SIMULATION OF WATER QUALITY DURING UNSTEADY FLOW IN THE CHICAGO WATERWAY SYSTEM

Charles S. Melching, Emre Alp, Ram Lal Shrestha, and Richard Lanyon
Department of Civil and Environmental Engineering
Marquette University
P.O. Box 1881
Milwaukee, WI 53201-1881

ABSTRACT

The Chicago Waterway System (CWS) is composed of the Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag Channel, North Shore Channel, lower portion of the North Branch Chicago River, South Branch Chicago River, Chicago River, and Little Calumet River. In total, the CWS is a 76.3 mi (122.8-km) branching network of navigable waterways controlled by hydraulic structures in which the majority of flow is treated sewage effluent. The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) will soon be faced with a number of difficult water-quality management issues including the impact of reduced discretionary diversions from Lake Michigan for water-quality improvement in the summer, the outcome of a use attainability analysis for the CWS, and development of total maximum daily load allocations. To evaluate these management issues and their impact on water quality in the CWS, a model capable of simulating water-quality processes under unsteady-state flow is being developed to assist in water-quality management and planning decision making.

The DUFLOW model developed in The Netherlands was selected for simulation of the CWS. The model hydraulics were calibrated using hourly stage data at three gages and verified at five gages operated by the MWRDGC within the CWS and at the downstream boundary at Romeoville. The water-quality model was calibrated using monthly grab sample data at 21 locations and hourly dissolved oxygen (DO) data at 27 locations all collected by the MWRDGC. The model was run at a 15-min. time step for the period of April 1 to May 4, 2002. The stage simulation agreed with the measured data nearly always within two percent relative to the flow depth. The simulated DO values agreed well with the observed values. The model then was applied to evaluate the effect of a proposed change in CWS navigational rules on the water quality in the CWS. Allowing lower water levels in the CWS immediately after storms that were improperly forecast could reduce the amount of water diverted from Lake Michigan. The reduced diversion was found to have a maximum average impact on DO of -2 mg/L on the South Branch of the Chicago River near the main Lake Michigan Diversion point, this was reduced to an average impact on DO of -0.4 mg/L on the downstream reaches of the CSSC. The effects on the North Branch Chicago River and Calumet-Sag Channel were far smaller.

Keywords: Water-quality modeling, water-quality management, unsteady flow, dissolved oxygen

INTRODUCTION

The Chicago Waterway System (CWS) is composed of the Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag Channel, North Shore Channel, lower portion of the North Branch Chicago River, South Branch Chicago River, Chicago River Main Stem, and Little Calumet River (North). In total, the CWS is a 76.3 mi (122.8 km) branching network of navigable waterways controlled by hydraulic structures in which the majority of flow is treated sewage effluent. The dominant uses of the CWS are for commercial and recreational navigation and for urban drainage, i.e. draining combined sewer overflows, stormwater runoff, and treated wastewater from the Chicago area away from Lake Michigan. The Calumet and Chicago River Systems are shown in Figure 1.

There have been several studies on the water quality in the CWS and the Upper Illinois River in the past. In particular, CDM (1992) used QUAL2EU to simulate dissolved oxygen (DO) on the Chicago Waterway and Upper Illinois River. This QUAL2EU model has been used by the MWRDGC throughout the 1990s for water-quality management in the CWS.

The MWRDGC will soon be faced with a number of difficult management issues including the impact of reduced discretionary diversions from Lake Michigan for water-quality improvement in the summer, the outcome of a use attainability analysis for the CWS, and development total maximum daily load allocations. Because of the dynamic nature of the CWS the available QUAL2EU model was considered inadequate to evaluate these management issues and their impact on water quality in the CWS. A model capable of simulating hydraulics and water-quality processes under unsteady-flow conditions was needed to assist the MWRDGC in the water-quality management and planning decision making processes. Therefore, the MWRDGC entered into an agreement with Marquette University to adapt the DUFLOW model developed in The Netherlands (DUFLOW, 2000) for simulation of the hydraulics and water-quality processes of the CWS. This paper describes the development, calibration, and application of the water-quality model for the period of April 1 to May 4, 2002.

Before the water-quality model was calibrated, the previously calibrated DUFLOW hydraulic model (Shrestha and Melching, 2003) was tested for the water-quality calibration study period. Hydraulic verification of the previously calibrated model for the time period of April 1 to May 4, 2002, is presented in the second section of this paper. Model hydraulics were calibrated using hourly stage data at three gages operated by the MWRDGC along the CSSC and at the downstream boundary at Romeoville, and daily flow data collected near the Chicago River Controlling Works (CRCW) and O'Brien Lock and Dam (O'Brien) upstream boundaries. Calibration of the water quality-model is described in the third section of this paper. Data used in calibration, assumptions, and calibration results are explained in this section. Finally, the application of the model to evaluate the effects of a proposed change in navigational water levels in the CWS on water quality is presented in section 4 of this paper.

