Effectiveness of combined sewer overflow treatment for dissolved oxygen improvement in the Chicago Waterways

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Abstract An Use Attainability Analysis (UAA) has been initiated to evaluate what water-quality standards can be achieved in the Chicago Waterway System (CWS). There are nearly 200 combined sewer overflow (CSO) locations discharging to the CWS by gravity. Three CSO pumping stations also drain approximately 140 km^2. Because of the dynamic nature of the CWS the DUFLOW model that is capable of simulating hydraulics and water-quality processes under unsteady-flow conditions was used to evaluate the effectiveness of water-quality improvement techniques identified by the UAA including CSO treatment. Several CSO treatment levels were applied at gravity flow CSOs to evaluate improvement in dissolved oxygen (DO). The results show that pollutant removal at CSOs improves DO to a certain degree, but it still was not sufficient to bring DO concentrations to 5 mg/L or higher for 90% of the time during wet weather at most locations on the CWS. Flow from the pumping stations results in substantial stress on DO since a huge amount of un-treated water with a high pollution load is discharged into the CWS in a short period of time at a certain location. The simulation results indicate that CSO treatment does not effectively improve DO during wet-weather periods on the CWS.
Keywords Combined sewer overflows; diffuse pollution; dissolved oxygen; water-quality modelling

Introduction

The Chicago Waterway System (CWS) is composed of the Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag Channel, North Shore Channel (NSC), lower portion of the North Branch Chicago River (NBCR), South Branch Chicago River (SBCR), Chicago River Main Stem, and Little Calumet River (North). The CWS is a 122.8 km branching network of navigable waterways controlled by hydraulic structures in which the majority of flow is treated sewage effluent from three of the largest wastewater treatment plants in the world. The dominant uses of the CWS are for commercial and recreational navigation and for urban drainage, i.e. draining combined sewer overflows (CSOs), stormwater run-off, and treated wastewater from the Chicago area away from Lake Michigan, which is the water supply for Chicago. The Calumet and Chicago River Systems are shown in Figure 1.

The Illinois Pollution Control Board regulations (Title 35, Section 302.206 and Section 302.405) state that for General Use waters the dissolved oxygen (DO) concentration shall not be less than 6 mg/L during at least 16 hours of any 24 hour period, nor less than 5 mg/L at any time. In the CWS, only the upper NSC and the Chicago River Main Stem are considered General Use waters. The remainder of the CWS is considered Secondary Use waters wherein the DO concentration shall not be less than 4 mg/L at any time except that the Calumet-Sag Channel shall not be less than 3 mg/L at any time. This regulation was established in 1972 with a modification for the Calumet-Sag Channel in 1988,

