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Three-dimensional model to capture the fate and transport of combined sewer overflow discharges: A case study in the Chicago Area Waterway System

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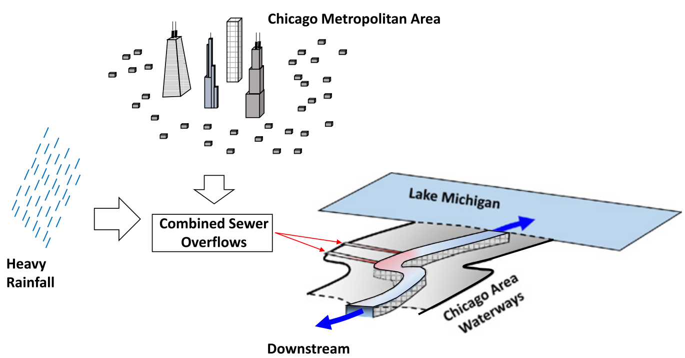
HIGHLIGHTS

- During heavy storms, CSOs impact the hydrodynamics and water quality of the waterways.
- CSOs caused a reversal flow with a plume of constituents traveling upstream.
- Water quality was significantly more affected under the heavy storm than the middle storm.
- Dilution during the heavy storm allows to maintain the water quality standards at the downstream boundary.

GRAPHICAL ABSTRACT



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ABSTRACT

We used a numerical model to analyze the impact of combined sewer overflows (CSOs) in the hydrodynamics and water quality of the Chicago Area Waterway System (CAWS). We coupled the Environmental Fluid Dynamics Code (EFDC) with the Water Quality Analysis Simulation Program (WASP) to perform three-dimensional simulations of the hydrodynamics and water quality in CAWS. The analysis was performed for two different storms: (i) May 6, 2009 representing a 6-hour duration 4-month return period, and (ii) September 12, 2008 representing a 48-hour duration 100-year return period. Results from the simulations show distinct differences between the two storms. During the May 2009 storm there was only one major CSO pumping event with negligible impact on the water quality of CAWS. During the September 2008 storm there were several CSOs that impacted the hydrodynamics and water quality of CAWS. In particular, CSOs during the September 2008 event induced a reversal flow in CAWS, with a plume of constituents that traveled in the opposite direction as water does under normal conditions. However, the simulation results show that CSOs events in CAWS take place during periods of high rainfall, thus the discharge of CSOs is significantly diluted along the CAWS. As a result, the concentrations of organic matter and inorganic nutrients observed at the downstream boundary in CAWS were significantly lower than those recorded at the CSOs outfalls and are within the limits established in the regulation for regular effluents. These results suggest that even during storms events with significant CSOs into the CAWS there is a significant dilution that reduce the impact in the water quality at the system boundaries.

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1. Introduction

According to the World Health Organization the percentage of human population in urban areas grew from 34% in 1960 to 54% in 2014. In addition, this pattern will be more acute in the subsequent years, with a prediction of 70% of human population living in urban areas by 2070 (WHO, 2014). A major impact of the concentration of human population in urban areas lies in the production of human waste that represents a challenge to treat and dispose. This threat has the highest impact on the surrounding water bodies that now receive significant amount of organic loads that were not received before (Even et al., 2007; Marsalek, 1998). In particular, there is a concern in urban areas with combined sewers, where combined sewer overflows (CSOs) to nearby water bodies take place during heavy rainfall events. In this study we use a numerical model to analyze the impact of CSOs on the hydrodynamics and water quality of the Chicago Metropolitan Area (CMA) during heavy rainfall events.

CSOs are a global water pollution concern. In the United States only, approximately 860 cites experience CSOs during storm events (Combined sewer overflows, 2016). Although characterization of constituents in CSOs has been studied in various cities during the last decades (Srinivasan et al., 2012), the real impact of CSOs under different storms is still arguable. It is important to investigate and analyze the impact of CSOs under different storm events in order to take proper decisions. Previous studies have analyzed different measurements such as pH, fecal coliforms, heavy metals, viral concentration, and microbial dynamics at different locations (Irvine et al., 2005; Gooré Bi et al., 2015; Li et al., 2013; Passerat et al., 2011; Rodríguez et al., 2012; Wang, 2014) to assess the impact of CSOs on the water quality of receiving waters under different storm intensities. However, CSOs take place during heavy rainfall conditions that impede water sampling. In addition, monitoring stations can be located only on specific locations. Therefore, it is challenging to have a detailed description of the fate and transport of different constituents released from CSOs using data measurements only. As a result, hydrodynamic and water quality modeling in urban streams represent an important alternative to assess the impact of CSOs in receiving water bodies.

