Predicting CSOs for Real Time Decision Support

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ABSTRACT
This paper presents a novel data-driven method for modeling combined sewer overflows (CSOs) in real-time. This method treats CSO event generation as a threshold process that is triggered by increasingly intense rainfall events, and predicts the likelihood of a CSO given input conditions using a Bayesian network. The fusion of relevant data from multiple agencies into a unified data stream in real time is described, and a hierarchical modeling strategy is proposed that will facilitate the exploration of the causes of CSOs and direct research into the adaptive management of combined sewer systems using the Chicago wastewater system as a case study.

INTRODUCTION
In many municipalities, the wastewater infrastructure is divided into two systems, one that conveys municipal and industrial wastewaters (i.e. sanitary sewers) and one that conveys stormwater runoff (i.e. storm sewers). However, 746 communities located in 32 states, including many of the nation's largest cities, have combined sewer systems (CSSs) that rely on a common infrastructure to convey all wastewater [EPA 2004]. Precipitation events, in particular, cause critical loading of the wastewater infrastructure resulting in sewer "overflow" events (i.e. events where wastewater is discharged untreated into the environment in order to relieve pressure within the sewer system). From the 9,348 regulated combined sewer overflow (CSO) outfalls in the United States, the EPA estimates that about 850 billion gallons of untreated wastewater and storm water are released as CSOs each year [EPA 2004].

Recently, because of the health affects associated with the discharge of untreated wastewater by CSOs, there has been an interest in adaptive management of CSS. Such management, however, will rely on an understanding of the causes of CSOs throughout a CSS and the ability to forecast their occurrence. In CSSs, wastewater from a particular region is routed to a CSO connecting structure. Using an analogy to watersheds, the region drained to a CSO connecting structure is referred to as a sewershed. Wastewater entering this connecting structure can be either routed to the wastewater treatment facility (WWTF) via a sewer interceptor, or discharged, untreated directly into the environment as a CSO as shown in Figure 1. Fundamentally, CSOs occur when wastewater enters the CSO connecting structure more quickly than it can be leave via the interceptor; however, while this condition is overwhelmingly the result of intense precipitation [EPA 2004], the infrastructure-

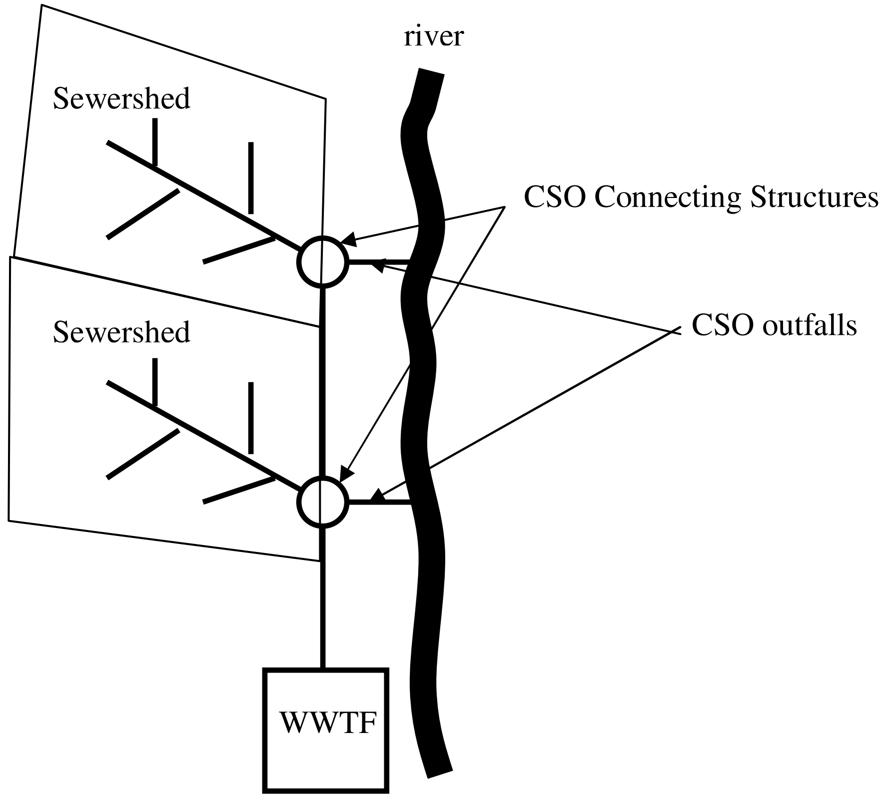

Figure 1. Diagram of a combined sewer system showing two sewersheds (A and B) that are connected to the same wastewater treatment facility (WWTF).

related causes of CSOs in a particular sewershed are often unknown, and likely to vary spatially (i.e., between sewersheds) and temporally.

