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

Juan C. Quijano*, Zhenduo Zhu, Viviana Morales, Blake J. Landry, Marcelo H. Garcia

Department of Civil and Environmental Engineering, Ven Te Chow Hydrosystems Laboratory, University of Illinois at Urbana-Champaign, 205 North Mathews Ave., Urbana, IL61801–2352, United States

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.

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.

© 2016 Published by Elsevier B.V.

* Corresponding author.
E-mail address: quijano2@illinois.edu (J. Quijano).
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., 2013; 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 through 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. 1 refer 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 hydraulic model for the CMA developed by the University of Illinois (Luo et al., 2014). CS-TARP uses InfoWorks 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
model comprises of 143,680 segments distributed in 8 vertical layers. More specific properties about the 3D mesh are listed in Table 1. The water quality model was built based on the hydrodynamics structure and using the fluxes and volumes at every cell predicted from the hydrodynamic model (see Fig. 3b). This approach assumes fully mixed conditions at every cell but keeps the same fine resolution used in the hydrodynamic model.

2.3. Boundary conditions and loads

All the boundary conditions (BCs) and loads are displayed in Fig. 1. The model has different types of BCs including WRPs, tributary inflows, pumping stations and street CSOs, and lake boundaries. Online Supplement Section 2 provides details about the sources of data implemented in the BCs for both the hydrodynamics and the water quality model. There are three BCs that connect the CAWS with Lake Michigan (Fig. 1): (i) Wilmette, (ii) Chicago River Controlling Works (CRCW), and (iii) O’Brien Lock and Dam (O’Brien). These connections with Lake Michigan are controlled by a series of hydraulic gates and locks that are operated by the District. The operation of these structures is included in the model and is described in Online Supplement Section 3.

2.4. Period of simulation

Two different storms are considered in this study. Fig. 4a and d shows the hyetographs for both storms:

May 6–7, 2009: The duration of this storm is approximately a day, with a high maximum intensity of 28 mm/h. This storm is considered as a medium size storm event and corresponds
Fig. 2. Schematic representation of the models used in this study. There is a unidirectional connection, with no coupled feedback, between CS-TARP, the Environmental Fluid Dynamics Code (EFDC), and the Water Quality Analysis Simulation Program (WASP). CS-TARP simulates the hydrology and hydraulics in the Chicago Metropolitan Area (CMA) and predicts the combined sewer overflow Discharges into the CAWS. EFDC uses the CSOs inflows predicted by CS-TARP together with inflow data from the tributaries, water reclamation plants, and operation of hydraulic structures connected to Lake Michigan to simulate the hydrodynamics in the CAWS. Finally, WASP uses the hydrodynamics results predicted by EFDC as the transport field for all the water quality constituents.

approximately to a return period of four months with a duration of 6 h.

September 12–15, 2008: The duration of this storm is approximately two days, with a high maximum intensity of 18 mm/h. This storm is considered as an extreme event and corresponds approximately to a return period of 100 years with a duration of 48 h.

Fig. 4a and d (brown lines) displays the shortwave (SW) radiation during the storms. As expected the SW radiation is higher in May than September. Similarly, Fig. 4b and e displays the water and air temperature during the storms. There is a higher variation in air temperature than in water temperature. The water temperature in Fig. 4b and e is used to simulate the different water quality processes, and the temperatures are assumed to be uniform throughout the spatial domain. Fig. 4c and f shows the major water inflows during the storms. The inflows from both Stickney and O’Brien WRPs are on the same order of magnitude for both events. However, there are important differences in pumping station flows and street CSOs. During the May 2009 event, the flow from NBPS is negligible, and there is only one major pumping event in RAPS. In contrast, RAPS and NBPS are active during the September 2008 storm, and the flow rate from RAPS is higher than that from Stickney WRP for September 13 to 15, 2008 period. Note that the contribution from all the street CSOs (as predicted by CS-TARP) is higher than RAPS and represents the most prominent inflow within the system during September 13 to 15, 2008.

The model is initialized using available information of different water quality constituents recorded by the District at 10 Ambient Water Quality Monitoring (AWQM) stations distributed along the waterways. Linear interpolation utilizing the closest measurements in time and space is performed to determine the concentration of the different constituents throughout the numerical domain. Section 4 in the Online Supplement shows the initial conditions (IC) that are used for ammonia (NH$_3$), nitrate (NH$_4^+$), inorganic phosphorus (IP), carbonaceous biochemical oxygen demand CBOD, and phytoplankton, for both storms. Note that the IC are similar for both May 2009 and September 2008 for all the constituents except phytoplankton. As expected, the concentration of phytoplankton is significantly higher in May.