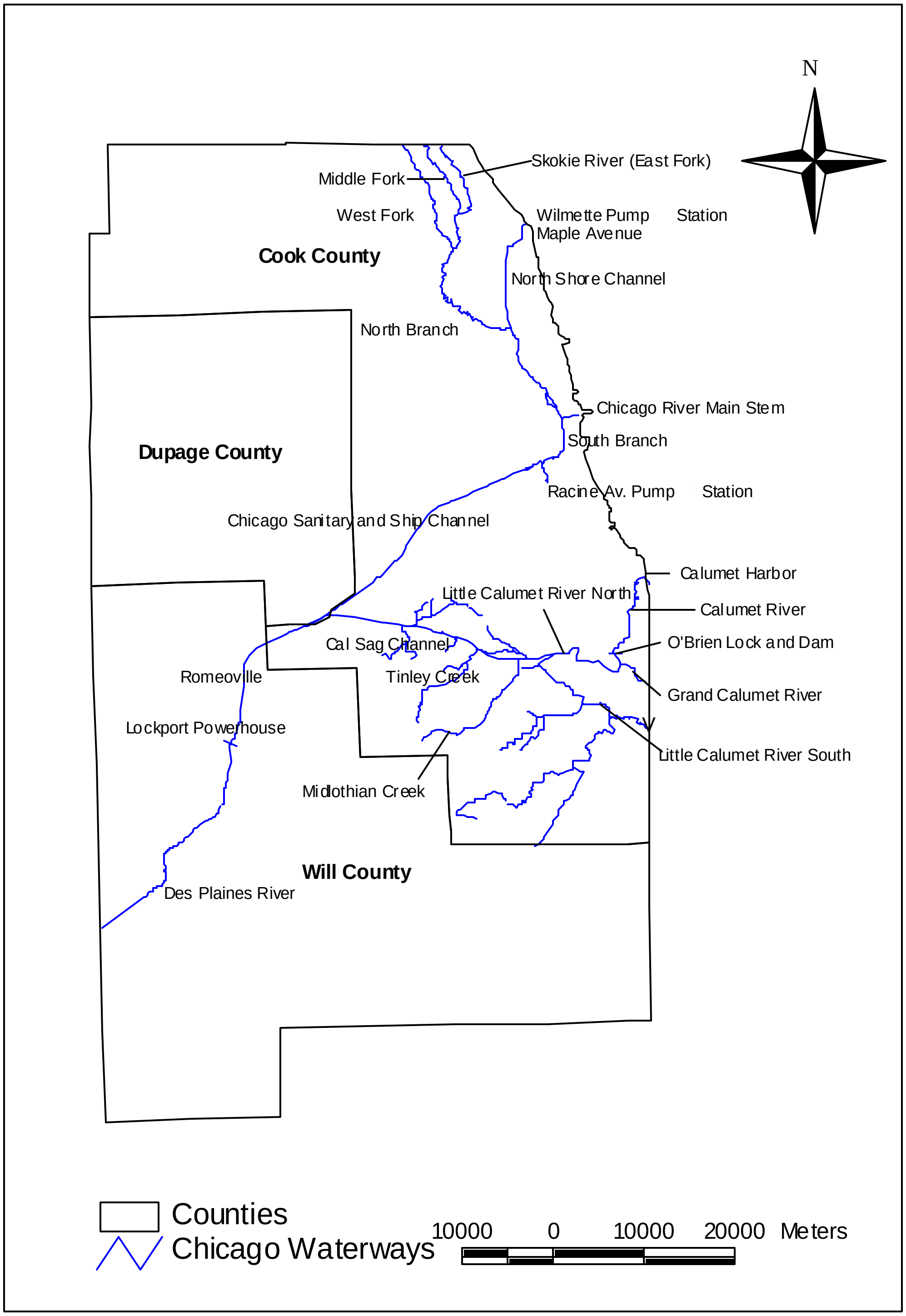


Figure 1 -The Calumet and the Chicago River Systems

HYDRAULIC MODEL VERIFICATION

Introduction

The unsteady-flow model for the CWS was calibrated and verified by comparing the simulation results to measured values for eight different periods between August 1, 1998 and July 31, 1999 (Shrestha and Melching, 2003). The model was calibrated using hourly stage data at three gages operated by the MWRDGC along the CSSC and at the downstream boundary at Romeoville operated by the U.S. Geological Survey (USGS), and using daily flow data collected by the USGS near the CRCW and O'Brien upstream boundaries.

In the water-quality calibration, data from the period between April 1 and May 4, 2002, were used to verify the previously calibrated hydraulic model (Shrestha and Melching, 2003). The model was run at a 15-min. time step and measured and simulated stage values were compared for a 60-min. time interval. Assumptions, data used, and results are presented in the following subsections.

Hydraulic Data used for the Model Input

Since all data needed for the model are not available, some assumptions were made to estimate missing data, ungaged tributaries, and ungaged watersheds. In the following subsections hydraulic data used in the model are explained.

Measured Inflow, Outflows, and Water-Surface Elevations

The hydraulic and hydrologic data available for the CWS have been compiled from different agencies. The USGS has established discharge and stage gages at three primary locations where water is diverted from Lake Michigan into the CWS. These locations are:

i) The Chicago River Main Stem at Columbus Drive (near CRCW)
ii) The Calumet River at the O'Brien Lock and Dam
iii) The North Shore Channel at Maple Avenue (near the Wilmette Pump Station)

The data from these gages are used as upstream elevation versus time (hourly) boundary conditions for the unsteady-flow water-quality model. Flow versus time data (on a 15-minutes basis) from the USGS gage on the CSSC at Romeoville are used as the downstream boundary condition for the model. The data from the USGS gage on the Little Calumet River (South) at South Holland provide a flow versus time upstream boundary condition for the water-quality model. Two tributaries to the Calumet-Sag Channel are gaged by the USGS, Tinley Creek near Palos Park and Midlothian Creek at Oak Forest. The USGS gage on the Grand Calumet River at Hohman Avenue at Hammond, Ind. is a tributary flow to the Little Calumet River (North). Flow on the North Branch Chicago River is measured just upstream of its confluence with the North Shore Channel at the USGS gage at Albany Avenue. All of these gages are shown in Figure 2.

