall selection methods. The event-based results were slightly lower than the CSO volumes determined by quasi-continuous simulation in the case of Chicago storms of 3 or 6 h-duration; whereas single IDF value derived storms noticeably underestimated CSO volume thresholds. Single 1 h-IDF value derived storms all had a different time distribution of the rain, but led to similar simulated CSO volumes, even in the case of a uniform rainstorm. Even if the uniform 3 h-storm has the same duration as the time of concentration of the catchment, it still underestimated the total CSO volume compared to quasi-continuous simulation. When simulating single events IDF derived storms, the results show that the total volume of the design storm has an impact on the resulting CSO volumes whereas the hyetograph shape has almost none.

Differences in volume obtained from synthetic events compared with quasi-continuous simulation can be explained partly by the uncertainty associated with the application of IDF derived design storms. Drawbacks of applying design storms for CSO control design include the necessity to decide on the duration of the simulated event and its return period (Watt and Marsalek, 2013).

For comparison, Calabrò (2004) denoted that applying Chicago and triangular shape storms having durations similar to the time of concentration of the catchments, resulted in higher overflow discharges to receiving water bodies compared to rectangular storms and longer storms. On the other hand, Vaes et al. (2001) specifically indicated that the non-linearity of the system response (when the outflows are not directly linked to the storage capacity of the catchment) increased for design storms having a high recurrence compared to lower recurrence ones, thus limiting application of design storms for CSO control. Guo (2001) concluded that design storms provided simulation results generally close to continuous simulation when sizing flood control detention ponds for the city of Chicago, Illinois. The design criteria of his study was however based on large return periods (100 years), which is quite different from our small return period criterion. Müller et al. (2017) found that rainfall events' asymmetry has an impact on CSO statistics such as discharged volume, concluding on the importance that synthetic time series should represent observed rainfall asymmetry.

2.6.5 Comparison of simulated results per overflow structures

The CSO volumes threshold simulated under the different rainfall data selection methods compared previously were lastly analysed more thoroughly per overflow structure. The aim was to evaluate if the local characteristics associated to each structure could have an influence on the relative performance of one method compare to another. Table 2.3 provides local characteristics of the ten assessed overflow structures as well as the minimum and maximum simulated CSO volume threshold. As shown, larger tributary area or higher impervious area coverage does not necessary lead to higher overflows in terms of maximum simulated volumes by the assessed rainfall selection methods. The number of overflows structures located upstream and the regulated maximum flowrate capacities seem to help in reducing overflow volume. For example, structure J has the highest tributary area and a relatively high imperviousness, but its maximum simulated overflow volume threshold is almost the same as for overflow structure B, which is located at the outlet of a much lower area but has limited regulation capacity.

Figure 2.6 shows for all overflows structures the percentage difference in simulated CSO volume thresholds of each method with the results from quasi-continuous simulation. It could be seen that the overflow structures B, D, E, G, H, I and J follow generally the same tendency, i.e. have similar increasing or decreasing CSO volume trends for the same assessed method whereas the overflow structures A, C and F are generally outliers. These three structures are associated to the smallest overflow frequencies and volumes (see Table 2.2). Interestingly, the remaining structures have local characteristics varying greatly but that did not seem to impact much the general trends of the results.

Figure 2.6 also permits to highlight that simulating a continuous record of just one season (the wettest year or the year having the most frequent large rainfall events) provide an estimation of critical CSO volume closer to those obtained under quasi-continuous simulation of the full record of years available (% difference in volumes closer to zero) compared to event-based simulation results and with almost no influence from the structures local characteristics. All the remaining methods consisting of simulating one single historical or synthetic rainfall event do perform not as well and the individual results for each overflow structure are generally more widely distributed. Finally, by looking at the methods falling between the ± 25% marks indicated by dashed lines in Figure 2.6, it could be noticed that the Chicago storms of 3 or 6 h as well as the historical rainstorms selected based on rainfall maximum intensity over longer durations (180 min and sometimes 120 min) provide more acceptable results than the remaining methods for a majority of the overflow structures.

Table 2.3 Local characteristics of overflow structures

Overflow structure	Maximum capacity of regulator upstream (10^{-3} m^3/s)	Tributary area (ha)	Impervious area (%)	Number of overflow structure upstream	Concentration time (HH:MM)	Minimum simulated CSO volume from all assessed methods (m^3)	Maximum simulated CSO volume from all assessed methods (m^3)
A	3.4	9.99	25.5	1	01:40	0	119
B	4.3	10.68	25.4	1	00:30	167	814
C	3.6	3.80	19.4	0	00:30	0	147
D	25.1	37.49	32.6	0	01:00	963	4110
E	23.5	32.86	20.8	1	00:45	293	1929
F	5.5	0.47	100	0	01:00	0	49
G	30.8	40.26	33.3	1	01:00	96	497
H	10.1	12.68	37.3	0	01:00	374	1684
I	11.4	9.77	31.2	0	00:45	143	1005
J	77.0	93.36	27.3	3	02:15	242	1167

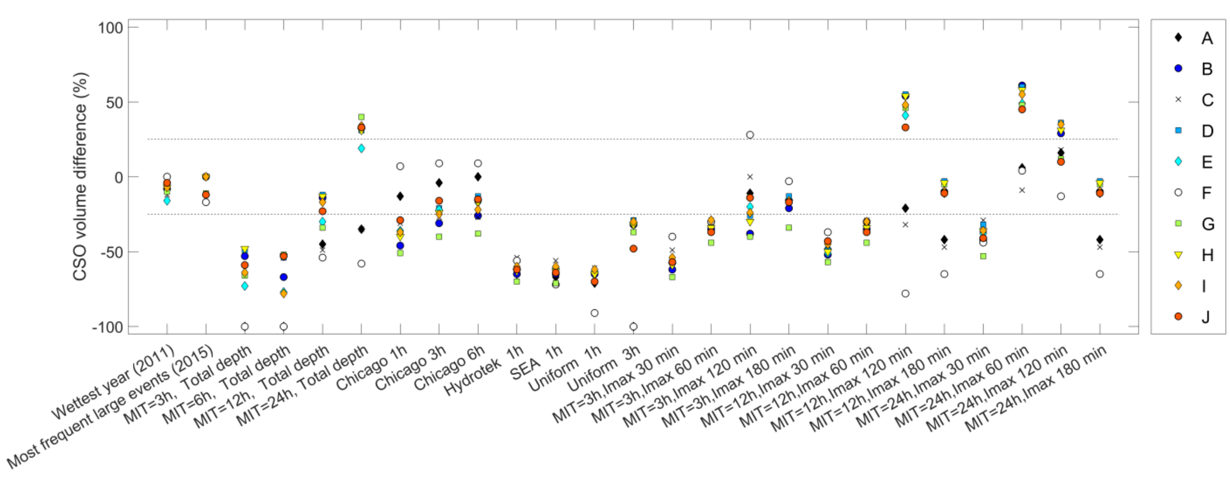

Figure 2.6 CSO volume thresholds difference of all rainfall selection methods with quasi-continuous simulation per outfall structures

Note: The dashed lines show the limits for a volume difference of ± 25 %

2.7 Conclusion

This study addressed the knowledge gaps on the proper use of available rainfall data for sizing CSO reduction solutions. Actual rainfall data selection methods for CSO analysis and management were described and include continuous simulation, synthetic design storms, historical rainfall events, and rainfall depth threshold. Thereafter, three rainfall data selection methods for volume design of stormwater control solutions to comply with a specific maximum annual CSO frequency were compared.

The first method was quasi-continuous simulation of the nine years of available seasonal precipitation record, which permitted to obtain CSO volume threshold values for each overflow structures separately. However, reducing the number of years in the analysis rapidly impacted the estimated volumes due to the loss of inter-annual variability of rainfall data. Alternatively, continuous simulation of the seasonal record of a single year having the most frequent rainstorms exceeding a specific total rainfall depth can give a good approximation of CSO volumes for solution design and without distinction of overflow structures local characteristics.

For the second rainfall selection method, the design rainstorms were identified based on either their total rainfall depth or their maximal rainfall intensity for durations of 30, 60, 120 or 180 min. CSO volume thresholds were obtained under event-based simulation of the selected critical events. The high inter-events variability of the simulation results demonstrated the non-linearity of CSO volumes with the rainfall event characteristics (total depth or maximum intensities) and its disputable applicability as design criteria for CSO control.

Finally, simulated CSOs under Chicago storms derived from rainfall daily maxima resulted in an underestimation of CSO volume thresholds. On the other hand, the simulation of other standard synthetic storms (Hydrotek, AES type 2, and uniform 1 h storms) having a total rainfall volume equivalent to a single IDF value underestimated more drastically the CSO volumes. Under single event simulation for CSO control purpose, design storms involving multiple IDF values such as Chicago storms should be prioritized. However, it is still difficult to determine the best design storm duration as this factor could considerably affect the results.

Because CSO processes are site specific and sensitive to a variety of rainfall characteristics, it is difficult to identify one design event that will ensure compliance with specific annual CSO frequency for design guidelines. Therefore, it is recommended that the use of design rainfall events should be restricted to preliminary assessment of CSO control measures, whereas the final solution sizing should be reviewed under continuous simulation or quasi-continuous simulation to ensure appropriate volume estimations. CSO analysis would definitely benefit from larger rainfall datasets.

Further work could focus on integrating CSO volume calculations with solution type, location and operation on a river basin scale for refining CSO control design. Moreover, as the number of years included in the analysis impact the CSO retention volume, a method should be developed to extrapolate the design volume with a safety margin according to the number of years available for the analysis. Finally, the impact of applying the same rainfall selection method, but considering heterogeneous rainfall data compared to homogeneous rainfall data over the study area, should be assessed.

2.8 Acknowledgments

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3 OPTIMISATION DU CONTROLE EN TEMPS REEL ET DE LA CONCEPTION D'INFRASTRUCTURES VERTES ET GRISES POUR UNE ATTENUATION RENTABLE DES DÉBORDEMENTS DE RÉSEAUX D'ÉGOUT UNITAIRES

Optimization of Real-Time Control with Green and Grey Infrastructure Design for a Cost-Effective Mitigation of Combined Sewer Overflows

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Contribution des auteurs :

Tous les auteurs ont contribué à la conceptualisation de l'étude et au développement de l'approche méthodologique. Les première et deuxième auteures, Marie-Ève Jean et Camille Morin, ont effectué le travail de modélisation et d'analyse des résultats. Marie-Ève Jean était responsable de la rédaction du manuscrit et tous les auteurs ont contribué à la révision du document.

Lien entre l'article ou les articles précédents et le suivant :

L'article précédent a permis d'évaluer l'impact de différents types de données pluviométriques sur l'estimation des volumes de rétention nécessaires au contrôle des DRU pour le respect de fréquences cibles de débordement par saison. Les résultats ont montré que l'utilisation de pluies synthétiques, telles que la pluie de Chicago, dérivée à partir de plusieurs points d'une courbe Intensité, Durée et Fréquence (IDF), fournit des résultats acceptables par rapport aux autres pluies historiques ou synthétiques analysées. Toutefois, cet article a recommandé que l'utilisation des pluies de conception doit être limitée à la conception préliminaire des solutions de contrôle des DRU et que leurs dimensionnements finaux doivent être validés avec la simulation en continu de données pluviométriques. Ces recommandations ont directement été appliquées dans le cadre méthodologique développé dans le présent article, ce qui permet de faire l'optimisation de manière itérative à l'aide de pluies de conception et de simulations en continu d'une série pluviométrique historique afin d'intégrer la conception de différentes solutions pour le contrôle des DRU.

3.1 Key Points

- Green and grey infrastructure design and real-time control rules optimization are applied to improve management of combined sewer overflows
- Simulations and optimizations are performed on a case study watershed for two design storms and for a period from 2006 to 2015
- Integration of real-time control with green and grey infrastructure is the most cost-effective option given performance uncertainty

3.2 Abstract

An innovative optimization-simulation framework is applied to a case study of the Province of Quebec, Canada, to optimize the spatial distribution of green infrastructure (GI), the capacity and location of grey infrastructure and the parameters specific to real-time control (RTC) operating rules of a sewer system for reducing combined sewer overflows (CSOs) frequency and volume. GI, grey infrastructure and RTC are applied either individually or in integration through eight optimization scenarios which are simulated over a nine-year period of historical rainfall data. Among all scenarios, spatial optimization of GI with RTC leads to maximal CSO volume reduction (98%) and is the most cost-effective option analyzed (70$/m^3 of seasonal average CSO reduction compared to 140$/m^3 for the scenario involving grey infrastructure alone). However, it requires a high GI implantation level and the CSO frequency under this scenario is sensitive to varying GI design parameters. The findings suggest that the best alternative for CSO control is the integration of the optimization of green and grey infrastructures with RTC as it still provides high CSO volume reduction (95%) and remains a cost-effective solution (90$/m^3 of CSO reduction), while providing robustness under cost and design uncertainties.

Keywords: Urban water solution design; Cost minimization optimization; Hydrological and hydraulic simulation; Green infrastructure; Source control measure; Sustainable urban drainage systems; Particle swarm optimization; Continuous rainfall simulation

3.3 Plain Language Summary

An innovative method is applied to a case study of the Province of Quebec, Canada, to optimize the spatial distribution of green infrastructure (GI), the volume and location of storage facilities and the operational rules of a smart control strategy of a sewer network for reducing the number and volume of overflows of untreated wastewater (CSO) during rainfall events. GI, storage facilities and smart control strategy are applied either individually or in different combinations through eight different scenarios. Spatial optimization of GI with smart control leads to maximal CSO volume reduction (98%) at the lowest cost (70$/m^3 of seasonal average CSO reduction compared to 140$/m^3 for the scenario involving storage facilities alone) as compared to other options, but requires a high GI implantation level and the GI design parameters can considerably impact its performance. The results suggest that the best alternative for CSO control, providing robustness under cost and design uncertainty, is the integration of the optimization of GI and storage facilities with smart control as it still provides high CSO volume reduction (95%) and remains a cost-effective solution (90$/m^3 of CSO reduction).

3.4 Introduction

Combined sewer networks are sewage systems that collect both wastewater and stormwater in the same pipe network. These systems were commonly constructed in many cities of the developed and developing world up to the mid-twentieth century (Burian et al., 1999). Due to the high variability in stormwater volume and flowrate that characterize urban areas, the wastewater treatment capacity and/or transport capacity of these networks were not designed to cope with the magnitude of most rainfall events, excepting the most frequent, smaller ones. This type of combined system thus permits overflows or spill of a mix of wastewater and stormwater to the environment; these are known as combined sewer overflows (CSOs). CSOs have been recognized as one of the major causes of degraded water quality in urban rivers (Bi et al., 2015; Passerat et al., 2011), contributing to the degradation of aquatic habitats, increasing drinking water treatment cost and reducing the attractiveness of aquatic recreational activities (Madoux-Humery et al., 2015). The environmental, economic and social impacts of CSOs are associated with corresponding policies to limit CSO event frequency, volume and/or pollutant load (Tibbetts, 2005; Osseyrane, 2014). For instance, in the Province of Quebec (Canada), since 2014, all sewer extension projects must demonstrate compensatory actions to avoid increasing the seasonal frequency of CSO events (MELCC, 2014). In addition, the government plans to reduce CSO frequency down to a fixed limit determined for each receiving water body for the 2040s horizon. In this context, municipal actions are required to cope with CSO regulations in the most cost-efficient manner.

Among the existing solutions available for controlling urban runoff and resulting CSO impacts to the environment, many researchers are promoting source control of stormwater, including Green Infrastructure (GI) practices in contrast with traditional grey infrastructure practices involving the construction of large-scale retention infrastructure (Alves et al., 2016; Tavakol-Davani et al., 2015; Joshi et al., 2021). A variety of terminologies are associated with source controls, including GI, low impact development (LID), Source control measures (SCM), Sustainable urban drainage systems (SUDs), etc., but all these terms generally mean that runoff is managed as close to the source as possible, with the goal of replicating predevelopment conditions (Fletcher et al., 2015). Common source control measures include bioretention cells, rain gardens, permeable pavement and green roofs which are implemented to capture and treat runoff from surrounding impervious surfaces or simply to reduce the area of impervious surfaces. These approaches are recognized for their numerous transversal benefits, such as improving the urban landscape aesthetic and natural water balance, providing some water treatment through natural processes and reducing the community's vulnerability to climate change (Dagenais et al., 2014). In general, these infrastructure practices involve infiltration, retention or a combination of both processes for accumulating runoff, before releasing it more gradually in the network or through infiltration and evaporation losses in the environment (Eckart, 2017).

Different studies assessed the potential of applying a large number of GI units at the watershed scale for reducing CSO impact. In particular, many studies demonstrated CSO volume reductions (Mailhot et al., 2014; Patwardhan et al., 2005; Radinja et al., 2018; McGarity et al., 2017; Joshi et al., 2021, Torres et al., 2018), or both CSO volume and frequency reductions (Alves et al., 2016; Lucas and Sample, 2015). Moreover, CSO control can be improved under high implementation level of GIs (Autixier et al., 2014; Chaosakul et al., 2013; Smullen et al., 2008; Stovin et al., 2013) or when grey infrastructures (i.e. storage tanks) are combined with GIs (Alves et al., 2016, Dong et al., 2017; Montalto et al., 2007; Liao et al., 2015, Fu et al., 2019; Tavakol-Davani et al., 2016). A few authors also applied various optimization techniques to quantify and locate GI practices at the lowest cost possible while mitigating peak flows in combined sewer networks (Sebti et al., 2016) or CSO volumes (Fu et al., 2019; Joshi et al., 2021; Torres et al., 2018). In general, past studies found that GI leads to reductions in the investment costs for CSO control as compared to grey infrastructures (Joshi et al., 2021, Lia et al., 2015; Montalto et al., 2007).

The use of real-time control (RTC) techniques with the aim of improving the use of existing sewer network capacity for CSO control have also been largely studied in the past (Schutze et al., 2004). RTC management involves dynamic control of the network infrastructure based on real-time measurements or predictions of process variables, such as rainfall intensity, water levels, and flowrates, amongst others. RTC strategies can be developed to meet either local or global performance objectives and can rely on various control algorithms such as rule-based derived methods (i.e. if-then-else rules) or more complex optimization-based approaches (i.e. model predictive control) (Lund et al., 2018; García et al., 2015). RTC can also be reactive if only real-time measurements of the current state of the system are considered as the input variables or predictive if rainfall forecasts are also included as an input of the decision rules (Shishegar et al., 2018). The scientific literature reports that RTC management is a cost-efficient solution for CSO volume and frequency reduction, both from the perspective of real-world applications (Entem et al., 1998; Fuchs and Beeneken, 2005; Pleau et al., 2005; Seggelke et al., 2013) and theoretical studies (Dirckx et al., 2011; Joseph-Duran et al., 2018; Kroll, 2019; Maiolo et al., 2020; Nielsen et al., 2010).

As suggested by Piro et al. (2019), RTC and GIs are the newest and most adequate techniques to alleviate urban drainage problems. Indeed, a few research works were conducted to evaluate the joined impact of applying RTC on the network and distributing GI over the watershed area; they showed improved CSO volume reductions (Frehmann et al., 2002, Altobelli et al., 2020) and improved cost effectiveness (Frey et al., 2013) under the joined solutions scenarios. More recently, it has been suggested that source control measures performance could largely benefit from RTC technologies for improving operational control on site (Xu et al., 2020a; Brasil et al., 2021). More particularly, studies demonstrated greater CSO volume reductions (Lund et al., 2019; Oberascher et al., 2021a), or both CSO volume and frequency reductions (Lewellyn, 2018; Lucas and Sample, 2015) when GI are dynamically controlled compared to passive GI design.

Whereas previous studies highlighted the potential of optimizing the spatial distribution of GI for CSO abatement, and the added benefit of combining RTC and grey infrastructure within the network or RTC and GIs on site, only a few research works analyzed the combined impact of RTC of the network with GI. More importantly, none of them considered the impact of RTC of the network while optimizing the spatial distribution of GI.

This research was conducted with an overarching goal of integrating the optimization of RTC, GI spatial distribution and grey infrastructure design volumes to reduce CSO frequency and volume, and simultaneously reduce costs. The hypothesis guiding this research work is, on one hand, the fact that RTC decisions are greatly influenced by the quantity, timing and spatial distribution of the runoff entering the combined sewer network and, on the other hand, that the impact of large-scale implementation of green and grey infrastructure could be maximized if they are located where excess runoff cannot be managed by RTC alone. More specifically, this paper aims at 1) describing how integrating rule-based RTC with green and grey infrastructure spatial optimization at the watershed scale has an impact on CSO frequency and volume reduction in comparison to their individual application, and 2) assessing how the cost necessary to reach specific CSO frequency targets could be reduced with the proposed RTC- green and grey infrastructure optimization framework.

3.5 Methodology

3.5.1 Case study and modeling tool

This research was conducted for a sub-area of the combined sewer network of a medium-sized municipality located in the Province of Quebec, Canada. The case study was modeled using PCSWMM (CHI, 2020). The sub-area totalizes 181 ha (divided in 44 sub-catchments), 15.2 km of pipes (diameters varying from 0.2 m to 1.5 m) and 11 overflow structures with combined and pseudo-separated sewer sub-catchments (i.e. sub-catchments where only flat roofs are drained to the combined sewer pipes). The average imperviousness of the study area is 30%, with individual sub-catchment imperviousness varying from 12 to 100%. Some portions of the network have steep slopes (up to 8.5%), whereas the interceptor is generally flat (with slopes varying from 0.1 to 2%). Under current conditions, the network experiences severe and frequent overflows throughout the year. A description of the model calibration and validation process for the full network can be found in Jean et al. (2018). Even if the research was based on a sub-area of the entire municipality, inflows from the upstream part of the network were injected in the model upstream node to mimic the real catchment total inflows.

Static regulators are currently located downstream of 10 of the 11 overflow structures (O-01 to O-10 in Figure 3.1) to restrict the flowrate reaching the interceptor toward the wastewater treatment facility. The interceptor is fully saturated with upstream inflows. Therefore, this research considered increasing the capacity of the interceptor and regulators to represent future upgrades of the system. This modified state of the network was considered as the base case situation to ensure that the performance of the tested solutions in the study area is not affected by uncontrolled upstream inflows. From the 11 overflow structures distributed across the network, six are associated with CSO problems and were further analyzed.

In the Province of Quebec, CSO regulation is based on a maximal seasonal frequency from May to November. The provincial legislation for the 2040s horizon imposes a maximum of seven CSO spills per overflow structure and per season.

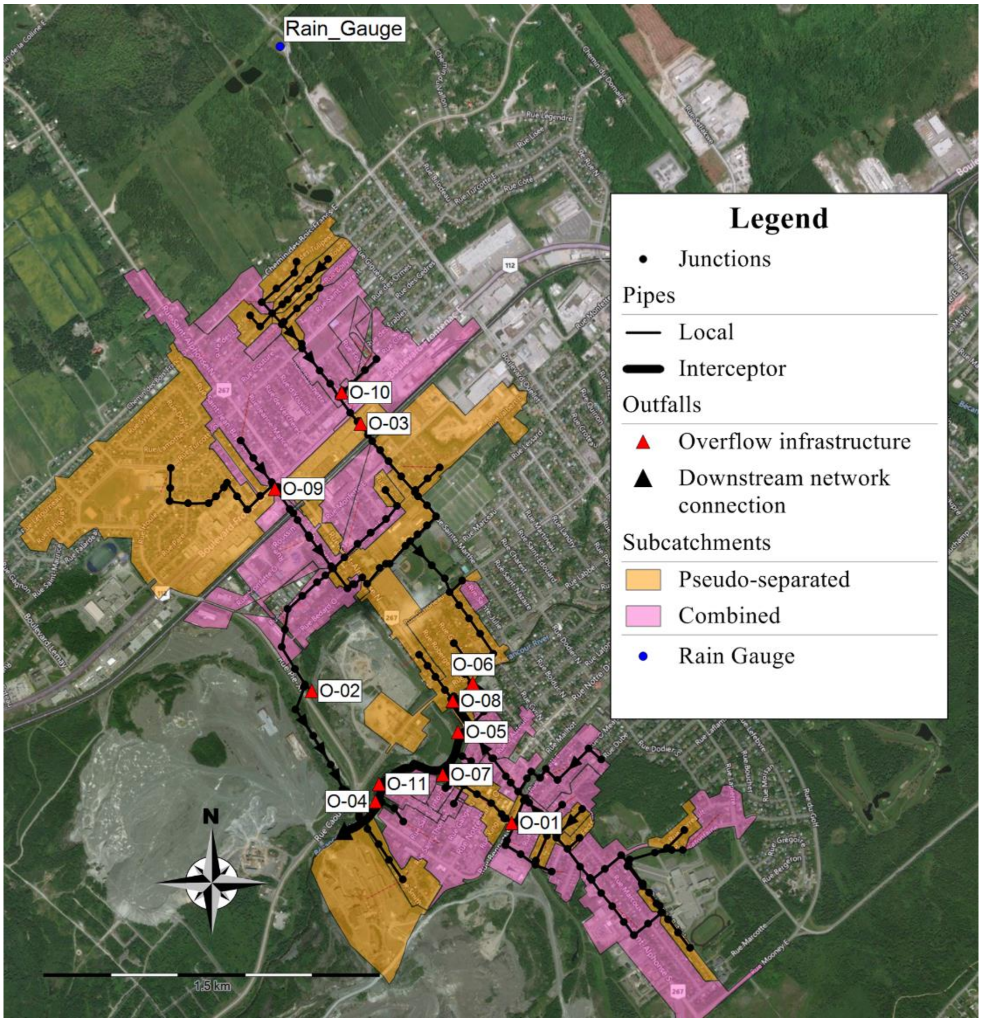

Figure 3.1 Case study sub-area

Note: the six overflow structures O-01 to O-06 are exceeding their CSO frequency limit

3.5.2 Rainfall data

3.5.2.1 Historical rainfall data

Continuous rainfall data recorded every 5 minutes over 9 years (2006-2009 and 2011-2015) were available from the municipal rain gauge station located less than 1 km north of the case study area. Only the wet weather months from May to November were simulated for CSO control as those are the months for which CSO maximal frequency targets are applicable in Quebec. Rainfall events are frequent, with seasonal rainfall depth ranging between 730 to 960 mm. Through the selected years, maximal rainfall intensity over 5 minutes varied from 60 to 130 mm/h and the average rainfall intensity per event from 3.5 to 5.2 mm/h. More details on the historical rainfall data set are available in Jean et al. (2018).

3.5.2.2 Design rainfall events

The optimization routine was first deployed for various scenarios using design rainfall events. The aim was to apply rainfall events that would correspond to the target CSO frequency (7 CSOs/season) as optimization design input. The different scenarios were afterwards submitted to continuous simulation of the available 9 seasons of rainfall data. Indeed, as demonstrated in Jean et al. (2018), it is not possible to determine one single rainfall event that would produce the same effect on all of the outfall structures in terms of CSO volume and frequency and, thus, continuous simulation is essential to refine the designs and validate their performance.

Two design rainfall events were used in the optimization process. The first design rainfall event is based on the synthetic Chicago rainfall distribution for high frequency intensity-duration-frequency (IDF) curves and a return period of 1/month (which is equivalent to the target frequency of 7 CSOs/season), as proposed in Jean et al. (2018). The second selected design rainfall event is a historical rainfall event that occurred on 30 July 2015. It was selected because it produced a CSO event volume approximately equal or above the maximum of the seventh largest annual CSO event volume among the nine years simulated for all the CSO outfalls, as determined from the continuous simulation of the base case scenario. Therefore, this historical event was considered to be representative of the target frequency of 7 CSO spills/season. The temporal distribution of the synthetic and historic rainfall events is shown in Figure 3.2. It should be noted that the historical rainfall data are simulated using a 5 min interval, whereas the Chicago storm is based on 10 min interval. Both events have similar total duration (between 180 and 200 min) and total rainfall depth (between 20 and 25 mm) but, as shown in Figure 3.2, the Chicago storm has a much higher maximal intensity.