This study will use modeling of CSOs to explore the causes of CSOs and to direct research into the adaptive management of CSSs using the Chicago wastewater system as a case study. Traditionally, CSOs models have employed complex physics-based flow routing models (e.g. Rouault et al. [2008]). Unfortunately, many such models cannot accurately represent the effects of special hydraulic structures (especially CSO connecting structures); resulting in significant uncertainties in their predictions [Garcia-Salas & Chocat 2006]. Additionally, as is the case in Chicago, CSO data needed to calibrate these models are often unavailable. For these reasons, this study employs a novel approach to CSO modeling that treats the CSO connecting structure as a low pass filter that transmits the stormwater from low and moderate intensity storms to the WWTP, while stormwater from more intense storms is only partially routed to the WWTP with the remainder being discharged as a CSO. This conceptual model, referred to as threshold filtering, has been successfully applied to other hydrologic systems in which behaviors are triggered by increasingly extreme conditions, such as rainfall-runoff modeling [Struthers et al 2007a and 2007b] and flooding [Kusumastuti et al. 2008]. Threshold filtering will be used to derive three increasingly complex models of CSO generation. In the first-order model, CSOs will be modeled as the result of locally intense (i.e., sewershed-scale) storms. The second-order model will extend the first-order model by adding global (i.e., CSS-scale) sewer loading to the first-order model, and the third-order model will extend the second-order model by adding time dynamics. The first- and second-order models will be implemented using Bayesian Networks (BNs), and the third-order model will be implemented using a Dynamic Bayesian Network (DBN). This hierarchal modeling strategy will facilitate inquiry regarding the relative importance of spatial scale of influence (local vs. global), location (i.e. is the CSO generation process space invariant), and time (i.e. is the CSO generating process time invariant).

CASE STUDY

The Chicago wastewater system will be used to drive the derivation of the CSO models as well as a testbed to use these models to explore the causes of CSOs. In the 1970's Chicago began construction on one of the largest civil engineering projects ever undertaken—the Tunnel and Reservoir Plan (TARP). The TARP system, whose completion is anticipated in 2019, consists of over 100 miles of underground tunnels connecting several reservoirs which can be used during wet weather events to store excess wastewater until it can be treated and discharged into the Chicago waterways system. Phase I of TARP, which consists of the tunnels and structures tying TARP to the sewer system was completed in 2005 and provides over 2 billion gallons of storage. When Phase II is completed, the reservoirs will further increase the capacity of the TARP system by 15.6 billion gallons.

The goal of the completed TARP system is to drastically reduce the volume of untreated wastewater that is discharged into the environment by CSOs. However, observations since the completion of Phase I indicate that despite the currently available storage CSOs still occur at times when storage is available within the TARP system. For example, on Aug 23, 2007, a storm passed over Chicago dropping 1.9 inches of rain in 7.5 hours. The storm resulted in significant flooding in the Chicago area, 189 CSO events and forced the reversal of the North Branch of the Chicago river (a last-resort management decision, which had not been used for 5 years prior), however, at the conclusion of this storm, there was still approximately 500 million gallons (25%) of storage still available in TARP. Events such as this suggest that local behaviors, such as locally heavy rains or bottlenecks in the conveyance of wastewater may result in CSOs. Spatio-temporal analysis of CSO events from Nov. 2004–Dec. 2007 identified a subset of the Chicago sewersheds that generated significantly more CSO events than average. While many of these "critical" sewersheds are clustered in the northeastern region of the system, they are not spatially contiguous and are interspersed with non-critical sewersheds. This observation suggests that CSOs in the critical sewersheds are more influenced by local factors (e.g. local infrastructure differences or locally intense storms) than by system-wide sewer loading. In addition to a moderate seasonal trend, the spatio-temporal analysis also revealed distinct time periods in which CSOs were more likely to occur throughout the Chicago system, which tend to correspond with periods of unusually large quantities of precipitation. This result indicates the importance of precipitation variability to the generation of CSOs.