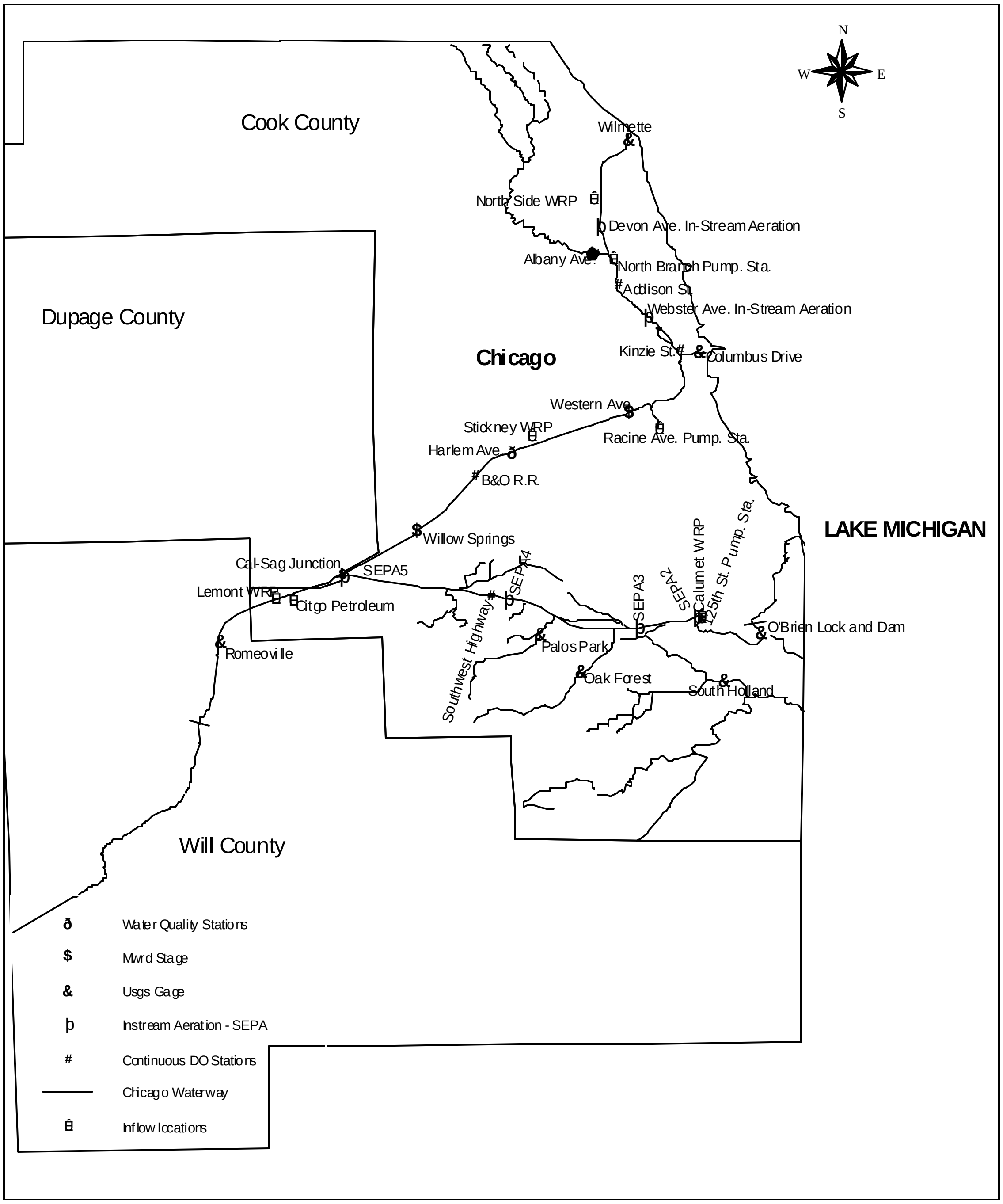


Figure 2 - Locations of the Dissolved Oxygen, Water Quality, and Stage Measurement Stations mentioned in this Paper, Sidestream Elevated Pool Aeration (SEPA) and In-Stream Aeration Stations; and Major Inflows to the Chicago Waterway System

There also are inflows coming from MWRDGC facilities. Hourly flow data are available from the MWRDGC for the treated effluent discharged to the CWS by each of the North Side, Stickney, Calumet, and Lemont Water Reclamation Plants (WRPs) (Figure 2). In addition, flows discharged to the CWS at three combined sewer overflow (CSO) pump stations (North Branch, Racine Avenue, 125th Street Pump Stations, see Figure 2) were estimated from operating logs of these stations.

Estimation of Flow for Ungaged Tributaries and Combined Sewer Overflows

It is necessary to estimate the inflows from ungaged-tributary watersheds. The same procedure was followed as applied in the original hydraulic calibration of the model (Shrestha and Melching, 2003). Flows on Midlothian Creek were used to estimate flows on ungaged tributaries using drainage area ratios. In total, flows from 107.45 mi^2 of ungaged drainage areas were estimated from Midlothian Creek flows.

Three pump stations discharge to the CWS. The Racine Avenue Pump Station worked for 10 hours on April 8-9, the North Branch Pump Station worked for 9.5 hours on April 8-9, and the 125th Street Pump Station worked for 12 hours on April 9. Flows from these stations were estimated from pump operation records.

The flow from other CSO drainage areas during storms has a substantial effect on the CWS. There are more than 190 dropshafts from the combined sewers to the Tunnel and Reservoir Plan tunnels and nearly 300 CSOs in the CWS drainage area. Since it is practically difficult to introduce all CSO locations in the modeling, 28 representative CSO locations were identified and flow distribution was done on the basis of drainage area for each of these locations.

During the April 8th event the measured and estimated inflows assuming no CSO flows were insufficient to maintain simulated water-surface elevations at Romeoville near measured water-surface elevations. If the simulated water-surface elevation is substantially below the observed value, the hydraulic model is artificially dewatering the CWS in order to match the observed flow at Romeoville indicating that the CWS is receiving insufficient inflow without including CSO flow. Thus, CSO inflow was added until reasonable water-surface elevations were simulated at Romeoville. This CSO volume is proportioned on the basis of CSO drainage area and applied uniformly in time over the period of operation of Racine Avenue Pump Station. For the April 8th event a total CSO volume of 140 m^3/s for 10 hours was input to the CWS simulation.