Fig. 3. Overview of the Chicago Area Waterway System modeling domain. Insets (a.i) and (a.ii) show bathymetric information provided by the Metropolitan Water Reclamation District of Greater Chicago at two locations of the river for illustrative purposes. Based on this bathymetry we generated a three dimensional mesh to perform the simulations. Insets (a.iii), (a.iv), and (a.v) show the 3D mesh generated in three locations of the river. Inset (b) shows a schematic representation of the connection between the EFDC and WASP models. WASP simulations were implemented with the same numerical grid as the grid generated for EFDC. EFDC provides information of volume and magnitude of velocity at every cell, and inflows at every link between cells.
Table 1
Properties of the numerical mesh and time step implemented in the simulation.

<table>
<thead>
<tr>
<th>Grid property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells Ncells</td>
<td>143,680</td>
</tr>
<tr>
<td>Number of interfaces Nint</td>
<td>388,884</td>
</tr>
<tr>
<td>Number of vertical layers Nk</td>
<td>8</td>
</tr>
<tr>
<td>Number of horizontal segments NL</td>
<td>17,960</td>
</tr>
<tr>
<td>Time step</td>
<td>2 s</td>
</tr>
</tbody>
</table>

3. Results

3.1. Comparison with data measurements

3.1.1. Hydrodynamic simulations

Fig. 5 shows the comparison between the stage predicted by the hydrodynamic model and the stage recorded in two stations of the United States Geological Survey, for both storms. The hydrodynamic simulations were implemented with rugosity and turbulence parameters used in previous simulations in the CAWS (Sinha et al., 2013, 2012). Specific details about these parameters can be obtained in these studies. Fig. 5a, b, d, and e shows the time series comparison while Fig. 5c and f shows the scatter plots between the model simulations and data measurements. The numerical simulations are more accurate during the May 2009 storm. For the September 2008 storm the numerical model underestimates the stage. The difference between the model and the measurements in the September 2008 storm is associated with uncertainties during extreme events in the CAWS. However, from Fig. 5d and e, the model is able to predict the main trend in the water stage observed in the measurements.

The May 2009 event represents a medium size event and the waterways are able to take the inflows with no major flooding and no flow reversal to Lake Michigan. However, during the September 2008 storm, the inflows are significantly higher. The District opened the gates at the lake boundaries to reduce flooding in urban areas (see the time series with the gates and lock operation in Section 3 in the Online Supplement), causing flow reversal to Lake Michigan. This flow reversal to Lake Michigan was predicted by the numerical simulations. To analyze the model prediction during the reversal flow, Online Supplement Section 5 provides additional validation of flow as well as stage in a location close to the lake boundaries during the September 2008 event. We observe that the flow pattern and magnitude predicted by the model during this event compares well with the data available along the CAWS. Although there is no available continuous data at the lake boundaries to validate the flow hydrographs during the reversal to Lake Michigan, the District has approximate records of total volume during the reversal. Section 5 in the Online Supplement provides the total volume released into the lake during the September 2008 event, for both the reported by the District and the predicted by the model. We can see that the volume during the reversal flow to Lake Michigan predicted by the model is on the same order of magnitude as the records obtained by the District, which is close to 18 Mm³ in CRCW, and 10 Mm³ in Wilmette.

3.1.2. Water quality simulations

Information of nutrients and phytoplankton in the CAWS is only available at the Ambient Water Quality Monitoring (AWQM) stations, recorded at every month approximately. To estimate the water quality parameters for the CAWS, we use a 1D model to perform long-term simulations and evaluate the model prediction using available information in the AWQM stations. Section 6 in the Online Supplement describes the 1D model, including the parameters that were
evaluated and their respective values. The parameters from the long-term simulations using the 1D model were implemented in the 3D water quality model during the storms analyzed in this study. The simulations performed with the 3D model were tested using continuous measurements of dissolved oxygen (DO) throughout the waterways recorded by the District. Section 7 in the Online Supplement shows hourly time series of DO for both storms and for several stations along the waterways where DO data was available. It can be observed that the model is able to capture the most important trends of DO during the storms. However, the model is unable to capture the variability at high frequencies below the daily time scale. This is expected as the BCs implemented in the model range from hourly to monthly time scales.

