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

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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;

1. 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. 2002, Vaes et al. 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. 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.

2.2 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. 2017, 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.

2.3 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 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 24h-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 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 non-linearity 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. 2017, 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. 2002), water quality (Calabrò 2004) or both quantitative and qualitative impacts (Andrés-Doménech et al. 2010).

2.5 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.

3. 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.

3.1 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 Fig. 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 Fig. 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.

[Fig. 1. Combined sewer network and selected CSO structures]

3.2 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 as 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.

3.3 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 2016). The case-study network has about 1 360 links and 1 310 nodes, totalizing 78 000 m 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 CSO (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) ± 0.10 m for measured water levels. The RDII unit hydrograph method (Rossman and Huber 2016) 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.

3.4 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 (see Fig. 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.

3.5 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.

3.5.1 1st 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).

3.5.2 2nd 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 (MDDEP 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 1 presents the main characteristics of the rainfall events for each MIT criterion.

Table 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 influent driver of CSO quantity at the main CSO outlet of the city of Berlin (Germany).

3.5.3 3rd 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 x 9 seasons).

The identified rainfall intensities for the nine assessed durations (5 to 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 3h-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).

4. Results and discussion

4.1 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). Fig. 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 proportion 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 3.3), the model is considered adequate to simulate CSO events.

[Fig. 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.]

4.2 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 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 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. CSO modelling results under quasi-continuous simulation

Overflow structure	Average number of CSO spills per year	Maximum CSO volume per event from all years (m^3)	CSO volume threshold for 7 spills/year maximum (m^3)	Average percentage of seasonal rainfall overflowing under quasi-continuous simulation (%)
A	25	518	102	1.8
B	62	1,758	505	13.2
C	35	542	125	6.1
D	65	8,535	2,574	19.6
E	54	4,671	1,297	10.0
F	13	190	38	11.5
G	58	1,079	336	2.3
H	63	3,336	1,064	23.6
I	60	2,413	650	18.8
J	57	2,786	807	2.4
Total	494	25,827	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. Fig. 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 6,500 to 7,500 m^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 4,900 m^3; a difference of 35% with the largest value obtained from the simulation of all the available years.

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. Fig. 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 Fig. 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.

[Fig. 3. Sensitivity to the number of years simulated of the total CSO volume thresholds estimated for the ten overflow structures]

[Fig. 4. Comparison of rainfall data selection methods for determining CSO volume thresholds from simulation]

4.3 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.

4.3.1 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. Fig. 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, Fig. 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 Fig. 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.

4.3.2 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. Fig. 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=3h and 6h, only the results obtained from the MIT=3h 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 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.

[Fig. 5.Total CSO volume thresholds for the ten overflow structures based on the annual 7^{th} greatest rainstorms in terms of total rainfall depth and MIT=3, 6, 12, and 24h]

4.4 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 25.2, 30.1 and 33.6 mm. For the other tested standardised hyetographs, a cumulative rainfall depth of 10.5 mm was applied for the 1 h-duration and 19.0 mm for the 3h-duration, both determined by frequency analysis for a return period of 1/month.

Fig. 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 hours-duration; whereas single IDF value derived storms noticeably underestimated CSO volume thresholds. Single 1h-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 3h-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, 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.

4.5 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 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.

Fig 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). Interestingly, the remaining structures have local characteristics varying greatly but that did not seem to impact much the general trends of the results.

Fig. 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 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 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 minutes and sometimes 120 minutes) provide more acceptable results than the remaining methods for a majority of the overflow structures.

Table 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 assed methods (m^3)	Maximum simulated CSO volume from all assed 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	27.8	3	02:15	242	1167

[Fig. 6. CSO volume thresholds difference of all rainfall selection methods with quasi-continuous simulation per overflow structures. Note: The dashed lines show the limits for a volume difference of ± 25 %.**]**

5. 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.