Channel Geometry and Roughness Coefficient

The channel geometry is represented in the hydraulic model as a series of 193 measured cross sections provided by the U.S. Army Corps of Engineers. The DUFLOW model uses Chezy's roughness coefficient, C, to calculate hydraulic resistance. For verification purposes, calibrated C values, which are listed in Table 1 together with equivalent Manning's n values and the values used in the U.S. Army Corps of Engineers UNET model of the CWS (Barkau, 1992), were used in this study.

Table 1 - Comparison of Manning's and Chezy's coefficients, n and C, respectively, for the U.S. Army Corps of Engineers UNET model (Barkau, 1992) and the DUFLOW calibrated values.

Reach No.	Reach Name	Hyd. Radius (meters)	UNET		DUFLOW	
			N	C	C	n
2	North Shore Channel	2.37	0.05	23	38	0.030
3	North Branch	3.08	0.05	24	38	0.032
4	Goose Island West	4.86	0.05	26	38	0.034
5	Goose Island East	4.86	0.05	26	38	0.034
6	South Branch	4.86	0.05	26	38	0.034
7	Chicago River Main Stem	5.59	0.03	44	44	0.030
8	Chicago Sanitary and Ship Canal (CSSC)	4.61	0.05	26	60	0.022
9	Little Calumet River South	0.93	0.20	5	6	0.165
10	Little Calumet River North	2.16	0.03	38	50	0.023
11	Calumet-Sag Canal	2.93	0.03	40	47	0.025
12	Romeoville reach of CSSC	6.26	0.04	34	41	0.033

Model Verification Locations

Although flow in the various branches of the CWS is not measured, water-surface elevation recorded at different locations was used for calibration and verification of the model. The water-surface elevation recorded at Western Avenue, Willow Springs, and Sag Junction by the MWRGC and at Romeoville by the USGS (see Figure 2) was used for model calibration and verification by Shrestha and Melching (2003). For this study, in addition to these locations, data from two new stations, North Branch Chicago River at Lawrence Avenue (i.e. the North Branch Pump Station) and Calumet-Sag Channel at Southwest Highway (Figure 2), were also used for verification purposes.

Flow Balance

The inflow to the CWS is comprised of flows from tributaries, water reclamation plants, stormwater pump stations, CSOs, and from Lake Michigan at the controlling structures. All the inflows to the system are measured as outflow at Romeoville. Missing data from gaged sites, ungaged tributaries, and CSO flows have been estimated by various mathematical and statistical methods described in detail in Shrestha and Melching (2003). During the calculation of the flow balance, it is assumed that the difference in the water balance due to the travel time and change in storage are negligible. Comparison of the summation of all inflows (except CSOs) to the system and outflow at Romeoville is shown in Figure 3. Over the full study period the inflows (except CSOs) were 3.4 % lower than the outflow at Romeoville. Because the upstream boundary conditions at the lakefront structures are water-surface elevation versus time, the computed flows at these structures were increased during computations above the measured values at these locations so that a system-wide flow balance was achieved.

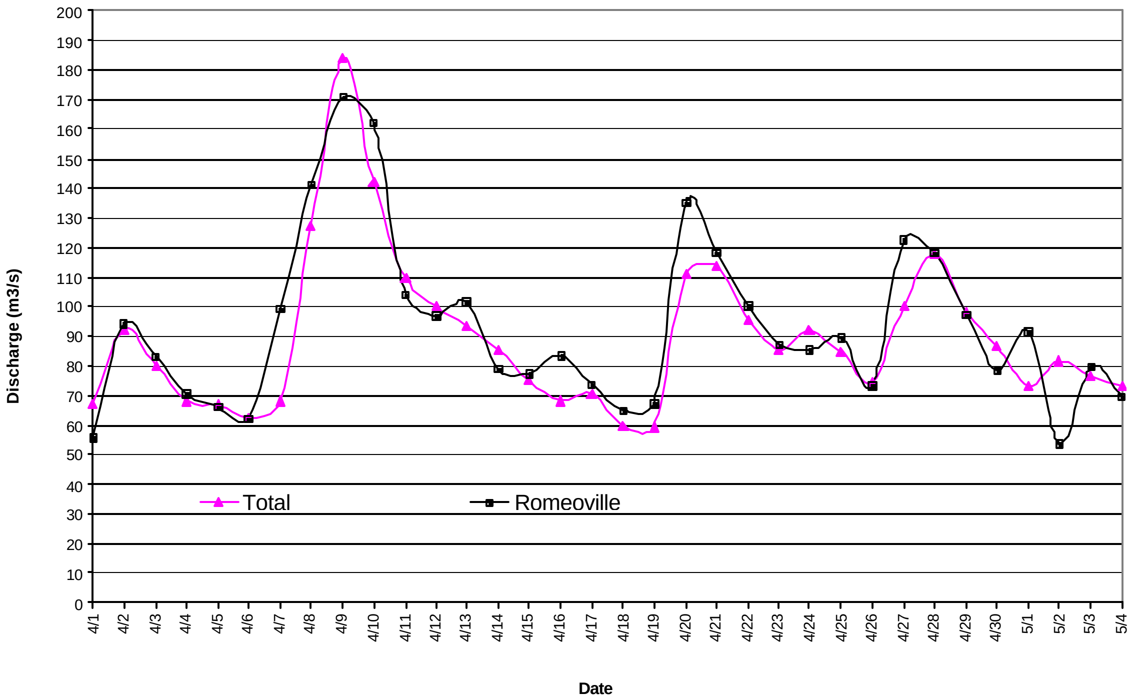


Figure 3 - Comparison of the summation of all measured or estimated (except combined sewer overflow) inflows (Total) and the measured outflow at Romeoville

