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Relationships between rainfall and Combined Sewer Overflow (CSO) occurrences

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SUMMARY

Combined Sewer Overflow (CSO) has been recognized as a major environmental issue in many countries. In Canada, the proposed reinforcement of the CSO frequency regulations will result in new constraints on municipal development. Municipalities will have to demonstrate that new developments do not increase CSO frequency above a reference level based on historical CSO records. Governmental agencies will also have to define a framework to assess the impact of new developments on CSO frequency and the efficiency of the various proposed measures to maintain CSO frequency at its historic level. In such a context, it is important to correctly assess the average number of days with CSO and to define relationships between CSO frequency and rainfall characteristics. This paper investigates such relationships using available CSO and rainfall datasets for Quebec. CSO records for 4285 overflow structures (OS) were analyzed. A simple model based on rainfall thresholds was developed to forecast the occurrence of CSO on a given day based on daily rainfall values. The estimated probability of days with CSO have been used to estimate the rainfall threshold value at each OS by imposing that the probability of exceeding this rainfall value for a given day be equal to the estimated probability of days with CSO. The forecast skill of this model was assessed for 3437 OS using contingency tables. The statistical significance of the forecast skill could be assessed for 64.2% of these OS. The threshold model has demonstrated significant forecast skill for 91.3% of these OS confirming that for most OS a simple threshold model can be used to assess the occurrence of CSO.

1. Introduction

Combined sewer systems are designed to overflow occasionally during heavy rainfalls leading to untreated wastewater discharge into nearby receiving waters. These Combined Sewer Overflows (CSOs) can result in high concentrations of microbial pathogens, solids, debris and toxic pollutants in receiving water as well as oxygen deficits (through the input of degradable organic components), creating significant public health, stress on aquatic organisms, and water quality concerns (House et al., 1993; Walsh et al., 2005; Passerat et al., 2011; Holeton et al., 2011; Madoux-Humery et al., 2013).

Currently, there is no federal legislation directly pertaining to CSO in Canada. However, the Canada-wide *Strategy for the Management of Municipal Wastewater Effluent*, endorsed by the Canadian Council of Ministers of the Environment (CCME) in 2009, has set the focus on wastewater management to improve environmental and human health protection (CCME, 2009, 2014). For instance, some provinces like Quebec, adopted some rules to restrict CSO according to this strategy (MDDELCC, 2014).

To be in accordance with the *Strategy for the Management of Municipal Wastewater Effluent*, municipalities and developers will have to demonstrate that new developments will not result in an increase of the frequency of CSO. Land surface planning will have to be integrated within projects to limit overall runoff. Reference CSO frequencies will be established from available CSO records. It is therefore important to estimate the CSO frequency, expressed as the number of days with CSO during the May to October period, determined from available archived records pertaining to CSO occurrence. The development of an adapted approach was required, since recorded CSO data do not provide a direct estimate of the frequency of CSO and because various CSO recording devices are used (see Section 2 for further explanations). Once a reference level is established, governmental agencies need to be able to assess if the observed annual CSO frequency during a given year is consistent with the rainfall records during the same period.

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If this is not the case, exceedance of the CSO reference level may indicate that runoff volumes have increased and that measures should be put in place to control increasing runoff volumes.

Previous studies have proposed approaches to link CSO to rainfall characteristics. Schroeder et al., 2011 analyzed CSO datasets from four catchments of the Berlin (Germany) combined sewer system. Comparison of rainfall event characteristics (duration, maximum hourly intensity, total depth) with CSO volumes showed that the total rainfall event depth was the best determinant of CSO occurrence. Based on their results, the authors proposed the definition of a critical rainfall depth for each catchment, above which CSO is expected to occur. Such a model, according to Schroeder et al., 2011, enables an evaluation of the effectiveness of CSO control measures to be implemented.

Some studies have investigated CSO and rainfall relationships using hydraulic models to estimate outflow occurrence and volumes from rainfall series. For instance, Yu et al., 2013 have investigated relationships between CSO characteristics (total overflow volume, number of outfalls with overflows, average response time, average overflow duration) and rainfall event characteristics (total depth, maximum hourly intensity, duration) for 67 CSO outfalls located in the northern part of Tokyo (Japan). Similarly, Thorndahl and Willems, 2008 used a commercial urban drainage model to simulate an 18-year rainfall series to establish the relationships between system failure (including CSO occurrence) and rainfall event characteristics (duration, total depth and maximum intensity over 20 min) for a catchment in Denmark. The authors concluded that CSO occurrence was well-described by depth and duration of rainfall events.