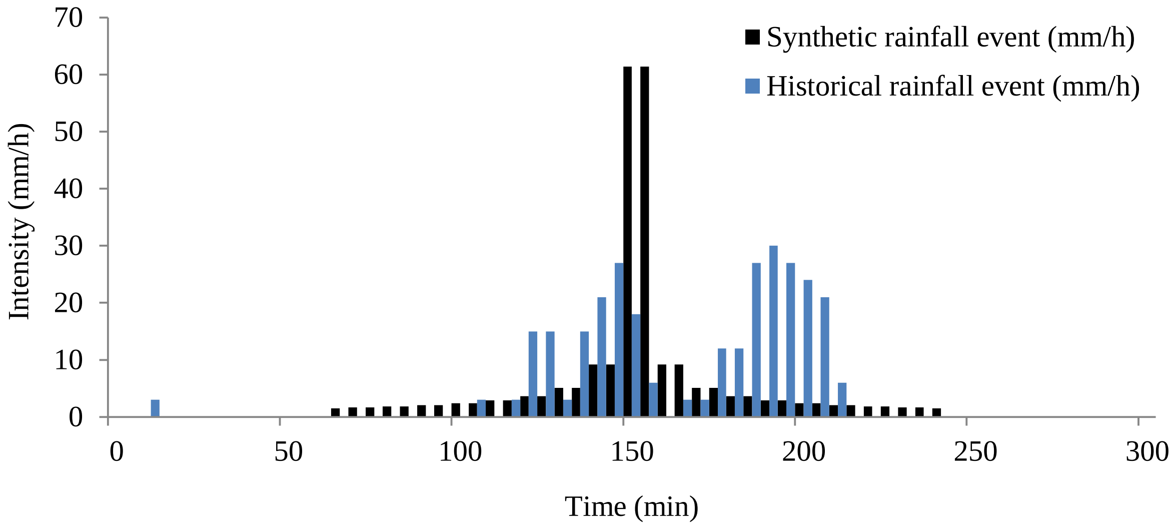

Figure 3.2 Design rainfall events temporal distribution

3.5.3 Optimization framework

The methodology relied on an optimization tool, called "Integrated Planning and Optimization Program" (iPOP). This software combines SWMM 5.1 (Rossman, 2015) for hydrological/hydraulic simulations and Parallel Swarm Oriented-Particle Swarm Optimization (PSO-PSO) for the optimization of any SWMM input parameter (such as LID design values, volume of storage units and control rules variables).

The workflow diagram of the optimization routine is shown in Figure 3.3. Input data include the design rainfall event, described previously, and the penalty weights, cost functions and optimization objectives which are presented in section 3.5.4. In terms of processes, the optimization routine was completed in two steps, followed by a validation step. The *1st optimization step* was conducted with iPOP to optimize, either jointly or separately depending on the assessed scenarios: i) the number and location of bioretention cells (i.e. GIs), ii) the number, location and volume of off-line storage tanks (i.e. grey infrastructures), and iii) the *if-then-else* rule parameters for partial closure and opening of gate settings at each RTC control point (i.e. replacement of the actual regulators by RTC sluice gates).

The *2nd optimization step* included two iterative loops. The first loop consisted of a manual adjustment of the gate setting parameters to complete the formulation of the RTC rules. The rules final setting of the gate opening state was conducted manually because they should not overlap the iPOP optimized values for the gate-closing state. The second iterative loop permits to adjust manually the total number of bioretention cells required to meet the optimization objectives. The procedure consisted of verifying if any bioretention cell could be withdrawn without exceeding the downstream capacity of the network or causing CSO volume when taking into account the complete optimized RTC operating rules. The 2nd optimization step could have been avoided if the gate-closing parameters would have been optimized during the 1st optimization step. However, opening and closing rules overlapping could potentially not have been avoided in this way.

Finally, as the optimization problem was solved for one of the two rainfall events, the solution was validated through continuous simulation of nine years (2006-2009 and 2011-2015) in SWMM (*validation step*). The RTC parameters optimized previously for a given scenario were kept unchanged during the validation step. For the scenarios involving grey infrastructure, a third iterative loop was conducted after validation to manually refine the total volume of the storage units to make sure that the CSO frequency target was achieved for each outfall with the lowest storage volume possible.

In the case of the scenarios integrating green and grey infrastructure with RTC, all the aforementioned steps in Figure 3.3 were conducted except those steps outlined in blue, which were bypassed for the scenarios involving static management. Similarly, the steps identified in grey were omitted when no storage tanks were being implemented, and the steps identified in green were bypassed for scenarios which did not involve GI.

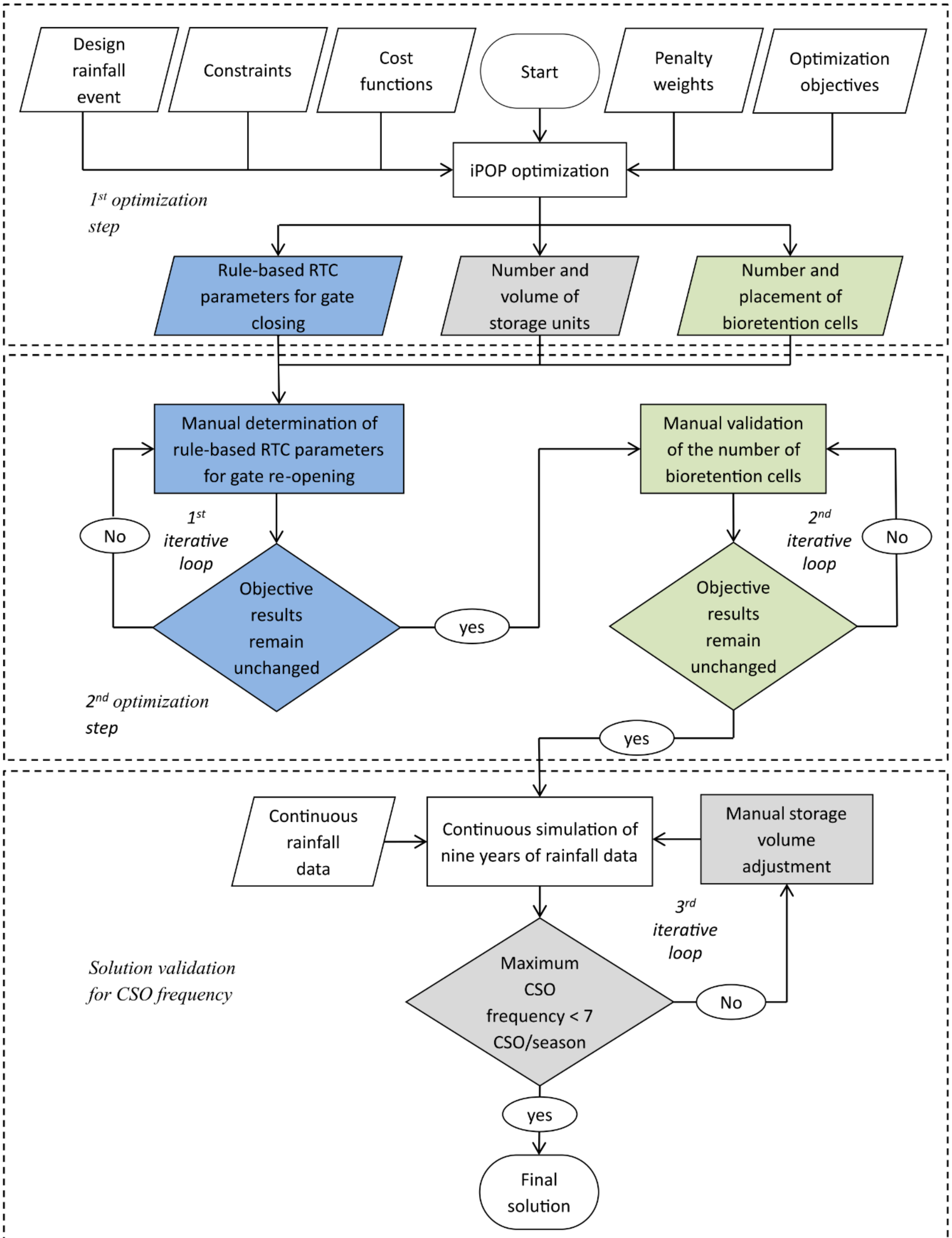

Figure 3.3 **Design Optimization routine for integrating rule-based RTC with green and grey infrastructure design**

Note: The blue steps were omitted when the optimization routine was applied to the static management scenarios and the grey and/or green cells were omitted when the scenarios did not involve grey or green solutions respectively

3.5.4 Optimization problem

The optimization problem consisted of defining the values of the following variables:

- Number of bioretention cells per sub-catchment ($\mathrm{BIO_{SC}}$)
- Volume of potential underground off-line storage units ($\mathrm{VOL_s}$) upstream of each problematic outfall (O-01 to O-06 in Figure 3.1)
- Rule-based RTC parameters for each of the potential nine control points ($\mathrm{D1_{CP}}$, $\mathrm{D2_{CP}}$, $\mathrm{G1_{CP}}$)

The values of the optimization variables were defined to minimize the objective function presented below, while fulfilling the following constraints. The hydraulic constraints attached to the laws of conservation of mass and momentum are not detailed here as they are embedded in the SWMM model and can be found in Rossman (2015).

Objective function:

$$\sum_{SC=1}^{n_{SC}} BIO_{SC} \text{ x } \mathrm{B}_{BIO} \text{ x } \mathrm{A}_{BIO} + \sum_{s=1}^{n_{STO}} (\mathrm{A}_{STO} + VOL_s \text{ x } \mathrm{B}_{STO}) + \sum_{i=1}^{n_{outfall}} W_i \text{ x } max(0, CSOvol_i - Target_i)$$
$$+ \sum_{D=1}^{n_{Node}} W_D \text{ x } \max(0, SurDepth_D - Target_D) + W_F \text{ x } max(0, Q_{cap} - Target_F)$$

Equation 3-1

Constraints:

$$0 \le BIO_{SC} \le BIOmax_{SC} \;\forall\; l = 1, 2, \dots, n_{SC}$$

Equation 3-2

$$0 \le VOL_S \le VOLmax_S \;\forall\; S = 1, 2, \dots, n_{STO}$$

Equation 3-3

$$0 \le D1_{CP} \le Diam_{CP} \;\forall\; CP = 1, 2, \dots, 9$$

Equation 3-4

$$0 \le D2_{CP} \le (D1_{CP} - 0.1) \;\forall\; CP = 1, 2, \dots, 9$$

Equation 3-5

$$Fmin \leq G1_{CP} \leq 1 \ \forall \ CP = 1, 2, \dots, 9$$

Equation 3-6

Where:

n_{SC} = Total number of combined sub-catchment (25 sub-catchments)

BIO_{SC} = Number of bioretention cell units of 10 m^2 for each sub-catchment SC

B_{BIO} = Capital cost per unit area of bioretention cell (CAN \$/m^2) = 300 CAN \$/m^2

A_{BIO}= Area occupied by one bioretention cell unit (m^2) = 10 m^2

n_{STO} = Total number of storage units (varies from 0 to 6)

VOL_s= Volume for each storage unit (m^3)

A_{STO} = Minimal cost per storage unit (CAN \$) (3,000,000 CAN \$)

B_{STO} = Supplementaty capital cost per unitary stored volume (CAN \$/m^3) (600 CAN \$/m^3)

$n_{outfall}$ = Total number of outfall structures

W_i = Cost weight factor associated to a given outfall infrastructure i for one unit of $CSOvol_i$ above the $Target_i$ (50,000,000 CAN \$/m^3)

$CSOvol_i$ = Simulated total CSO volume for a given outfall infrastructure i as taken from the status report of SWMM (1,000 x m^3);

$Target_i$ = Target CSO volume associated with a given outfall structure i (0 x 10^3 m^3)

n_{Node} = Total number of selected nodes to estimate network surcharges located downstream of each outfall structure (8 nodes)

W_D = Cost weight factor associated to a given selected node D for one unit of $SurDepth_D$ above the $Target_D$ (50,000,000 CAN \$/m)

$SurDepth_D$ = Simulated maximal node depth value for a given selected node D as taken from the status report of SWMM (m)

$Target_D$ = Target node depth associated with a given selected node D to avoid excessive surcharge (m) (generally 0.15 m above the downstream crown height)

$\mathrm{W_F}$ = Cost weighting factor associated to the downstream capacity of the network for one unit of Q_{cap} above the $Target_F$ (500,000,000 CAN \$ s/m^3)

Q_{cap} = Simulated maximum downstream flowrate as taken in the status report of SWMM (m^3/s)

$Target_F$ = Target maximum flow corresponding to the network downstream capacity (1 m^3/s)

$BIOmax_{SC}$ = Maximum number of bioretention cells of 10 m^2 that can be implemented in each sub-catchment SC

$VOLmax_S$ = Maximum volume of underground storage units S (m^3)CP = Potential control points for RTC implementation

$D1_{CP}$ = Depth at the downstream confluence with the interceptor that will trigger the CP gate partial closure

$D2_{CP}$= Depth at the downstream confluence with the interceptor that will trigger the CP gate reopening

$Diam_{CP}$ = Diameter of the pipe in which the water depth is measured in real-time for each CP gate control

$G1_{CP}$ = Fraction of opening at which the CP gate should be maintained when the gates are partially closed

$Fmin$ = Minimum gate opening fraction during its closing state (a value of 0.1 is applied)

The objective function embedded in iPOP consisted of minimizing the sum of the total infrastructure costs for green and grey infrastructure and the system penalties associated with exceedance of three performance targets on i) CSO volume, ii) node surcharges, and iii) downstream network capacity. Therefore, the objective function aims to avoid CSO under the design rainfall event. No RTC cost was directly applied through the optimization framework as an input parameter, because this cost was marginal compared to the other parameters. However, the calculated potential cost by each RTC control point was considered when evaluating the cost effectiveness of each scenario.

In terms of constraints, the feasible implementation range for bioretention cells detailed in Eq. 3.2 varied from zero to a maximal value determined for each sub-catchment either from the site suitability criteria map or the maximal impervious area that can be treated (see section 3.5.4.1 for more details). Regarding the storage volume bounds in Eq. 3.3, the upper limit was set large enough to ensure the CSO control objective could be met. The option to build a storage unit just upstream of the WWTP is not considered as the interceptor is already saturated. For rule-based RTC definition, the constraint defined by Eq. 4 aimed at avoiding network surcharges and/or exceeding the downstream capacity. The constraint represented by

Eq. 3.5 ensures that the depth triggering the gate reopening is different enough from the depth triggering its closure so that the changes in gate states do not cause continuous oscillations between its closed and open positions. The last constraint (Eq. 3.6) aimed at avoiding the gates full closure, which could be a risk for the network upstream in case of gate malfunction.

More details about the variables, constraints, modeling choices and optimization algorithms are given in the following sections.

3.5.4.1 Green infrastructure

The spatial distribution of only one type of GI was optimized (i.e. bioretention cells) and, to reduce the uncertainty associated with the selected GI scenarios, a sensitivity analysis of the bioretention cell costs and design input parameters was conducted.

Specific land suitability criteria were applied to define the upper implementation level limit of bioretention cells for each combined sewer sub-catchment based on design recommendations from the literature (see Supplementary Material). Spatial analysis was conducted by the Geographic Information System (GIS) software ArcGIS and data from orthophoto pictures, land use shape files and soil characterization map. Based on this analysis, the maximal available area for bioretention cells implementation and the maximal impervious area that could be potentially treated by bioretention cells were determined.

The loading ratio between the surface occupied by bioretention cells and the treated impervious surface was set equal to 1:10 (i.e. the bioretention cells can treat water from impervious areas totalizing 10 times their surface), which is a conservative value as recommended by CSA (2018) for the most contaminated runoff.

Bioretention cells implementation was simulated on a per-unit basis using the LID control module of SWMM (Rossman and Huber, 2016b). The parameters of the vertical layers constituting the bioretention cells design are specified in Table 3.1 and were primarily based on calibrated values from a previous monitoring study of GI implemented in the Province of Quebec (Bilodeau, 2018) and Canadian design guidelines for bioretention cells (CSA, 2018). The US EPA recommended values (Rossmanand Huber, 2016b) were applied for the remaining parameters (Table 3.1). Finally, the bioretention cells design values defined for the sensitivity analysis of the GI performance were based on the minimal and maximal design values reported in Table 3.1.

Table 3.1 Bioretention Cells Design Parameters for SWMM LID Control Module

Layer	Parameter	Selected design value	Canadian guidelines (CSA, 2018) [a]	EPA SWMM guidelines (Rossman and Huber, 2016b) [b]	Min LID value [c]	Max LID value [c]
Surface	Berm height (mm)	300	(300)	150-300	150	300
	Vegetation volume (fraction)	0.1	-	0-0.2	0.2	0.1
	Surface roughness [b]	0.3	-	0.03-0.2	0.3	0.03
	Surface slope (%)	0.5	-	0.5-3	0.5	3
Soil	Thickness (mm) [b]	450	> 300 (450)	600-1200	450	600
	Porosity (fraction)	0.437	-	0.45-0.6 (0.52)	0.437	0.6
	Field capacity (fraction) [b]	0.105	-	0.15-0.25 (0.15)	0.105	0.25
	Wilting point (fraction) [b]	0.047	-	0.05-0.15 (0.08)	0.047	0.047[d]
	Conductivity (mm/h)	140	-	50-140 (120)	50	140
	Conductivity slope (%)	30	-	30-55 (40)	30	55
	Suction head (mm) [b]	110	-	50-100 (50)	110	50
Storage	Thickness (mm)	600	>300 (600)	150-900	300	900
	Void ratio (fraction) [b]	0.5	-	0.2-0.4	0.2	0.5
	Seepage rate (mm/h)	5	-	-	5	15
	Clogging factor (fraction)	0	-	-	400	0

[a] The values in parentheses correspond to the recommended value if applicable

[b] Values slightly outside the EPA SWMM range guidelines were based on calibrated values (Bilodeau, 2018)

[c] The minimal and maximal design values represent the values leading to a net decrease or increase in the LID CSO reduction performance, respectively

[d] The best CSO reduction performance is obtained for a greater difference between the wilting point and the field capacity fractions, which explains why only the field capacity fraction is increased for the Max LID value case

3.5.4.2 Real-time control implementation

The rule-based RTC strategy was implemented for potentially nine control points (overflow infrastructure O-01 to O-09 on Figure 3.1).The most upstream regulator (located beside the outfall O-10) was not included in the analysis as it drains only a small portion of the network. The optimization scheme also permitted optimizing the total number of RTC control points by evaluating if applying a dynamic control on all gates or only on some of them provides similar benefits.

3.5.4.3 Cost evaluation

The bioretention cells cost calculations embedded in the objective function was simplified as a linear function of the bioretention cells implementation area. The cost values applied were based on an estimation of the construction cost considering the bioretention vertical layers design recommendations of the literature presented in Table 3.1 and material and construction costs encountered in the Province of Quebec. A cost estimation of 300 CAD $/m^2 was calculated, which corresponds with the mid-range value of various bioretention cells projects led in the Province of Quebec (costs varying from 150 to 400 CAD $/m^2 reported by Bilodeau, 2018).

Similarly, values applied for storage units cost evaluation were based on three previous construction projects realized in other sub-catchment areas of the case study. The reported projects correspond to concrete underground storage tanks of various sizes with gravitational outflow and self-cleaning mechanism (personal communication with Bilodeau, 2020). Based on this information, an initial investment of about 3,000,000 CAD$ was considered necessary for grey infrastructure implementation in addition to a per-volume cost of 600 CAD$/m^3.

Finally, the RTC implementation cost, which is the investment cost required to replace each static regulator with a moveable gate and RTC technology, was determined based on costs applicable to the Province of Quebec, which are approximately 1,150,000 CAD$ per site (personal communication with Lussier, 2021).

More details on the cost data are presented in the Supplementary Material section.

3.5.4.4 Optimization algorithm

The optimization tool (iPOP) was applied to solve the optimization problem using the Parallel Swarm Oriented-Particle Swarm Optimization (PSO-PSO). The PSO-PSO algorithm is an evolutionary population-based search algorithm where a series of solution candidates (i.e. particles), are evolving at each iteration (i.e. generation). When applying PSO-PSO, the population is further divided in parallel sub-swarms, each grouping an equal number of particles. Therefore, the algorithm takes into account the sub-swarm best solution in addition to the particles and population best solutions (Gonsalves & Egashira, 2013). The equations of the PSO-PSO algorithm are given in the Supplementary Material section.

The number of particles per generation, the number of sub-swarms and the total number of generations are user-specific parameters of iPOP. For this research, four swarms of 50 particles and 60 generations were simulated, for a total of 12 000 particles (1 particle = 1 design alternative) per scenario assessed. At each generation, iPOP modifies the input file of a SWMM reference scenario to produce different SWMM input files, each corresponding to one PSO particle. By applying the PSO-PSO algorithm, iPOP will converge toward an “optimal” or “near-optimal" SWMM input file which corresponds to a specific design alternative in terms of GI distribution and/or storage volume and/or RTC rule-based definition.

3.5.5 Scenarios

The scenarios compared can be differentiated according to the design rainfall event used in the optimization process and the three potential types of design outputs optimized: 1) the rules parameters for RTC gates, 2) the number and spatial distribution of GI, and 3) the spatial distribution and volume of grey infrastructure. Table 3.2 provides a summary of all scenarios compared when all permutations of these design parameters were considered.

Table 3.2 Description of the Scenarios

Scenario name	Type of control	Green infrastructure	Grey infrastructure	Design rainfall event
1. Base case	Static	-	-	N/A
2A. RTC- Chicago	RTC	-	-	Chicago
2B. RTC- July	RTC	-	-	30 July 2015
3. GreyDesign[1]	Static	-	X	N/A
4A. RTC-Grey- Chicago	RTC	-	X	Chicago
4B. RTC-Grey-July	RTC	-	X	30th July 2015
5A. GreyGreen- Chicago	Static	X	X	Chicago
5B. GreyGreen-July	Static	X	X	30 July 2015
6A. RTC-GreyGreen- Chicago	RTC	X	X	Chicago
6B. RTC-GreyGreen-July	RTC	X	X	30 July 2015
7A. Green- Chicago	Static	X	-	Chicago
7B. Green-July	Static	X	-	30 July 2015
8A. RTC-Green- Chicago	RTC	X	-	Chicago
8B. RTC-Green-July	RTC	X	-	30 July 2015

[1] Scenario 3 only involves grey infrastructure whose final sizing was based on the continuous simulation, therefore the final optimal storage volume and tanks distribution over the catchment area were not impacted by the two design rainfall events

3.6 Result and discussion

3.6.1 Scenarios performance

The Table 3.3 presents the optimization results for each scenario in terms of cost, infrastructure designs and CSO performance by indicating the number of outfalls for which the maximum allowable CSO frequency target of 7 CSO/season was exceeded. As shown, the CSO frequency objective cannot be achieved without the construction of grey infrastructure, but the integration of GI and RTC permit to significantly reduce the costs of the designed solutions. From all the scenarios studied, the scenario 6A, integrating green and grey infrastructures with RTC, is the one that achieves the objectives at the lowest cost.

Indeed, whereas the scenarios involving RTC alone were the cheapest solutions, they could not reach the CSO frequency targets for 6 problematic outfalls. In contrast, the addition of grey infrastructure was an effective solution under both static and RTC management and required similar investment costs (between approximately 23 to 24 million CAD$). Also, the total design storage volume could be reduced considerably by RTC.

Moreover, all the solution alternatives involving static control and grey infrastructure alone or in integration with GI (scenarios 3, 5A and 5B) reached the design objectives with similar investment costs (about 24 million CAD$), while static control combined with GI alone (7A and 7B) required half the investment costs, but failed to achieve CSO target goals at four outfalls. The upper limit on the maximum number of bioretention cells that could be implemented was reached for almost all the sub-catchments in scenario 7A, but it was not sufficient to reduce the CSO occurrence below an acceptable level. On the contrary, if the option of implementing RTC was applied in integration with GI or with a mix of green-grey infrastructure using the Chicago storm (scenarios 6A or 8A), the total solution cost remained among the lowest (12.5 to 15.2 million of CAD$, respectively) and still achieved the CSO frequency target or nearly so (in scenario 8A, only outfall O-06 exceeded its CSO frequency target, during one year). Interestingly, this means that the cost for upgrading the network to reach its CSO frequency objective under static control remained approximately the same for scenarios involving grey infrastructure even if GI was integrated in the design process, because the statically controlled regulators have a fixed capacity, and any water in excess must be either captured upstream with GIs or off-line with grey infrastructure. In contrast, optimizing RTC and GI (with or without grey infrastructure) permits to control both the surface runoff and the flowrate within the network; providing the highest flexibility for CSO reduction and potential cost savings. Therefore, for the case study assessed, RTC benefits are mostly obtained when distributed GIs are integrated in the design solution, because this type of infrastructure can be implemented where RTC is less effective, and because this solution is cheaper to implement than centralized underground storage units.

Differences in performance results between the solutions optimized with the synthetic event (scenarios A) and historical event (scenarios B) is often marginal but, in general, optimization with the synthetic event is slightly more effective in terms of maintaining the CSO target limits for all outfalls and all years. For instance, scenarios involving RTC and green and grey infrastructure optimized under the Chicago storm (6A) did respect the CSO frequency objective as opposed to the same scenario optimized under the historical event (6B), which exceeded the maximal CSO occurrence for two outfalls (see Table 3.3). The exceedance occurs only during one simulated year, and could be easily avoided by integrating more bioretention cell units (i.e. 2.25 ha such as optimized for the scenario 6A instead of 1.86 ha for the scenario 6B). Therefore, only the optimization results obtained with the synthetic rainfall event are further detailed here while the remaining results obtained with the historical event are presented in the Supplementary Material section.

Table 3.3 Optimized Solutions Costs, Infrastructure and Performance

Scenarios	$ CAD	Total storage volume (m^3)	Total bioretention area (ha)	Number of RTC gates	Number of outfalls with CSO frequency > target
1. Base case	0	-	-	-	6
2A. RTC- Chicago	1,150,000	-	-	9	6
2B. RTC- July	1,150,000	-	-	9	6
3. Grey-Design	23,940,000	9,900	-	-	0
4A. RTC-Grey- Chicago	23,075,000	7,500	-	5	0
4B. RTC-Grey-July	22,530,000	6,400	-	6	0
5A. GreyGreen- Chicago	24,075,000	6,300	1.77	-	0
5B. GreyGreen-July	23,625,000	6,600	1.56	-	0
6A. RTC-GreyGreen- Chicago	15,220,000	2,800	2.25	7	0
6B. RTC-GreyGreen-July	13,820,000	2,200	1.86	8	2
7A. Green- Chicago	12,060,000	-	4.02	-	4
7B. Green-July	11,880,000	-	3.96	-	4
8A. RTC-Green- Chicago [1]	12,545,000	-	3.99	5	1
8B. RTC-Green-July	11,855,000	-	3.76	5	2

[1] For scenario 8A, nine CSOs were simulated in 2011 for outfall O-06, but volumes of the two smallest CSO events exceeding the limit remained relatively small (< 11 and 5 m^3 respectively)

The total CSO volume simulated for the entire study area and the maximal seasonal CSO frequency reached for each problematic outfall during the nine simulated years are presented in Figure 3.4 and Figure 3.5, respectively.

In general, scenarios in which RTC and/or GI are implemented improve CSO volume and frequency reduction such as expected according to previous literature reported in the introduction. More specifically, whereas the scenario involving RTC alone (2A) exceeds the maximal allowable CSO frequency limit, it can still reduce by 40% the total CSO volume compared to the base case scenario. GI can further reduce CSO volume by up to 98% when this green alternative is implemented with RTC (8A) or by about 95% when a mix of green and grey infrastructures are integrated with RTC (6A). In the last case, the reduction percentage is lower even if storage units are added to the network as under the design rainfall event, the addition of grey infrastructures is balanced with a reduction of about half of the green infrastructures. When the network is submitted to a longer rainfall time series, this combination of solutions is slightly less effective in reducing annual CSO volumes even if the CSO control performances were similar under the design rainfall event.

Under static control of the network, the amount of CSO volume reduction is still considerable when GI is implemented, with a CSO reduction of about 89% for the scenario involving GI alone (7A) and about 93% in the case of the scenario mixing green and grey infrastructures (5A). However, Figure 3.5 shows that for three outfalls, scenario 7A results in high CSO frequency as the maximal CSO frequency simulated at these locations is between 50 to 60 events per season. This poor performance is explained by the constraint on the maximal number of bioretention cells that can be implemented, according to the spatial analysis, and the restrictive flow rate that can pass through the static regulators. Stovin et al. (2013) also found that GI alone was not sufficient to cope with CSO problems in all the sub-catchments analyzed. In contrast, the scenario integrating RTC and GI without grey infrastructure (8A) is able to maintain a frequency of seven spills per year for almost all outfalls as the RTC management offers more flexibility than the static regulators where GI space availability is more restrictive.

These results demonstrate that the scenarios involving a mix of green and grey infrastructures are generally more robust in maintaining the maximal allowable CSO frequency targets for similar CSO volume reduction and that their integration with RTC permits to further reduce the investment cost. Results obtained by Altobelli et al. (2020) for a combined sewer system submitted to similar climatic conditions in northern Italy suggested that RTC alone or in combination with either green or grey infrastructures can contribute to reducing CSO volume compared to scenarios involving only a static control of the system, and that grey infrastructure is still necessary for eliminating CSO occurrence. In the same vein, Lucas and Sample (2015) conducted a study for a small combined sewer catchment in Virginia, USA, and found that GI combined with RTC tend to reduce the CSO volume by a greater amount as compared to grey infrastructures, while the latter perform better in terms of reducing CSO frequency.