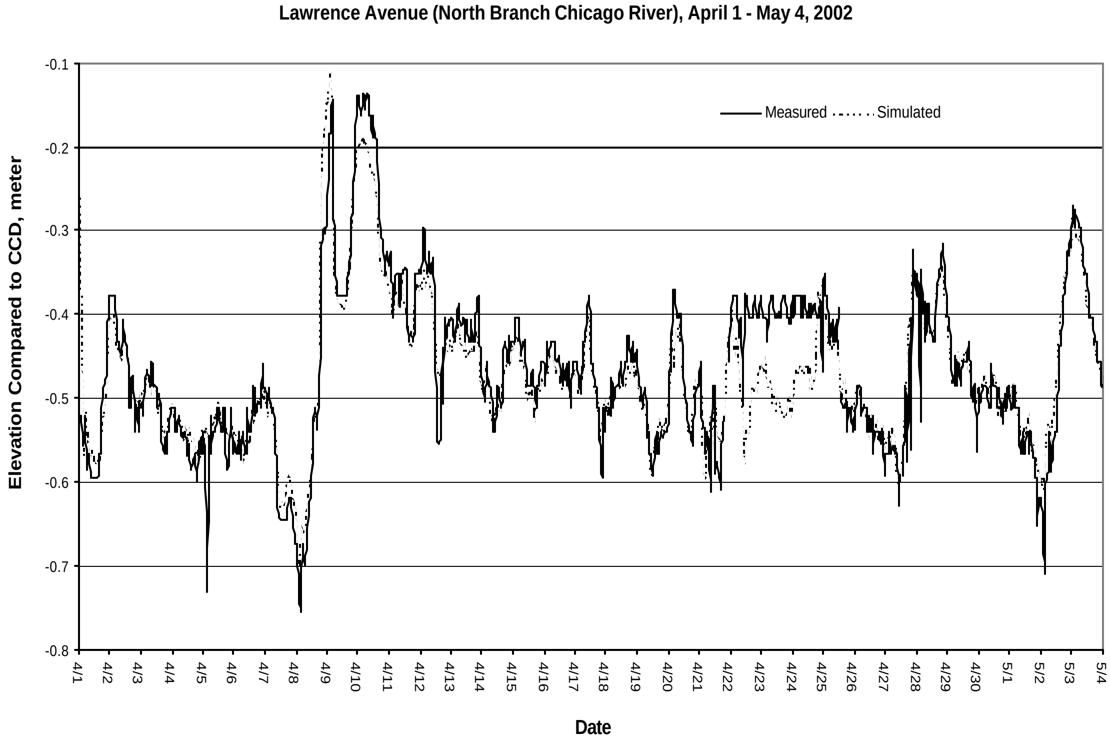
Results of the Hydraulic Verification

The comparison of measured and simulated water-surface elevations at the two new locations used in this study is shown in Figure 4. Although data from Lawrence Avenue on the North Branch Chicago River and Southwest Highway on the Calumet-Sag Channel were not used for calibration, verification results showed that the model could estimate measured water-surface elevations at these locations with high accuracy. Statistical analysis given in Table 2 shows that the simulated water-surface elevations were within 1 percent of the measured values with respect to the depth for 70.2-95.5% of the values and within 2 percent for 87.8-99.8% of the values. These high percentages of small errors and the high correlation coefficients (0.8-0.94) indicate an excellent hydraulic verification of the model. Since the calibrated model can predict stages throughout the CWS with high accuracy, this model can be safely used for the water-quality calibration.

CALIBRATION OF THE WATER QUALITY MODEL

The DUFLOW Water-Quality Model

The DUFLOW modeling system, DMS (DUFLOW, 2000) provides a water manager with a set of integrated tools, to quickly perform simple analyses. But the system is


Lawrence Avenue (North Branch Chicago River), April 1 - May 4, 2002

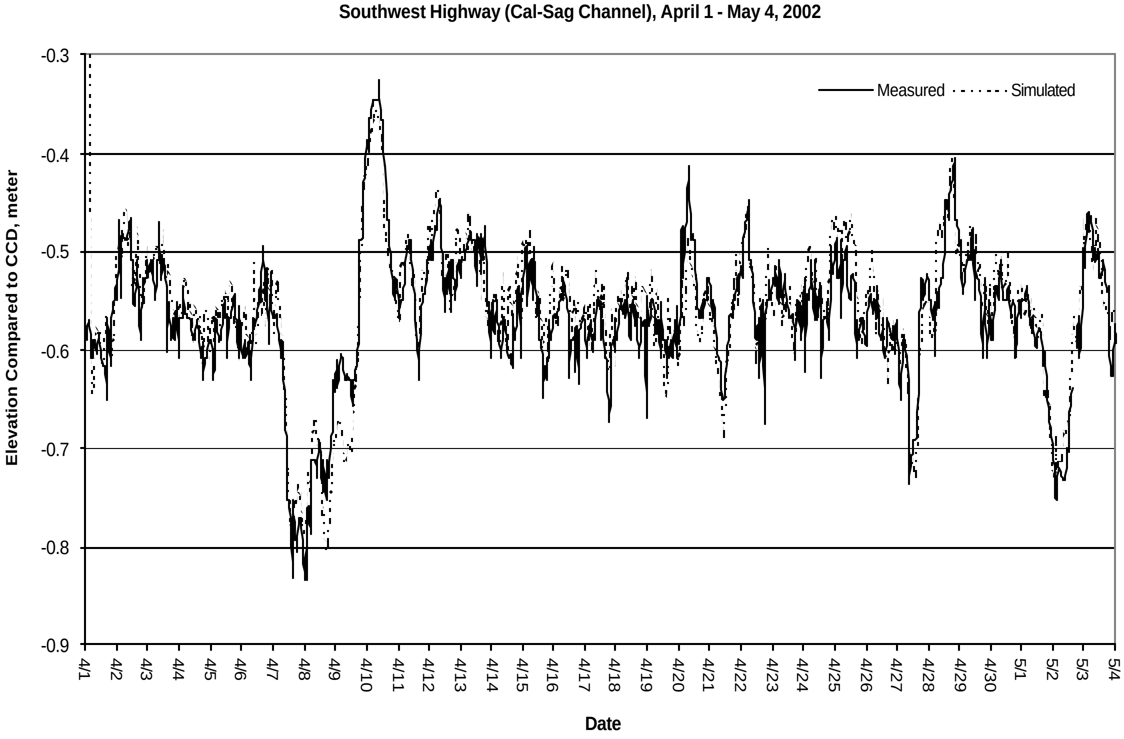

Southwest Highway (Cal-Sag Channel), April 1 - May 4, 2002

Figure 4 - Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at two locations on the Chicago Waterway System.