Mounce et al., 2014 proposed the use of an artificial neural network to link local rainfalls to the water level within a downstream CSO structure. This data-driven approach does not require that a hydraulic model be put in place, however large amounts of data are necessary. It also requires rainfall radar data which are not always readily available.

More recently, Fortier and Mailhot, 2014 studied the possible impact of climate change on CSO frequency and durations. These authors developed a simple model relating CSO occurrence to rainfall event characteristics. Using available CSO datasets and the corresponding hourly rainfall series, they concluded that CSO occurrence is best explained by rainfall event total depth, a result similar to Schroeder et al., 2011. The proposed model is based on the hypothesis that CSO occurs when the total event rainfall depth exceeds a given threshold, but unlike the model proposed by Schroeder et al., 2011, this relationship is not represented by a stepwise function but a probabilistic one.

Although interesting, approaches proposed in the literature cannot be readily applied to a large number of outfalls since they implicate the use of hydraulic models (e.g, Thorndahl and Willems, 2008, 2013) or proceeding to detailed analyses and comparisons of CSO occurrences and rainfall series (as for, Schroeder et al., 2011, 2014). In order to meet strategy requirements, assess the efficiency of control measures, and account for limited CSO monitoring (in terms of both duration of datasets and the types of variables monitored), a simple approach is needed. This approach should use readily available CSO and rainfall datasets, and therefore be applicable to a wide range of situations.

2. CSO monitoring devices and available data

Available CSO records at the various overflow structures (OS) are archived by the *Ministère des Affaires Municipales et de l'Occupation du Territoire* (MAMOT) in the *Suivi des ouvrages municipaux d'assainissement des eaux* (SOMAE) database. Data about CSO must be collected and regularly transfered by the municipalities to the MAMOT. The *Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques* (MDDELCC) is in charge of evaluating if municipalities comply with CSO regulations.

In Québec, three types of devices are used to monitor the occurrence of CSO at the various OS. The first, and most common device, is a marker (usually a piece of polystyrene foam or wood attached to a rope) placed on top of the OS. The marker is moved by the water flow each time a CSO occurs. Each OS is regularly visited by a municipal employee who notes any movement of the marker and, if necessary, replaces the marker on top of the OS. The monitoring of OS by this method only provides information about whether one or more CSO have occurred (or not) during the period between consecutive visits. However, this method provides no indication of the number of days with CSO. Many OS are visited on a weekly basis, but the day of the visit may change from week to week. The archived data in SOMAE indicate the date of the visit and if the marker has moved or not.

The two other CSO monitoring systems measure the total duration time of CSO. The first one, called a continuous recording device, records the total CSO duration between two consecutive visits to the OS. At each visit, the employee notes the recorded total duration and resets the recording device. The archived data in SOMAE include the date of the visit and the total number of hours with CSO since the previous visit.

The second device, called a daily recording device, records the total CSO duration each day (or 24-h period). Available data indicate the date and the corresponding CSO duration (in hours). However, it should be noted that the exact definition of 'day' may change from one OS to another (personal communication from João Moreira of the MAMOT, *Direction des infrastructures* division).

Table 1 presents the number of OS using the various recording devices. In some instances, more than one device has been used over time. Table 2 provides the number of OS with each device combination. The dates when recording devices were changed are unknown. In the case when markers were replaced by continuous or daily recording devices, dates of replacement could be estimated from the available records, since CSO durations began to be archived on that time. It was not possible, however, to estimate this date when continuous recording devices were replaced by daily recording devices.

Many errors may alter archived CSO data, the most obvious ones, although difficult to detect, result from data entry. The only inconsistencies that can be systematically identified are those from daily recording devices. In this case, since daily values should normally be reported in the database, the daily value following a missing value or a sequence of consecutive daily missing values were

Table 1
Number and percentage of OS equipped with the various CSO recording devices.

Recording devices	Number (%)
Marker	1944 (45)
Continuous recording	368 (9)
Daily recording	179 (4)
Combination	1757 (41)
Unknown	37 (1)

Table 2
Number and percentage of OS where more than one recording devices were installed over time.

Recording devices	Number (%)
Marker and continuous recording	1512 (86.0)
Marker and daily recording	207 (11.8)
Continuous and daily recording	8 (0.5)
Marker, continuous and daily recording	30 (1.7)