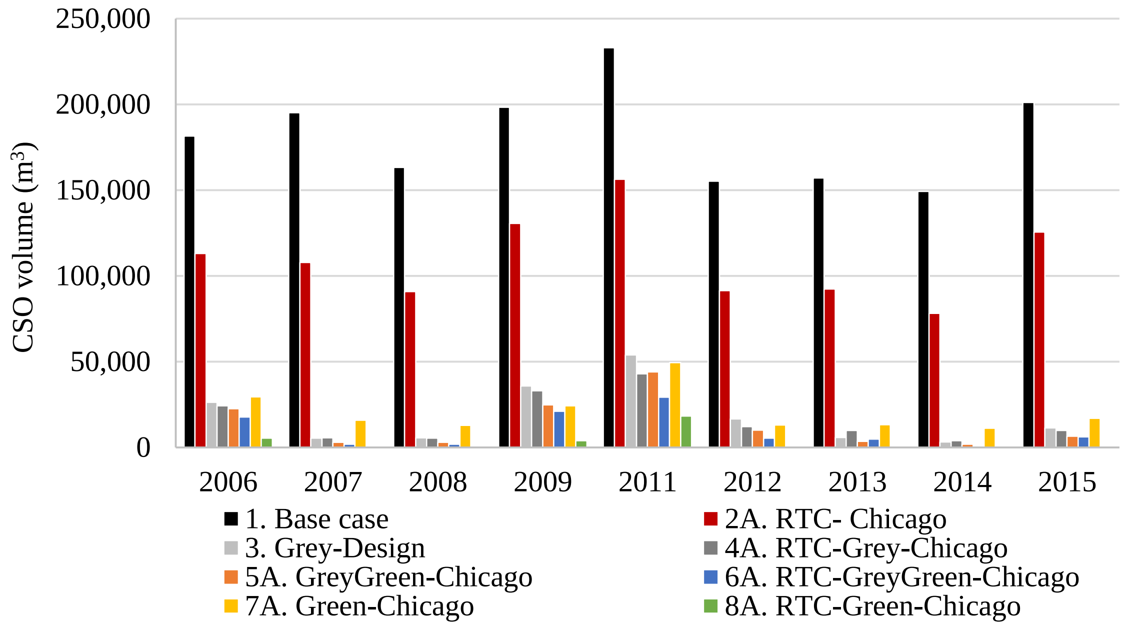

Figure 3.4 Total CSO volume for all optimized scenarios

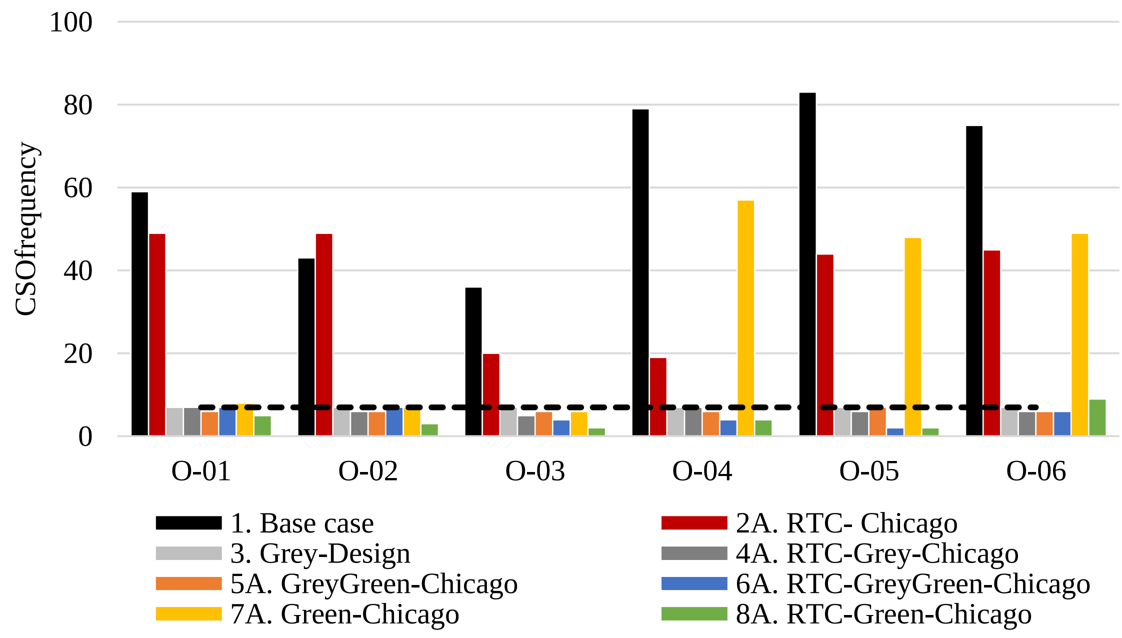

Figure 3.5 Maximal seasonal CSO frequency reached per outfall for all 9 simulated years

Note: The dashed line represents the seasonal CSO frequency limit of 7 CSOs/season

3.6.2 Cost-benefit analysis

The cost-benefit ratio of the mean CSO volume reduction (i.e. the total scenario cost divided by the difference in simulated mean seasonal CSO volume between the base case scenario and the assessed scenario) was calculated for each scenario optimized under the synthetic rainfall event and for which the maximal CSO target frequency was not exceeded, as well as for scenario 8A (one exceedance). Therefore, results for a total of five scenarios are presented in Figure 3.6.

The uncertainty attached to the estimated grey and green infrastructures cost is illustrated through error bars representative of a variation in the storage and bioretention cells costs of ± 50%. A greater cost uncertainty is attached to scenarios having a greater total volume of grey infrastructure as this type of solution is, on average, more costly than GI. The scenario integrating RTC and GI (8A) remains the most cost-effective solution considering cost uncertainties (the cost of scenario 8A is about 70$/m^3$ of average seasonal CSO volume reduction compared to about 90-150 $/m^3$ for the remaining scenarios). This scenario, however, requires a high number of bioretention cells to reach the CSO frequency target, with the upper limit on the number of bioretention cells reached in almost all sub-catchments, as compared to the scenario integrating RTC with both green and grey infrastructure (6A), which requires about half the bioretention cells. As compared to scenario 8A, scenario 6A might be more readily applicable and practical due to its more modest implementation of bioretention cells; it is also one of the most cost-effective alternatives. Alves et al. (2016) also found that combining green and grey infrastructures was the most cost-effective solution for CSO abatement as centralized storage units can be implemented where space availability limits GI implementation.

As a comparison, the analysis of Montalto et al. (2007) suggested that for high GI cost, storage tanks become a more cost-effective solution for CSO abatement, but as GI cost decrease, the opposite effect is obtained. The study of Joshi et al. (2020) also suggests important cost reduction when GIs are implemented rather than grey infrastructures. In our case, the scenarios integrating RTC with GI, with or without storage units, are always more cost-effective than any other option that does not include GI, even considering a high cost variation. Similarly to what we obtained, Frey et al. (2013) suggested that a combination of RTC and green and grey infrastructures permits important cost savings. Other studies which did not include RTC in their analysis concluded that mixing green and grey infrastructures is the best option for balancing the network performance and cost (Dong et al., 2017; Liao et al., 2015; Tavakol-Davani et al., 2015).

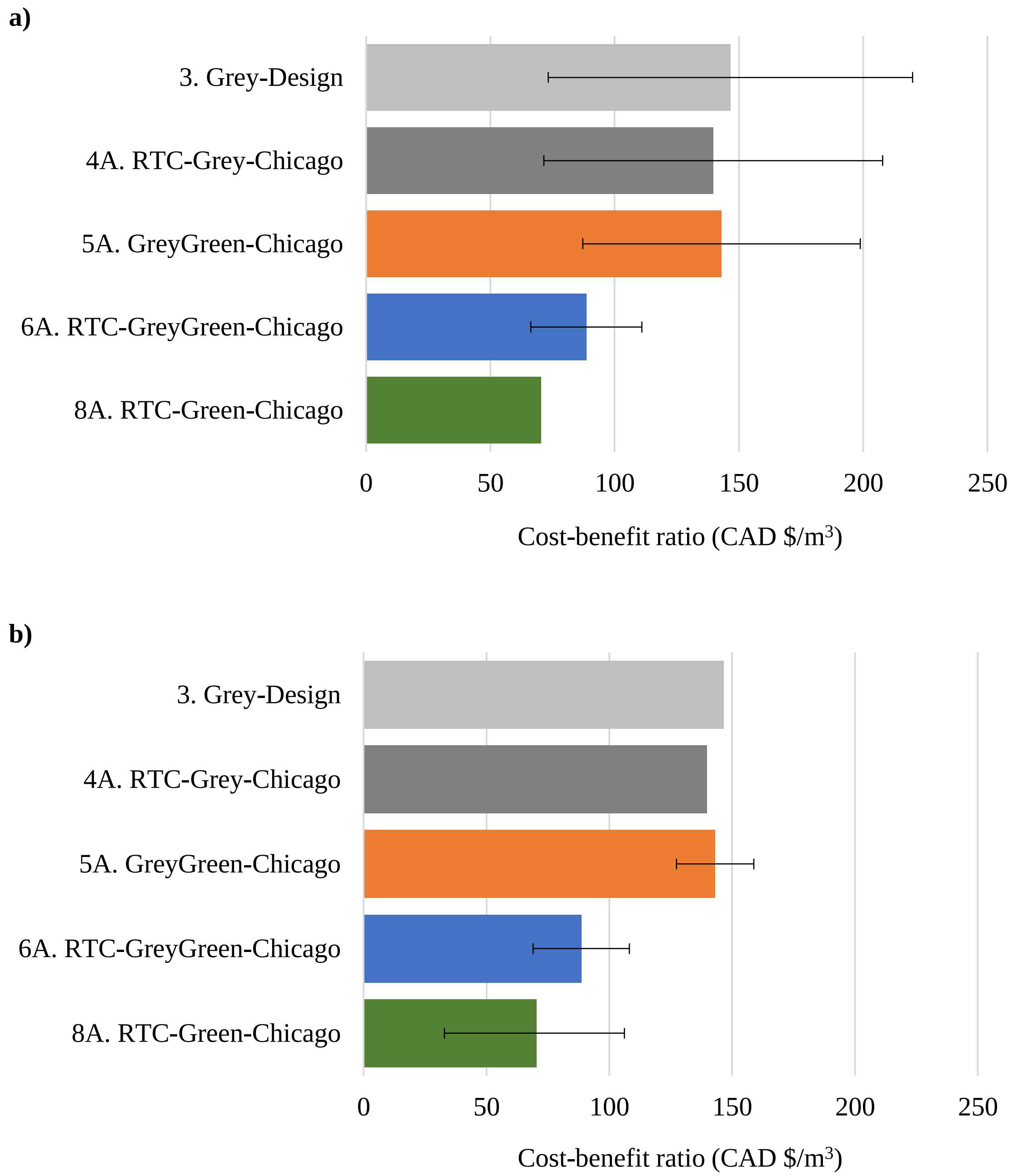

Figure 3.6 **Cost-benefit ratio for selected scenarios: a) Cost-benefit ratio for storage price variation of ± 50%; b) Cost-benefit ratio for bioretention cells price variation of ± 50%**

3.6.3 Cost-benefit analysis

GI design parameters sensitivity was assessed for scenarios based on the Chicago rainfall event combining green and grey infrastructures with RTC (6A) and integrating RTC with GI (8A), as they present the best cost-benefit ratios. The two scenarios were simulated for the nine years of available continuous rainfall data for four different sets of LID input parameters in SWMM, without changing their optimized RTC rules, the bioretention cells spatial distribution nor their storage units volume (in the case of scenario 6A). More specifically, the LID design parameters were changed for the minimal and maximal design values listed in Table 4.1 (scenarios LID-MIN and LID-MAX respectively), and for a LID loading ratio increased to 1:15 and 1:20.

As shown in Figure 3.7, the maximal CSO frequency reached over the continuous simulation period for each outfall was not necessarily increased or decreased by the changes in the LID input parameters, particularly in the case of scenario 6A. The storage units provided additional runoff capture when the bioretention cells became more rapidly saturated due to either decreased design performance or increased loading ratio. Scenarios are less sensitive to an increase in GI performance as bioretention cells are saturated only for a few larger rainfall events and those rainfall events are, for the most part, the same ones as those responsible for the CSOs occurring in the original scenario. Moreover, Figure 3.7 indicates that a ratio of 1:20 is not sustainable for the two analyzed scenarios, but that a ratio of 1:15 or lower LID design values are still acceptable when grey infrastructure is integrated with GI and RTC, as opposed to the scenario involving only GI and RTC. Similarly, Lewellyn et al. (2018) found that GI performances were not impacted by back-to-back rainfall events if the native soil conductivity was sufficiently high. Indeed, under appropriate design and implementation site selection, GIs are likely to provide sufficient runoff capture under a variety of rainfall events.

According to the presented results, integrating the optimization of green and grey infrastructures with RTC might present a safer option to achieve high CSO volume and CSO frequency reductions even under GI performance uncertainty.

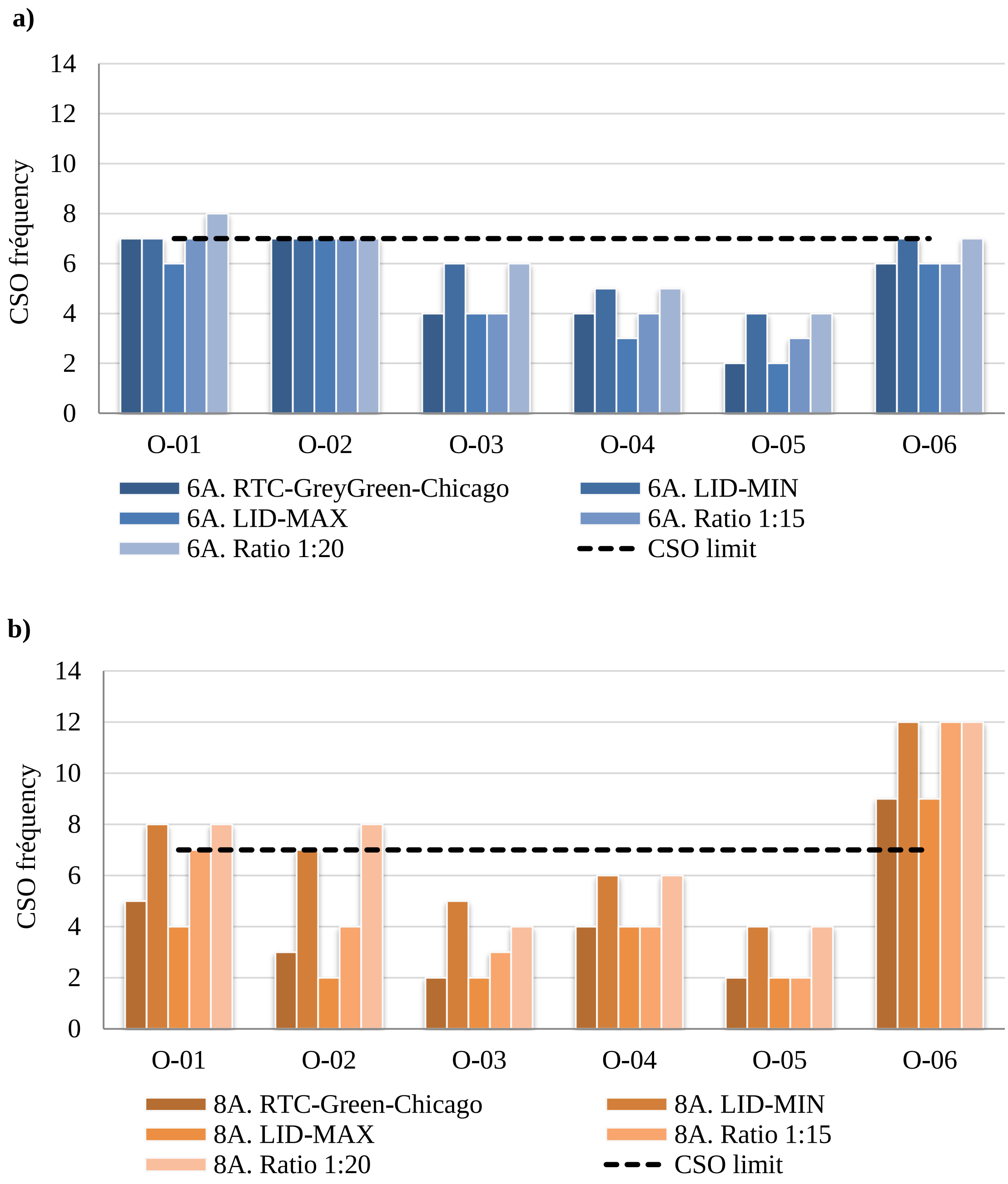

Figure 3.7 GI design sensitivity on maximal annual CSO frequency per outfall: a) 6A. RTC-GreyGreen-Chicago scenario; b) 8A. RTC-Green-Chicago scenario

Note: The dashed line represents the seasonal CSO frequency limit of 7 CSOs/season

3.7 Conclusion

CSO regulations are requiring municipal actions toward implementing cost-effective solutions for combined sewer network upgrades. This study aimed at orienting the design of those solutions through an innovative optimization framework. Results demonstrated that:

- Under static control of the network, the total cost to reach CSO frequency targets:
  - remains similar for solutions integrating grey infrastructure alone or in combination with GI;
  - is higher than the cost of solutions involving RTC.
- Spatial optimization of GI with RTC leads to maximal CSO volume reduction at the lowest investment cost, as compared to static control or traditional combination of RTC and grey infrastructure, however, it:
  - requires a high number of GI everywhere in the catchment area;
  - results in a CSO frequency that is more sensitive to a variation in GI design parameters as compared to the scenario integrating RTC with green and grey infrastructure.
- Integration of the optimization of a mix of green and grey infrastructure with RTC presents the safest option for CSO control, as it:
  - provides one of the most cost-effective solutions;
  - ensures robustness under varying GI design parameters and solution design costs.

This study contributes to improve the development of CSO control solutions that are potentially more affordable, efficient, and adaptable to a variety of networks, rainfall conditions, and CSO control objectives. The applied methodology could easily be reproduced by adapting the optimization parameters according to any combined sewer context.

Future research work should assess the impact of GI design for CSO abatement of more complex RTC schemes, such as model predictive control, to evaluate if additional benefits could be obtained from a more optimal control of network flowrates. Moreover, the impact of integrating both RTC applications (within the network and on distributed GIs on site) should be assessed in terms of CSO performance objectives. A better understanding of the impact of large-scale implementation of GI on CSO frequency and volume could improve the design of such novel solutions for combined sewer networks. Finally, the optimization framework should be applied for various case studies and climatic data to evaluate the potential benefits and robustness of combining RTC with green and grey infrastructure under a variety of conditions.

3.8 Acknowledgments, Samples, and Data

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- The authors declare to have no real or perceived financial conflicts of interests.
- Data supporting this research are available from the municipality used as the case-study, with agreements requirement for use, and are not accessible to the public or research community directly. Access could be requested through an official data sharing agreement.

The optimization model supporting this research is available from Jamie M. Brescol from Tetra Tech CSO. Access could be requested through an official data sharing agreement.

3.9 Supplementary Material

3.9.1 Introduction

The content of the supplementary material provides more details on optimization algorithm in text S1, additional scenario performances in Figures 3.8 to 3.10, site suitability criteria applied for green infrastructure implementation in Table 3.4 and information on the solution cost calculations in Tables 3.5 to 3.7. More specifically, Text S1 describes the main equations and attributed coefficient values for the application of the Parallel Swarm Oriented-Particle Swarm Optimization (PSO-PSO) algorithm of the optimization routine developed for the presented study. The equations and coefficients are based on the work and experimentation of Gonsalves & Egashira (2013). Figures 3.8 and 3.9 illustrate the combined sewer overflow (CSO) abatement performances in terms of volume and frequency for the scenarios optimized under the historical rainfall event. These scenarios remain less effective in mitigating CSO volume and frequency as compared to the scenarios optimized under the synthetic event, for which the results are presented in the main text. Figure 3.10 presents the total CSO volume simulated over the study period for different bioretention cells design scenarios in order to evaluate the sensitivity of the green infrastructure performances on the best optimized solutions. Table 3.4 presents the site suitability criteria for green infrastructure implementation according to best practice recommendations applicable for the case study area. Finally, Tables 3.5 to 3.7 present reported and estimated costs for bioretention cells, underground storage units and real time control solutions based on current design costs in the study area.

3.9.2 Text S1

The main PSO-PSO algorithm equations and the coefficient values applied for our study are detailed below. Further is a synthesized description of the code for iPOP optimization routine. At each iteration *t*, and for each particle *i* within the sub-swarm *j,* the velocity *v* and the position *x* are adjusted according to the following Equations S1 and S2. The coefficient w represents the inertia weight of the preceding iteration, whereas the parameters c_1, c_2 and c_3 define the acceleration. The values attributed to these coefficients are based on the literature and experimentation (Personal communication with Brescol, 2020). The other coefficients r_1, r_2 and r_3 correspond to random numbers whose value is between 0 and 1. The *v* value used to update the particle position *x* is the smallest calculated value between the update velocity *v* and the quarter of the difference between the greatest and the smallest particle values. More details on the PSO-PSO algorithm can be found in Gonsalves & Egashira (2013).

$$v_{\mathrm{ij}}(t) = \min \begin{cases} w\, v_{\mathrm{ij}}(t-1) + c_1 r_1 \left(P_{\mathrm{ij}}(t-1) - x_{\mathrm{ij}}(t-1)\right) + c_2 r_2 \left(Ps_{\mathrm{j}}(t-1) - x_{\mathrm{ij}}(\mathrm{t}-1)\right) + \\ c_3 r_3 \left(Pg(t-1) - x_{\mathrm{ij}}(\mathrm{t}-1)\right) \\ \frac{1}{4}\left(\max\left(P_{\mathrm{ij}}(t)\right) - \min\left(P_{\mathrm{ij}}(t)\right)\right) \end{cases}$$

Equation 3-7

$$x_{ij}(t) = x_{ij}(t-1) + v_{ij}(t)$$

Equation 3-8

Where:

$w = 0.745$

$c_1 = c_2 = 1.49$

$c_3 = 0.36$

PSO-PSO optimization steps :

1. Step 1. Initialize the Swarms

   For each particle (i.e. SWMM input file)

   i. Initialize the position of each design variable, random distribution within the upper and lower constraints

   ii. Initialize velocity of each design variable, random distribution within the upper and lower velocity limits

2. Step 2. Repeat until *Termination Criteria* are met

   For each particle

   i. Model Simulation
      - Simulate SWMM model for each particle
      - Extract results from SWMM *.rpt file and/or SWMM *.out file

   ii. Evaluate the Objective function
      - Calculate Capital costs
      - Calculate Penalties for each objective
      - Calculate the total (Capital + Penalties)

   iii. Identify next set of Particle positions
      - Calculate random numbers (r_1, r_2, r_3)
      - Calculate new velocity (v_{ij}) for each decision variable within the upper and lower velocity limits
      - Calculate new position (x_{ij}) for each decision variable
      - Confirm new position (x_{ij}) is within upper and lower constraints. If value outside constraints, assume a random value within constraints.
      - Confirm this combination of decision variables has not been previously simulated. If yes, then mutate decision variables until an untested combination has been identified.

Test for Termination

i. Exit Step 2 if

- Numbers of particles exceed upper limit

3. Output reporting

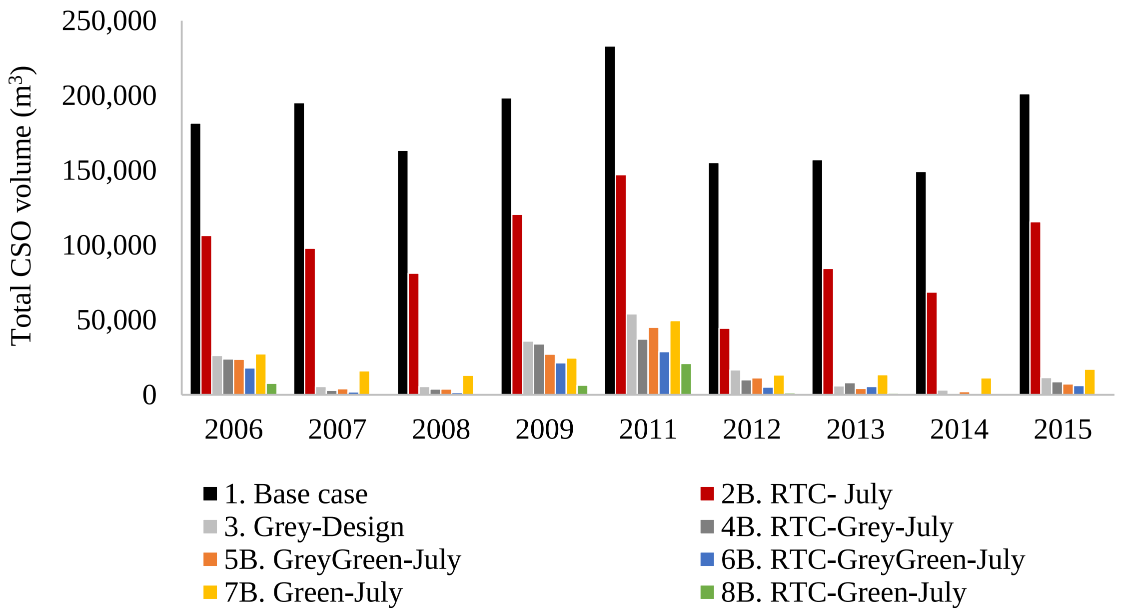


Figure 3.8 **Total CSO volume for all optimized scenarios under the historical rainfall event**

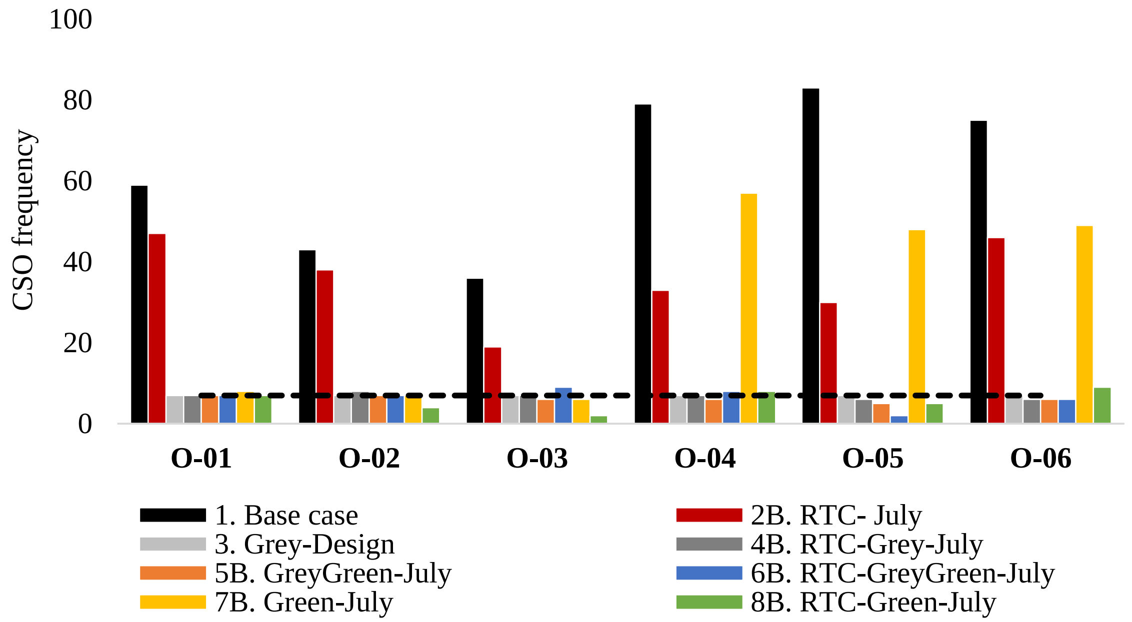
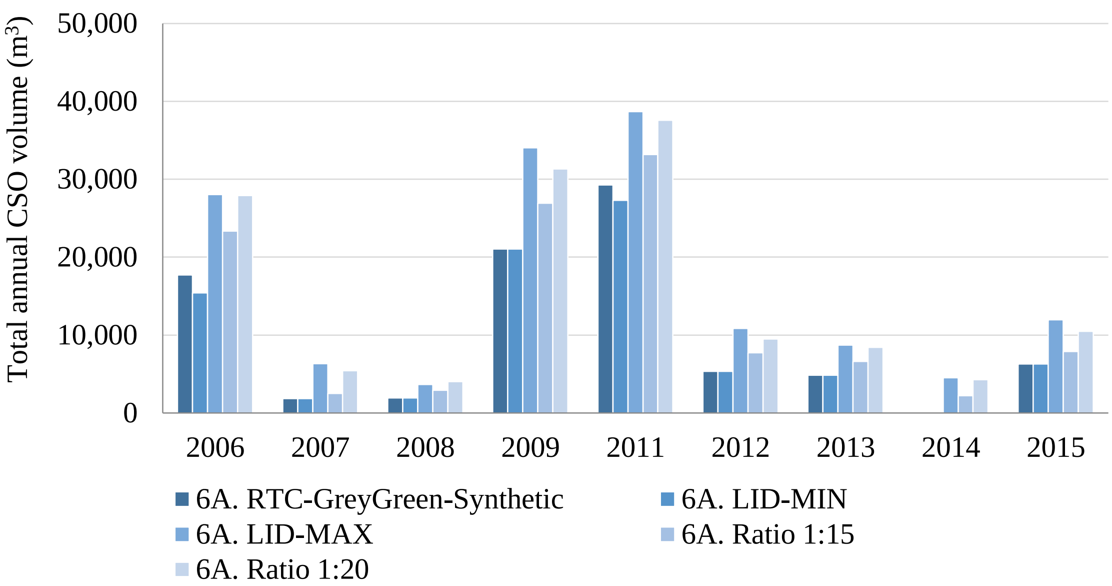