3.2. Combined sewer overflow dynamics

CSOs locations are scattered throughout the CAWS. However, in order to illustrate the results obtained with the model we selected the dynamics associated with RAPS that is the most prominent pumping station in the CAWS.

3.2.1. Dynamics under a medium size event

CSOs are a major source of CBOD and ammonia. As shown in Fig. 4, RAPS remains active during both the medium size and the extreme storm events. Fig. 6 shows the concentration of CBOD in Bubbly Creek during a RAPS pumping event in the May 2009 storm. The pumping event in RAPS generates a distinct plume of CBOD in Bubbly Creek, as the base concentration in the waterways before the pumping was close to 3 mg/l and the concentration pumped by RAPS is assumed as 71.6 mg/l (Online Supplement Section 2). When the plume reaches CSSC the concentration of CBOD increases from 4 to 50 mg/l in some locations of CSSC. The plume then travels south following the flow direction in the CAWS under normal conditions, and the concentration of CBOD in CSSC returns to 4 mg/l. This pattern is expected in pumping events under small and medium size storms such as May 2009. The location of Bubbly Creek downstream of Wilmette and CRCW makes it difficult that pumped constituents from RAPS reach the lake boundaries.

During the May 2009 storm, the contribution of street CSOs is insignificant. Therefore, street CSOs discharges are isolated events that behave similar to a pulse discharge that is transported downstream or vanish along the CAWS. Online Supplement Section 8 shows the plume of ammonia released by three street CSO outfalls during the May 2009 storm in outfalls from dropshafts DS-M66 along the Chicago River, and dropshafts DS-M56 and DS-M57 along the Main Stem. The plume released by DS-M66 travels downstream following the water direction, while the plumes released by DS-M56 and DS-M57 remain in Main Stem and dilutes (and nitrifies) with time. This pattern is expected under normal flow conditions where isolated street CSOs may occur at different locations.

3.2.2. Dynamics under an extreme storm event

During an extreme event the contribution of both street and pumping stations CSOs is significant. Fig. 7 shows the distribution of
CBOD in the CAWS at different instants in time during the September 2008 storm. The initial concentration of CBOD is approximately 3 mg/l. The first CSO discharges in RAPS, NBPS and Street inflows (see Fig. 1 for location) increase the concentration of CBOD in the Chicago River and Bubbly Creek (Fig. 7b). The plume of CBOD released by RAPS travels south following a similar pattern as the one observed in the middle size event (Fig. 7c). In contrast to the May 2009 event, it is not possible to observe distinct plumes from isolated street CSO events. Instead a large plume of CBOD over the Chicago River (light blue in Fig. 7b and c) is observed. This plume is the result of many discharges from both street and NBPS CSOs.

The rainfall conditions forced the District to open both the gates at Wilmette and the gates and lock at CRCW during September 3th (see black open circle 7b). This allows to reduce flooding by directing water towards Lake Michigan. Therefore, part of the CBOD plume along the Chicago River traveled towards CRCW through Main Stem (Fig. 7c, d, e and f). However, a new rainfall pulse on September 14, 2008 induced an increase in the pumping rate at RAPS. A third peak in the pumping rate in RAPS (see the time series located over the top left in Fig. 7) released a plume of CBOD that overpassed the capacity in the CSSC. As a result, the plume of CBOD traveled upstream towards CRCW along the Chicago River moving in the opposite direction as it would do under normal conditions (Fig. 7e). After a few hours, the plume changed direction and started to travel southwards CSSC (Fig. 7f).

According to these results, the presence of CSOs during an extreme storm event induced a flow reversal in the CAWS, allowing a plume of CSOs to travel in the opposite direction as it did in the medium size event. The plume moved towards Main Stem, an important area of the CMA where downtown is located. However, the simulations showed that the plume released in RAPS did not reach Main Stem nor the boundaries with the lake. Although the water pumped in RAPS did not reach Main Stem, CSOs from NBPS and street CSOs along the Chicago River flowed towards Lake Michigan thorough the boundary at CRCW. This is observed in Fig. 7b, c and d.