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Figure captions:

Fig. 1. Combined sewer network and selected CSO structures

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***Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

HIGHLIGHTS

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

Graphical Abstract (for review)

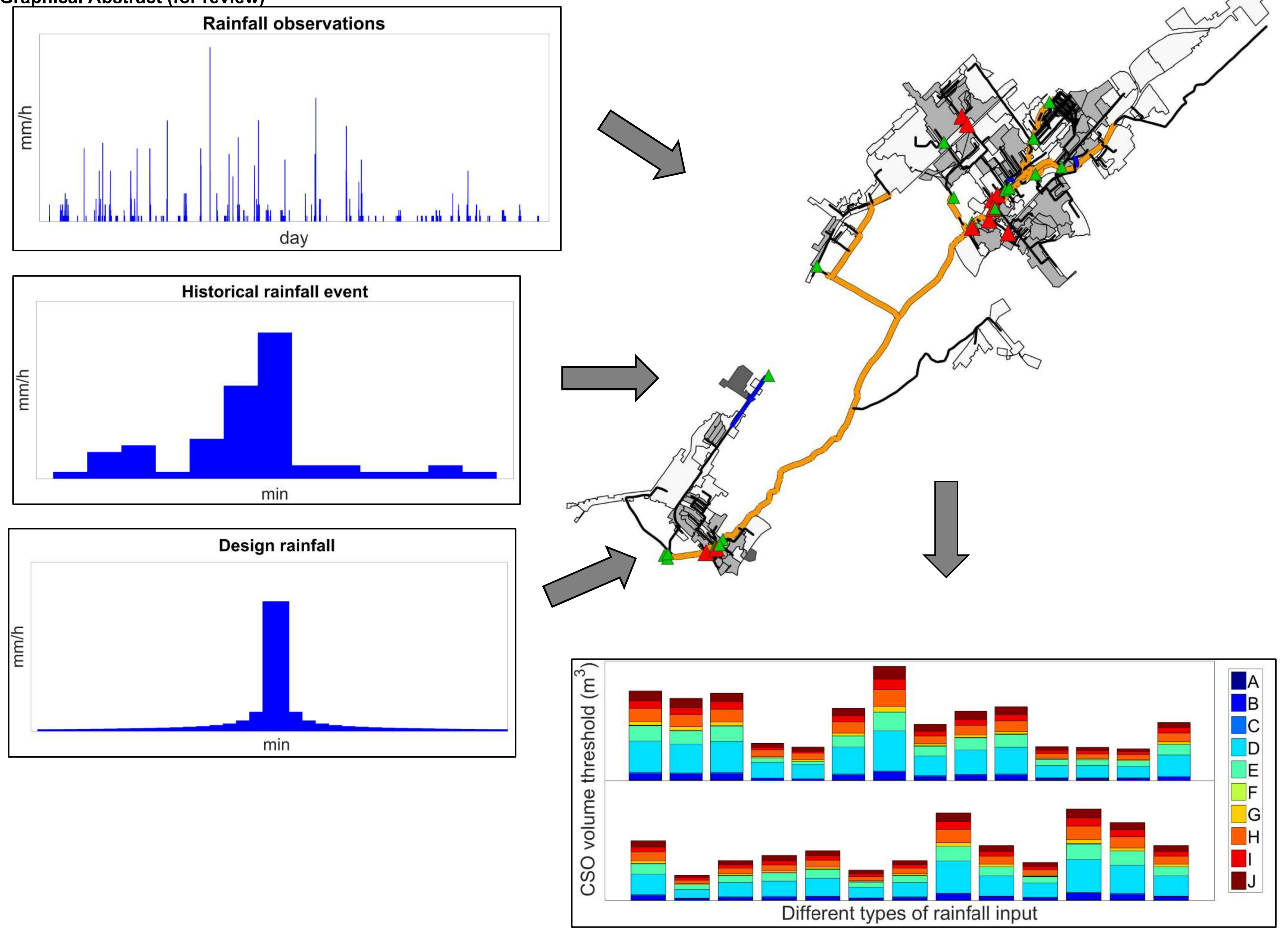

FIGURE CAPTIONS

Fig. 1. Combined sewer network and selected CSO structures

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Fig. 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 %.