Table 2 – Correlation Coefficient and percentage of the hourly water-surface elevations for which the error in simulated versus measured values relative to the depth of flow is less than the specified percentage

Location	Correlation Coefficient	Percentage <±1% of D	Percentage <±2% of D
Lawrence Avenue (North Branch)	0.90	70.2	87.8
Southwest Highway (Cal-Sag Channel)	0.87	68.7	94.8
Western Avenue (CSSC)	0.93	95.5	99.8
Willow Springs (CSSC)	0.88	88.5	99.4
Sag Junction	0.80	70.3	94.2
Romeoville (CSSC)	0.94	87.1	97.5

equally suitable for conducting expensive, integral studies. It enables water managers to calculate unsteady flows in networks of canals, rivers, and channels. It also is useful for simulating the transport of substances in free-surface flow. More complex water-quality processes can be simulated as well. DUFLOW runs on a personal computer with a graphical user interface. It can, therefore, be operated in most scientific or engineering environments.

The DMS allows for a number of processes affecting water quality to be simulated, such as algal blooms, contaminated silts, salt intrusions, etc., to describe the water quality and it is able to model the interactions between these constituents. Two water-quality models are included in the DUFLOW modeling system as EUTROF1 and EUTROF2. EUTROF1 calculates the cycling of nitrogen, phosphorus, and oxygen using the same formulations as applied in the U.S. Environmental Protection Agency WASP version 4 (Ambrose et al., 1988). EUTROF1 is particularly suitable to study the short-term behavior of systems. If the long-term functioning of a system is of interest the other eutrophication model, EUTROF2, is more appropriate (DUFLOW, 2000). In addition to these two built-in water-quality models, there are an abundance of formulations proposed in the literature. DUFLOW gives great freedom to the user in formulating the production or destruction of biological or chemical constituents because users may write their own water-quality simulation routines and easily incorporate them in DUFLOW (DUFLOW, 2000).

In this study, EUTROF2 was selected as the appropriate unsteady-flow water-quality model for the CWS. In EUTROF2, three algal species can be defined, and the model also describes the interaction between the sediment and the overlying water column. The interaction between the bottom layer and the mass above is an important topic in water-quality problems on the CWS. EUTROF2 distinguishes among constituents flowing in the water column, constituents in the pore water of the upper/active sediment layer, and the lower/inactive sediment layer. The following state variables which are represented as both water and sediment components are included in the EUTROF2 model: algal biomass species, suspended solids concentration, total inorganic phosphorus, total organic phosphorus, total organic nitrogen, ammonia nitrogen, nitrate nitrogen, DO, and biochemical oxygen demand (BOD).

Water-Quality Input Data

The water quality in the modeled portion of the CWS is affected by the operation of four Sidestream Elevated Pool Aeration (SEPA) stations and two instream aeration stations (Figure 2). The CWS also receives pollutant loads from four water reclamation plants, nearly 300 CSOs (condensed to 28 representative locations to facilitate the modeling), direct diversions from Lake Michigan, and eleven tributary streams or drainage areas. Assumptions used to consider the effects of the aeration stations on water quality and to determine the various pollutant loadings are discussed in this section as are the constituent concentrations for the various inflows to the CWS. Complete details on the input data assumptions can be found in Alp and Melching (2004).

SEPA stations

The SEPA concept involves pumping a portion of the water from the stream into an elevated pool. Water is aerated by the pump turbulence and by flowing over a cascade of waterfalls, and the aerated water is returned to the stream. There are five SEPA stations along the Calumet-Sag Channel, Little Calumet River (North), and Calumet River. Four of these SEPA stations are within the water-quality model study area. Finally, even though SEPA station #2 is downstream from the Calumet WRP, the distance is too small (0.1 mi) for the Calumet WRP to have much effect in reducing DO concentrations. Thus, at SEPA station #2 upstream DO concentrations were very close to saturation during the study period, and the DO load input by SEPA station #2 was felt to be minimal and was not included in the modeling. The SEPA station locations are given in Table 3 and shown in Figure 2.

Two previously conducted studies (Butts et al., 1999 and 2000) were used to examine the efficiency of and calculate oxygen load from the SEPA stations. In the water-quality modeling, the oxygen load from the SEPA stations was calculated using the following formula:

$$\text{OXYGEN LOAD} = Q_P \text{ x } \alpha \text{ x } (C_{SAT} - C_{UPSTREAM})/1000 \text{ in kg/s}$$

where Q_P = Flow through SEPA station, m^3/s, = Number of Pumps Operating x Pump Capacity; C_{SAT} = Saturation concentration of dissolved oxygen, mg/L, (determined from continuous in-stream temperature data and system elevation); $C_{UPSTREAM}$ = Dissolved oxygen concentration (mg/L) upstream of SEPA station from continuous in-stream monitoring data; and α = Fraction of saturation achieved = f(number of pumps in operation, Table 3). These oxygen loads were directly input to the CWS as a point source in the DUFLOW water-quality simulation.

Flow through the SEPA station was calculated using the pump operation schedule and pump capacities. The pump operation schedule was provided by the MWRDGC. During the study period (April 1- May 4, 2002), SEPA stations were in use most of the time and just one pump was operating. Design features of SEPA stations are given in Table 4.