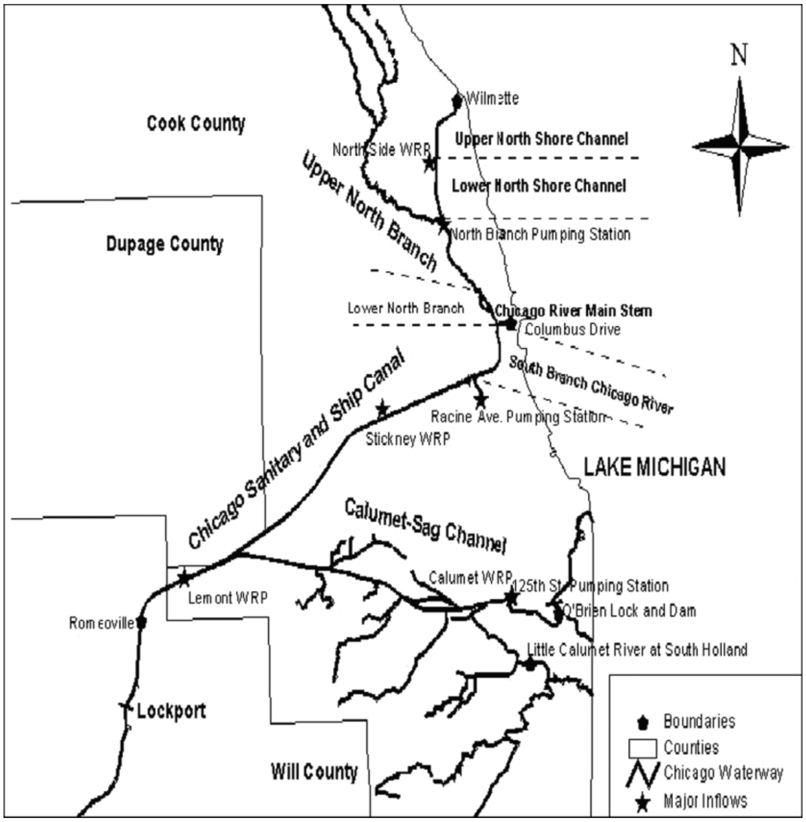

Figure 1 Schematic diagram of the Calumet and the Chicago River Systems

and since that time the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) has made many improvements to the wastewater treatment plants (water reclamation plants), CSOs, and aeration resources of the CWS. Thus, in 2003 the Illinois Environmental Protection Agency initiated an Use Attainability Analysis (UAA) for the CWS to see if DO in the CWS could be brought closer to the General Use standard at a reasonable cost. In anticipation of this UAA and to meet other water-quality management needs the MWRDGC began an intensive sampling of hourly DO and temperature throughout the CWS in 1998, and entered into an agreement with Marquette University in 2000 to develop a water-quality model for the CWS that was suitable for simulating constituent concentrations during unsteady-flow conditions.

The DUFLOW (2000) water-quality model developed in the Netherlands was selected for this study for the following reasons.

(1) Includes several options for water quality simulation, one that is identical to the WASP4 model of the U.S. Environmental Protection Agency (Ambrose *et al.*, 1988) and another that adds the Di Toro and Fitzpatrick (1993) sediment flux model to the WASP formulation.
(2) Compatible with Geographic Information Systems.
(3) Microsoft Windows based including a powerful graphical user interface.
(4) Low license cost.
(5) Low computational time.
(6) Successfully applied to several European rivers (e.g., Manache and Melching, 2004).

DUFLOW was calibrated and verified for the periods of July 12 to November 9, 2001, and May 1 to September 23, 2002, respectively. An extensive data set including hourly in-stream

DO data at 25 locations, monthly in-stream water-quality measurements at 18 locations, daily treatment plant effluent measurements, and detailed hydraulic data were used to calibrate and verify the model at a 1-hour output time step. Details of the calibration procedure and results are given in Alp and Melching (2006) and Melching *et al.* (2004).

The UAA found that although treatment plant effluent concentrations meet the applicable standards and most reaches of the CWS meet the applicable water-quality standards, periods occur when DO standards are not met in the CWS, especially during and after wet-weather periods with CSOs. CSO treatment was recommended in the UAA as a means to improve DO concentrations during and after storms. This paper evaluates CSO treatment effectiveness on the basis of DUFLOW model simulations.

CSO loads

Water-quality parameters were measured by the MWRDGC at the North Branch and 125th Street Pump Stations for selected storms in 2001. Because detailed storm loading data were available for 2001, this period became the focus of the evaluation of CSO treatment alternatives. When there were no measured data for a storm in 2001, the average of all Event Mean Concentrations (EMCs) for storms sampled in 2001 for the given pumping station were assigned to this storm. For the simulation period in 2002, none of the pumping stations were sampled. Therefore, average values from all available historic EMC data were used (2001–2002 and 1995–1999 and 2001–2002 for the North Branch and 125th Street Pumping Stations, respectively). The range and average EMCs of carbonaceous biochemical oxygen demand ($CBOD_5$), ammonium as nitrogen (NH_4-N), and DO for the pumping stations are listed in Table 1 to give an idea of the pollutant loads from the CSOs.

Since no measured data are available for the Racine Avenue Pumping Station for 2001, $CBOD_5$ and ammonium concentrations were determined as a function of discharge using a regression equation based on EMC data collected in 1995–1999 and 2002. DO concentrations were determined on the basis of regression relations between EMC and discharge for the North Branch Pumping Station.