Figure 1

Click here to download high resolution image

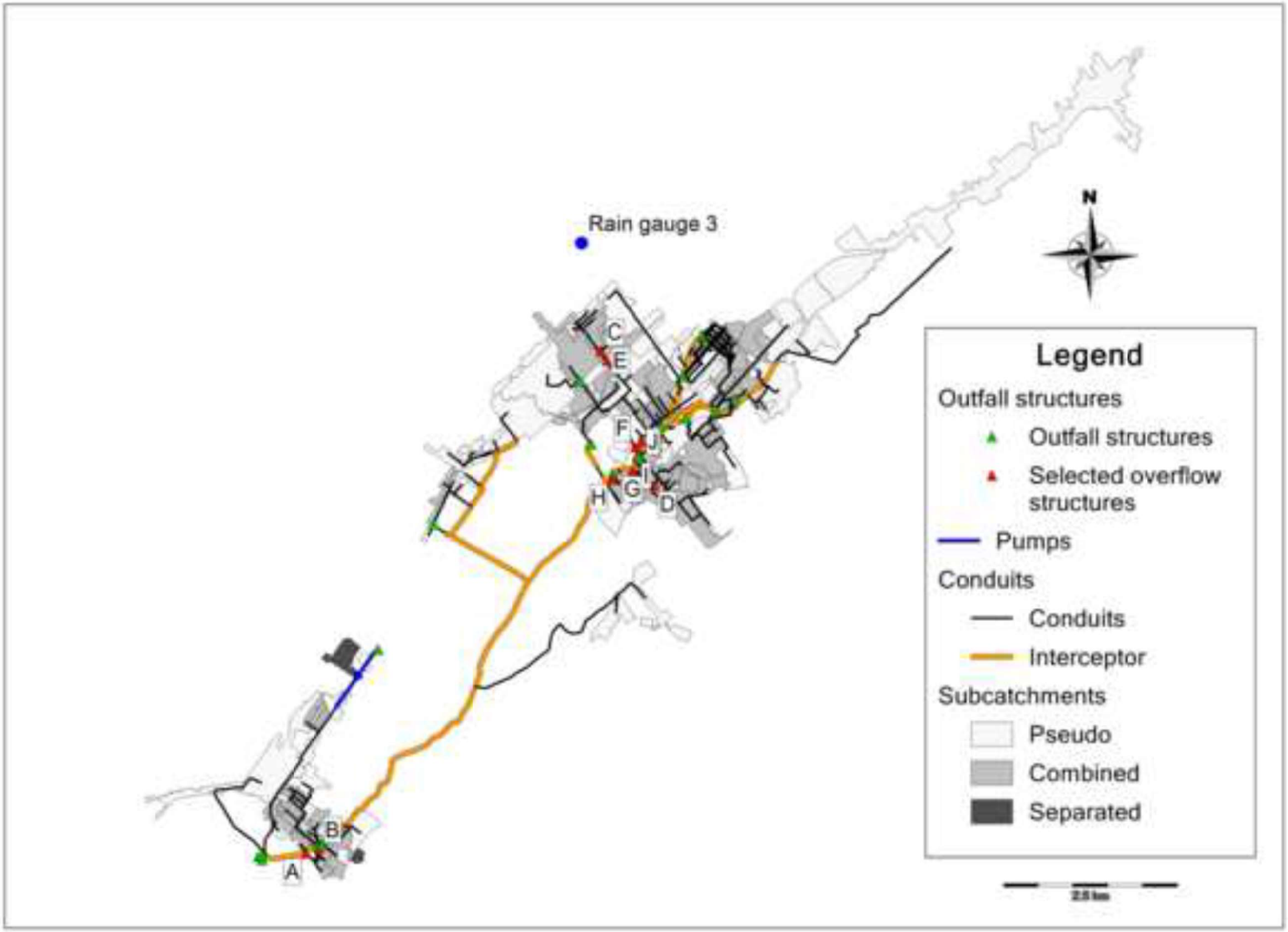