METHODS

The partitioning of stormwater runoff from a sewershed between sewer conveyance, storage, and overflow can be viewed as a hierarchy of threshold processes that are triggered by increasingly severe precipitation events. The first threshold corresponds to the storm intensity necessary to require the use of wastewater storage, while the second threshold corresponds to the storm intensity necessary to trigger a CSO. Thus, during light precipitation events, all the stormwater can be conveyed to the WWTF via the sewer network. During moderate storms the system becomes conveyance limited and the wastewater that cannot be conveyed to the WWTF must be stored (if storage is available) until the conveyance limitation is lifted. Finally, during severe storms, the system is both conveyance and storage limited, thus, excess wastewater must be discharged as a CSO. While continuously valued properties (e.g. volume) can be attributed to a CSO, the overflow itself is a discrete temporal event (i.e. it has a well-defined beginning and end).

The models developed in this study predict whether or not the intensity of a given storm exceeds the CSO triggering threshold. Because of the variability in the processes that govern the generation and routing of wastewater through the sewer network, the threshold that triggers CSO events is uncertain. For this reason, it makes sense to model CSO events probabilistically. The probability that a CSO event occurs given the conditions described by a vector of random variables X can be calculated using Bayes' Theorem as

$$\mathrm{P}(CSO \mid X) = \frac{\mathrm{P}(X \mid CSO)\mathrm{P}(CSO)}{\mathrm{P}(X)} \tag{1}$$

where $\mathrm{P}(\cdots)$ indicates the (conditional) probability density function and CSO is a Boolean (yes/no) variable that indicates whether or not a CSO occurs. Thus, given a realization of $X = X'$, whether or not a CSO occurs can be predicted by determining if the likelihood that a CSO occurs (CSO=yes) is greater or less than the likelihood that a CSO does not occur (CSO =no) given X' . This can be expressed mathematically as

$$\arg\max_{CSO} \mathrm{P}(CSO \mid X = X') \tag{2}$$

BNs are graphical models that represent a set of variables and their dependencies as directed acyclic graphs, whose nodes represent the variables and whose arcs represent the conditional dependencies among them. The graphical structure of the BN facilitates Bayesian inference (i.e. solving Equation 2).

Creating a model of the form shown in Equation 2 requires a historical record of precipitation, TARP storage, and whether or not a CSO occurred. Since these data are measured at different spatial and temporal frequencies, it is first necessary to fuse these data (i.e. combine the diverse data sets into a unified data set that has a consistent spatial and temporal resolution). Because the models will be used for real-time forecasting, the fusion process must be automated to continuously process new data as it is collected. This study uses custom transformations that are implemented as a workflow within a semantically enhanced digital watershed to continuously fuse the data. These transformations define virtual sensors, as discussed by Liu et al. [2008], and result in new streams of data that can be used as input to the model or for updating the model parameters.

Historical records of the amount of water in the TARP storage and CSO events from 2004 through 2007 were provided by the MWRD. The storage data are encoded as a time series with irregular frequency, while the CSO data are encoded as event data (i.e. for every CSO event, a start and stop time was recorded). These data are fused to create a time series with uniform 10-minute intervals. The fusion process