4. Impact of CSOs on water quality in the CAWS

In this section, we analyze the impact of CSOs on the water quality in the CAWS. We perform this analysis by contrasting water quality results at different locations in time and space during the two storm events that are considered in this study.

4.1. Time series along the river

Fig. 8 shows the time series of CBOD, ammonia, and IP during both storms events. Six different locations in the CAWS are displayed in Fig. 8, including the boundary with Lake Michigan at Wilmette, CRCW, and O’Brien. We observe that during the May 2009 event there is only one major CSO event in RAPS that increases the concentration of CBOD, ammonia, and IP at CSSC upstream of Stickney WRP (dark grey lines in Fig. 8b, c and d). However, downstream of the Stickney WRP and the confluence of the Calumet Sag Channel the concentration of these constituents are significantly diluted (light grey lines in Fig. 8b, c and d). Apart from this event, there are no major alterations in the water quality along the CAWS for the May 2009 event.

On the contrary, for the September 2008 storm there is a significant volume of CSOs from both street and pumping stations. Therefore, the water quality in the river is more affected than during the May 2009 event. There are two major peak concentrations of CBOD, ammonia, and IP in CSSC upstream of Stickney (dark grey lines in Fig. 8f, g and h). The first peak corresponds to the CSO pumping events from RAPS during September 13 (Fig. 4) when the plume
travels south as in normal conditions (shown in Fig. 7b). The second peak corresponds to the CSO pumping event in RAPS during September 14, 2008. During this pumping event, the flow from RAPS travels in the upstream direction in the South Branch Chicago River towards the Main Stem (see Fig. 7e) inducing a peak in the concentration in this reach (black lines in Fig. 8f, g, and h). At the end of September 14, the plume retreats south towards CSSC causing the second peak at CSSC upstream of Stickney (dark grey lines in Fig. 8f, g, and h).

CSOs during the September 2008 impact significantly the water quality within the CAWS, with maximum concentrations of CBOD over 65 mg/l in the CSSC and close to 29 mg/l in the South Branch Chicago River and the North Shore Channel. These concentrations are above the minimum ranges established by different regulations for water effluents. However, these concentrations were observed only during the storm. At the end of the storm the concentrations reduced to normal conditions: 3.5 mg/l, 0.1 mg/l, and 0.6 mg/l for CBOD, ammonia, and IP, respectively. An important fraction of all the constituents released by the CSOs leave the system through the downstream BC at the Lockport Lock and Dam. However, the additional flow from the Stickney WRP and the Calumet Sag Channel represent a significant contribution that affects the water quality significantly, diluting the concentration leaving the system at Lockport.

Fig. 7. Distribution of carbonaceous biochemical oxygen demand (CBOD) in the CAWS at different periods during the September 2008 storm. The spatial domain includes the Chicago River and the north part of the Chicago Sanitary and Ship Canal (CSSC). The different insets (a–g) show the CBOD at different snapshots in time. The initial event in Racine Avenue Pumping Station (RAPS) releases a plume of CBOD that travels south to the CSSC (inset b), following the water direction expected during normal conditions. However, it is possible to observe that the third peak event at RAPS induces a reversal flow in the CAWS and the plume of CBOD travels north along the Chicago River instead of south (inset e). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Fig. 8f, g, and h (light grey) show the time series of CBOD, ammonia, and IP at CSSC after the Calumet Sag Channel Confluence. During the
period with high rainfall intensity (September 13 to September 15) the concentrations leaving the CAWS reached a peak of 20.7 mg/l, 1 mg/l, and 1.25 mg/l for CBOD, ammonia, and IP, respectively. These values, in particular for CBOD and ammonia, are below the 25 percentile of the concentrations recorded in CSOs. However, the 20.7 mg/l is above the percentile 75 of the data recorded in the WRPs outfalls.