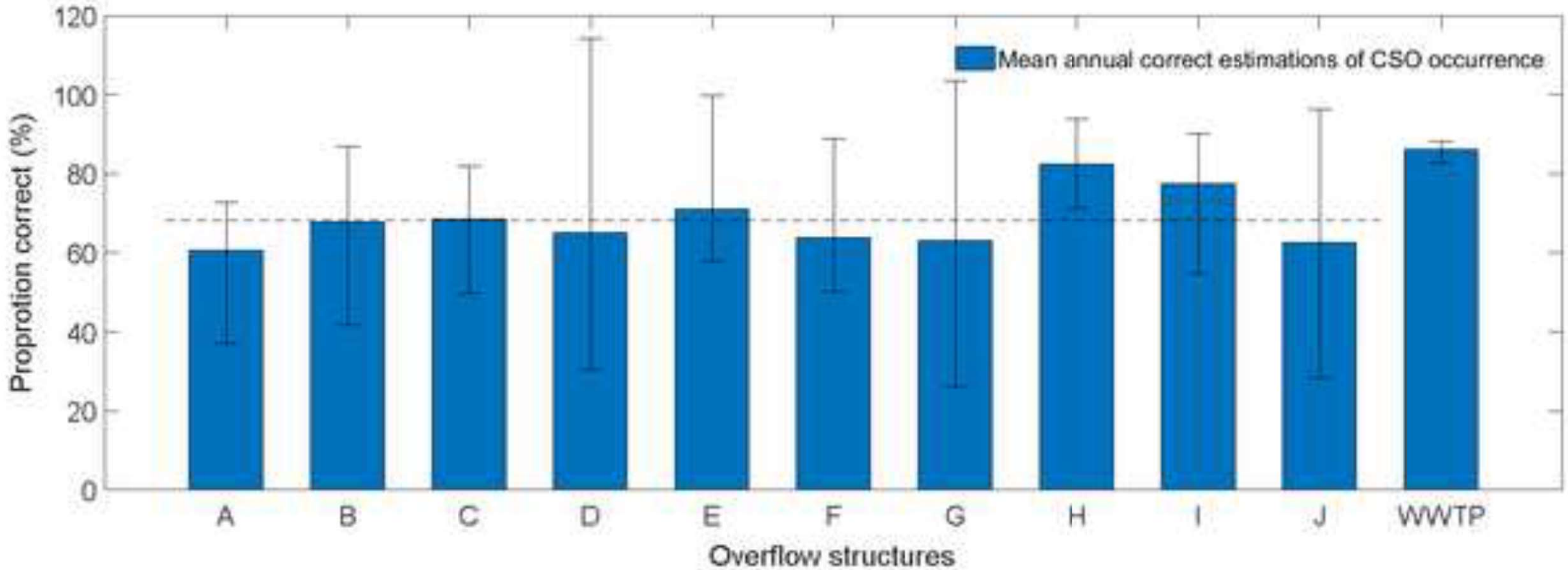
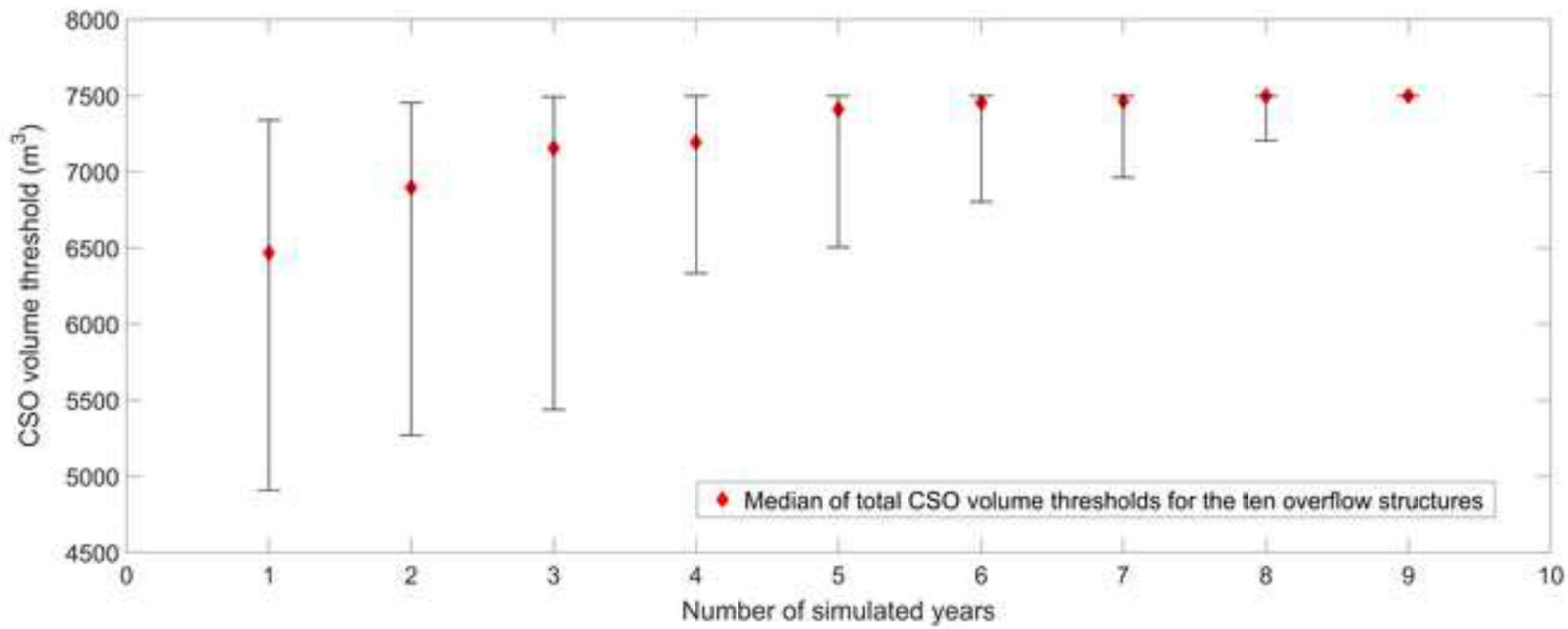