Figure 3.9 **Maximal seasonal CSO frequency per outfall for all optimized scenarios under the historical rainfall event**

Note: The dashed line represents the seasonal CSO frequency limit of 7 CSOs/season

a)



b)

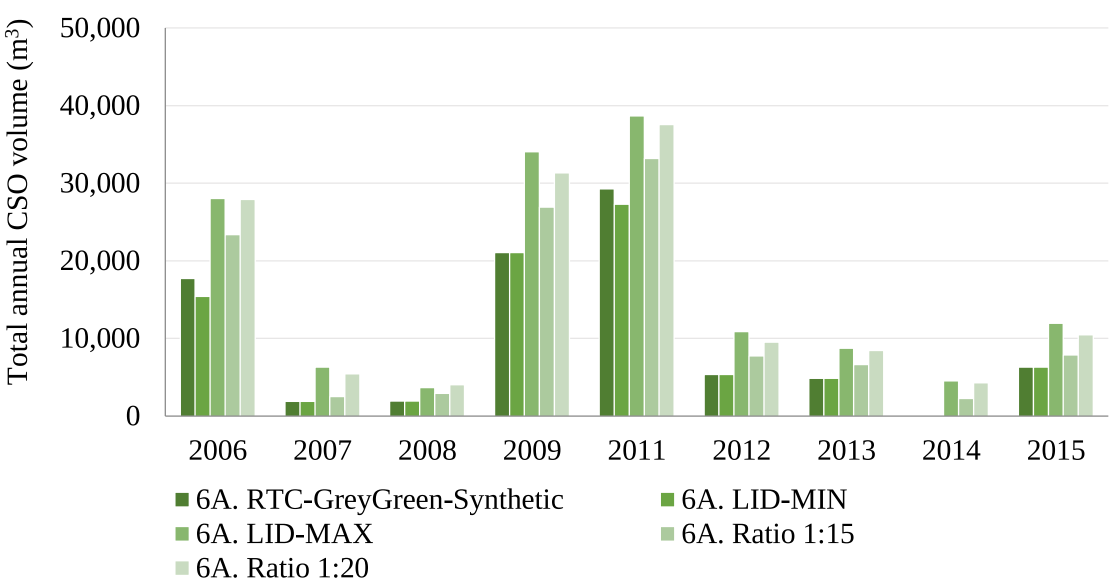


Figure 3.10 Sensitivity of total seasonal CSO volume to GI design: a) scenario 6A. RTC-GreyGreen-Synthetic; b) scenario 8A. Green-Synthetic

Table 3.4 Site suitability criteria for bioretention cells

Criteria	Design value
Soil type [a]	Hydrologic Soil Groups A or B [b]
Slope (%) [c]	≤ 5%
Minimum distance from surface streams or drinkable water wells (m) [d]	30 m
Minimum distance from buildings (m) [a]	4

[a] CVC and TRCA (2010)

[b] Classification of soil (Groups A, B, C, and D) according to their minimal infiltration rate, which is obtained for bare soil after prolonged wetting as defined by SCS (1986)

[c] MELCC (2010)

[d] Lanarc et al. (2012)

Table 3.5 Calculated cost for a 10 m^2 bioretention cell

Description	Quantity	Unit	Unit cost (CAD $)	Total (CAD $)
1- Excavation/Backfilling [a]	25.00	m^3	12.00	300.00
2- Mulch [b]	1.00	m^3	75.00	75.00
3- Topsoil [b]	4.50	m^3	55.00	247.50
4- Granular filter (sand) [b]	1.00	m^3	45.00	45.00
5- Drains and fittings [c]	0.00	-	30.00	0.00
6- Storage (25-50mm river roller) [b]	6.00	m^3	40.00	240.00
7- Vegetation (mature shrubs and perennials) [d]	10.00	m^2	80.00	800.00
8- Geotextile [1]	50.00	m^2	2.75	137.50
Subtotal				1 845.00
Contingency (+30%)				2 398.50
Engineering costs (+10%)				2 638.35
Taxes (+15%)				3 046.60
Rounded Total CAD $/$m^2$				**300.00**

[a] Personal communication with Aqua Ingenium (2020)

[b] Jardin Eden (2019)

[c] Uda et al. (2013)

[d] Glorieux (2017)

Table 3.6 Storage units reported cost from literature and simulated cost

Volume (m^3)	Reported cost[a] (CAD $)	Simulated cost (CAD $)
3,750	5,500 000	5,250,000
8,000	7,600 000	7,800,000
14,000	11,200 000	11,400,000

[a] Personal communication with Bilodeau (2020)

Table 3.7 Cost for on-line RTC sluice gate implementation

Description	Quantity	Unit	Unit cost [a] (CAD $)	Total (CAD $)
1- Outdoor control unit with electrical components	1	-	24,000	24,000
2- Electrical input	1	-	2,500	2,500
3- Automated panel and UPS	1	-	16,000	16,000
4- Valve (including installation)	1	-	20,000	20,000
5- Modulating actuator	1	-	5,000	5,000
6- Planning, drawings, plans and others	100	h	85	8,500
7- Programming	100	h	85	8,500
8- Installation and start-up	120	h	85	10,200
9- Sensor/monitoring probe	1	-	1,800	1,800
10- Probe wiring and installation	500	m	10	5,000
Subtotal				101,500
Administration and profits (+15%)				15,225
Rounded Total CAD $/m^2				**115,000**

[a] **Personal communication with Lussier (2021)**

4 DISTRIBUTION OPTIMALE DES INFRASTRUCTURES VERTES ET GRISES AVEC LE CONTROLE EN TEMPS REEL POUR LE CONTROLE DES DEBORDEMENTS DE RESEAUX D'EGOUT UNITAIRES COMME MESURE D'ADAPTATION AUX CHANGEMENTS CLIMATIQUES

Optimal Distribution of Green and Grey Infrastructures with Real Time Control for Combined Sewer Overflows Control as an Adaptation Measure to Climate Change

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Contribution des auteurs :

Tous les auteurs, sauf Juan Esteban Ossa Ossa, ont contribué à la conceptualisation de l'étude et au développement de l'approche méthodologique. Les trois premiers auteurs, Marie-Ève Jean, Camille Morin et Juan Esteban Ossa Ossa, ont effectué le travail de modélisation et d'analyse des résultats. Marie-Ève Jean était responsable de la rédaction du manuscrit et tous les auteurs ont contribué à la révision du document.

Lien entre l'article ou les articles précédents et le suivant :

Cet article se base sur le cas d'étude et la méthodologie développés dans le cadre de l'article précédent. Plus précisément, certains scénarios d'application de solutions de contrôle des DRU qui ont été définis précédemment sont directement réutilisés dans le présent article pour réaliser des analyses supplémentaires et pour mieux évaluer leurs performances.

4.1 Abstract

Optimization of the spatial distribution of green infrastructures (GIs) is performed for a combined sewer system located in the Province of Quebec, Canada, using a simulation-optimization tool with the aims of reducing seasonal combined sewer overflows (CSOs) to a fixed frequency target. The performance of four CSOs control alternatives: 1) GIs alone, 2) with storage tanks, 3) with real time control (RTC) of the sewer network gates, or 4) with both storage tanks and RTC) is evaluated for a nine-year simulation period of historical rainfall data. Those scenarios are further submitted to a 20%-increased rainfall data (representative of potential climate change impact) and compared to the base case situation. Various GI implementation levels and two distribution strategies, based on spatial optimization and space availability, are also analysed. It was found that the optimization of GI's spatial distribution alone as a CSO control strategy was insufficient to cope with CSO frequency target and had a limited reduction capacity on total CSO volumes induced by potential climate change, as compared to the other scenarios. The 20%-enhanced rainfall intensities conditions increased considerably the CSO frequencies for all scenarios, but the scenario integrating RTC and GIs was the least impacted, followed by the one integrating RTC, storage tanks and GIs. 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 climate change 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. Adapting GI's number and location according to optimal GI distribution for CSO control rather than according to GI's space availability reduces CSO frequency, particularly for the scenarios integrating storage tanks and GIs, with or without RTC, whereas the GI's distribution strategy had only a slight impact on CSO volume reduction.

Keywords: Continuous simulation; Genetic algorithm; Rule-based control; Source control measure; Sustainable urban drainage systems; Low impact development; Nature based solution;

4.2 Introduction

Water management challenges are numerous in urbanized areas where impervious surfaces are generally predominant. These surfaces act as a barrier for water infiltration and limit water losses by evapotranspiration. Ultimately, these hydrological changes generate an increase in the intensity and quantity of stormwater runoff as compared to undeveloped lands (Akan and Houghtalen, 2003). For areas drained by combined sewers systems, that collect and transport both sanitary and stormwater in the same network, increased stormwater runoff due to urban land development necessarily leads to more frequent discharges of wastewater into receiving watercourses which exacerbate environmental degradation (Bi et al., 2015; Madoux-Humery et al., 2015; Passerat et al., 2011). This phenomenon, also known as combined sewer overflows (CSOs), is a growing problem considering the impact of climate change (CC) and increased imperviousness in the urban landscape (Alves et al., 2016; Botturi et al., 2021).

Regarding CC impact on CSOs in particular, authors are generally expecting an increase in CSO frequency (Kilic et al. 2022; Mailhot et al. 2014), in CSO volume (Gooré Bi et al., 2015b, Kim et al., 2022), or in both CSO volume and frequency (Dirckx et al., 2018, Nie et al., 2009, Nilsen et al., 2011, Semadeni-Davies et al., 2008). Alternatively, other works suggested a decreasing trend when sustainable urban development strategies are applied (Abdellatif et al., 2015, Mahaut and Adrieu, 2019) or variations on a monthly basis (Fortier et al., 2014).

To mitigate the impact of urbanization on water resources, sustainable stormwater management consists in reducing runoff volumes, reducing and delaying peak flows and lowering pollutant loads to the receiving environments (CERIU, 2016). Compared to traditional stormwater management, which focused on efficient collection and transportation of runoff through pipe networks, sustainable stormwater management aims at reproducing hydrological conditions that prevailed before urban land development through source control measures (SCMs). This approach seems essential to water resources quality and viability, municipal infrastructure cost-efficiency and community well-being (Boucher 2010). Among the existing SCMs dedicated to a sustainable management of water, green infrastructures (GIs) have been widely applied in order to transform the urban grey landscape into a more natural, permeable and thus water-friendly environment. For instance, GIs include solutions such as bioretention systems, green roofs, and vegetative swales, which facilitate infiltration, evaporation and sometimes permit the temporary retention of rainwater rather than its direct runoff (Fletcher et al., 2015). The implementation of distributed GIs in stormwater drainage networks to mitigate the adverse impacts of urbanization on stormwater runoff quantity and quality has been widely studied (Boening-Ulman et al., 2022; Eckart et al., 2017). Regarding CSO control in particular, studies have assessed the impact of applying various types of GIs and various levels of GIs implementation on CSO volume, frequency, and sometimes water quality (Autixier et al. 2014; Kim et al. 2022, McGarity et al. 2017; Montalto et al., 2007; Riechel et al., 2020; Struck et al., 2010). Other research works aimed at improving GI cost effectiveness through spatial location optimization (Jean et al., 2021; Fu et al., 2019; Joshi et al., 2020; Sebti et al., 2016; Torres et al., 2021; Torres et al., 2018).

Moreover, to improve CSO volume or frequency control, some studies suggested that a large number of GIs should be implemented (Jean et al., 2022; Stovin et al., 2013). Nonetheless, challenges still exist for the applicability of GIs in combined sewers due mainly to socio-political barriers including space limitation, cost constraints, ownership issues, lack of knowledge, etc. (Liu and Jensen, 2018; Rivard, 2017).

As an alternative, many authors recommend that GIs should be implemented in combination with conventional grey infrastructures (i.e. storage tanks) (Alves et al., 2016; Bakhshipour et al., 2019; Dong et al., 2017; Eckart et al., 2017; Fu et al. 2019; Liao et al., 2015; Montalto et al., 2007; Tavakol-Davani et al. 2015) and/or real-time control (RTC) technologies at the GI site scale (Brasil et al., 2021; Lewellyn, 2018; Lucas and Sample, 2015; Lund et al., 2019; Oberascher et al., 2021b; Xu et al., 2022; Xu et al., 2020a) or RTC within the network (Altobeli et al., 2020; Jean et al., 2022; Jean et al., 2021). Whereas GIs act directly on the amount and timing of runoff entering the sewer networks, grey infrastructure and RTC applied on sewer systems generally influence water flows when stormwater has already reached the underground pipe network. More specifically, RTC can be described as an intelligent control of the drainage infrastructure based on data measured in real time (and sometimes predictive data), in order to maximize the retention capacity and to minimize CSOs or other control objectives. The RTC scheme could be implemented within the network through smart control of sluice gates, pumping stations or other hydraulic infrastructure controlling the flowrate within the underground system, or through decentralized smart operation of GIs (Webber et al., 2022).

In terms of the influence of rainfall magnitude on the solutions' performance, it was found that under rainfall events of higher intensities, the performance of GIs (Eckart et al., 2017; Joshi et al., 2020) and RTC (Wang et al., 2021) was reduced compared to their performance for controlling rainfall events of lower intensities. Some studies also demonstrated the potential of GIs for coping with predicted CC impact in terms of CSOs control (García-Terán et al., 2019; Kim et al., 2022; Lucas and Sample, 2015; Semadeni-Davies et al., 2008). Alternatively, it was found that GIs were not sufficient to cope with CC impact when aiming at maintaining specific CSO control objectives (Mailhot et al., 2014). It was similarly reported that RTC could contribute significantly to mitigate CSO volume, but that it might not be sufficient to cope with potential CC impact (Dirckx et al., 2018).

Considering that previous research generally assessed the performance for CSO control of various GIs and RTC implementation strategies in a separate manner, either with or without grey infrastructure, it is considered that the performance of integrating GIs, grey infrastructure, and RTC should be better understood, particularly under more extreme rainfall conditions like those that can be induced by CC. Based on the above identified research opportunities, this study builds on the work conducted by Jean et al. (2021), which applied an optimization framework to optimize, either individually or in integration, the distribution of GIs with the design of storage tanks and RTC rules. This previous study evaluated costs and benefits of GIs as an individual or integrated solution for CSO control, and demonstrated the cost effectiveness of integrating a large number of distributed GIs with RTC and underground storage tanks to improve CSO control performance. The present study applies the same optimization framework, but assesses the contribution of solutions integrating GIs, RTC and grey infrastructure for CSO control by understanding how the system performance is impacted by changing the GIs implementation strategy and by evaluating how these solutions can cope with increasing rainfall intensities due to CC.

This research thus aims at evaluating CSO volume and frequency reductions from the individual or integrated implementation of distributed GIs with RTC and grey infrastructure and how these reductions can vary according to 1) GI implementation levels, 2) GI distribution strategies (based on optimization or space availability), and 3) under increased rainfall intensities associated to CC.

4.3 Material and methods

4.3.1 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. It corresponds to a sub-area of a medium-sized municipality where CSO problems are frequent, but where CSO mitigation measures have yet to be implemented. Particularly, 97% of the drained area consists of combined sub-catchments and the remaining 3% corresponds to impervious surfaces from flat roofs directly connected to sub-catchments where runoff is directed towards a separate stormwater network. 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 4.1. Runoff is drained toward the 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 4.1. These regulating devices are restricting flows and any excess water is spilled to nearby streams. As seen in Figure 4.1, 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. Only the months corresponding to the rainy season (end of spring, summer and fall seasons; i.e. May to November) are considered for CSO management, even if CSOs can sometimes occur during winter under thawing conditions.

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).

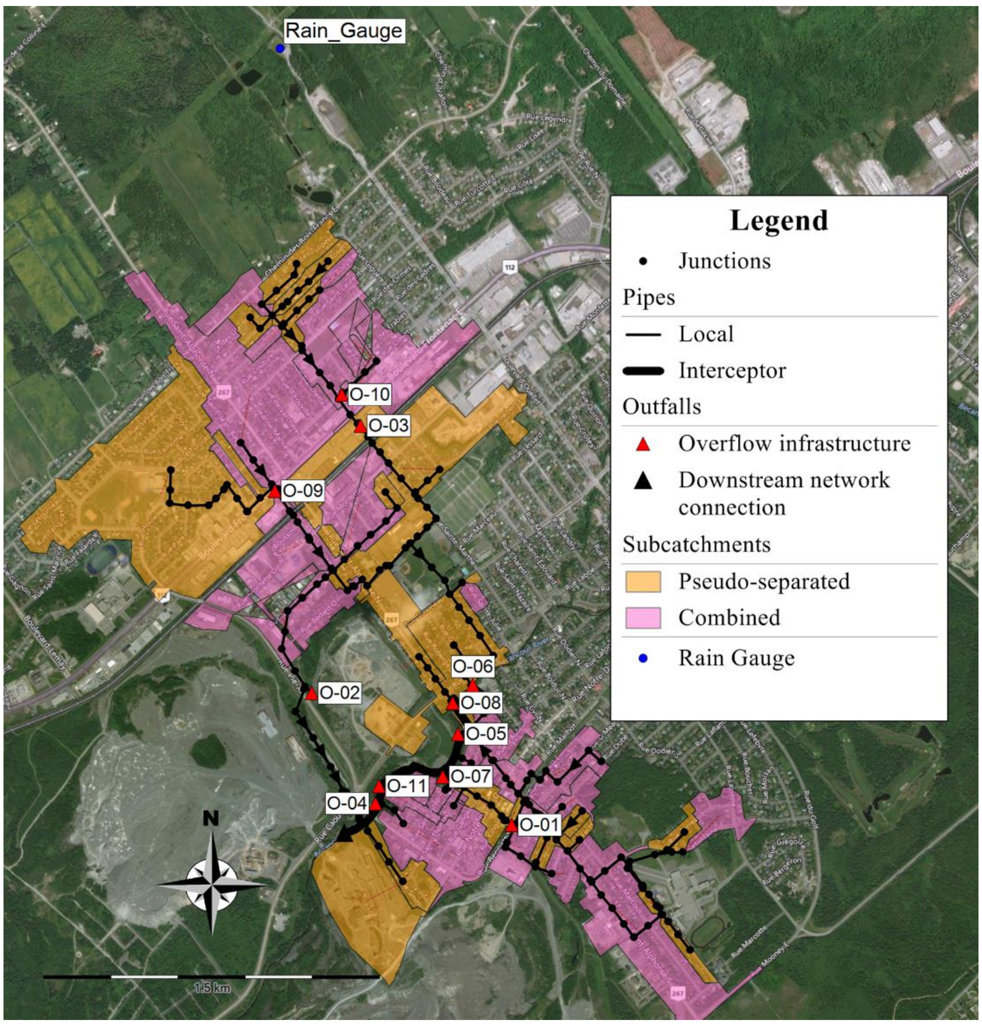

Figure 4.1 Case study sub-area (from Jean et al. 2021)

4.3.2 Rainfall data

4.3.2.1 Historical rainfall data

Rainfall data at a 5-min interval was available at the nearby rain gauge station (located in Figure 4.1) 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 maximal 10-min rainfall intensity reached is 61 mm/h, while the total rainfall depth is 20 mm (see Supplemental Material).

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 optimization scheme is performed for a design rainfall event rather than a longer continuous time series as the optimization problem solving time is prohibitive for simulation periods longer than a few hours.

Total seasonal rainfall depths and seasonal average of the maximal 5-min rainfall for each event, considering a minimum inter-event time of 12 h, are indicated in Figure 4.2 for the study period. As illustrated, the year 2011 (followed closely by 2015) is the wettest and is the one having the most intense rainfall events, on average. This year was thus considered for further analysis of GI performance under gradual implementation levels and various spatial distribution strategies.

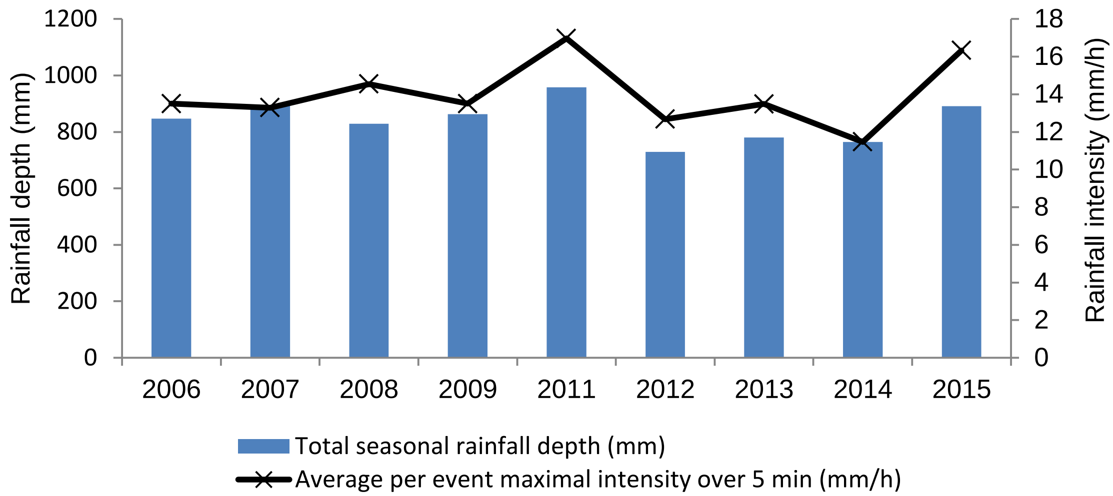

Figure 4.2 **Seasonal rainfall data (May-November period for 2006-2009 and 2011-2015)**

4.3.2.2 Climate change impact on rainfall data

The CC potential impacts on precipitation characteristics for the case study area have been assessed through different studies over the past decade and are summarized in Table 4.1. These studies generally predict large increases in annual precipitation maxima, especially for the shortest durations and for the longest return periods (i.e. rare and extreme rainfall events). However, CC modelling usually involves regional climate models (RCMs) simulations, which are based on a relatively large spatial scale (i.e. about 15-50 km-grids) and many studies are also based on daily or longer timescale as indicated in Table 4.1. As a result, these studies provide limited information regarding specific CC impact on rainfall estimations for small spatial- and short time-scale urban hydrology processes which are causing CSOs. Values presented in Table 4.1 are thus used to determine a multiplying factor on rainfall intensities applicable to the historical data set which could be approximately representative of a potential impact of CC. This factor is then used to evaluate the resiliency of CSO mitigation measures under changing rainfall intensities rather than specifically assess CC impact on CSOs. This analysis would be out of the scope of the research main objective.

As shown in Table 4.1, studies showed increased annual maximal precipitation ranging from 3 to 42.5% depending on rainfall durations, return periods and CC scenarios. Based on these results, a constant and uniform increasing factor of 20% was applied to the entire nine-year period of rainfall data to simulate more extreme rainfall intensities and compare scenarios performance in the average range of expected CC impact.

Table 4.1 CC impact on precipitation in the Province of Quebec (Canada)

Reference	Projection horizon and location	CC scenarios	Projected impact on rainfall
Singh et al. (2022)	2006–2100 Canada	Canadian Regional Climate Model (CanRCM4) combined with the Canadian Earth System Model 2 (CanESM2) global climate model under the Representative Concentration Pathways 8.5 (RCP8.5) forcing scenario and for an increase in 1.5-4 ◦C above the pre-industrial (1850-1900) average temperature compared to the base period of 1986–2005	3% to 17% average increase in total annual precipitation 9% to 36% average increase in precipitation extremes[1]
Maihot et al. (2021)	2040-2070 2070-2100 North America	Coordinated Regional Climate Downscaling Experiment for North America (NACORDEX) under the RCP4.5 and RCP8.5 forcing scenarios	9.5 to 18.6% median increase in rainfall depths for various durations (24, 48 and 72 hours) and for different return periods (2, 5, 10, 25 and 50 years)
Innocenti et al. (2019)	2020-2040 2040-2060 2060-2080 2080-2100 Southern Quebec Province area (Canada)	50-member Canadian Regional Climate Model v5 (CRCM5-LE) under the RCP8.5 forcing scenario	4.5 to 42.5% increase in rainfall depths for various durations (1, 2, 6, 12, 24, 48 and 72 hours) and for different return periods (2,25, and 100 years)
Zhang et al. (2019)	2031–2050 2081–2100 Quebec Province (Canada)	Median of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) multi-model ensemble under the RCP2.6 and RCP8.5 forcing scenarios	7.1 to 22.5% median increase in annual mean precipitation relative to 1986–2005 6.0 to 26.5% median increase in daily precipitation for different return periods (10, 20 and 50 years)
Mailhot et al. (2018)	2040-2069 Greater Montreal area (Canada)	Canadian Regional Climate Model Version 5-Large Ensemble (CRCM5-LE) under the RCP8.5 forcing scenario	10 to 26% increase in rainfall depths for various durations (1, 2, 6, 12 and 24 hours) and for different return periods (2, 5, 10 and 25 years)
Mailhot et al. (2012)	2041-2070 Canada	Regional climate models (RCMs) and Global climate models (GCMs) driving data of the North American Regional Climate Change Assessment Program (NARCCAP) ensemble of simulations under the Special Report on Emissions Scenarios (SRES) A2 scenario	12 to 18% median increase in rainfall depths for various durations (6, 12, 24 and 120 hours) and for different return periods (2, 5, 10 and 20 years)

[1] Sum of daily precipitation on all days in a year in which precipitation exceeds the 99th percentile of daily rainfall depth in the baseline period

4.3.3 Optimization problem

Details about the optimization problem are given in Jean et al. (2021). Stated briefly, 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 rules-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. Under the iterative optimization process developed by Jean et al. (2021), 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.

4.3.3.1 Optimization-simulation tool

The optimization problem was solved by the simulation-optimization tool Integrated Planning and Optimization Program (iPOP). As described in Jean et al. (2021), 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). iPOP successively compares the performance of multiple SWMM scenarios in which the input parameters to be optimized are constantly updated based on the previous simulation results. At each iteration, the input parameters are gradually converging towards the best combination of values that will minimize the total solution costs and penalties described in the optimization problem.

4.3.4 Solution design

4.3.4.1 Green infrastructures

Bioretention cells were used to represent GI implementation over the case study area through the SWMM LID control module (Rossman and Huber, 2016b). Bioretention cells area was fixed to 10 m^2 and the loading ratio (ratio between treated area and LID area) was also constant and equal to 1:10. GI implementation levels and spatial distribution were represented by varying the number of units in each sub-catchment. The exact location of each GI unit within a sub-catchment is not defined, as the impact of GIs on CSOs is assessed at the watershed scale.

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 land suitability criteria recommended by the provincial government (MELCC, 2010) were applied and included:

1) Minimal distance with buildings (4 m) and water sources (30 m);

2) Maximal slope of drained area (5%);

3) Type of soil (A or B as defined in SCS 1986);

4) Type of surface (pervious area).

The choice of bioretention cell design parameter values was based on previous monitoring work (Bilodeau 2018), Canadian design guidelines (CSA 2018) and SWMM literature (Rossman and Huber 2016b).

4.3.4.2 Storage tanks

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.

4.3.4.3 Local rule-based control

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.

4.3.5 Scenarios

Table 4.2 gives the details on the 26 scenarios that were assessed. The base scenario (scenario 1) 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.

Additional scenarios were defined in which GI units were limited to 1000 bioretention cells (for a total GI area of 1 ha) to assess the potential benefits and limitations of distributed GIs for CSO control integrated with complementary solutions considering an equal number of GI units for all the control strategies (scenarios 11 to 18) and for the wettest historical rainfall year (2011). In the previous scenarios, the number of GI units was determined by optimization to meet the CSO control target at each outfall and could vary from one scenario to the next, whereas in scenarios 11 to 18, the GI level of implementation is the same for all control strategies. Bioretention units were implemented gradually by an increment of 250 units in each sub-catchment according to two different distribution strategies: either 1) proportionally to the optimized number of GIs as obtained from the optimization framework (scenarios 11, 13, 15, and 17), or 2) proportionally to the space available for GI in each sub-catchment from the spatial analysis (scenarios 12, 14, 16, and 18). Therefore, the second GI distribution strategy could be equivalent to the first if in the optimal solution all the space available for the GIs is used. The aim was to assess GI performance under various implementation strategies instead of limiting the results to the optimized situation. Finally, these scenarios were also submitted to a 20%-increased in rainfall intensities of the 2011 year (scenarios 19 to 26) to further evaluate CSO mitigation measures resilience.