4.2. Water quality in reversal flows to Lake Michigan

The September 2008 storm induced a reversal flow to Lake Michigan at the three lake boundaries. Fig. 8 shows the concentration of CBOD, ammonia, and IP predicted by the model at the three lake boundaries (red, orange, and green in Fig. 8). At some points in time we observe a peak in the concentration such as the CBOD concentration of 29 mg/l at CRCW during September 13. However, the magnitude of the flow reversal varies in time throughout the period of simulations (see Online Supplement Fig. 6c), including periods with no flow reversal at all. Therefore, the most meaningful description of the water quality during the reversal flow is to compute a mean concentration of the water released to the lake during the reversal. To estimate this mean concentration we use the formulation below:

$$\bar{C}_r = \frac{M_r}{V_r} = \frac{\sum_{i} Q_{r,i} C_{0,i} \Delta t}{\sum_{i} Q_{r,i} \Delta t}$$

Fig. 8. Time series of predicted concentrations by the model at six different locations in the Chicago Area Waterways System (CAWS) (see map on the top left inset). Three of these locations correspond to the boundaries with Lake Michigan (Wilmette, CRCW, and O’Brien), and the other three locations where selected along the CAWS. Insets (b, f) show the evolution of carbonaceous biochemical oxygen demand (CBOD), insets (c, g) shows the evolution of ammonia, and inset (d, h) shows the evolution of inorganic phosphorus (IP) during the May 2009 (insets on the left) and September 2008 (insets on the right) storm events. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
Table 2
Mean concentration of carbonaceous biochemical oxygen demand (CBOD), ammonia, nitrate, and inorganic phosphorus (IP) in the reversal flow to Lake Michigan during the September 2008 storm. The mean concentrations are listed for the three main boundary conditions with the lake.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Wilmette</th>
<th>CRCW</th>
<th>O’Brien</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBOD [mg/l]</td>
<td>10.89</td>
<td>13.57</td>
<td>5.42</td>
</tr>
<tr>
<td>Ammonia [mg/l]</td>
<td>0.69</td>
<td>0.86</td>
<td>0.59</td>
</tr>
<tr>
<td>Nitrate [mg/l]</td>
<td>2.48</td>
<td>1.53</td>
<td>1.11</td>
</tr>
<tr>
<td>IP [mg/l]</td>
<td>0.39</td>
<td>0.43</td>
<td>0.45</td>
</tr>
</tbody>
</table>

where $\bar{C}_r$ is the mean concentration of a particular constituent released into the lake during the storm, $M_r$ is the total mass of constituent, and $V_r$ is the total volume of water released into the lake during the storm. The term $Q_r$ is the reversal flow into the lake at time $i$, $C_{bi}$ is the concentration predicted by the model for a particular constituent in the river at the lake boundary at time $i$, $N_t$ is the number of time steps, and $\Delta t$ is the time step used in the simulations.

Table 2 shows $\bar{C}_r$ for CBOD, ammonia, nitrate, and IP estimated by the numerical simulations for the water released into the lake during the reversal flow in the September 2008 storm. The highest concentrations of CBOD and ammonia are found at CRCW, while the highest concentration of nitrate was observed at Wilmette. Fig. 9 compares the $\bar{C}_r$ values predicted by the model with recorded concentrations at both WRPs effluents and isolated sampling measurements in RAPS and NBPS. We observe the next:

**CBOD**: $\bar{C}_r$ in Wilmette and CRCW lies above the 90% percentile reported in the effluent from Stickney and O’Brien WRPs. However, $\bar{C}_r$ is lower than the minimum value reported in RAPS and close to the 12% percentile recorded in the NBPS (Fig. 8c).

**IP**: The mean concentration predicted for the reversal flow lies below the 25% percentile recorded in the effluent of all the WRPs as well as in the CSOs (Fig. 8d).

From this analysis, we observe that there is a significant dilution in the river before the CSO plumes reach the lake. However, the concentrations of CBOD in the water released to Lake Michigan are close to 10 mg/l which is higher than the 75% percentile expected from a WRP effluent and represents an important flux of organic matter to the lake during the storm. However, the concentrations of both nitrate and IP are actually lower than the concentrations expected from a WRP effluent. In the case of nitrate this is due to the lower concentrations in the CSOs and not enough time for nitrification during a storm time scale, while in the case of IP this is related to the low base level concentration the river had before the storm (as reported by the AWQM stations, Fig. S2 Online Supplement).

### 4.2.1. Water quality regulation

4.2.1. Water quality regulation

Table 3 shows the effluent standards in the state of Illinois, US. We observe that the concentrations of CBOD, ammonia, nitrate and IP at the downstream BCs and the Lake Boundaries are lower than the maximum standards for regular effluents. However, the restrictions for CBOD is more strict for effluents to Lake Michigan. Although the plume from RAPS does not reach any of the lake boundaries, and there is a significant dilution, the mean concentration of CBOD at the lake boundaries are above the regulation of 5.6 mg/l.