The North Branch Pumping Station water-quality parameters were used for NSC and NBCR CSOs, the Racine Avenue Pumping Station water-quality parameters were used for the Chicago River Main Stem and SBCR CSOs, and the Calumet-Sag Channel and Little Calumet River CSO water-quality parameters were determined using concentrations

Table 1 Range and average EMCs of $CBOD_5$, NH_4-N, and DO at the various pumping stations used in the simulations

Statistic	$CBOD_5$ (mg/L)	NH_4-N (mg/L)	DO (mg/L)
North Branch			
Minimum	14.9	1.8	2.4
Average	35.4	2.9	4.2
Maximum	71.4	5.8	6.7
Racine Avenue			
Minimum	33.2	0.8	3.4
Average	52.1	2.9	6.1
Maximum	92.6	3.7	9.0
125th Street			
Minimum	8.4	0.3	4.3
Average	25.7	1.0	4.3
Maximum*	24.4	1.2	4.3

*For $CBOD_5$ and NH_4-N the maximum is for the three measurements in 2001, whereas the average reflects the overall average including data from 1995–1999 and 2002.

measured at the 125th Street Pumping Station. The reasonableness of this approach was shown in Neugebauer and Melching (2005).

CSO treatment simulations

Evaluation of hypothetical pollutant removal scenarios

Removal scenarios. There are nearly 200 CSOs in the modeled portion of the CWS drainage area and in the DUFLOW water-quality model, 28 CSO locations were used to represent the whole system of gravity flow CSOs. In addition to gravity flow CSO locations, there are 3 CSO pumping stations draining an area of approximately 140 km^2. It was considered infeasible to treat the CSO flows at the pumping stations because of high flows (up to 140 m^3/s at Racine Avenue) with short durations. Thus, treatment at only the gravity flow CSOs was considered, and, initially, a "proof of concept" approach was tried wherein treatment would be applied uniformly to all gravity flow CSOs and any hypothetical treatment level would be considered in order to reach DO concentration goals of 4, 5, and 6 mg/L regardless of the site feasibility and feasibility of treatment levels. The calibration and verification periods were selected as the test simulation periods because 2001 was a relatively wet year and 2002 was a relatively dry year giving an acceptable variety of flows for the simulations.

Four different BOD and ammonium treatment removal levels (30, 60, 90, and 100%) were applied to all 28 gravity flow CSOs. A simulation with increased DO concentration in conjunction with 100% BOD and ammonium removal at gravity flow CSOs has also been completed. This last simulation is referred to 100% treatment with raised DO. The MWRDGC measured DO concentrations and temperature for certain storms at the North Branch and 125th Street Pumping Stations in 2001. According to measured data, temperatures at the pumping stations vary from 20 to 25 °C, and the average temperature is around 23 °C. Hence, the saturation DO concentration of 8.5 mg/L at 23 °C was used for the 100% treatment with raised DO simulation.

Results. The percentage of time that the target DO concentration of 5 mg/L is equaled or exceeded in the periods of July 12 to November 9, 2001 and May 1 to September 23, 2002 for various CSO treatment scenarios during wet weather is shown in Figures 2 and 3 for the NSC-NBCR-SBCR-CSSC and Little Calumet River (North)-Calumet-Sag Channel reaches, respectively. Throughout the CWS simulations wet weather has been defined as extended periods when flow at Romeoville exceeds 100 m^3/s (this definition is also

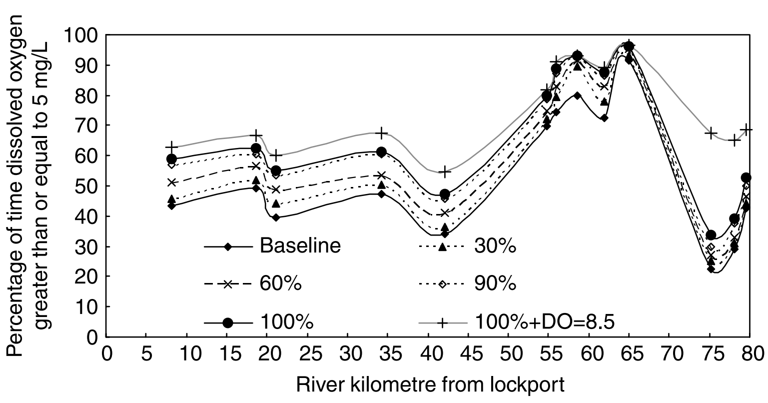

Figure 2 Percentage of time that DO concentrations are greater than 5 mg/L during wet weather along the NSC, NBCR, SBCR, and CSSC for the 2001 and 2002 test periods for various CSO treatment scenarios