Table 4.2 Scenarios simulated

Scenario name		Distribution of GIs based on optimized values for CSO control	Distribution of 1000 GI units proportionally to optimized locations determined for CSO frequency control	Distribution of 1000 GI units proportionally to space availability	Underground storage tanks	Rule-based control of network gates	Rainfall time series
1.	Base						9 years historical
2.	Static-Grey-Green	X			X		9 years historical
3.	RTC-Grey-Green	X			X	X	9 years historical
4.	Static-Green	X					9 years historical
5.	RTC-Green	X				X	9 years historical
6.	Base+20						9 years+20%
7.	Static-Grey-Green+20	X			X		9 years+20%
8.	RTC-Grey-Green+20	X			X	X	9 years+20%
9.	Static-Green+20	X					9 years+20%
10.	RTC-Green+20	X				X	9 years+20%
11.	Static-Green-Grey-opt		X		X		2011 historical
12.	Static-Green-Grey-space			X	X		2011 historical
13.	RTC-Green-Grey-opt		X		X	X	2011 historical
14.	RTC-Green-Grey-space			X	X	X	2011 historical
15.	Static-Green-opt		X				
16.	Static-Green-space			X			2011 historical
17.	RTC-Green-opt		X			X	2011 historical
18.	RTC-Green-space			X		X	2011 historical
19.	Static-Green-Grey-opt+20		X		X		2011+20%
20.	Static-Green-Grey-space+20			X	X		2011+20%
21.	RTC-Green-Grey-opt+20		X		X	X	2011+20%
22.	RTC-Green-Grey-space+20			X	X	X	2011+20%
23.	Static-Green-opt+20		X				2011+20%
24.	Static-Green-space+20			X			2011+20%
25.	RTC-Green-opt+20		X			X	2011+20%
26.	RTC-Green-space+20			X		X	2011+20%

4.4 Results and discussion

4.4.1 Spatial distribution of GIs

Figure 4.3 presents the optimized distribution of GIs over the study area for the four assessed CSO control strategies involving GI implementation alone or in integration with storage tanks and/or RTC (scenarios 2 to 5) based on the optimization framework developed by Jean et al. (2021). As shown in Figures 4.3, the distribution of GIs and storage tanks varies according to the type of control applied in the network. Indeed, RTC reduces the total amount of storage units required to meet the optimization objective compared to the static management case (a total of two reservoirs are implemented in the RTC-Grey-Green scenario instead of five units for the Static-Grey-Green scenario). To avoid overflows under static management, it is more economical to implement storage units downstream of almost all outfalls (apart from O-03) rather than increasing the number of GIs. In the dynamically controlled system, water depths in the pipes upstream of the overflow structure can be regulated with more flexibility by the moveable sluice gates. With RTC, adding distributed GIs allows to avoid CSOs under the design rainfall event for the majority of the outfalls (only O-01 and O-02 require reservoirs). In both scenarios with green and grey infrastructures (2 and 3), fewer GIs are implemented in the sub-catchments located upstream of a storage unit compared to those with no storage. The initial investment cost for off-line retention is high compared to the cost of increasing the storage capacity. Therefore, for a given outfall where grey solutions are inevitable for mitigating CSOs, the optimization framework converges toward bigger storage facilities instead of mixing a high number of GI units with storage. As a result of this cost-efficiency criteria and increased number of storage units implemented in the Static-Grey-Green scenario as compared to the RTC-Grey-Green scenario, the upstream/downstream distribution of GIs is different in each scenario. In the Static-Grey-Green scenario, GIs are distributed mostly in all upstream sub-catchments, whereas in the RTC-Grey-Green one, GIs are concentrated particularly in the sub-catchments where no storage units are found.

In contrast, the scenarios involving only GIs with or without RTC (4 and 5) have a very similar GI distribution. RTC slightly reduces the total number of GI units required in some of the sub-catchments, but the difference remains marginal. As the upper limit on the maximal number of GIs that can be implemented according to the site suitability criteria is reached in many areas (see Table 4,3) in the Static-Green scenario or is close to be reached in the case of the RTC-

Green scenario, it is possible that a greater difference in the GI distribution could have been obtained under fewer constraining GI implementation limits.

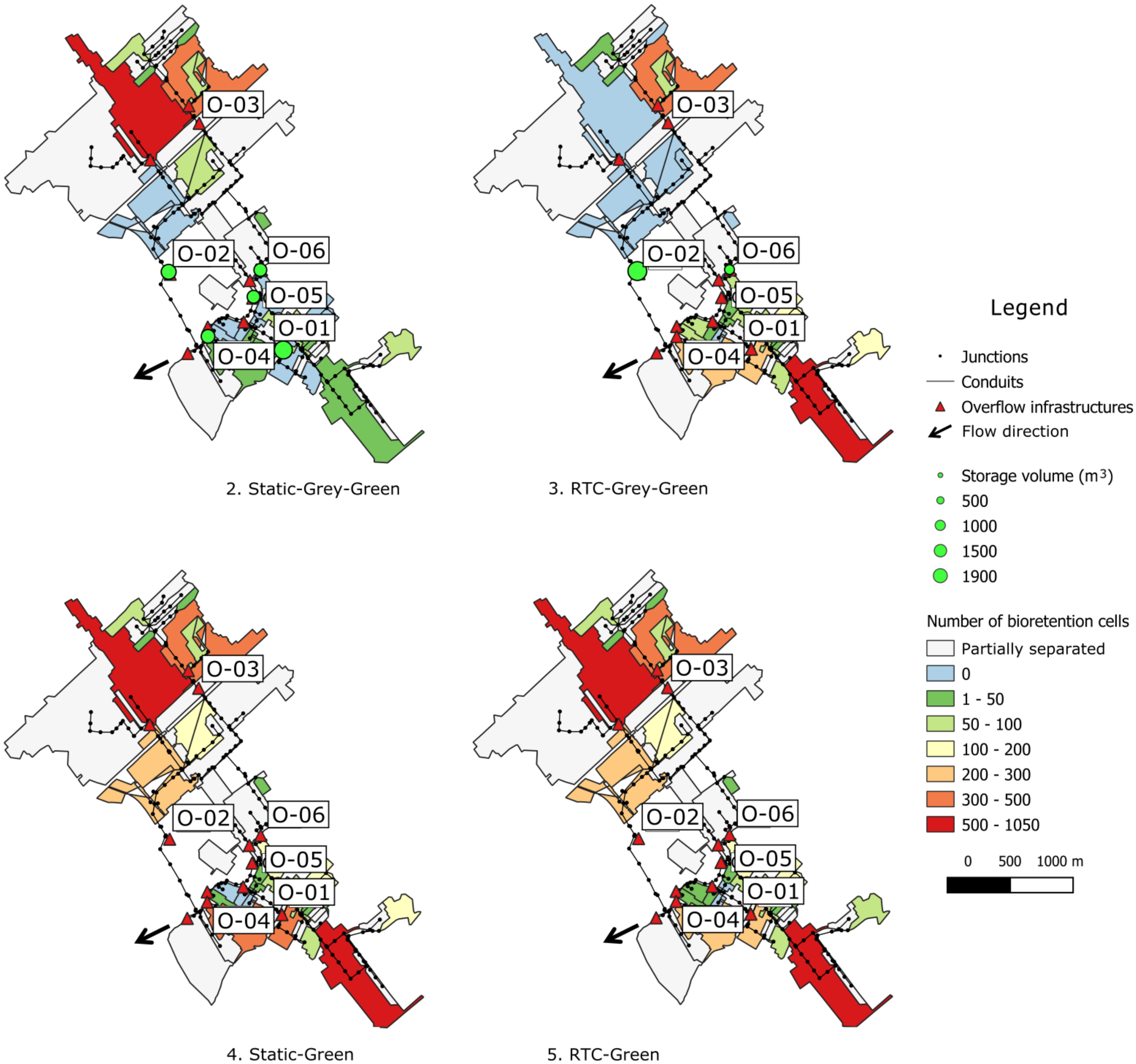

Figure 4.3 **Bioretention cells and storage tanks distribution over the study area for scenarios 2 to 5, integrating GIs alone or with storage tanks and/or RTC of the network**

Note: No GI is implemented in the partially separated sub-catchments where only flat roofs are drained to the combined sewer pipes

Table 4.3 GIs implementation level

Outfall	Space available for GIs (ha)	Percentage of available space occupied by GIs (%)			
		2. Static-Grey-Green	3. RTC-Grey-Green	4. Static-Green	5. RTC-Green
O-01	1.10	90	90	10	100
O-02	0.63	0	97	11	87
O-03	0.50	92	100	98	100
O-04	0.32	83	87	13	100
O-05	0.39	81	94	21	100
O-06	0.03	0	100	67	100
Total	3	68	93	27	97

4.4.2 Impact on CSO frequency of GIs integrated to RTC and/or grey storage

The seasonal median CSO frequency at each outfall for the nine simulated years is considerably reduced for the four scenarios involving CSO control solutions (scenarios 2 to 5) in comparison to the base situation (scenario 1), as reported in the upper part of Table 4.3. Scenario 4, involving GIs alone, has, however, a median seasonal CSO frequency above the maximal CSO frequency target of 7 CSOs/season for half of the analysed outfalls. The upper limit on the maximal number of GIs that can be implemented results in unavoidable CSO events. While the RTC-Green and Static-Green scenarios have a similar GI spatial distribution (see Figure 4.3), the integration of RTC and GIs allows controlling the CSO frequency in the most saturated areas of the network where the static control proved to be insufficient. Previous work that also optimized spatial distribution of GIs highlighted that space availability is one of the main constraints for GI implementation, which can be compensated by the addition of grey infrastructure when CSO control objectives require it (Alves et al., 2016; Fu et al., 2019; Torres et al., 2021).

From Table 4.3, it can be noticed that for two outfalls, the median CSO frequency may be slightly higher when integrating the three types of solutions (scenario 3) compared to the scenario integrating only the GIs and RTC (scenario 5). As the optimization aims to avoid any CSO volume for the design rainfall event, the specific optimized RTC rules, volume of storage and/or number of GIs for these two outfalls are different from one scenario to another. For instance, upstream of outfall O-02, almost no GI is implemented in scenario 3, since it is more cost-efficient to implement a small reservoir and RTC to avoid CSO at this outfall under the design rainfall event, while hundreds of GIs are required under scenario 5.

The lower part of Table 4.3 shows the seasonal median CSOs frequency for each outfall when the different scenarios integrating GIs, with or without storage tanks and RTC, are submitted to a 20% increase in rainfall intensities for the nine-year time series. As shown, the base scenario where no CSO control solutions are implemented (scenario 6) suffers the most from the wetter conditions, with 4 to 7 additional CSO events per outfall per season. The statically controlled network where GI distribution is optimized without grey infrastructure or RTC (scenario 9) has an increase in median CSO frequency varying from 2 to 5, whereas the remaining scenarios have a median increase in CSO frequency varying from 0 to 4 events per outfall, with scenario 8 being the less impacted.

The interpretation of the results should, however; take into consideration that all scenarios have been optimized under a single design rainfall event. This means that for some outfalls, the optimized combination of green, grey and RTC solutions might present residual capacities for CSO control for some rainfall events other than the design event.

Table 4.4 Median number of CSO events per season and per outfall

	Median number of CSO events per season under historical rainfall data				
	1. Base	2. Static-Grey-Green	3. RTC-Grey-Green	4. Static-Green	5. RTC-Green
O-01	53	3	2	5	2
O-02	31	3	4	2	0
O-03	26	2	1	2	0
O-04	66	3	2	50	1
O-05	71	5	0	36	0
O-06	62	3	2	40	4
	Median number of event per season under 20% increase in rainfall intensities				
	6. Base +20	7. Static-Grey-Green+20	8. RTC-Grey-Green+20	9. Static-Green+20	10. RTC-Green+20
O-01	60	6	3	8	3
O-02	38	5	7	4	2
O-03	30	2	2	4	2
O-04	70	6	3	55	3
O-05	78	7	2	41	2
O-06	68	7	5	44	8

Figure 4.4 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 (i.e., instead of the median CSO frequency, it is the maximal CSO frequency that is compared). 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.

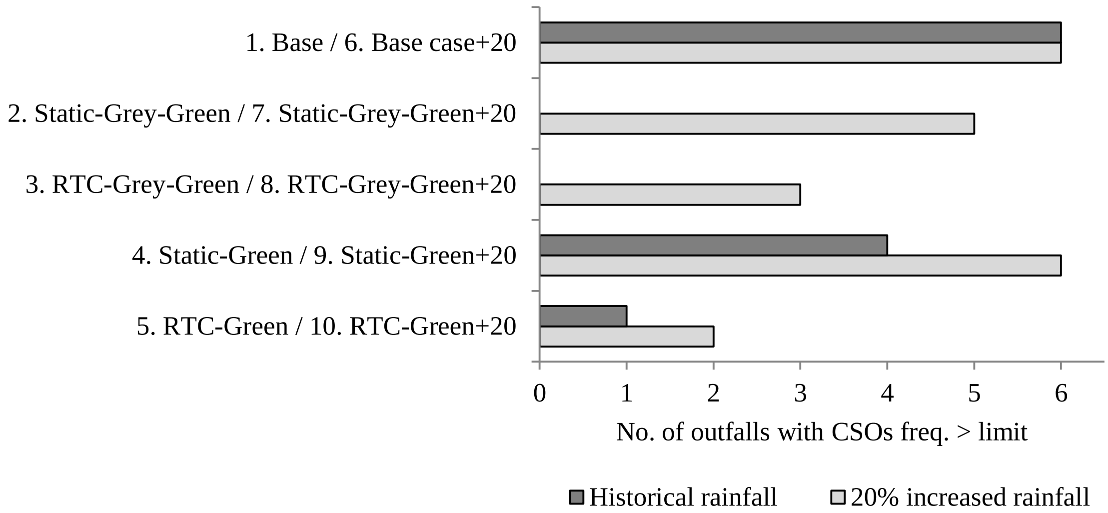

Figure 4.4 Number of outfalls for which the CSO frequency is above the limit of 7 CSOs/season for at least one year

4.4.3 Impact on CSO volume reduction of GIs combined with RTC and/or grey storage

Impact of GIs on CSO volume per outfall was evaluated by comparing the simulated results for the nine-year period of continuous seasonal rainfall data. Table 4.4 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. However, as scenarios 4 and 9 resulted in the greatest number of CSO events (see Table 4.3), these scenarios are also the ones that have the lowest total CSO volume reductions, particularly when considering the potential impact of CC. In fact, the difference between the performances of the scenarios in which RTC is implemented and the scenarios under static control are greater under the simulation of the increased rainfall time series. For instance, the CSO volume reductions between scenarios 4 and 1 is about 90%, but drops to 77% under increased rainfall intensities (difference in total CSO volumes between scenario 9 and 6), whereas the CSO volume reduction varies from 98% to 96% in the case of scenarios 5 and 10, respectively.

This means that considering the applied design rainfall event and the optimization routine integrating GIs to RTC provides additional resilience under increased rainfall intensities in terms of total CSO volume reduction.

Table 4.5 Total CSO volume reduction per outfall

Historical rainfall data					
	Total CSO volumes (m^3)				
	1. Base	2. Static-Grey-Green	3. RTC-Grey-Green	4. Static-Green	5. RTC-Green
O-01	448,464	38,629	8,558	15,339	8,518
O-02	221,802	27,383	59,973	13,500	7,135
O-03	70,832	4,708	2,571	6,944	1,860
O-04	219,014	14,338	785	51,087	1,886
O-05	228,180	15,573	851	19,867	707
O-06	444,370	17,339	15,536	79,345	8,404
Total CSO volume (m^3) (% reduction compared to scenario 1.)	**1,632,662 m^3**	**(93 %)**	**(95 %)**	**(89 %)**	**(98 %)**
20% increase in rainfall intensities					
	Total CSO volumes (m^3)				
	6. Base+20	7. Static-Grey-Green+20	8. RTC-Grey-Green+20	9. Static-Green+20	10. RTC-Green+20
O-01	532,001	71,671	21,803	79,891	19,802
O-02	286,964	54,071	80,666	50,696	33,427
O-03	94,681	13,653	7,255	22,209	4,704
O-04	256,478	24,854	3,355	82,781	3,381
O-05	228,491	27,202	2,695	53,118	1,639
O-06	522,390	33,693	27,804	144,930	21,433
Total CSO volume (m^3) (% reduction compared to scenario 6.)	**1,921,004 m^3**	**(88 %)**	**(93 %)**	**(77 %)**	**(96 %)**

The total CSO volume increase for the nine simulated years, calculated from the difference between the 20% increased rainfall intensities and the historical time series, is presented in Figure 4.5. As shown, the greatest CSO volume differences are associated with scenarios 6 and 9 as those scenarios were the most saturated initially. In fact, the increase in CSO volume is about 18% between scenarios 1 and 6, which is close to the simulated increased rainfall of 20%. When no runoff control solutions are applied, almost all the additional runoff attributed to an increased rainfall time series ends as an overflow volume. Under scenario 9, the additional runoff is basically all translated into CSO volume, as the difference in increased CSO volume between the two scenarios is about 14%. On the contrary, all the other scenarios involving RTC and/or storage units in addition to GIs permit to considerably lower the additional CSO volume associated to the 20% increase in rainfall intensities. The two scenarios involving RTC (8 and 10) provide the greatest benefit, as they reduce by about 81% the total CSO increase in volume as compared to the base situation.

Again, the performance of scenarios can be partly attributed to the fact that for some outfalls the combination of green, grey and RTC solutions optimized under the design rainfall event might present residual capacities for CSO control for rainfall events other than the design event.

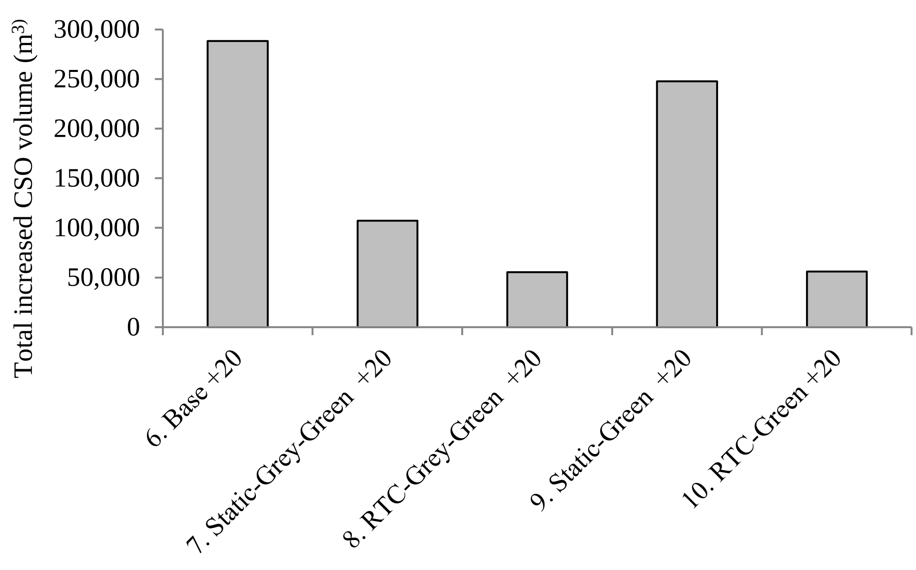

Figure 4.5 Total increases in CSO volume for the nine simulated years between the historical data set and a 20% increase in rainfall intensities

4.4.4 Impact of GIs combined RTC and/or grey storage for two spatial distribution strategies

To assess the specific impact of GIs on CSOs, only the first 1,000 bioretention cells of the different scenarios involving GIs alone, or in integration with storage tanks and/or RTC, are implemented gradually. The CSO volume and frequency reductions simulated based on GIs gradual implementation are assessed for year 2011 as it is the wettest year among the simulated nine-year period.

Figure 4.6 presents the difference in simulated CSO volume between the scenarios involving gradual GIs implementation (scenarios 11-26) and the base case conditions considering historical (scenario 1) and the 20% increased rainfall intensities (scenario 6). These scenarios represent the various GI implementation levels proportional, in each sub-catchment, to: 1) the optimized number of GIs, as obtained from the optimization framework (blue lines in Figure 4.6), and 2) the available space for GIs in each sub-catchment obtained from the spatial analysis conducted by Jean et al. (2021) (red lines in Figure 4.6) under historical rainfalls and a 20% increase in rainfall intensities for the 2011-time series (dashed lines in Figure 4.6).

As shown, the two distribution strategies do not impact CSO volume reductions, as most of the lines differentiating the two distributions (blue and red in Figure 4.6) overlay each other. Indeed, results from scenarios 15 and 16, as well as 23 and 24, are exactly the same, while the remaining scenarios are very close. In these two cases, in particular, all the space available for GIs had to be converted to GIs to meet the CSO control objective, which explains why the two GI distribution strategies are equivalent. For the other scenarios which combined GIs and grey infrastructure (scenarios 11-14 and 19-22), those in which the distribution of GIs is optimized slightly increases the CSO reduction volume because GIs are located where they are needed the most in terms of CSO control.

Moreover, for all analysed scenarios, CSOs are reduced by a greater volume when the rainfall time series is increased by a factor of 20% compared to the historical rainfall and this reduction increases as more GI units are added to the network. Even if GIs' runoff capturing capacity can be limited on an event scale when looking at the most intense rainfall events, Figure 4.6 shows that GIs can still contribute to reduce CSO volumes on a seasonal scale, even with increased rainfall intensities. Almost all scenarios have a similar curve shape describing how CSO volume reduction follows the number of implemented GI units. As a comparison, Joshi et al. (2020) noted a logarithmic increase in CSO volume reduction associated to incremental bioretention cell implementation, but their study involved a greater ratio between the bioretention coverage area and total study area.

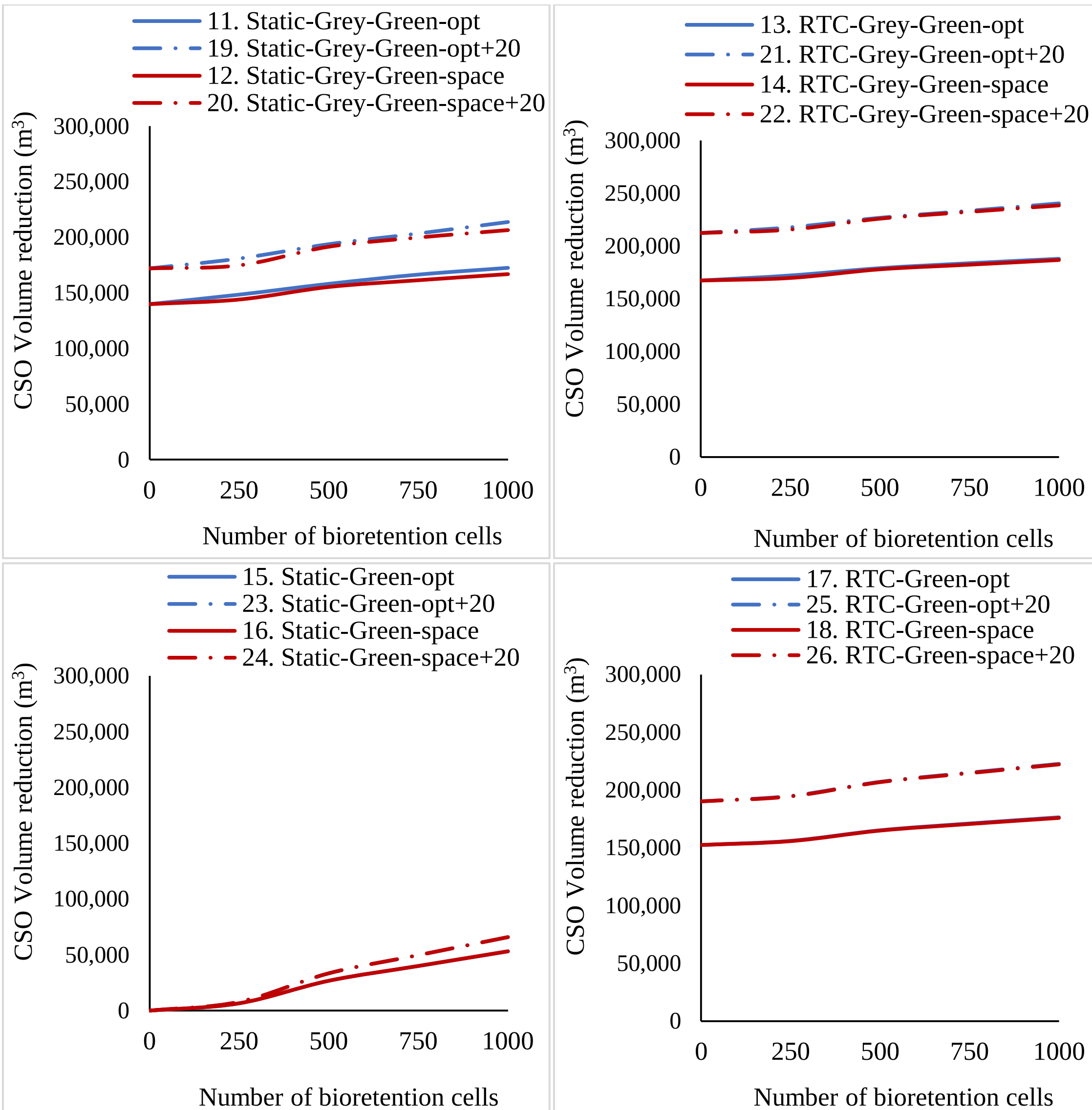

Figure 4.6 CSO volume reduction rate according to gradual GIs implementation levels based on spatial optimization (-opt) or spatial availability (-space) under historical and 20%-increased rainfall intensities

Note: The difference is calculated by subtracting the simulation results between each scenario and the base case scenario for the historical and 20% increased rainfall time series. As the two GI distribution strategies produced similar CSO reductions, most red lines overlay the blue lines

Figure 4.7 shows how the GI implementation strategies impact the weighted CSO frequency. This value is calculated by weighting the CSO frequency simulated during the year 2011 for each outfall proportionally to their respective total CSO volume (see Eq. 4.1) in order to compare CSO frequency performances with one value.

The scenarios involving storage tanks and GIs are more sensitive to the location of the bioretention cells as compared to the other alternatives involving only GIs, with or without RTC. Sub-catchments located upstream of a storage unit do not require a high number of GI units to avoid CSO events. As a result, in order to maximize their impact, GI units should be distributed in priority in the areas where no storage tank can mitigate CSOs. For comparison, Jean et al. (2022), where GIs were combined with underground storage units that could be controlled statically or by RTC, also found that under static control, the GI spatial implementation strategy had a greater impact on the system performance compared to RTC.

While scenarios 15-16 and 23-24 had the lowest CSO volume reduction by implementing GI units (Figure 4.6), it is the ones for which the highest number of GI units are necessary to reduce CSO frequency (Figure 4.7). As CSO volumes are larger and more frequent when no GI is being implemented, a higher number of GI units are required to capture a sufficient amount of runoff to completely avoid CSO events, in comparison to scenarios that rely on other CSO mitigation measures. These results agree with Bakhshipour et al. (2019), who found that as grey infrastructure capacity is replaced by higher GI implementation levels, the network becomes more vulnerable under more severe rainfall events. Similarly, Alves et al. (2018) suggested that the combination of green and grey infrastructures is usually preferred when considering risk and cost evaluation criteria for developing stormwater control solutions.