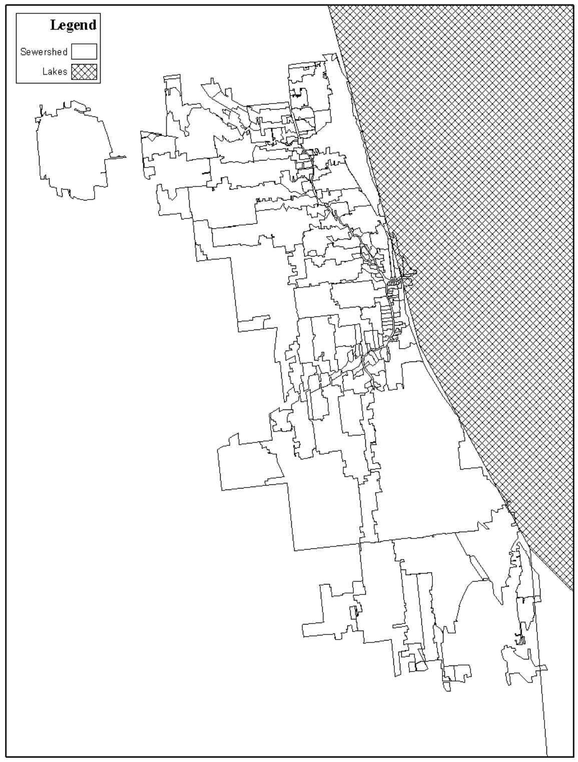

Figure 2: TARP sewersheds.

involved defining the discrete points to fall every 10 minutes starting at midnight (i.e. 00:00, 00:10, 00:20, etc.) and interpolating the CSO and storage records to these points.

The average rainfall rate over each sewershed was estimated using weather radar data from the Next Generation Weather Radar (NEXRAD) system, since, like many other cities [Vieux and Vieux 2005, Sempere-Torres et al. 1999], Chicago does not have a rain gauge network that is dense enough resolve the spatial heterogeneity of rainfall at the sewershed scale. Because no high level radar product (e.g. Level III or MPE) exists that can provide precipitation measurements at the space (~1 km^2) and time (~10 minutes) scales required for the CSO models developed in this study [Smith et al. 2007], NEXRAD Level II data are used. These data are the base reflectivity measurements made by the radar at irregular intervals (5, 6, or 10 minutes between scans), depending on the current operating mode of the radar [Fulton et al. 1998]. These data are georeferenced using a polar grid centered at the radar.

The City of Chicago occupies an area of approximately 525 km^2, which is subdivided into roughly 200 sewersheds that range in size from approximately 0.5 to approximately 70 km^2 as shown in Figure 2. The boundaries of the TARP sewersheds that drain the City of Chicago have been delineated by the Chicago Department of Water through analysis of the sewer network and field studies. These boundary data are encoded and georeferenced as vector polygons in Keyhole Markup Language (KML).

Integrating the NEXRAD and sewershed boundary data to determine the timeseries of spatially averaged rainfall for each sewershed requires several steps. First, a local grid is defined that discretizes the City of Chicago into 0.5x0.5 km