5. Discussion

We have implemented a detailed numerical simulation of the hydrodynamics and water quality in the Chicago Area Waterways System (CAWS) during two storm events representing a return period of 4 months (medium event) and 100 years (extreme event).
We observed that combined sewer overflow (CSO) discharges significantly impact the hydrodynamics and water quality in the CAWS. In particular, we observe CSOs during the extreme event induced a reversal flow in the CAWS. Previous studies analyzed potential impacts of CSOs on stream dynamics (Irvin et al., 2005; Gooré Bi et al., 2015; Li et al., 2013; Passerat et al., 2011; Rodríguez et al., 2012; Wang, 2014), and other studies highlighted flow reversals on different streams induced by different dynamics (Cao et al., 2003; Quinn, 1988). However, to our knowledge this is the first time that a reversal flow induced by CSOs describing a plume of pollutants traveling in the opposite direction as water does in normal conditions, is reported. This analysis highlights that CSOs inflows during extreme events could significantly impact the hydrodynamics and the fate of pollutants.

In our simulations, we observed there was a significant inflow of CSOs during the extreme event, and this inflow impacted significantly the water quality in the CAWS. In particular, we observed that the maximum concentrations of CBOD and ammonia in different regions of the CAWS were above the standard regulations for effluents, and these concentrations could impact significantly the ecology in this system (Arthur et al., 1987; Randall and Tsui, 2002). However, external inflows increase proportionally with the rainfall intensity, and we observe there is an important dilution in the CAWS associated with other inflows such as tributaries and water reclamation plants that compensate the concentrations from the CSOs under extreme events. As a result, the maximum concentrations at the system boundaries are well below the maximum concentrations observed within the CAWS.

The results obtained in this study does imply that CSOs during extreme events impact the concentrations at the river boundaries. In fact the CBOD concentration at the downstream boundary condition increased almost seven times (from 3 to 20.7 mg/l) during the extreme storm event, and was almost five times larger than the maximum concentration observed during the medium storm event (4.2 mg/l). However, the values obtained at the boundaries during the extreme event are still far below the maximum observed within the CAWS (69 mg/l). As expected, the net impact caused by the CSOs increases significantly in the extreme events but the overall implications downstream of the system should be analyzed cautiously and with reliable data of all the other inflows.

We have used available information recorded in ten water quality stations to initialize, and force the numerical model. In addition, we have developed an external one-dimensional model that helped us to find realistic parameters for the water quality simulations. Although the hydrodynamic simulations compared well with the available data recorded at three USGS stations, there are still important uncertainties associated with the water quality simulations. In particular, the kinetic parameters and the unavailability of continuous data records at both street and pumped CSOs are major drawbacks that could impact the predicted concentration at different locations of the CAWS. Nevertheless, our major conclusion highlighting the dilution observed in the CAWS during extreme storm is likely to remain under different combination of parameters and concentrations at the CSOs.

Acknowledgments

The authors gratefully acknowledge the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) for providing the required information for this study. The opinions and findings presented in this paper are solely of those of the authors of the manuscript and do not represent the opinions of any state and federal agencies mentioned in the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.08.191.

References


### Table 3

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Regular effluent</th>
<th>Lake Michigan effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BOD</strong>v [mg/l]</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td><strong>CBOD</strong>a [mg/l]</td>
<td>29.2</td>
<td>5.9</td>
</tr>
<tr>
<td><strong>CBOD</strong>v [mg/l]</td>
<td>25</td>
<td>–</td>
</tr>
<tr>
<td><strong>CBOD</strong>v [mg/l]</td>
<td>29.2</td>
<td>–</td>
</tr>
<tr>
<td>Ammonia [mg/l]</td>
<td>2.5</td>
<td>–</td>
</tr>
<tr>
<td>Nitrate [mg/l]</td>
<td>–</td>
<td>29.2</td>
</tr>
<tr>
<td><strong>TP</strong> [mg/l]</td>
<td>1</td>
<td>–</td>
</tr>
</tbody>
</table>

a **CBOD** computed from **BOD** regulation and using a ratio **BOD**/**CBOD** = 1.25.

b **CBOD** computed from **CBOD** regulation.