As opposed to what was observed for the CSO volume reduction, the 20%-increased rainfall time series generally resulted in a lower reduction in weighted CSO frequency from GIs, because the CSO volumes are larger and more frequent. Almost all scenarios depicted in Figure 4.7 have a reduced performance in terms of frequency reduction under the increased rainfall intensities (dashed lines) as compared to the historical data (solid lines), apart from scenarios 19 and 20. For this scenario, the simulated CSO events are more frequent but remain small and can be avoided as GI units are gradually implemented. However, as the number of GI units increased, the RTC scenarios (21, 25 and 26) start to perform better in terms of CSO frequency reduction under the 20%-increased rainfall time series, particularly when the GI spatial distribution is optimized (scenarios 21 and 25). Similarly, the study of Montoya-Coronado et al. (2022) demonstrated that sewer separation and the permeabilization of surfaces were two CSO control strategies that had a stronger impact on CSO frequency than volume when considering CC impact on precipitation.

$$Freq_{Weighted} = \sum_{i=1}^{n} \frac{CSO_{Vol,i}}{TotCSO_{Vol}} x CSO_{Freq,i}$$

Equation 4-1

Where:

$Freq_{Weighted}$ = Weighted CSO frequency (number of CSO events)

n = Total number of outfalls

$CSO_{Vol,i}$ = Total CSO volume at outfall i for all CSO events

$TotCSO_{Vol}$= Total CSO volume for all outfalls and all CSO events

$CSO_{Freq,i}$ = CSO frequency at outfall i

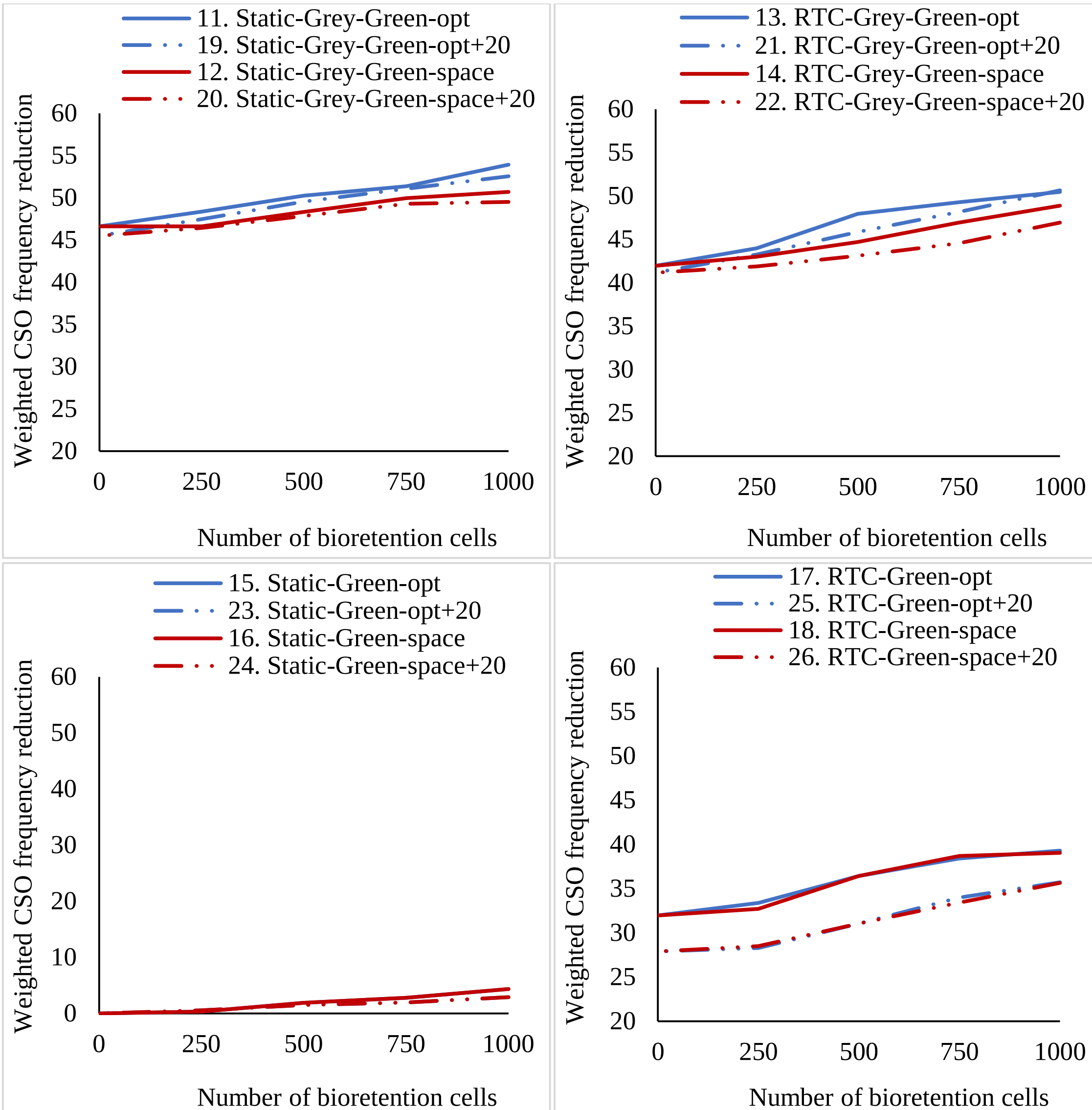

Figure 4.7 CSO frequency reduction rate according to gradual GIs implementation levels based on spatial optimization (-opt) or spatial availability (-space) under historical and 20%-increased rainfall intensities

Note: The difference is calculated by subtracting the simulation results between each scenario and the same scenario in which all GI units are removed. The 15. Static-Green-opt and 16. Static-Green-space lines overlay as well as the 23. Static-Green-opt-20 and 24. Static-Green-space-20

4.5 Conclusion

In order to mitigate the impact of urbanization on water resources and particularly to cope with CSO problems, GIs have been widely applied for their runoff capture potential and other benefits, all contributing to the improvement of sustainable stormwater management in urban areas. GIs act directly on runoff at the source, thus modifying the timing, intensity and volume of the sewer network's inflows. Other CSOs control solutions, such as underground storage tanks or implementation of RTC, can complement GIs by increasing the sewer system capacity once the stormwater runoff has reached the underground pipes network. The main objective of this paper was thus to understand how the spatial optimization of large-scale deployment of GIs with complementary solutions (RTC and conventional grey infrastructure) can contribute to CSO volume and frequency reductions. This analysis also included various GI implementation levels and GI spatial distribution strategies and looked at the impact on solutions performance of increased rainfall intensities.

In terms of CSO frequency reduction, results showed that:

- CSO frequency can only be improved by an integrated implementation of GIs with RTC and/or storage tanks;
- CSO frequency reductions are sensitive to the GI spatial distribution strategy for the scenarios integrating GIs and storage tanks (with or without RTC);
- Under the simulated 20% increased rainfall intensities, all CSO control scenarios could not maintain the CSO frequency under the prescribed seasonal limit, but the scenario integrating RTC and GIs was the least impacted followed by the one integrating RTC, GIs and storage tanks.

In terms of CSO volume reduction, results demonstrated that:

- GIs are particularly efficient in reducing CSO volume, for various types of control (static or dynamic) and distribution strategies (spatial optimization or space availability);
- When only GIs are implemented, either in integration with RTC or static control, CSO events tend to be frequent but of smaller magnitude in terms of volume as compared to the scenarios where storage tanks are also integrated;
- Under the simulated 20% increased rainfall intensities, all CSO control scenarios decreased CSO volumes but the performance of the scenario involving GIs alone is the most impacted by CC.

These results are useful to guide CSO mitigation measures design considering CSO control objectives which can vary from one region to another. However, future studies should consider the following limitations:

- Only one network is considered, but the methodology could be duplicated in a variety of systems to assess if other networks can lead to different observations

- The limited number of years and the homogeneity of the rainfall over the study area considered in the analysis, whereas RTC takes advantage of the heterogeneity in rainfall conditions;
- The simulated uniform 20% increased rainfall intensities to represent future CC impact is a simplification, which does not represent a shift in events frequency such as less frequent but more intense rainfall events;
- The approach used to determine the optimized integration of GIs with RTC and storage tank is based on a single design rainfall event, which can lead to over-dimensioned solutions and residual capacities for some scenarios;
- Whereas the impact on CSO frequency and volume was assessed in detail, this study did not consider CSO water quality aspects, which is sometimes included in CSO regulations.
- The rules involved in the application of the rule-based RTC scheme could be improved to a more optimal RTC strategy, such as model predictive control (MPC) or other optimization based control algorithms, to improve the performance of the scenarios involving RTC.
- Only bioretention cells were considered as GIs, whereas considering a greater variety of GIs could lead to more realistic results.

Future work should assess how RTC and GI design optimization strategies could be developed for improving real-world applications at minimal cost considering both water quantity and quality aspects.

4.6 Acknowledgements

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4.7 Supplementary Material

Design rainfall event

Figure 4.8 provides the temporal distribution of the synthetic Chicago design rainfall event applied for the optimization routine which was developed to determine the optimal number and location of GIs, number and volume of storage tanks and RTC rule parametrization for CSO control. This design rainfall event is derived from the intensity-duration-frequency (IDF) curves of the same return period as the CSO frequency target of 7 CSOs/season, or a return period of 1/month. The rainfall event duration is 3 h, the maximal rainfall intensity reached over 10 min is 61 mm/h, and total rainfall depth is 20 mm.

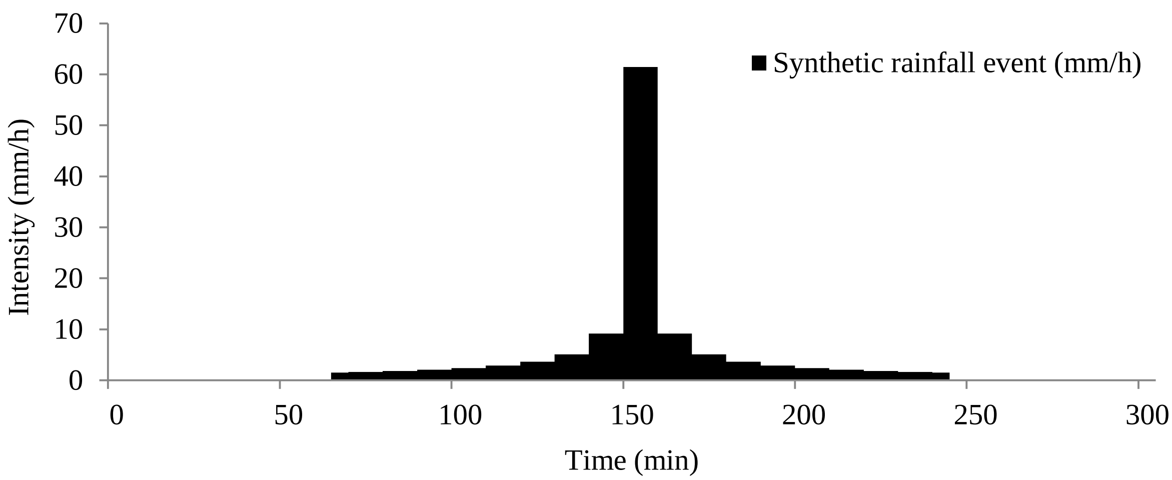

Figure 4.8 Optimization routine design rainfall event (Chicago distribution, 3h duration, return period=1/month)

5 CONTROLE EN TEMPS REEL PAR MODELISATION PREDICTIVE ET BASE SUR DES REGLES AVEC DES INFRASTRUCTURES VERTES POUR REDUIRE LES DEBORDEMENTS DE RESEAU D'EGOUT UNITAIRES

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

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Contribution des auteurs :

Tous les auteurs ont contribué à la conceptualisation de l'étude et au développement de l'approche méthodologique. Les première et deuxième auteures, Marie-Ève Jean et Camille Morin, ont effectué le travail de modélisation et d'analyse des résultats. Marie-Ève Jean était responsable de la rédaction du manuscrit et tous les auteurs ont contribué à la révision du document.

Lien entre l'article ou les articles précédents et le suivant :

Le cadre méthodologique développé pour le deuxième et le troisième article de la thèse a orienté le développement de la méthodologie du quatrième article. En effet, comme il n'était pas possible d'appliquer le même outil d'optimisation et de simulation développé précédemment pour faire l'optimisation intégrée de divers types de solutions de contrôle des DRU, une autre méthode d'intégration itérative des SCS, du CTR et des ouvrages de rétention a été mise en œuvre afin de considérer deux méthodes d'application du contrôle en temps réel.

5.1 Highlights

- Green infrastructures are added to static, rule-based and model predictive control
- Green infrastructures are effective to reduce combined sewer overflow volumes (CSO)
- Model predictive control reduces CSO impact considering environmental priorities

5.2 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.

Keywords: Model predictive control; Rule-based control; Real-time control; Urban drainage modelling; Source control measure; Low impact development

5.3 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 (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 facilitate 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 grey 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 grey infrastructures design as well as RTC rules parametrization. In comparison, applications of various RTC strategies in combination with grey 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).

5.4 Methodology

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.

5.4.1 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 sub-catchments 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 Figure 5.1). 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 5.4.4.

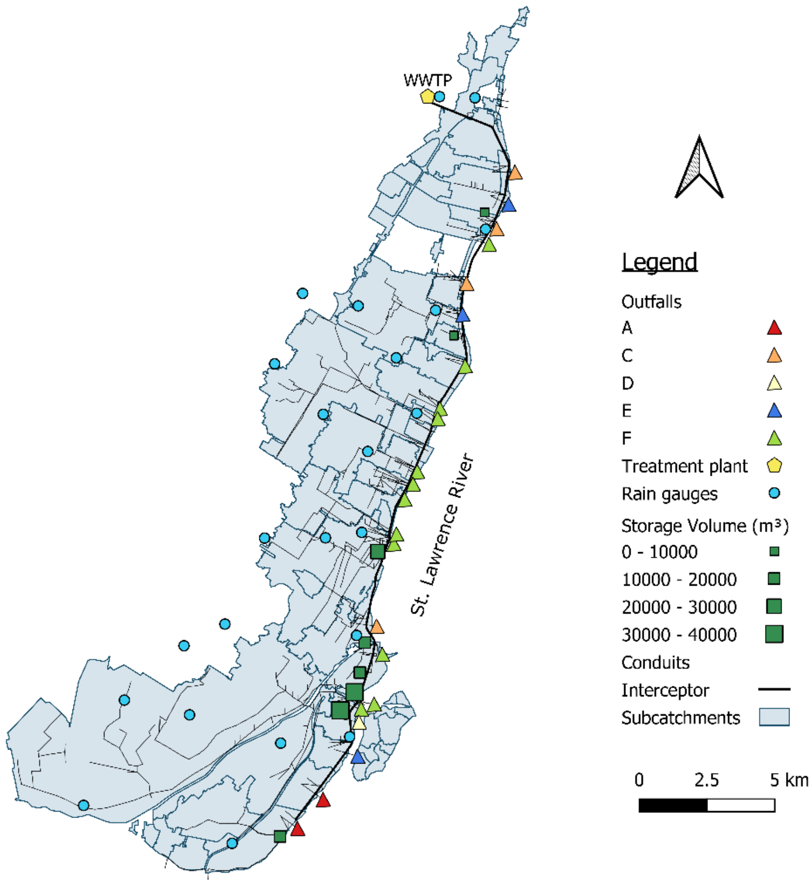

Figure 5.1 Case study map

5.4.2 Rainfall data

5.4.2.1 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 Figure 5.1). 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.

5.4.2.2 Design rainfall event

A design rainfall event, illustrated in Figure 5.2a, 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 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.

5.4.2.3 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 Figure 5.2b. 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.

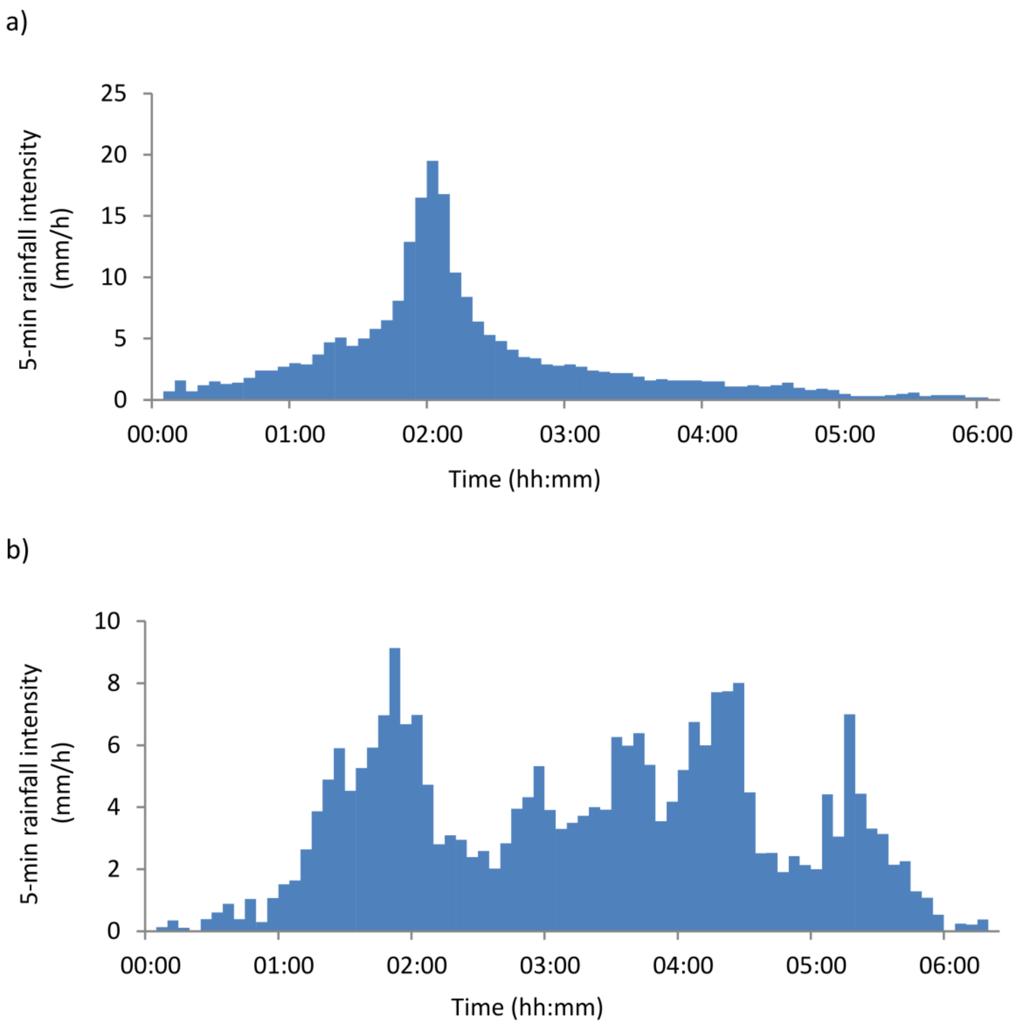

Figure 5.2 **a) Design rainfall hyetograph b) Historical rainfall event of August 21,, 2016 (area-weighted value of the 23-rain gauge stations)**

5.4.3 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 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 sub-models and their calibration are provided in the Supplementary Material section.

5.4.4 Real-time control scheme

Figure 5.3 details the RTC scheme for the three studied control strategies (MPC, RBC and static). As shown in this figure, 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 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).

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

Equation 5-1

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 links where 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 58,000 binary variables, 94,000 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.

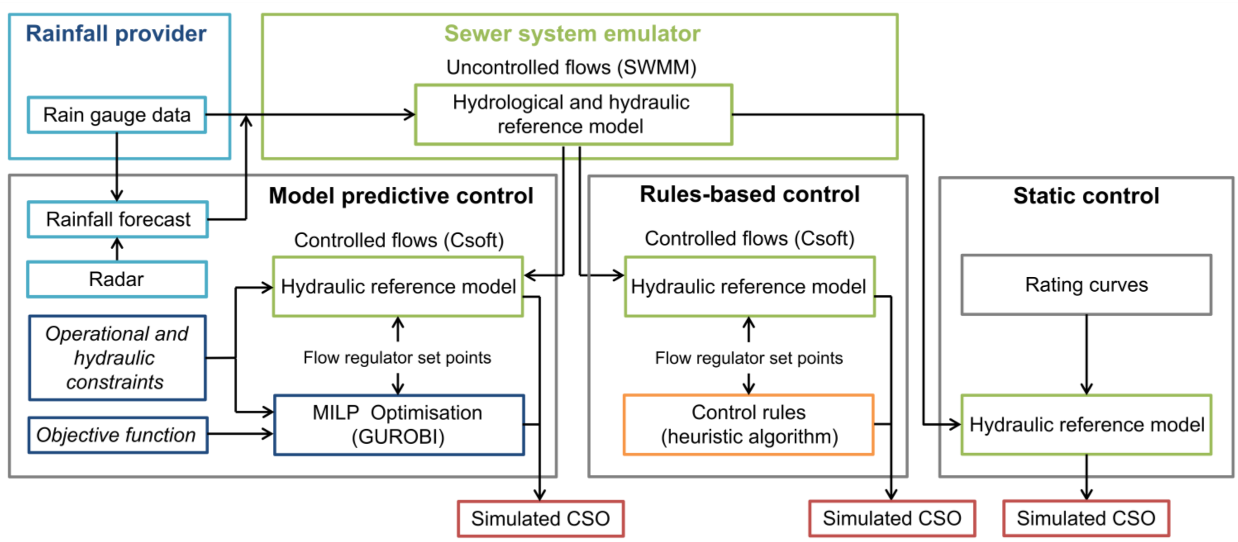

Figure 5.3 **Real-time control and static control scheme**

5.4.5 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.

5.4.5.1 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 m^2 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.

$$BPmax_j = \frac{\mathrm{A}_j}{A_{tot}} * \mathrm{Imp}_j * \mathrm{BP}_{tot} \quad \text{for j} = 1, \dots, \mathrm{n}_{sc}$$

Equation 5-2

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)

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 m^2 (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.

5.4.5.2 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 m^2. Table 5.1 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 and Huber, 2016b). 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 5.1 **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**

5.4.5.3 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 5.2, over the whole watershed area until there is no CSO for the MPC strategy applied under the design rainfall event (see section 5.4.2). Figure 5.4 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 5.2, 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.

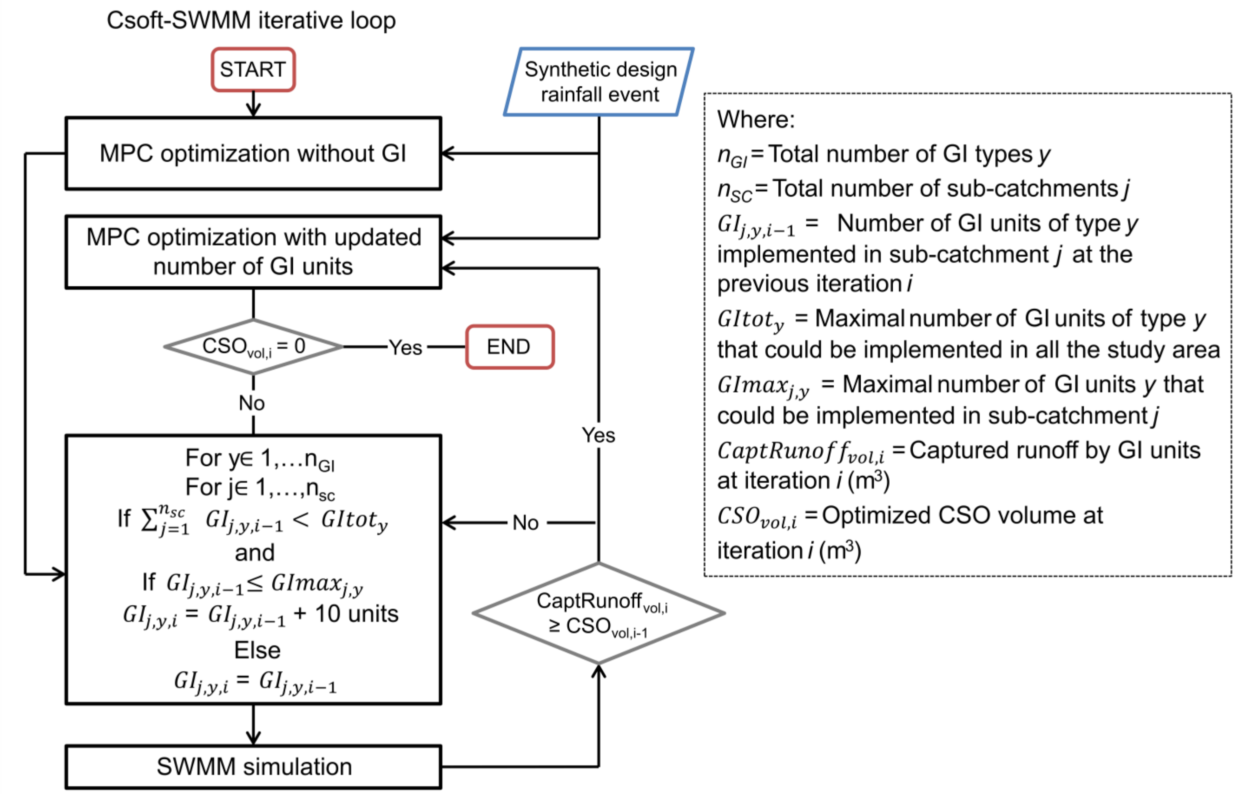

Figure 5.4 GIs spatial distribution iterative process

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 column of Table 5.2. More specifically, this ranking was based on the GI cost per treated area as indicated in column 4 of Table 5.2.

Table 5.2 GIs implementation priority based on cost and efficiency

GIs cost-efficiency priority	GI type	GI unitary cost ($/unit)	GI cost per treated area ($/m^2)
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

ME = Moderate efficiency; HE = High efficiency

5.4.6 Scenario development

Table 5.3 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 5.3 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

5.5 Result and discussion

5.5.1 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 when GIs are integrated to the MPC strategy 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).

Figure 5.5 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.

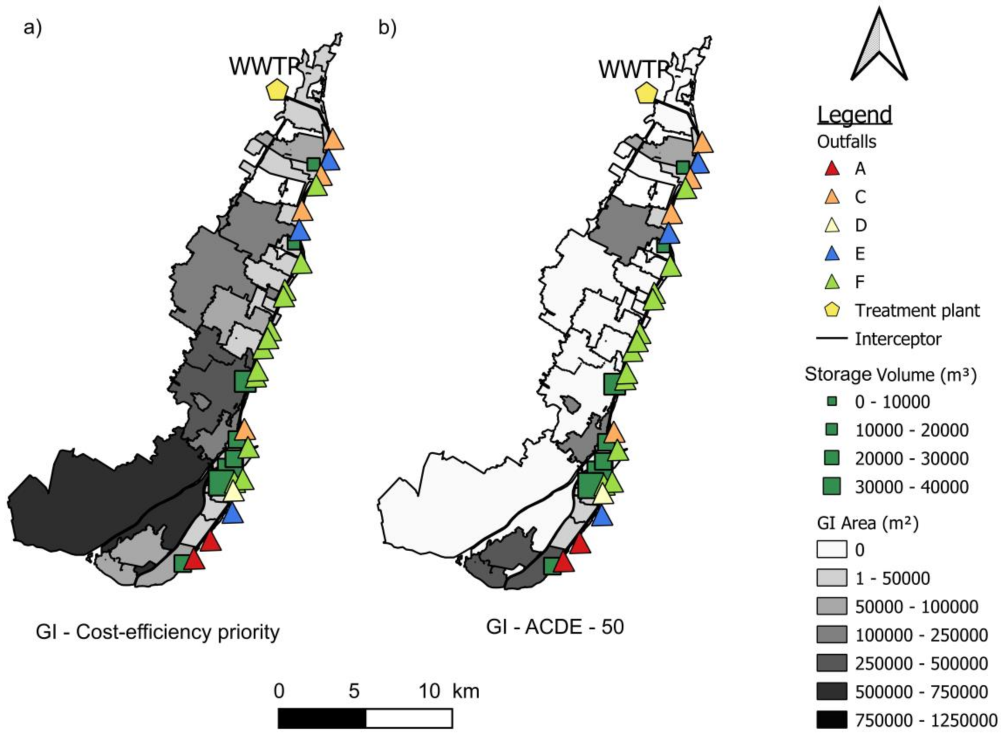

Figure 5.5 GIs distribution maps according to a) cost-efficiency priority, b) environmental priority in ACDE sub-catchments for 50% of the total GI units distributed according to cost-efficiency priority

5.5.2 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. Figure 5.6 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 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. These percentages are calculated by comparing each control strategy individually with and without GIs. Hernes et al. (2020) also found that large-scale implementation of GIs permitted to avoid CSO events for almost all rainfall events.

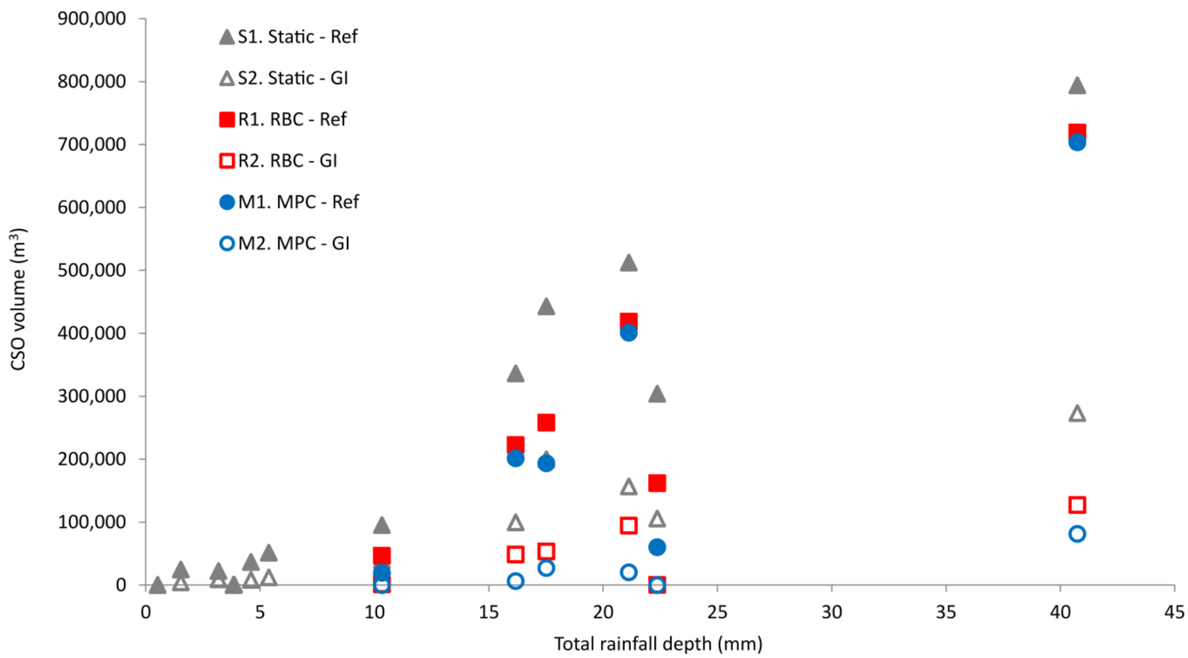

Figure 5.6 **Total CSO volume per rainfall event for the July-August 2016 period, omitting the August 16th event, for GIs distributed uniformly according to cost-efficiency priority**

Figure 5.7 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.