Figure 2



Mean annual correct estimations of CSO occurrence
Proprotion correct (%)
120
100
80
60
40
20
0
A
B
C
D
E
F
G
H
I
J
WWTP
Overflow structures

Figure 3



CSO volume threshold (m3)
8000
7500
7000
6500
6000
5500
5000
4500
0
1
2
3
4
5
6
7
8
9
10
Number of simulated years
Median of total CSO volume thresholds for the ten overflow structures

Figure 4

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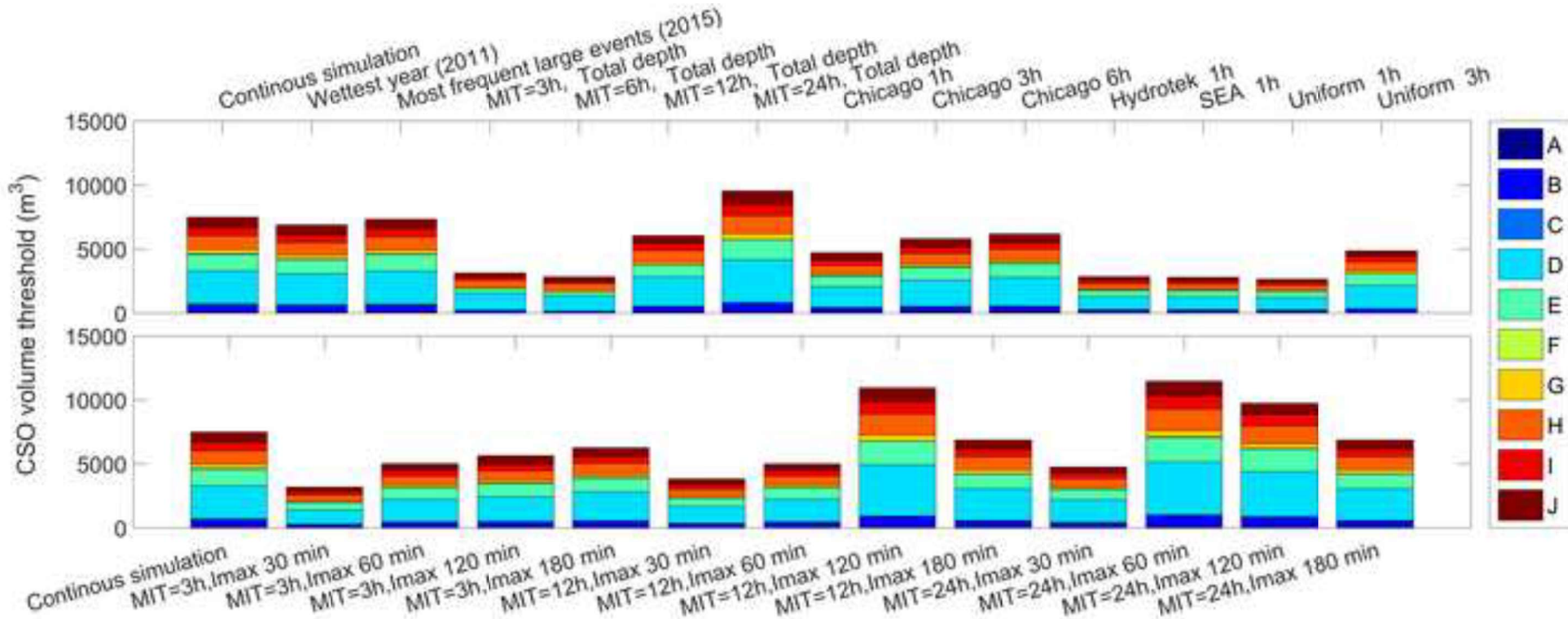
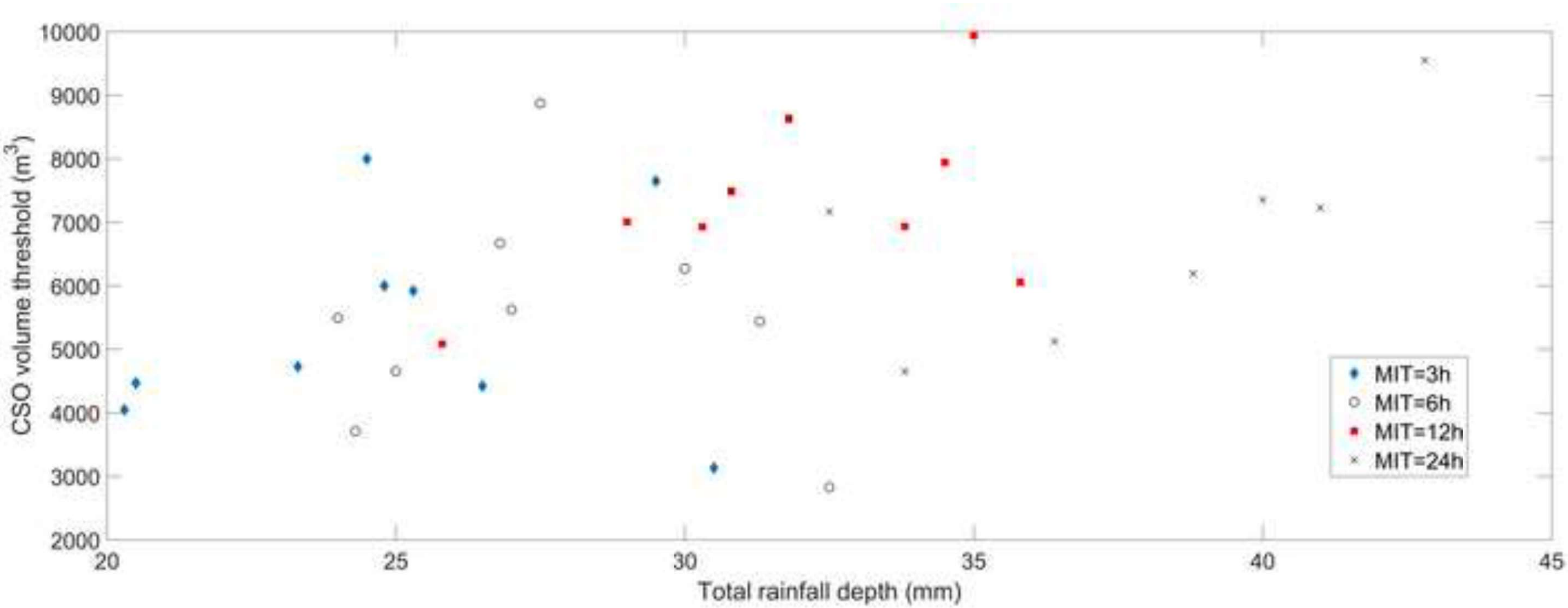


Figure 5



CSO volume threshold (m3)
10000
9000
8000
7000
6000
5000
4000
3000
2000
20
25
30
35
40
45
Total rainfall depth (mm)
MIT=3h
MIT=6h
MIT=12h
MIT=24h

Figure 6

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