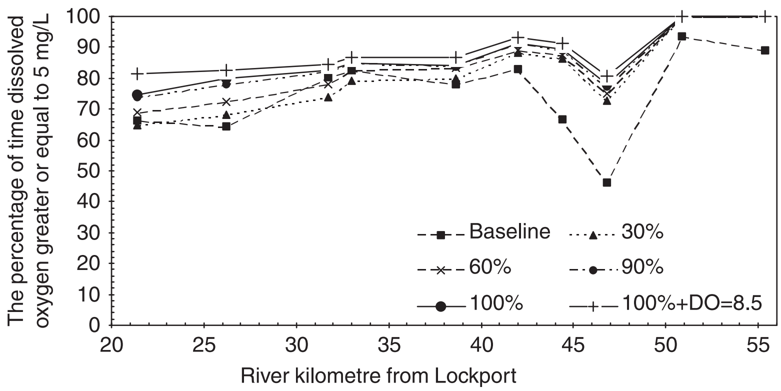

Figure 3 Percentage of time that DO concentrations are greater than 5 mg/L during wet weather along the Little Calumet River (North) and Calumet-Sag Channel for the 2001 and 2002 test periods for various CSO treatment scenarios

supported by hydrograph analysis of the major tributaries to the CWS, see Alp and Melching (2006)).

For the upper NSC (river kilometres (KM) 73.9–80.0) since the flows upstream from North Side Water Reclamation Plant are mainly dominated by CSO flows, the effect of CSO treatment is obvious particularly when the CSOs are aerated. Even though pollutant removal at CSOs improves the water quality conditions, DO concentrations do not get higher than 5 mg/L even 55% of the time during wet-weather periods along the upper NSC with 100% removal of BOD and ammonium (Figure 2). The DO criterion of 5 mg/L could be met 65–70% of the time for wet-weather periods in the upper NSC after 100% treatment with raised DO. For most events on the upper NSC the DO concentration of the CSOs was less than 4.5 mg/L, a 4 + mg/L increase in DO in the CSOs resulted in a big jump between 100% treatment and 100% treatment with raised DO. These results indicate that the poor quality of the stagnant water in the upper NSC prior to a storm and high sediment oxygen demand in the upper NSC cannot be easily counteracted.

For the lower NBCR (KM 55.1–68.1) the effects of CSO treatment are much smaller. Addison Street (KM 64.9) is downstream from the junction of the NBCR and the NSC. The flow at Addison Street is dominated by the North Side Water Reclamation Plant, North Branch Pumping Station, and the upper NBCR. Hence, the effect of pollutant removal at CSOs is not as significant as was observed along the upper NSC. It can be seen that the 100% treatment with raised DO results in attainment of DO concentrations in excess of 5 mg/L at Addison Street during wet-weather periods 96.6% of the time, which is about a 5 percentage point improvement over the baseline (calibration) conditions. At Kinzie Street (KM 56.0) the percentage compliance with the 5 mg/L target DO concentration increased from 74.3% for wet-weather periods for baseline conditions to 91.1% for wet-weather periods for 100% treatment with raised DO.

Compliance with the 5 mg/L target DO concentration is much smaller on the SBCR and CSSC upstream from the Stickney Water Reclamation Plant (KM 39.4–55.1). For Jackson Boulevard on the SBCR (KM 54.7) and Cicero Avenue on the CSSC (KM 42.3) the 5 mg/L target DO concentration is attained 81.8% and 54.7% of the time, respectively, during wet-weather periods for 100% treatment with raised DO. The great decline between Jackson Boulevard and Cicero Avenue reflects the dominating effect of the CSOs from the Racine Avenue Pumping Station, where flows greater than 100 m^3/s are common during storms.

Downstream from the Stickney Water Reclamation Plant (KM 39.4) the DO concentrations and compliance with target DO concentrations improves because of the large amount of highly treated effluent discharged by the plant. The percentage compliance with the 5 mg/L target DO concentration is between 60 and 70 percent for 100% treatment with raised DO in this reach. Romeoville is the downstream boundary of the modeled part of the CWS. Hence, it is possible to observe the effect of pollutant removal at all 28 CSOs at this location. The percentage compliance with the 5 mg/L target DO concentration increased from 43.6% for wet-weather periods during baseline conditions to 62.8% for wet-weather periods for 100% treatment with raised DO. Even with a 19.2 percentage point improvement in compliance with the 5 mg/L target DO concentration, compliance is still far below 90% of the time during wet-weather periods.