Table 3 – Location and fraction of dissolved oxygen saturation achieved by the Sidestream Elevated Pool Aeration (SEPA) stations with different pump operations (after Butts et al., 2000)

			Number of Pumps			
SEPA Station	Location	River Mile	1	2	3	4
3	Blue Island	27	1.01	1.01	0.99	
4	Harlem Avenue	20.7	1.01	1.05	1.02	
5	Sag Junction	12.3	0.93	0.98	1.02	1.02

Table 4 - Engineering design features of the Sidestream Elevated Pool Aeration (SEPA) stations (after Butts et al., 2000)

				Weirs			
	Pumps				Height (ft)		
Station No	Type	No	Size (in.)	No	Per Weir	Total	Design Maximum flow (cfs)
3	Screw	4	120	3	5	15	479
4	Screw	4	120	3	5	15	479
5	Screw	5	120	4	3	12	577

<u>In-Stream Aeration Stations</u>

The CWS includes two diffused aeration stations. The Devon Avenue station on the North Shore Channel was completed in 1979, and the Webster Street station on the North Branch of the Chicago River was completed in 1980. Results from a previous study (Polls et al., 1982) on the oxygen input efficiency of the Devon Avenue facility were used to determine oxygen loads from the in-stream aeration stations. Equations describing the effects of upstream DO saturation on downstream DO absorption with different numbers of blowers in operation are given below (Polls et al., 1982):

$DO_{increase} = 0.455 * DO_{saturation} + 61.75$ (3 blowers in operation)
$DO_{increase} = 1.048 * DO_{saturation} + 96.42$ (2 blowers in operation)
$DO_{increase} = -0.516 * DO_{saturation} + 45.57$ (1 blowers in operation)

where $DO_{increase}$ = Percent DO increase 0.30 miles downstream of the aeration station at Lincoln Avenue, and $DO_{saturation}$ = Percent DO saturation 0.12 miles upstream of the aeration station at Devon Avenue.

Although these regression equations were developed for the Devon Avenue aeration station, it was assumed that they also are valid for the Webster Street aeration station. Therefore, the same equations were used for both of the stations in the water-quality modeling. Blower operation hours were provided by the MWRDGC. Unfortunately only the total number of operating hours per day was provided. Since blower start and stop times are unknown, blower operation hours were carefully determined using time intervals where increases and decreases in DO concentrations were observed downstream of the aeration stations. The following equation was used to calculate DO load for input to the model:

$$\text{Load} = \%DO_{increase} * DO_{upstream} * Q$$

where Load = DO load from in-stream aeration station (g/s); $\%DO_{increase}$ = Percent DO increase downstream of the aeration station; $DO_{upstream}$ = Measured DO concentration upstream of the aeration station (mg/L); and Q = Discharge at the aeration station (m^3/s).

Discharge and DO concentration upstream of Devon Avenue were calculated using mass balance. The North Side WRP and North Shore Channel at Main Street continuous DO concentration and discharges were used to calculate DO and discharge upstream of the Devon Avenue aeration station. The Fullerton Avenue continuous DO monitoring site measurements were used for the Webster Street aeration station calculations.

Point Sources

Five point sources are used in the water-quality modeling. North Side WRP, Stickney WRP, Calumet WRP, Lemont WRP, and the Citgo Petroleum Corporation outfall. Measured daily concentrations were used in the model for the four WRPs. The load from Citgo Petroleum outfall was not considered in this study because of lack of water-quality data on this discharge and the insignificant amount of flow contributed by this discharger. Thermal inputs in cooling water discharges from two generating stations were not directly considered in this analysis, but their effects on temperature were included in the reach varying temperature input to the model.

Tributaries

Dry Weather Concentrations

Long-term average values are used for the dry-weather concentrations. All water-quality data used for dry-weather concentrations were collected as a part of the MWRDGC monthly waterway sampling program. Average concentrations (2001-2002) for the Little Calumet River at South Holland were calculated using data from the Little Calumet River at Wentworth Avenue (upstream of the South Holland gage) and at Ashland Avenue (downstream of the South Holland gage) and Thorn Creek at 170th Street (upstream of the South Holland gage). Concentrations measured (1990-2002) at the Grand Calumet River at Burnham Avenue were used for the concentrations at the Grand Calumet River at Hohman Avenue gage. Average concentrations (2000-2002) for the North Branch Chicago River at Albany Avenue were measured directly. Dry-weather concentrations for other tributaries are based on Little Calumet River concentrations because all of the other gaged and ungaged tributaries (e.g., the unnamed tributary streams in Figures 1 and 2) are on the southern portion of the Chicago metropolitan area and were assumed to be similar to the Little Calumet River drainage basin.

Wet Weather Concentrations

Event mean concentrations were calculated using water-quality data collected during storm events by the MWRDGC. In most cases, the total load resulting from the runoff event is more important than the individual concentrations within the event due to the fact that runoff events are relatively short, the receiving water body provides some mixing, and the concentration in the receiving water body is a response to the total load rather than the concentration variability within the event (Novotny and Olem, 1994, p. 484). Hence, event mean concentrations were used to characterize all storms in this study. Concentrations for the Little Calumet River at South Holland were calculated using storm data on the Little Calumet River at Ashland Avenue. Event mean concentrations for the North Branch Chicago River at Albany Avenue were measured directly. Other tributaries were based on Little Calumet River event mean concentrations.

Combined Sewer Overflows

There are nearly 300 CSO locations discharging to the modeled portion of the CWS and they are represented by 28 CSO locations in the model (Figure 2). In addition to CSO locations there are 3 CSO pump stations. Water-quality parameters were measured by the MWRDGC at the pump stations during the April 7-9 storm period. On April 9, 2002 a single DO concentration of 2.5 mg/L was measured at the Racine Avenue Pump Station and a single DO concentration of 4.3 mg/L was measured at the 125th Street Pump Station. Because of the substantial variability in DO concentrations during an overflow event, it was decided to determine the event mean DO concentration for all CSOs as part of the DO calibration for entire CWS. A DO concentration of 6.5 mg/L was selected. This value is reasonable compared to monthly samples of DO concentration for the Racine Avenue Pump Station for March 2002-November 2003, which range from 0-9.3 mg/L with a mean of 4.5 mg/L and standard deviation of 2.9 mg/L. Also DO concentrations of inflows entering the TARP drop shafts collected in 1997 and 1999 had a mean of 6.3 mg/L and a standard deviation of 2.1 mg/L.