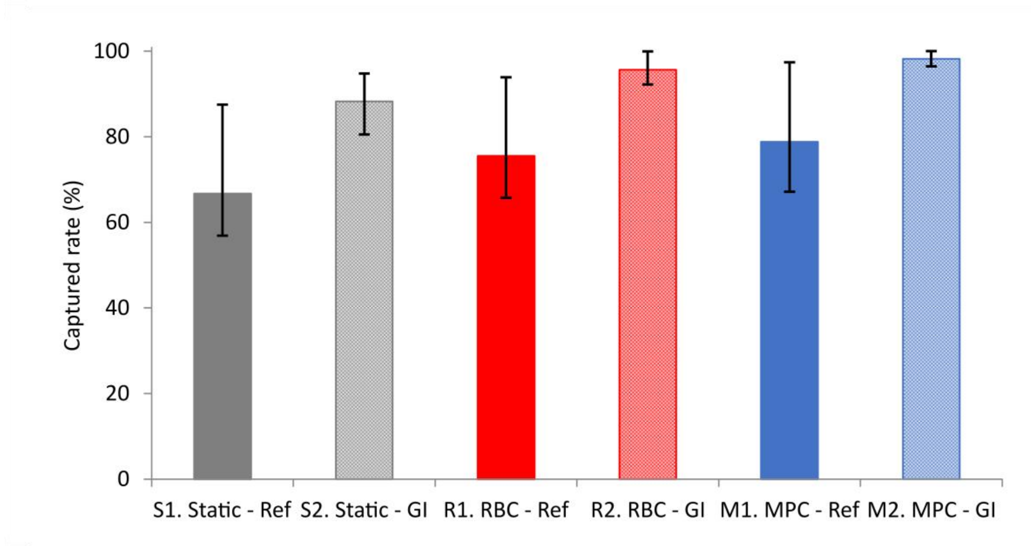

Figure 5.7 Total captured rate percentage for the July-August 2016 period, omitting the August-16th event. Note: the error bars show the variability among the simulated events

5.5.3 CSO environmental priority

The simulated CSO frequency classified according to the outfalls environmental priority categories is compiled in Figure 5.8 for the 14 rainfalls. 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 occurred at different outfalls having the same environmental priority, the frequency was 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 16th 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).

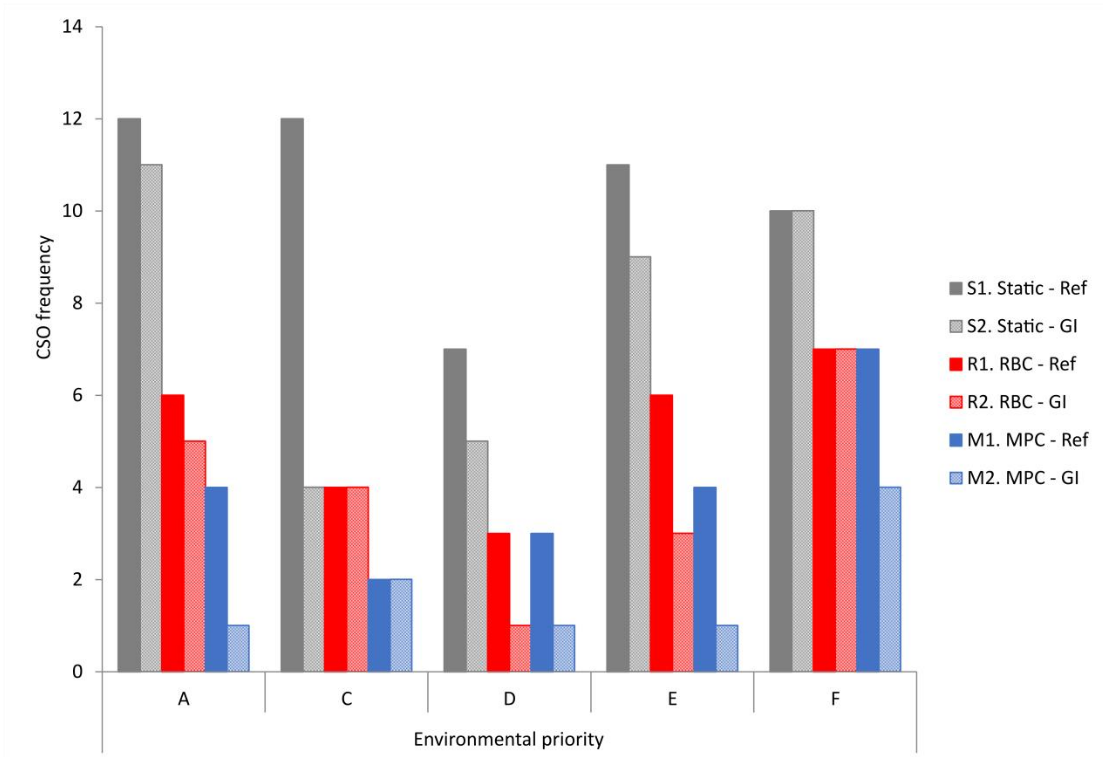

Figure 5.8 **Simulated CSO frequency per category of environmental priority for July-August 2016**

5.5.4 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 Figure 5.9a and 5.9b. Figure 5.9c and 5.9d 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 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.

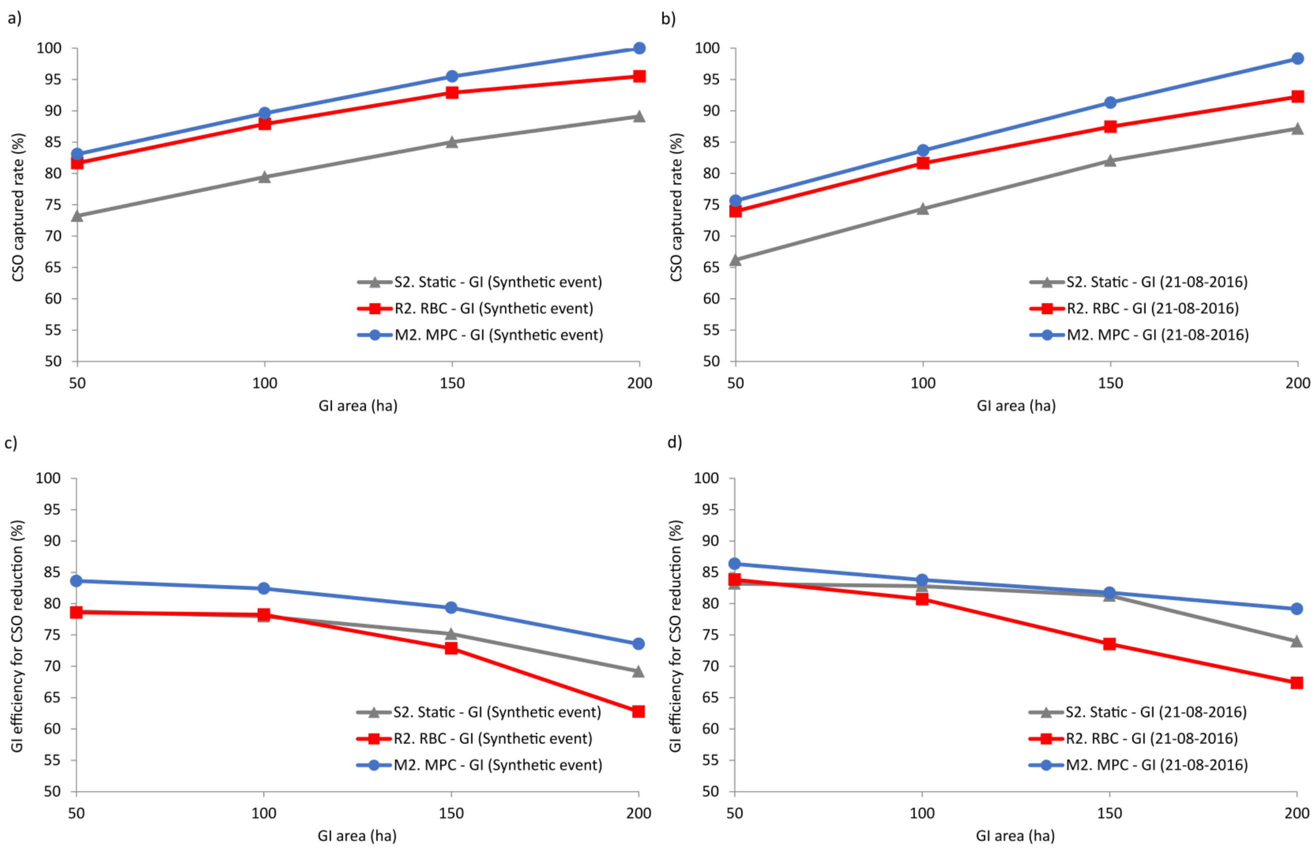

Figure 5.9 Resulting captured rates for a) the design rainfall event, b) the historical rainfall event of August 21st 2016, and the GIs efficiency for CSO volume reduction for c) the design rainfall event, and d) the historical rainfall event of August 21st 2016 under varying GIs implementation levels and sewer system control types

5.5.5 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. Figure 5.10 presents the results obtained for the two GIs distribution scenarios under the two rainfall events (synthetic design storm and historical event of August 16th 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.

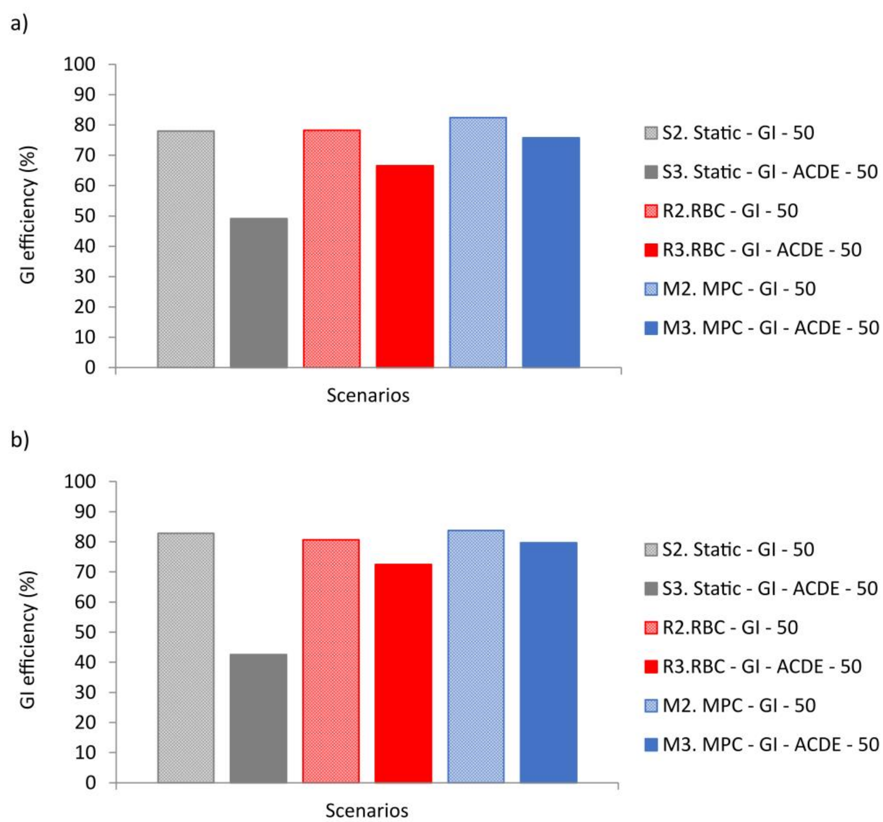

Figure 5.10 GIs efficiency for CSO volume reduction according to GIs distribution and sewer system control type under the a) synthetic design storm of 19 mm, and b) historical rainfall event of August 16th 2016

5.6 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:

- 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;
- Similarly, model errors associated to the optimization model during real-time operation of the MPC scheme are not considered which also contributes to potential MPC efficacy overestimations. Indeed, 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 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 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.

5.7 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.
- Green infrastructures efficiency (i.e. the ratio between reduced amount of CSO volume and runoff volume captured by GIs) was also higher under MPC as compared to both the static and RBC strategies.
- 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 grey 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) and model errors. Finally, GIs spatial distribution could be optimized in a closed-loop simulation with MPC for improving the integration of both technologies.

5.8 Acknowledgments

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5.10 Supplementary Material

5.10.1 Introduction

The content of the Supplementary material provides more details on the calibration and validation process of the sub-models of the simplified Control of Sewer Overflow SOFTware (Csoft) hydraulic model. The Csoft model is applied to achieve real-time control (both model predictive control and rule-based control) of the combined sewer system of the City of Montreal. The RTC framework implemented for model predictive control is based on a separation between controlled and uncontrolled flow simulations. The upstream-uncontrolled flows are simulated in SWMM and are used as input data for the downstream controlled portion of the network simulated through Csoft. This simplified Csoft model is applied on a limited portion of the combined sewer system, where only hydraulic routing (and not hydrological) is required.

5.10.2 Calibration of Csoft sub-models

5.10.2.1 Calibration of Csoft sub-models

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.

More details on the model and associated calibration is provided below for the flow conveyance, storage and water elevation models. The flow regulator and pump models were simply defined using rating and pumping curves known from monitored data and did not require calibration.

5.10.2.2 Flow conveyance model

The flow conveyance model is a Moving Average (MA) model:

$$Q(t) = \sum_{i=1}^{n_p} \sum_{j=0}^{d_p} \alpha_{i,j} * Q_{in_i}(t - j * \Delta t)$$

Equation 5-3

Where:

Q = flowrate at the pipe outlet (m^3/s)

t = time (s)

Q_{in_i} = flowrate at the pipe entry point i (m^3/s)

n_p = number of pipe inlets

d_p= maximal number of time steps to cover the transport time between the inlet pipes and the pipe outlet

Δt = time step (s)

α = flow routing coefficient calibrated based on monitored data

The α coefficients were obtained at each pipe section from SWMM simulation results (previously calibrated as explained below). The α coefficients for each time step and at each pipe inlet were obtained by minimizing the sum of the squared errors between the flow rates simulated by SWMM and those produced by the MA model. However, as multiple combinations of coefficients could lead to the same flows at the outlet, a constraint was introduced in the optimization problem to guarantee that the α coefficients distribution over time satisfied a distribution close to a Gauss (normal) distribution. Different rainfall events having high rainfall intensities were used to calibrate the α coefficients.

As an example of the obtained calibrated α coefficients, Figure 5.11 provides the α coefficients calibrated for each node along one of the south interceptor sections (conduit L8). The following Figure 5.12 compares SWMM simulated water depths and Csoft simulated water depths based on the calibrated α coefficients.

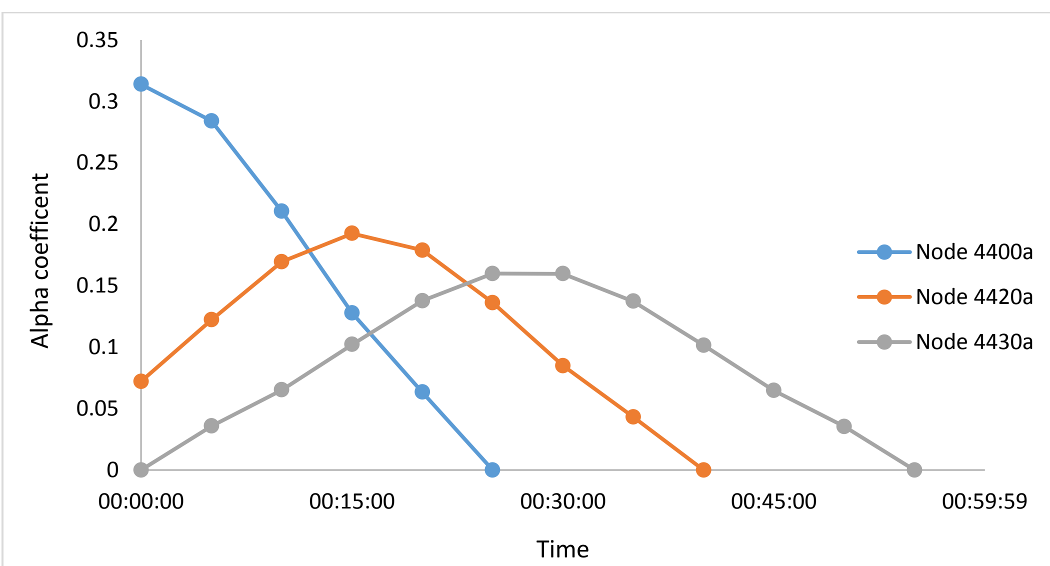

Figure 5.11 Alpha coefficients for the connecting nodes along the interceptor section L8

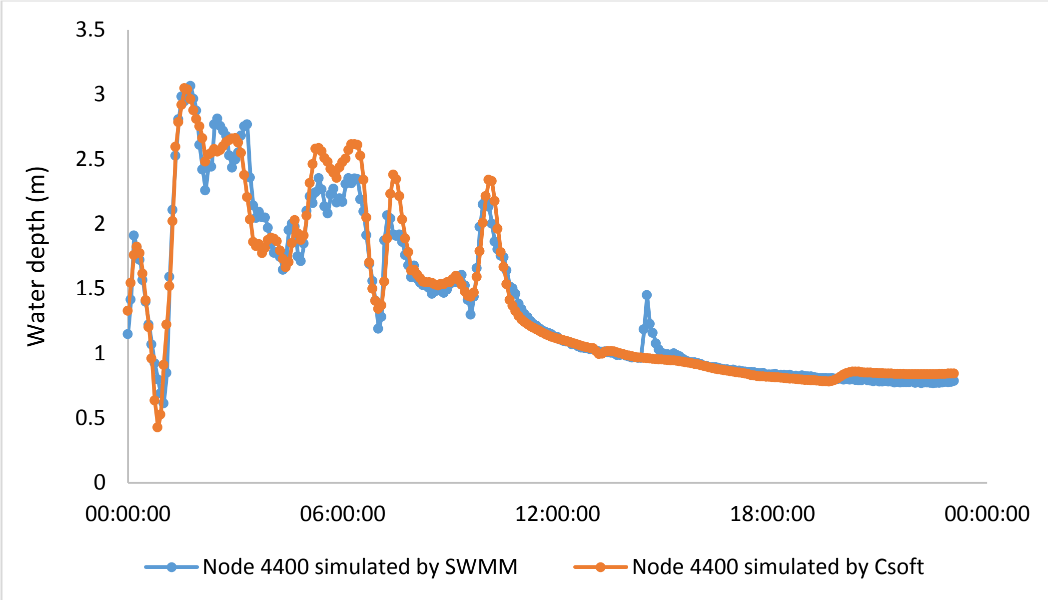

Figure 5.12 Comparison between SWMM simulated water elevations and Csoft simulated water elevations after alpha coefficients calibration in the interceptor section L8

5.10.2.3 Storage model

The storage model is based on the application of the continuity equation for determining reservoir and pipe stored volumes. The continuity equation can be detailed as:

$$V(t) = V(t - \Delta t) + \Delta t * (Q_{Sin}(t) - Q_{Sout}(t))$$

Equation 5-4

Where:

V = accumulated volume in the storage infrastructure (pipe or reservoir) (m^3)

t = time (s)

Q_{Sin} = inflow to the storage infrastructure (m^3/s)

Q_{Sout} = outflow of the storage infrastructure (m^3/s)

Δt = time step (s)

Bathymetric curves were used to determine the relationship between measured water levels and estimated volumes. Those curves were calibrated from several rainfall events simulated in the SWMM model to plot the volume of water in each pipe section where in-line storage occurs as a function of the downstream water level. Based on the obtained relationships, rating curves were defined by minimizing the sum of the squared errors and a 6th order polynomial equation.

The relationship between pipe section height and volume is not a constant, because the height was taken downstream and the volume depends on the piezometric line, which varies for different rainfall events.

As an example, the Figure 5.13 provides the bathymetric curves calibrated based on the SWMM simulation results obtained from one of the storage site.

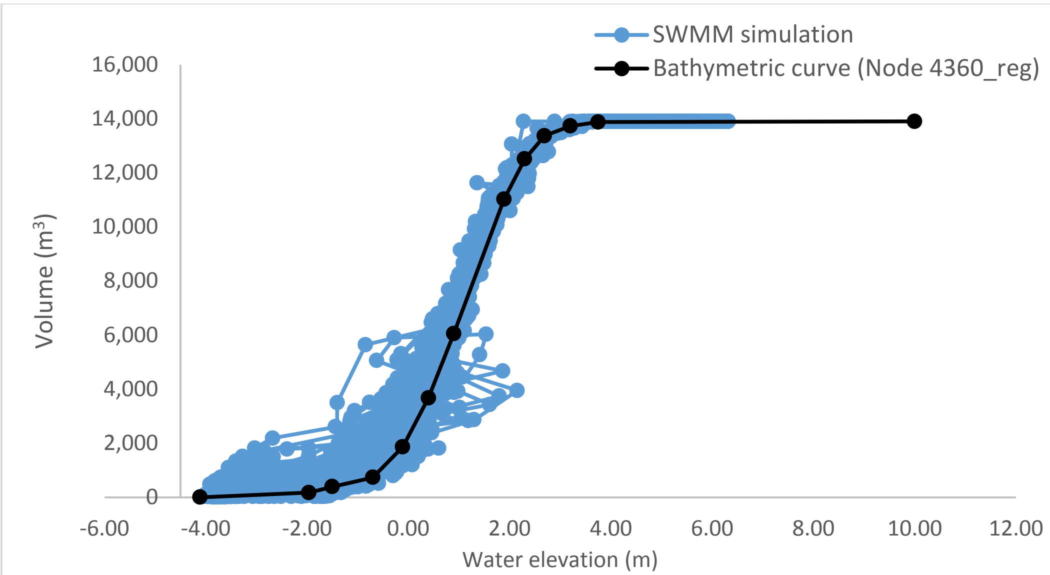

Figure 5.13 **Calibrated bathymetric curve based on SWMM simulation results at Riverside storage site**

Figure 5.14 provides the bathymetric curves calibrated for each storage site along the south interceptor.

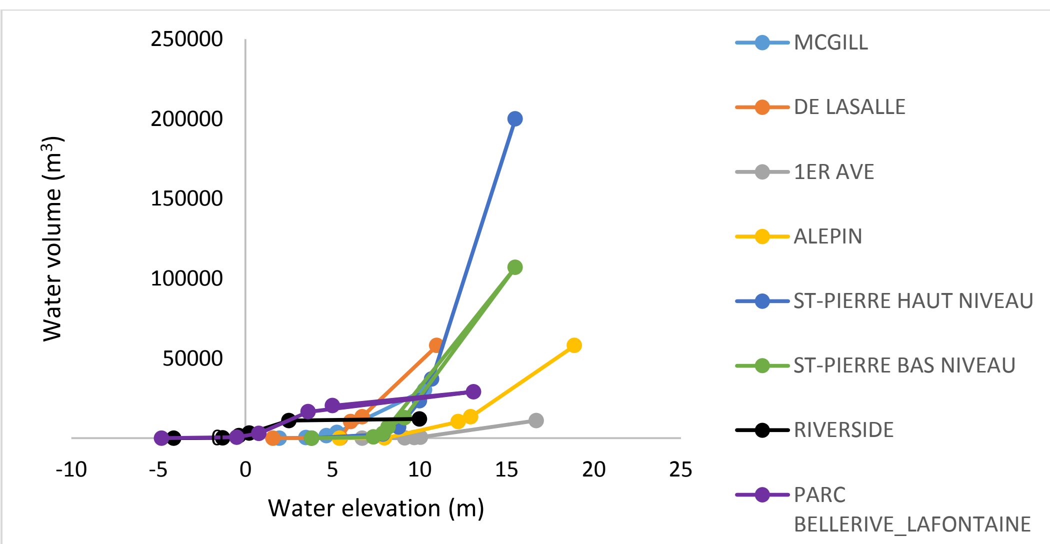

Figure 5.14 **Bathymetric curves**

5.10.2.4 Water elevation model

The water elevation model also based its calculation on the continuity equation (see Eq. S-2) and backwater curves for non-uniform flows as flowrates and pipe diameters along the interceptor are non-uniform.

Those backwater curves were determined from calibrated Manning's n friction coefficients. Manning's n coefficients along the interceptor of the case study were calibrated based on level measurements available in the interceptors from 20 level sensors located over the entire length of the interceptor. Flow rates were estimated using the pumped flow rates measured at the wastewater treatment plant (WWTP) and measured flow rates at the flow regulating structures. Based on the measured data and an estimation of the flowrate at each pipe section starting at the downstream end and moving upstream, Manning's friction coefficients were computed by minimizing the sum of the squared errors between measured levels and those computed using the Pavlovski formula for non-uniform flow (Kréménetski et al., 1984).

Table 5.4 presents the calibrated values of the Manning's n friction coefficients in the South interceptor.

Table 5.4 Manning's n friction coefficients in the South interceptor

Conduit name	Manning's N coefficient	Conduit name	Manning's N coefficient	Conduit name	Manning's N coefficient
L1	0.014	L28	0.0198	L48	0.014
L10	0.014	L29	0.0198	L4811	0.014
L10111	0.014	L2911	0.0198	L49	0.014
L106_a	0.014	L3	0.014	L5	0.014
L106_a_fict	0.014	L30	0.0198	L50	0.014
L11	0.014	L31	0.0198	L51	0.014
L11111	0.014	L311	0.014	L52	0.014
L12	0.0202	L3111	0.0198	L5211	0.014
L12a	0.0202	L32	0.0181	L53	0.014
L13	0.0202	L33	0.0208	L531	0.014
L14	0.02017	L34	0.0208	L54	0.014
L15	0.0202	L35	0.0208	L55	0.014
L16	0.02022	L36	0.0208	L551	0.014
L1611	0.0202	L36a	0.0208	L56	0.014
L17	0.0202	L37	0.014	L56a	0.014
L18	0.0202	L37a	0.014	L57	0.014
L1811	0.0202	L38	0.014	L571	0.014
L19	0.0221	L3811	0.014	L58	0.014
L19a	0.0221	L39	0.014	L59	0.014
L2	0.014	L4	0.014	L6	0.014
L20	0.0221	L40	0.014	L60	0.014
L21	0.0221	L41	0.014	L61	0.014
L22	0.0221	L42	0.014	L62	0.014
L23	0.0221	L43	0.014	L62_b	0.014
L24	0.0221	L44	0.014	L63	0.014
L25	0.0221	L45	0.014	L7	0.014
L2511	0.0221	L46	0.014	L7111	0.014
L26	0.0198	L47	0.014	L8	0.014
L27	0.0198	L47a	0.014	L9	0.014

After the calibration of the Manning's friction coefficients, the backwater curves were defined for each pipe section of the interceptor, using the same Pavlovski equation for non-uniform flow. Figure 5.16 presents backwater curves for the main intersections of the south interceptor with the local network branches.

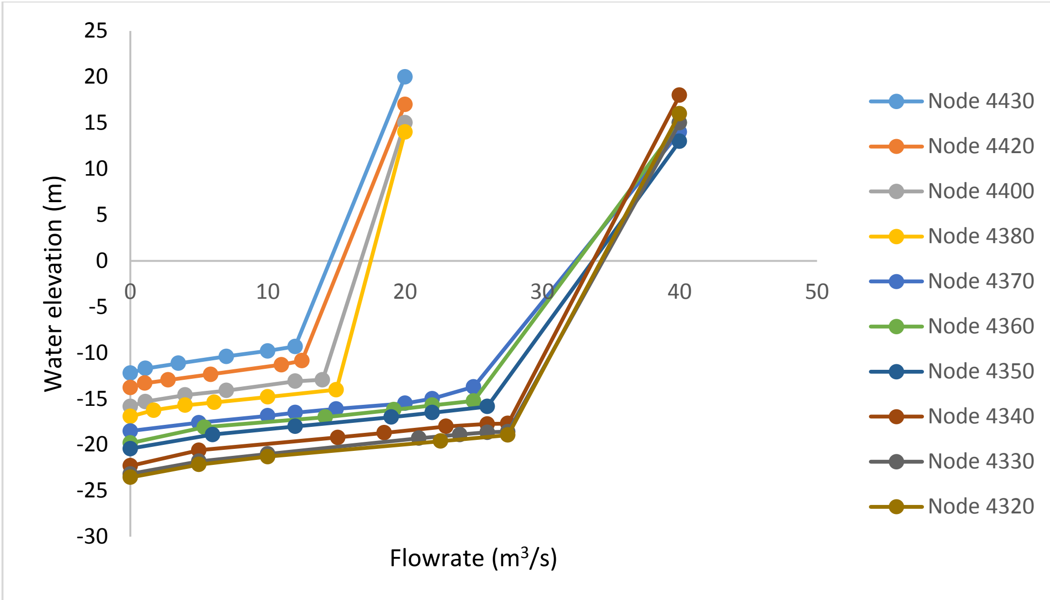

Figure 5.15 **Backwater curves along the south interceptor for the main intersections with local network**

5.10.3 Validation of Csoft

The simplified Csoft models were validated for several rainfall events over the years by comparing measured water levels and simulated ones. As an example, measured and simulated flow rates in the pump well of the south interceptor (which is located at the downstream end of the network just upstream of the WWTP) are plotted in Figures 5.17 and 5.18 provided below. The Nash–Sutcliffe efficiency coefficients calculated for these two events ranged from 0.88 to 0.99, whereas the coefficients of determination R^2 varied from 0.95 to 0.96.