In general water quality conditions along Little Calumet River (North) and Calumet-Sag Channel are better than those for the NSC, SBCR, and CSSC. Hence, the effect of CSO treatment is not large especially along Little Calumet River (North) (KM 46.0–57.1). The 5 mg/L target DO concentration is met or exceeded 80.7% of the time during wet-weather periods at Halsted Street (KM 46.8) for 100% treatment with raised DO. Even 30% removal of BOD and ammonium will result in 100% compliance with the 5 mg/L target DO concentration upstream of KM 50.

As expected, the effect of CSO treatment becomes more noticeable closer to the Calumet-Sag Channel and CSSC junction (Figure 3). The 5 mg/L DO target concentration is achieved 66.6% of the time during wet-weather periods even for the baseline simulation at Division Street (KM 44.4). Even just 30% BOD and ammonium removal at CSOs is sufficient to bring DO concentrations to 5 mg/L for 79.8% of the time during wet-weather periods at Harlem Avenue, and 100% removal of BOD and ammonia at CSOs with raised DO is necessary to obtain 5 mg/L for 81.3% of the time during wet-weather periods at Route 83 on the Calumet-Sag Channel (KM 21.4). Even though an improvement of 15.2 percentage points for 5 mg/L target DO concentration can be achieved by 100% CSO treatment with raised DO for wet-weather periods at Route 83, the 5 mg/L target DO concentration is attained far less than 90% of the time during wet-weather periods.

In general, the results show that pollutant removal at CSOs improves DO to a certain degree, but it was not enough to bring DO concentrations equal to or higher than 5 mg/L for 90% of the time during wet-weather periods at most locations on the CWS. Daily average discharges from gravity flow CSOs can reach significant amounts during storms. For most storms the total flow coming from gravity flow CSOs is higher than the total discharge from the three pumping stations. Since all CSOs are distributed along the CWS, their effect is diminished. Whereas pumping stations result in more stress on DO in the CWS since a huge amount of untreated water with a high pollution load is discharged into the river system in a short period of time at a certain location. For example, on August 2, 2001, the Racine Avenue Pumping discharge is higher than both the North Side and Calumet Water Reclamation Plant discharges. In addition, during the August 2, 2001 storm, the total amount of flow from the pumping stations (44.8 m^3/s) is almost as high as the Stickney Water Reclamation Plant flow (48.3 m^3/s) and BOD and ammonium concentrations (39.3 mg/L; 1.1 mg/L, respectively) from the Racine Avenue Pumping Station are 6.6 and 2.4 times, respectively, higher than Stickney BOD and ammonium concentrations (6 mg/L; 0.465 mg/L, respectively).

Evaluation of a feasible alternative

Feasible alternative. Field (1980) summarized the BOD and TSS removal efficiency of various methods that had been proposed for pollutant removal at CSOs. As part of the

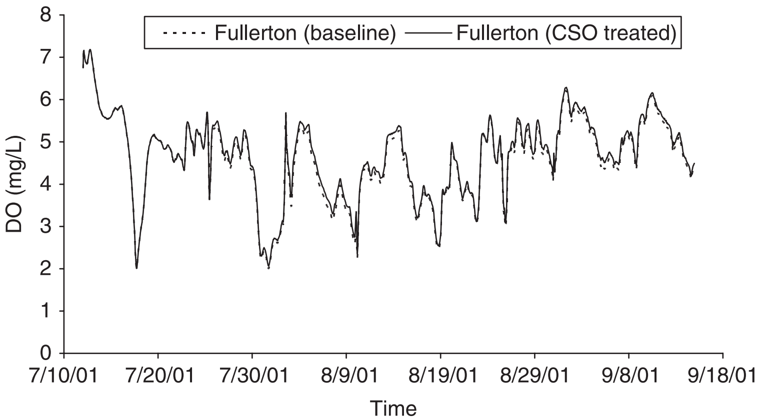

Figure 4 Simulated hourly DO concentrations at Fullerton Avenue for the baseline and treated CSO simulations for the period of July 12 to September 14, 2001

MWRDGC's response to the UAA, CTE Engineers examined 170 CSO locations along the NSC, NBCR, SBCR, and Chicago River Main Stem, and found that treatment was feasible at 105 of these locations, using Vortex separators that can achieve 30% of BOD and 50% of TSS removal efficiencies (this is consistent with Field's (1980) summary for swirl concentrators). Thus, in the modeling the loads of BOD and TSS were reduced by 30 and 50%, respectively, at 8 of the 12 representative CSO locations in these reaches.