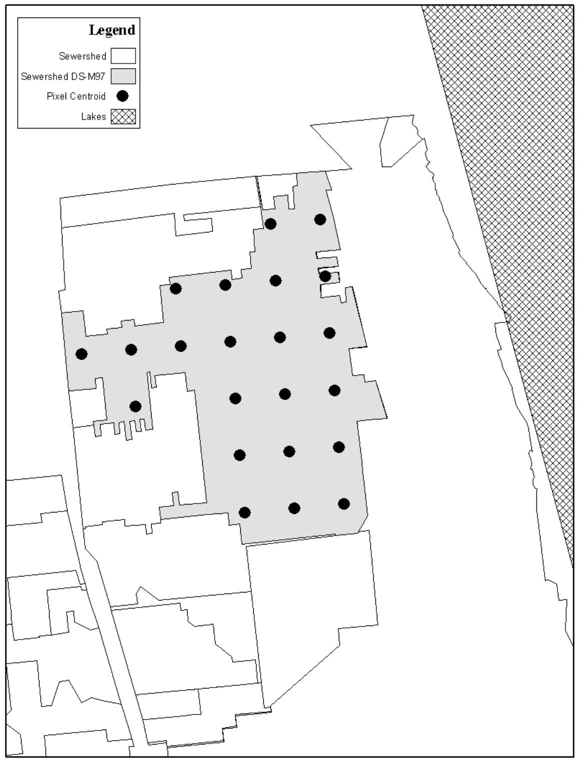

Figure 3: Centroids of the 0.5x0.5 km pixels within TARP sewershed DS-M97

pixels and is georeferenced using the same East-North-Up coordinate as the NEXRAD data. The pixel size for this grid was selected because Vieux and Farafalla [1996] noted that this resolution was sufficient to fill a rectangular grid from NEXRAD level II data. The average reflectivity of each pixel is then calculated using an inverse-distance-squared weighting technique suggested by Smith et al. [2007]. Then the polygon vertices of each sewershed are converted from World Geodetic System 1984 coordinates (used by KML) to the East-North-Up coordinates of the local grid, and a polygon filling algorithm is used to determine which pixels fall inside each sewershed. This algorithm parses the rows of the grid in South to North order once for each polygon, identifying the columns in each row through which an arc of the polygon passes. Assuming that the polygon falls completely within the grid, then processing the list of columns in East to West order quickly reveals the pixels that fall inside the polygon. The sewershed average reflectivity is calculated by averaging the reflectivity of the pixels falling in the sewershed polygon. For example, Figure 3 shows the 5.3 km^2 sewershed that drains into TARP dropshaft DS-M97 and the centroids of the 22 grid pixels that are used to calculate its average rainfall. The sewershed average reflectivity at each radar scan time *t* are then converted to rainfall rate in mm/hr using the standard convective rainfall-reflectivity equation [NWS-ROC 2003].

$$Z = 300R^{1.4} \tag{6}$$

where Z is the reflectivity and R is the rainfall rate. Finally, the sewershed average rainfall rate is averaged over 10 minute intervals to create a timeseries with a regular frequency.

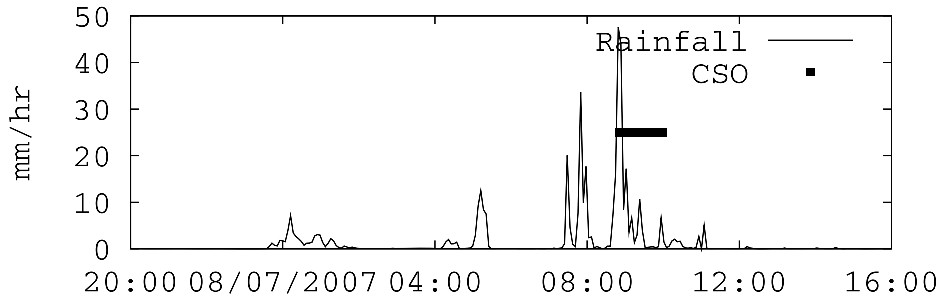

Figure 4: Fused CSO event and rainfall rate data from TARP sewershed DS-M97.

Figure 4 illustrates the result of fusing the CSO event and NEXRAD radar data. This figure shows a 24 hour window of the integrated CSO event and sewershed average rainfall timeseries for the sewershed that drains into TARP dropshaft DS-M97. During this window, there are 3 discrete storms, two low intensity storms that produce no CSOs, and one high intensity storm that results in a CSO event that lasts approximately 1 hour. This CSO event begins roughly halfway through the third storm (at about 9:00am) and is concurrent with the highest intensity rainfall peak in the storm of approximately 45 mm/hr.

The fused rainfall, CSO, and TARP storage timeseries will be divided into discrete storms using the criterion set up by the National Weather Service to define how much rain falls during a particular storm [Fulton et al. 1998]: storms are divided by periods longer than 1 hour where no rain falls. For example, if rain falls continuously from 10:00 until 10:30 and from 11:10 until 13:00 these rainfall events will be associated with the same storm. On the other hand, if rain falls continuously from 10:00 until 10:30 and from 11:35 until 13:00, these rainfall events will be defined as two separate storms. These data will be used to create three increasingly complex models of CSO generation as described in the remainder of this section.

First-Order Model: The first-order model assumes that causes of CSO events in a sewershed are well-described by the local (sewershed-scale) intensity of storms. Thus, the model does not resolve the effects of the storm in other sewersheds that may result in overwhelming the global sewer conveyance and/or storage capacity. These assumptions are valid if the causes of CSOs in a particular sewershed are only loosely dependent on the global system behavior (i.e. sewershed-scale factors drive CSO events), and success of the model to predict CSOs in a particular sewershed will indicate that global management strategies will be unsuccessful at alleviating CSOs in that sewershed, and local management should be pursued.

To characterize the intensity of sewershed-scale storm events the following properties are used: storm average rainfall rate over the sewershed i, storm duration t_r, and inter-storm period t_b. The average rainfall rate and the storm duration indicate the volume of wastewater generated within the sewershed, while the inter-storm period indicates the conditions of the sewer network prior to the storm, which is especially important when the local sewer system is capable of storing large volumes of wastewater.