Hydrodynamic and water quality models in streams (Cox, 2003; Sharma and Kansal, 2013; Sinha et al., 2012; Whitehead et al., 2009) and sewers (Mannina and Viviani, 2010; Morales et al., 2016; Obropta and Kardos, 2007) have been extensively applied in different domains and scales. In order to analyze the impact of CSOs in urban streams, it is important to couple dynamic inflows predicted by sewer models into stream models. This has been implemented at small spatial domains that analyze locally the effect of one or two CSOs (Chen et al., 2013). However, the coupled interaction of many CSOs is what makes them critical. Previous studies have developed models at the city scale including all the important CSOs in the urban area with one-dimensional (1D) simulation of the stream hydrodynamics (Alp et al., 2007; Alp and Melching, 2009; Even et al., 2007). 1D models are computationally efficient and able to capture the most important patterns induced by CSOs. However, major fluxes of CSOs occur during heavy storm events, where conditions in the stream become highly unsteady, characterized by rapid changes in water velocities and stages, that induce the generation of secondary flows. In these cases a 1D model is unable to capture important processes such as flow reversals and secondary flows. Few previous simulations of urban rivers have considered three-dimensional (3D) models in the stream including all major CSOs in the urban area (Blumberg et al., 1999; De Marchis et al., 2013). These approaches analyzed different processes including the thermal stratification (Kim et al., 2006) and fate of pollutants of receiving waters in the long-term, but more research is needed to understand the role of CSOs to alter the hydrodynamics and water quality of receiving streams under different storm events.

In this study, we use a detailed numerical model to understand the impact of CSOs on the hydrodynamics and water quality of the Chicago Area Waterways System (CAWS), a series of waterways that extend and drain most of the CMA, the most populated area located over the Great Lakes of North America. The CAWS is connected to Lake Michigan through two locks and a series of gates. As a result, heavy rainfall events could induce reversal flows to Lake Michigan threatening its water quality and ecology. The objectives of this study are to: (i) estimate the impact of extreme events on the hydrodynamics and water quality of the CAWS by comparing a medium size and extreme storm event, and (ii) to analyze and estimate the presence of reversal flows to Lake Michigan during these events, and quantify the volume and quality of water during the reversal.

2. Materials and methods

2.1. Area of study

We simulate the hydrodynamics and water quality of the CAWS, which are composed of a number of interconnected rivers and canals that connect Lake Michigan with the Mississippi River via the Lower Des Plaines and Illinois rivers. The CAWS includes the North Shore Channel, North Branch Chicago River, Chicago River, South Branch Chicago River, South Fork South Branch Chicago River (Bubbly Creek), Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag Channel, Little Calumet River, and the Calumet River. The specific domain of analysis included in this study can be observed in Fig. 1 and extends from the Wilmette lakefront (located north of downtown Chicago) to Lockport Powerhouse where the U.S. Army Corps of Engineers gauging station is located.

The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC, referred hereafter as the District) has adopted one of the most advances systems to deal with wastewater that is produced in the area, including a network of interceptors, deep tunnels, and several water reclamation plants (WRPs). This system is considered as a model urban water management project worldwide, and several cities including London (Tideway, 2015) have adopted a similar approach to deal with sewage production. Although this system has been successful to alleviate the disposal of wastewater of the CMA, still under extreme storm events it is unable to store and treat all the combined sewage water generated by the urban area. As a result, CSOs may be discharged into the waterways either as street CSOs that flow by gravity or as pumped CSOs that are disposed from pumping stations managed by the District. Red circles in Fig. 1refer to all the CSOs locations, and orange triangles show the three major pumping stations: Racine Avenue (RAPS), North Branch (NBPS), and 125th Street Pumping Stations.

2.2. Numerical model

Hydrodynamic and water quality simulations of the CAWS are performed in three dimensions coupling the Environmental Fluid Dynamics Code (EFDC) and the eutrophication model from the Water Quality Analysis Simulation Program (WASP). In addition, there are 123 discharges from Street CSOs that are dynamic inflows predicted by CS-TARP, an urban hydrological and hydraulical model for the CMA developed by the University of Illinois (Luo et al., 2014). CS-TARP uses Inforworks 12.5 to solve the unsteady hydraulics flow in the deep tunnels and their connections with municipal sewers and interceptors. Fig. 2 shows a schematic representation of the coupling between CS-TARP, EFDC, and WASP. Online Supplement Section 1 provides a brief description of these models.

The hydrodynamic model in the CAWS was developed based on a mesh created from the available bathymetric data provided by the District. Fig. 3a shows the bathymetric data and the mesh generated at different locations throughout the domain. In total, the