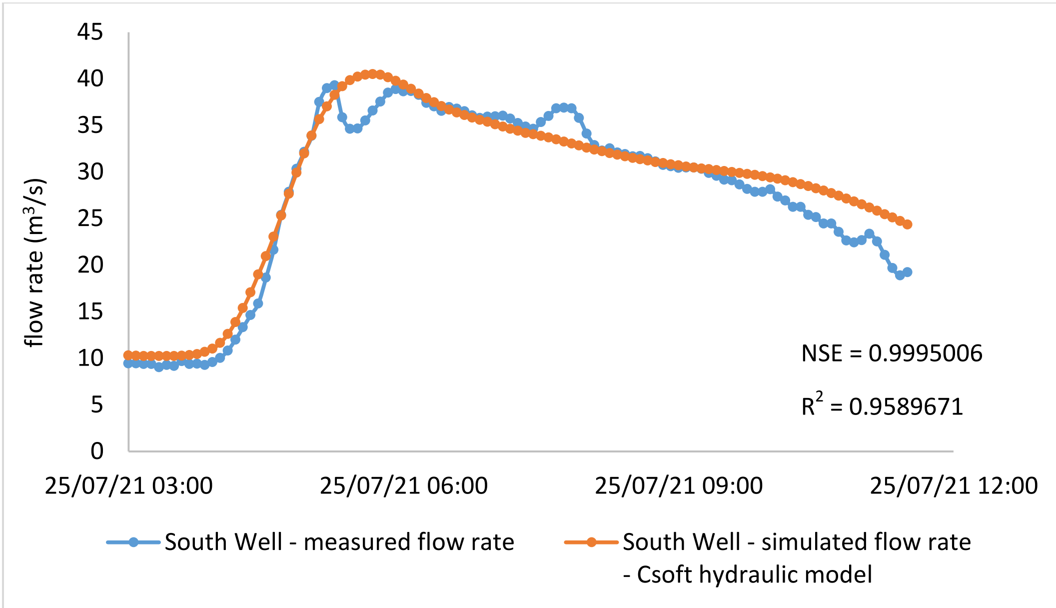

Figure 5.16 **South well measured and simulated flow rates for the rainfall event of July 25, 2021**

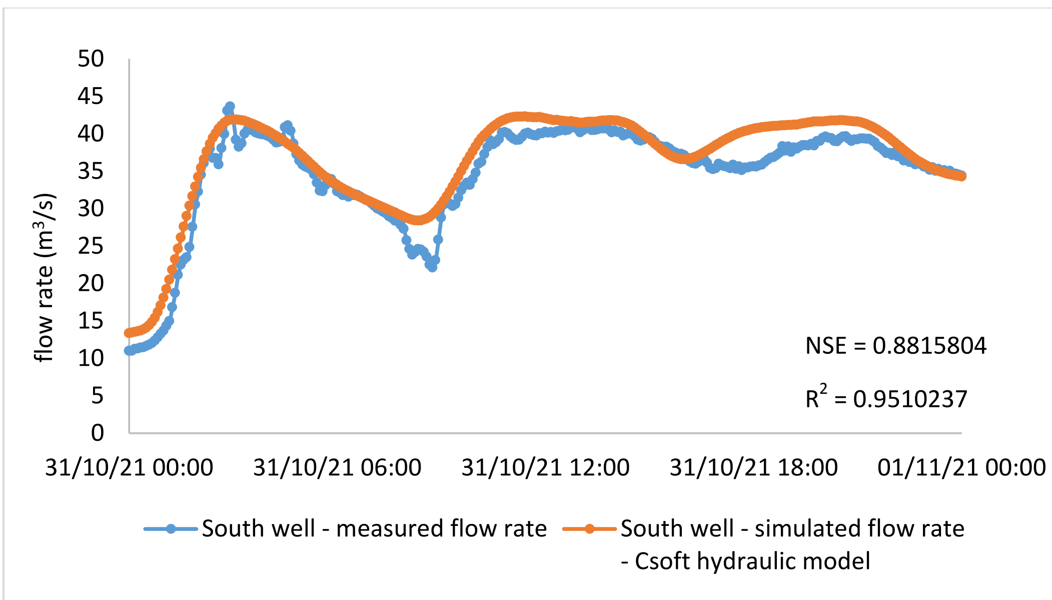

Figure 5.17 **South well measured and simulated flow rates for the rainfall event of October 31, 2021**

6 DISCUSSION GÉNÉRALE ET CONCLUSION

Le projet de recherche visait à évaluer le potentiel d’application de l’optimisation intégrée du CTR et de l’implantation de SCS à l'échelle du bassin versant comme solution de contrôle des DRU. Ces deux types de solutions agissent sur les débits de ruissellement à des niveaux différents, c’est-à-dire en amont du réseau de drainage dans le cas des SCS et une fois à l’intérieur de ce dernier dans le cas du CTR appliqué au réseau. Ainsi, il était escompté que les stratégies d’implantation du CTR et des SCS aient une influence mutuelle sur la performance du système et qu’une meilleure compréhension des modes d’application (tel que le type de CTR ou la stratégie d’implantation des SCS) et des performances attendues de la mise en œuvre optimisée de l’intégration du CTR et des SCS permettrait une diminution durable et rentable des DRU.

Pour arriver à ce constat, l’approche méthodologique générale consistait à combiner des outils d’optimisation et d’analyse spatiale à des modèles hydrologiques et hydrauliques de bassins versants urbains réels pouvant reproduire les processus physiques dynamiques de l’écoulement en surface et en réseau des eaux pluviales et sanitaires, pour différents ouvrages de débordement distribués sur le territoire et selon différents scénarios d’implantation de solutions de CTR, de SCS et d’ouvrages de rétention conventionnels. En effet, les ouvrages de rétention souterrains ont également été pris en compte dans l’approche méthodologique puisque ces infrastructures peuvent s’intégrer de manière complémentaire aux SCS ou au CTR.

D’abord, comme peu d’information était disponible pour orienter la sélection des données pluviométriques nécessaires au développement et l’analyse de solutions de contrôle des DRU, la première étape de réalisation du projet doctoral a concerné l’identification des intrants de pluie à utiliser pour l’application d’outils de simulation et d’optimisation. Les données pluviométriques analysées incluaient la simulation en continu, les événements pluviométriques historiques de conception et synthétiques ainsi que la hauteur seuil de précipitation associée à un DRU. Sur la base de ces informations, trois méthodes de sélection des données pluviométriques pour l’estimation des volumes de rétention permettant de se conformer à une fréquence cible de DRU ont été comparées.

La première méthode, soit la simulation en continu de séries temporelles pluviométriques, est la seule qui permettait d’obtenir des valeurs seuils de volume de DRU spécifiques pour chaque ouvrage de débordement. Cependant, les résultats ont montré que la réduction du nombre d'années incluses dans l'analyse peut rapidement avoir un impact sur les volumes estimés, en raison de la perte de variabilité interannuelle. Il a été observé, néanmoins, que sélectionner l'année ayant la fréquence la plus élevée d'événements pluviométriques dépassant une hauteur de pluie seuil peut être une alternative à la simulation d'un grand nombre d'années.

La deuxième méthode, soit la sélection d'événements historiques séparés par différentes périodes de temps sec inter événements, présentait des résultats très hétérogènes qui ne permettaient pas de faire ressortir la supériorité d'une variable de sélection par rapport à une autre.

Pour ce qui est de la troisième méthode, soit la sélection d'événements de pluie synthétiques dérivés des valeurs d'IDF dont la récurrence correspondait à celle de la fréquence saisonnière cible de DRU à ne pas dépasser, entraînait généralement une sous-estimation des volumes à retenir pour le contrôle des DRU. Parmi ces pluies synthétiques, les pluies de conception construites à partir de plusieurs valeurs IDF, telles que les pluies de Chicago, permettaient tout de même une estimation plus juste des volumes de rétention, mais une attention particulière devait être portée au choix de la durée de la pluie, car ce facteur pouvait affecter considérablement les volumes de DRU modélisés.

Ces résultats montrent qu'il n'était pas possible de confirmer totalement l'hypothèse initiale selon laquelle une méthode spécifique de sélection des données pluviométriques pouvant conduire à une meilleure estimation des volumes à retenir pour la conception de solutions de contrôle des DRU. En effet, dans le cas où il ne serait pas possible d'appliquer directement la simulation en continu des données pluviométriques et qu'un événement de conception devrait être utilisé (par exemple, pour l'utilisation d'outils d'optimisation qui impliquent des temps de calcul trop importants si l'intrant pluviométrique est trop long), les résultats montraient qu'aucun événement de pluie unique ne peut garantir la conformité d'une solution de contrôle des DRU. Il a été observé qu'aucune méthode de sélection d'événements pluviométriques de conception ne permettait une estimation des volumes de rétention requis tout à fait adéquate pour maintenir une fréquence saisonnière spécifique de débordements pour chacun des ouvrages d'un réseau donné. Par conséquent, il est recommandé que l'utilisation des événements pluviométriques de conception soit limitée à l'évaluation ou à l'optimisation préliminaire des solutions de contrôle des DRU, tandis que le dimensionnement des solutions finales devrait être revu dans le cadre d'une simulation en continu.

L'originalité de ces résultats consiste en l'amélioration des procédures de modélisation pour concevoir des solutions de contrôle des DRU permettant d'atteindre une fréquence saisonnière maximale de DRU, qui sont, en quelque sorte, la fondation sur laquelle pouvaient s'appuyer les étapes subséquentes du projet doctoral.

Par la suite, les recommandations précédentes en termes d'intrants pluviométriques à utiliser ont permis le développement d'une procédure d'intégration optimisée de la conception de solutions de contrôle des DRU pour étudier comment l'application du CTR, des SCS et des ouvrages de rétention à l'échelle du bassin versant a un impact sur la fréquence et les volumes de DRU par rapport à leur application individuelle. En particulier, l'impact sur le coût nécessaire pour atteindre les fréquences cibles de DRU du CTR réactif basé sur des règles, de la distribution spatiale de SCS à l'échelle du bassin versant et de l'ajout d'ouvrages de rétention traditionnels, de manière individuelle ou en intégration, a été évalué. L'hypothèse de recherche initiale, qui considérait que les bénéfices associés aux SCS et aux ouvrages de rétention pourraient être maximisés et ce, à moindres coûts, si ces solutions étaient situées là où la capacité du CTR à gérer les débits excédentaires est insuffisante, a été vérifiée.

Les résultats obtenus spécifiquement pour le réseau à l'étude montrent que les volumes de DRU peuvent être considérablement réduits par tous les scénarios testés (réduction de 40%, 89%, 90% dans les cas, respectivement, de l'implantation individuelle du CTR, des SCS et des ouvrages de rétention; réduction de 91% pour l'intégration du CTR et des ouvrages de rétention; réduction de 93% dans le cas de l'intégration des SCS et des ouvrages de rétention; réduction de 98% lorsque les SCS sont intégrées au CTR et de 95% dans le cas de l'intégration de toutes les solutions).

En contrepartie, les résultats montrent également que les fréquences maximales permises de DRU ne peuvent pas être respectées lors de l'application individuelle des SCS ou du CTR sans l'ajout d'ouvrages de rétention (fréquence de DRU supérieure à la limite saisonnière pour au moins un ouvrage parmi les neuf années modélisées).

Également, les résultats décrits indiquent que la réduction des volumes peut être légèrement plus faible lors de l'intégration des trois types de solutions comparativement au scénario intégrant seulement les SCS et le CTR, puisque le processus d'optimisation de la conception des solutions vise à assurer l'atteinte d'une fréquence cible de débordement à moindres coûts et, donc, un volume total de débordement plus élevé peut être associé à une fréquence similaire ou même plus faible selon le type de solutions implantées. En effet, sous l'implantation de SCS, les DRU ont tendance à être plus fréquents mais moins volumineux que dans le cas de l'ajout d'ouvrages de rétention.

Bien que ces résultats soient attachés au contexte local du réseau de drainage modélisé, il est estimé qu'une réduction accrue des volumes et des fréquences de DRU peut être obtenue dans des contextes variables lorsque les SCS, le CTR et les ouvrages de rétention sont mis à contribution comparativement à leur application individuelle.

En termes de coûts, l'analyse réalisée pour le cas d'étude soutient que le coût total pour atteindre les objectifs de fréquence des DRU reste similaire pour les solutions intégrant les ouvrages de rétention avec ou sans l'ajout de SCS ou de CTR. À l'opposé, l'optimisation spatiale des SCS intégrée avec l'application du CTR conduit à une réduction maximale des volumes de DRU et ce, au coût d'investissement le plus faible, par rapport au contrôle statique ou à la combinaison traditionnelle du CTR et de la rétention souterraine (environ 50% de réduction des coûts). L'intégration optimisée de la distribution spatiale des SCS, du CTR et de quelques ouvrages de rétention présente néanmoins l'option la plus favorable en termes de coûts-bénéfices pour le contrôle des DRU. En effet, lorsque ces trois types de solutions sont intégrés, le nombre total de SCS à implanter est plus réaliste et la fréquence des DRU est moins sensible à une variation des paramètres de conception des SCS et des coûts de conception de solutions; tout en restant beaucoup moins chère que les autres options sans CTR (environ 30% de réduction des coûts).

Le caractère innovant associé à ces résultats est le fait qu'ils mettent en lumière comment une optimisation intégrée du CTR et des SCS peut améliorer les performances de contrôle des DRU et diminuer les coûts de mise en œuvre par rapport à leur application individuelle, puisqu'elle permet d'éviter ou de limiter l'ajout d'ouvrages de rétention traditionnels souvent plus coûteux et offrant moins de bénéfices transversaux pour le réseau de drainage (comme la réduction de l'impact des îlots de chaleur et des changements climatiques, ainsi que le soutien à la biodiversité).

Afin de mieux comprendre comment l'application intégrée du CTR, des SCS et des ouvrages de rétention permet une plus grande réduction des volumes et de la fréquence des DRU par rapport à leur application individuelle sous une variété de conditions, diverses séries pluviométriques pour tenir compte de l'impact attendu des CC et diverses stratégies d'implantation de SCS ont également été appliqués aux scénarios précédemment analysés. L'hypothèse guidant ces travaux était que l'optimisation intégrée des SCS et du CTR pourrait améliorer le contrôle de la fréquence et des volumes de DRU pour des intensités de précipitation accrues et pour différents niveaux d'implantation des SCS, car ces deux solutions ont un impact sur le ruissellement du système à plusieurs niveaux, ce qui permettrait d’augmenter la résilience du réseau de drainage face à des conditions changeantes.

En termes de réduction de la fréquence des DRU, les résultats obtenus pour le réseau de drainage à l’étude ont montré que tous les scénarios de contrôle des DRU n’ont pu maintenir, pour tous les ouvrages de débordement, la fréquence saisonnière cible de DRU dans un contexte d'augmentation des intensités pluviométriques. Le scénario intégrant le CTR et les SCS a toutefois été le moins affecté, suivi de celui intégrant le CTR, les SCS et les ouvrages de rétention traditionnels (2 à 3 ouvrages de débordement dépassaient leur limite de fréquence de DRU plutôt que 5 à 6 pour les autres scénarios). De plus, il a été constaté que la fréquence des DRU est sensible à la stratégie de distribution spatiale des SCS pour les scénarios intégrant les SCS et les ouvrages de rétention et que le CTR ne réduisait pas cette sensibilité.

Toujours selon le cas d’étude modélisé, les résultats ont démontré que les SCS sont particulièrement efficaces pour réduire les volumes de DRU, et ce, peu importe la stratégie de contrôle (statique ou dynamique) ou de distribution spatiale (basée sur l'optimisation spatiale ou basée sur l'espace disponible). Toutefois, dans des conditions d’intensification des précipitations, l’intégration des SCS et du CTR (avec ou sans ouvrages de rétention) permet de minimiser l’augmentation des volumes de DRU de manière considérable comparativement aux scénarios où le contrôle statique est appliqué. En particulier, la performance du scénario impliquant les SCS seules est la plus affectée par l'impact potentiel des CC, puisque ce scénario permet de réduire de seulement 15% le volume total de DRU supplémentaire causé par les CC, par rapport au scénario de base, comparativement à une réduction d’environ 80% pour les scénarios où le CTR est aussi intégré au réseau.

Il peut donc être conclu que l’hypothèse a pu être vérifiée pour le cas d’étude analysé, puisque les performances des SCS sont moins sensibles à des conditions changeantes lorsque celles-ci sont intégrées au CTR, autant en termes de fréquence que de volume de DRU. L’intégration des SCS à des ouvrages de rétention sans l’ajout du CTR permet tout de même une certaine robustesse du système en termes de réduction des volumes DRU.

L’innovation découlant de ces travaux vient de la contribution des résultats obtenus à une meilleure évaluation des performances de l’intégration optimisée des SCS et du CTR en fonction de conditions de précipitations changeantes associées à l’impact potentiel des CC et de différentes stratégies d’implantation des SCS.

Finalement, il s’avérait nécessaire de mieux comprendre comment l’application intégrée du CTR, des SCS et des ouvrages de rétention a un impact sur la fréquence et la réduction des volumes de DRU par rapport à leur application individuelle, selon diverses stratégies de déploiement du CTR, puisque celles-ci peuvent varier grandement en termes de performance et de complexité d’application. Plus particulièrement, l'étude a évalué les performances obtenues par l'intégration à grande échelle des SCS distribuées dans un secteur densément urbanisé où se trouvent déjà des ouvrages de rétention et où il est possible d’appliquer deux méthodes de CTR (CTR basé sur des règles locales et réactives et CTR global par modélisation prédictive), selon divers scénarios de distribution des SCS, pour mieux évaluer l’influence des divers modes de contrôle sur les performances de réduction des DRU. L’hypothèse de recherche supposait que les performances des SCS, en termes de réduction des volumes et des fréquences de DRU, seraient améliorées lorsque ces solutions sont intégrées avec le CTR par modélisation prédictive par rapport au CTR de type réactif et local. Cette hypothèse se basait sur le fait que l’application d’une stratégie de CTR plus complexe peut permettre d’augmenter la flexibilité du réseau de drainage face à des débits de ruissellement variables dans le temps et l’espace. Il était ainsi escompté que cette hypothèse serait vérifiée même lors de l’application de différentes stratégies de distribution spatiale des SCS.

Les résultats ont montré que les SCS permettent une réduction considérable des volumes de DRU, peu importe le type de contrôle appliqué au réseau de drainage étudié et même en considérant des événements pluvieux de différentes ampleurs. En effet, les volumes de DRU peuvent être réduits de 65%, 82% et 92% en moyenne pour une variété d’événements pluviaux, selon, respectivement, un contrôle statique, par CTR local réactif et par CTR par modélisation prédictive.

Toutefois, l'intégration des SCS au CTR par modélisation prédictive conduit à une plus grande réduction des DRU, tant en termes de volume que de fréquence, tout en respectant les priorités environnementales et en conduisant à de plus grande efficacité des SCS (c’est-à-dire le ratio entre le volume de débordement en moins et le volume de ruissellement réduit par les SCS) des eaux de ruissellement plus élevés. Par exemple, la fréquence de DRU simulée pour deux mois de pluies en période estivale, aux ouvrages de débordement auxquels la plus grande priorité environnementale est attachée, varie de 11 dans le cas du contrôle statique à 5 dans le cas du CTR local réactif, tandis qu’elle est réduite à seulement 1 dans le cas du CTR par modélisation prédictive lorsque des SCS sont distribuées sur le territoire.

De plus, les performances du réseau contrôlé de manière statique peuvent être réduites de moitié lorsque les SCS sont implantées uniquement dans des sous-bassins spécifiques plutôt que plus uniformément sur tout le territoire, tandis que les deux stratégies de CTR n'ont qu'une légère baisse de performance. Dans le cas du contrôle statique, la capacité des SCS à réduire les volumes de DRU est réduite d'environ 30 à 50% lorsque la distribution spatiale des SCS n'est plus uniforme, tandis que la performance des deux stratégies de CTR déployées n'est réduite que d'environ 5 à 10%.

Ainsi, l'hypothèse est partiellement vérifiée dans le sens où il est vrai que pour le cas d'étude choisi l'impact des SCS sur les DRU peut être amélioré lorsque ce type de solutions est intégré au CTR par modélisation prédictive par rapport à d'autres types de CTR moins complexes. Par contre, cette amélioration des performances est parfois modérée lorsque les résultats obtenus sont comparés à ceux découlant de l'application du CTR réactif local. Il est donc escompté que pour les réseaux favorables au CTR qui comprennent un nombre important de sites de contrôle et où la vulnérabilité des cours d'eau récepteurs aux DRU varie spatialement, le CTR par modélisation prédictive offre une marge de manœuvre plus grande pour maximiser l'utilisation des infrastructures grises et des SCS par rapport à des réseaux où ce genre de contraintes seraient moins importantes.

Les résultats obtenus sont innovants, puisqu'ils permettent de comparer les performances obtenues à partir de l'application de différents types de gestion de CTR en association avec la distribution à grande échelle de SCS, alors que ces deux types de solutions ont rarement été appliqués de manière complémentaire pour résoudre la problématique des DRU.

Bien que les résultats présentés soient liés aux cas d'études modélisé, la méthodologie développée pourrait être transférée à d'autres sites où le CTR présente un potentiel afin d'améliorer son impact sur les DRU par une intégration optimisée des SCS sur le territoire. En effet, la méthode développée se base sur des outils d'optimisation et de modélisation hydrauliques et hydrologiques connus et transférables d'un réseau à l'autre.

Ces constats permettent donc de conclure que l'intégration des SCS et du CTR présente plusieurs bénéfices pour le contrôle des DRU, en termes de coûts et de performance, et que l'ajout d'ouvrages de rétention conventionnels est également favorable, particulièrement lorsqu'un critère de contrôle des fréquences de DRU est appliqué. Ces résultats sont toutefois assujettis aux limites inhérentes des hypothèses de recherche, ainsi qu'à la méthodologie développée pour y répondre. Les limites et les pistes pour réduire leur impact lors de travaux futurs comprennent :

- L’analyse des solutions s’est faite à l’échelle du bassin versant urbain afin d’inclure des critères de performance globale du système ce qui, en contrepartie, nécessitait l’utilisation de modèles hydrauliques et hydrologiques assez grossiers permettant de simuler les processus dynamiques du ruissellement en surface et en réseau avec une précision plus limitée que dans le cas de modèles plus fins. Bien que la capacité de ces modèles à représenter les DRU historiques ait été validée et qu’il soit pertinent de les utiliser pour la réalisation de la thèse, il est supposé qu’une analyse plus fine, sur un territoire circonscrit, permettrait de représenter de manière plus précise l’effet des SCS à petite échelle et pourrait contribuer à préciser les résultats de la thèse selon diverses échelles d’analyse. Par exemple, il est possible qu’à une échelle plus fine les SCS aient un impact moindre ou, au contraire, plus important sur la réduction des DRU.
- Lors du processus d’optimisation, seulement les coûts d’implantation des différentes solutions ont été pris en compte, puisque ceux-ci représentent l’investissement le plus important en comparaison des coûts d’entretien; toutefois, il aurait été pertinent d’inclure tous les coûts associés au cycle de vie des infrastructures et d’effectuer une analyse coûts-bénéfices qui inclurait les bénéfices transversaux des SCS. Comme la portée de l’étude concernait principalement l’applicabilité et les bénéfices potentiels de l’intégration des SCS et du CTR, l’évaluation complète des coûts et des bénéfices associés aux différentes solutions analysées n’était pas essentielle à cette première analyse, mais serait un complément à apporter aux travaux futurs dans ce domaine pour soutenir les résultats obtenus ou pour mieux les circonscrire.
- Dans un même ordre d’idées, il aurait été pertinent de mieux quantifier la flexibilité supplémentaire que confère le CTR dans le choix des infrastructures vertes à implanter sur le territoire en complexifiant davantage le problème d’optimisation par l’intégration d’un choix plus vaste de types d’infrastructures vertes et en considérant des coûts et des distributions spatiales différentes. Ainsi, la capacité du CTR à permettre la construction d’infrastructures vertes plus petites et à des localisations moins coûteuses aurait pu être davantage explorée.
- L’optimisation intégrée des SCS, du CTR et des ouvrages de rétention se basait sur un algorithme d’optimisation par essaimage de particules faisant partie de la famille des algorithmes évolutionnaires, qui sont utiles pour la résolution de problèmes multi-objectifs et non linéaires. Bien qu’il fût approprié d’utiliser ce type d’algorithme pour résoudre le problème d’optimisation visé par la thèse, et que la convergence des

résultats obtenus pouvait être validée par l'analyse des extrants d'optimisation, d'autres algorithmes pourraient être testés afin de vérifier la performance des outils utilisés.

- De même, l'approche utilisée pour déterminer l'intégration optimisée des SCS avec le CTR et les ouvrages de stockage est basée sur un seul événement pluviométrique de conception, ce qui peut potentiellement conduire à des solutions surdimensionnées pour certains scénarios, ce qui rend plus difficile la comparaison de leurs performances face à des intrants pluviométriques plus intenses.
- Seuls deux réseaux ont été considérés dans les analyses, mais la méthodologie appliquée pourrait être dupliquée dans une variété de systèmes pour évaluer si des applications sur d'autres réseaux peuvent conduire à des observations différentes.
- L'homogénéité de la pluviométrie sur le territoire considérée dans les analyses pourrait limiter les gains potentiels apportés par le CTR, car cette solution tire normalement profit des situations impliquant une plus grande hétérogénéité spatiale des conditions pluviométriques.
- La considération d'une augmentation uniforme des intensités de précipitations pour représenter l'impact des CC est une simplification qui ne permet pas de représenter un changement potentiel dans la fréquence des événements pluvieux, tels que des événements de précipitations moins fréquents mais plus intenses.
- Le CTR par modélisation prédictive a été appliqué avec une prévision parfaite des données pluviométriques et sans considérer les erreurs des modèles, alors que, dans un contexte opérationnel, l'incertitude attachée à l'état futur du système et aux débits dans le système pourrait diminuer les performances de ce type de contrôle par rapport aux autres stratégies analysées.
- L'impact des bris de fonctionnement des pompes, des dysfonctionnements des vannes, ou tout autre problème opérationnel potentiel n'a pas été pris en compte dans l'analyse des performances du CTR par modélisation prédictive et du CTR basé sur des règles locales et réactives.
- L'analyse spatiale réalisée pour déterminer le niveau maximal de mise en œuvre des SCS sur le territoire peut conduire à une surestimation de l'espace disponible pour les SCS. Ainsi, la surface traitée par les SCS pourrait être déterminée en fonction de la topographie plutôt que d'appliquer un ratio de traitement type par surface de SCS. Comme ce genre d'analyse demanderait un effort important, il pourrait être réalisé pour une partie du territoire, puis les résultats obtenus pourraient être transposés aux bassins de drainage de caractéristiques similaires.

- Le couplage entre SWMM et l’application du CTR par modélisation prédictive pourrait être appliqué à un réseau moins complexe et de plus petite taille que celui utilisé comme deuxième cas d’étude, afin de pouvoir optimiser de manière intégrée la distribution spatiale des SCS et le CTR. Ces résultats permettraient de mieux évaluer les bénéfices potentiels découlant d’une conception intégrée lors du déploiement de stratégies de CTR plus complexes.
- Finalement, l’impact d’intégrer le CTR directement sur certaines SCS distribuées sur le territoire afin de contrôler dynamiquement leur fonctionnement (par exemple, par l’application d’un contrôle intelligent de l’accumulation et relâche des débits) pourrait être évalué dans un contexte de contrôle des DRU.

Les limitations décrites ci-haut et les orientations proposées pour la réalisation de travaux futurs s’imbriquent aux résultats précédents pour mieux encadrer la conception de mesures d'atténuation des DRU. La thèse doctorale contribue, ainsi, à améliorer le développement de solutions de contrôle des DRU plus abordables, résilientes et efficaces, qui sont adaptables à une variété de réseaux, de conditions pluviométriques et d'objectifs de contrôle des DRU.

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