As discussed so far, the BN model can predict whether or not a storm with characteristic variable values i', t_r', and t_b' will produce CSOs. However, it is often desired to know when a CSO event begins and how long it lasts. If it is assumed that a storm's behavior (i.e. rainfall rate and persistence) in the future is independent of the storm characteristic variables, the storm can be addressed incrementally. That is to say, a given storm S that lasts from time t_0 to time t_S can be decomposed into sub-storms where sub-storm s_t has duration t_0 to t and $0 < t \leq t_S$. Since the storm characteristic variable t_b is dependent only on the conditions leading up to the storm, it will be the same for all sub-storms s_t of storm S, and since the characteristic variables i, t_r only depend on the storm conditions up to and including time t, the BN model can be used at any time during a storm to predict the probability of a CSO occurring at time t during a storm using the incremental values of i, t_r calculated over the duration of the sub-storm s_t.

Second-Order Model: The second-order model builds on the local, first-order model by adding the effects of global storm intensity and global sewer system storage in TARP. This model assumes that global storm intensity only affects the CSO generating process in a particular watershed through the filling of the TARP storage. The volume of remaining storage in TARP will be represented by the variable S , and sewer system-scale storms will be characterized using the variables I and T_r, the average rainfall rate and storm duration over the entire sewer system, respectively. A variable representing the sewer system-scale inter-storm period is not necessary, because the TARP storage variable S provides the antecedent conditions of the sewer system.

Like the first-order model, the second-order model can be applied incrementally to a storm event (if it is assumed that a storm's future behavior is independent of the storm characteristic variables) to determine when a CSO event is likely to begin and how long it will last.

Third-Order Model: The first- and second-order models explore the spatial-scale of influence of the CSO generating processes. The first-order model includes only sewershed-scale processes, while the second-order model includes both sewershed and sewer-system-scale processes. These models can also be applied incrementally during a storm to investigate the temporal region during a storm where CSOs are likely to occur if it is assumed that the future behavior of CSO generating processes are independent of their previous behavior. This may not be a reasonable assumption. For example, if a CSO event occurs at time t, it may be more likely to continue at time $t+\Delta t$ than if a CSO event does not occur at time t. For this reason, the third-order model adds temporal dependencies to the second-order model. Since this model can explicitly represent the temporal dependencies in the system, it can be compared with the second-order model applied incrementally during a storm to test the assumption that the future behavior of CSO generating processes are independent of their previous behavior, which allows the second- (and first-) order model to be applied incrementally.

CONCLUSION

Modeling CSO events is important for understanding the causes of CSOs and for providing decision support to reduce their occurrence. This paper proposes the real-time fusion of heterogeneous data streams for inclusion in the modeling process and a hierarchal modeling strategy that will facilitate inquiry regarding the relative importance of spatial scale of influence (local vs. global), location (i.e. is the CSO generation process space invariant), and time (i.e. is the CSO generating process time invariant). At the conference we plan to present the results of this modeling effort and address the following questions:

How important are global factors in predicting CSOs? The first-order model assumes that CSOs are driven by the intensity (over the sewershed) of storms. Thus, it does not explicitly resolve the effects of the storm on other sewershed, which may result in reducing the conveyance capacity of the sewer system and/or filling the TARP storage. Thus, if the first-order model performs well at predicting the CSO within the sewer system, it will suggest that the global factors are less important than the local factors and that strategies to reduce CSO occurrence should be focused at the sewershed scale. On the other hand, if the second-order model performs significantly better than the first-order model, it would suggest that global factors are important to the generation of CSOs within a sewershed.

Are the CSO generating processes space invariant? After selecting the necessary model complexity (i.e. first-, second-, or third-order) the model parameters can be evaluated across many sewersheds. If the distributions of the random variables in the BN model are not significantly different between sewersheds, this will imply that the CSO generating processes are space-invariant. Thus, one model can be used to predict CSO events in all sewersheds. This is unlikely to be the case, however, it may be likely that sewersheds can be grouped into a small number of clusters in which the CSO generating processes are the same (i.e. the same model can predict CSO events in all the sewersheds in one cluster). Then by comparing and contrasting the sewersheds within and between clusters, it may be possible to determine the underlying features that make these sewersheds similar.

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