Results. In general, DO concentrations in the CWS are slightly higher after the CSO treatment. However, the degree of DO increase varies from location to location. Figure 4 shows the simulated hourly DO concentrations at Fullerton Avenue (about 6.1 km upstream from the confluence of the NBCR and Chicago River Main Stem, essentially the center of the area with treated CSOs) for the simulation of baseline and treated CSO conditions for the period of July 12 to September 14, 2001. CSO treatment resulted in virtually no improvement in DO at this location, and this location is representative of results for the NBCR and SBCR. CSO treatment had a greater impact on the upper NSC where CSOs compose the majority of the flow but even here the decrease in the percentage of time less than a given target DO concentration was at most, 12 percentage points.

Conclusions

The simulations have shown that 100% removal of BOD and ammonium and increases in DO concentrations to 8.5 mg/L at the gravity flow CSOs are not sufficient to raise DO concentrations above the 5 mg/L target DO concentrations for large percentages of the time during wet-weather periods on the NSC, NBCR, SBCR, and CSSC. Compliance with these target DO concentrations is better for the Little Calumet River (North) and Calumet-Sag Channel. However, the most downstream locations on the Calumet-Sag Channel cannot achieve 90% compliance with the 5 mg/L target DO concentration during wet weather. The inability to treat the flows from the large pump stations and the stress placed on the WRPs during wet-weather periods are the most likely cause of the ineffectiveness of the pollutant removal at gravity flow CSOs in substantially improving DO concentrations. The simulation of actually feasible CSO treatment in terms of suitable sites and removal percentages of BOD and TSS found only minor improvement in DO concentrations. Thus, treatment of CSO flows does not appear to be a viable alternative for achievement of proposed DO standards throughout the CWS. Consideration of different DO standards during wet-weather periods or an allowance for 90% compliance with the DO standard may be necessary for the CWS. The latter has become a proposed target DO standard in the UAA related negotiations between the Illinois Environmental Protection Agency and MWRDGC.

References

Alp, E. and Melching, C.S. (2006). Calibration of a model for simulation of water quality during unsteady flow in the Chicago Waterway System and application to evaluate use attainability analysis remedial actions. *Technical Report 18*, Institute of Urban Environmental Risk Management, Marquette University, Milwaukee, WI, USA.

Ambrose, R.B., Wool, T.A., Connolly, J.P. and Schanz, R.W. (1988). WASP4, a hydrodynamic and water quality model–model theory, User's manual, and programmer's guide. U.S. Environmental Protection Agency, *EPA/600/3-87-039*, Athens, GA, USA.

Di Toro, D.M. and Fitzpatrick, J. (1993). *Chesapeake Bay Sediment Flux Model*. HydroQual, Inc. Mahwah, NJ. Prepared for U.S. Army Engineer Waterway experiment Station, Vicksburg, MS, USA. Contract Report EL-93-2.

DUFLOW (2000). *DUFLOW for Windows V3.3: DUFLOW Modelling Studio: User's Guide, Reference Guide DUFLOW, and Reference Guide RAM*, Utrecht, The Netherlands, EDS/STOWA.

Field, R. (1980). EPA research in urban stormwater pollution control. *Journal of the Hydraulics Division, ASCE*, **106**(HY5), 819–835.

Manache, G. and Melching, C.S. (2004). Sensitivity analysis of a water-quality model using Latin hypercube sampling. *Journal of Water Resources Planning and Management*, **130**(3), 232–242.

Melching, C.S., Alp, E., Shrestha, R.L. and Lanyon, R. (2004). Simulation of water quality during unsteady flow in the Chicago Waterway System. In *Proceedings CD-ROM, Watershed 2004*, Water Environment Federation, Dearborn, MI, USA, July 11–14, 2004.

Neugebauer, A. and Melching, C.S. (2005). Verification of a continuous water quality model under uncertain storm loads in the Chicago Waterway System, *Technical Report 17*, Institute of Urban Environmental Risk Management, Marquette University, Milwaukee, WI, USA.