North Branch Pump Station measurements were used for North Shore Channel and North Branch CSOs. The Chicago River Main Stem, South Branch, and CSSC CSO water-quality parameters were determined using concentrations measured at the Racine Avenue Pump Station. The Calumet-Sag Channel and Little Calumet River CSO water-quality parameters were determined using concentrations measured at the 125th Street Pump Station.

Boundaries

There are three upstream boundaries in the water-quality model: near the CRCW at the Chicago River at Columbus Drive, near the Wilmette Pump Station at the North Shore Channel at Maple Avenue, and O’Brien. Historic plots of data (1990-2002) show that there are seasonal and monthly variations at these locations and nitrogen compound concentrations for the Chicago River at Columbus Drive changed dramatically after 1997. For this reason monthly averages were determined and mean values for April and May were used in the water-quality model.

Calibration of the Water-Quality Model

The following parameters were set as space and time dependent: temperature, diffusive exchange rate constant, nitrification rate constant, BOD decay rate, and dispersion. The reaeration-rate coefficient is automatically calculated by the model using the O'Connor-Dobbins (1958) formula, and, thus, it was not used as a calibration variable.

As noted earlier, EUTROF2 is capable of simulating up to three algal species. However, in this study algal simulation was not done. Previous studies have found that algal concentrations and activity in the CWS typically are low (CDM, 1992). This would be especially true for April and early May.

In-Stream Water-Quality Data

The water-quality model was calibrated using monthly grab sample data at 21 locations and hourly DO data at 27 locations all collected by the MWRDGC. The locations of water quality and DO sampling stations are given in Table 5.

Temperature (°C)

Temperature is one of the key variables, which affects reaction kinetics and the DO saturation concentration. Hourly measured temperature values were input at each continuous monitoring location (node in the model). Therefore, temperature varies spatially and temporally in the water-quality model.

Diffusive exchange rate constant (m^2/day)

Oxygen demand by benthic sediments and organisms has historically represented a large fraction of oxygen consumption in the CWS (CDM, 1992). Sediment Oxygen Demand (SOD) is the total result of all biological and chemical processes in sediment that utilize oxygen. The SOD in the EUTROF2 model is described by:

$$SOD = E_{dif}/HB*(O2_w-O2_B)$$

where SOD = Sediment Oxygen Demand (g/(day*m^2); E_{dif} = diffusive exchange rate constant (m^2/day); HB = depth of sediment top/active layer (m); $O2_w$ = water column dissolved oxygen concentration (mg/L); and $O2_B$ = dissolved oxygen concentration in the pore water in the sediment bed (mg/L).

In November 2001, the MWRDGC did a survey of sediment depth and composition at 20 locations in the CWS. The sediment survey results were used to set E_{dif} values to nearly zero or zero where little bed sediment was found, thus, setting SOD to zero at these locations. Values of E_{dif} for other reaches were determined by calibration.

Dispersion (m^2/s)

The model requires entering dispersion coefficients at each node. The value of the dispersion coefficient, D, either can be defined by the user or can be calculated using the properties of the flow. During the calibration procedure, it was found that the dispersion

Table 5 – Metropolitan Water Reclamation District of Greater Chicago continuous monitoring stations and ambient water-quality sampling stations

Station Location	Data Available	Waterway	River Mile
Linden Street	DO*, WQ**	North Shore Channel	49.8
Central Street	WQ	North Shore Channel	49.4
Simpson Street	DO	North Shore Channel	48.5
Main Street	DO	North Shore Channel	46.7
Oakton Street	WQ	North Shore Channel	46
Touhy Avenue	WQ	North Shore Channel	45.2
Foster Avenue	WQ	North Shore Channel	44
Albany Avenue	WQ	North Branch Chicago River	45
Wilson Avenue	WQ	North Branch Chicago River	41.6
Addison Street	DO	North Branch Chicago River	40.4
Diversey Parkway	WQ	North Branch Chicago River	39.2
Fullerton Avenue	DO	North Branch Chicago River	38.5
Division Street	DO	North Branch Chicago River	36.4
Grand Avenue	WQ	North Branch Chicago River	35
Kinzie Street	DO	North Branch Chicago River	34.8
Controlling Works	DO	Chicago River Main Stem	36.1
Lake Shore Drive	WQ	Chicago River Main Stem	35.9
Michigan Avenue	DO	Chicago River Main Stem	35.4
Clark Street	DO	Chicago River Main Stem	34.9
Madison Street	WQ	South Branch Chicago River	34.3
Jackson Boulevard	DO	South Branch Chicago River	34
Loomis Street	DO, WQ	South Branch Chicago River	30.8
Damen Avenue	WQ	Chicago Sanitary and Ship Canal	30
Cicero Avenue	DO, WQ	Chicago Sanitary and Ship Canal	26.2
Harlem Avenue	WQ	Chicago Sanitary and Ship Canal	22.9
Baltimore and Ohio Railroad	DO	Chicago Sanitary and Ship Canal	21.3
Route 83	DO, WQ	Chicago Sanitary and Ship Canal	13.1
Mile 11.6	DO	Chicago Sanitary and Ship Canal	11.6
Stephen Street	WQ	Chicago Sanitary and Ship Canal	9.4
Romeoville	DO	Chicago Sanitary and Ship Canal	5.1
Lockport	DO, WQ	Chicago Sanitary and Ship Canal	0
130 th Street	WQ, DO	Calumet River	36
Conrail Railroad	DO	Little Calumet River (North)	34.4
Central and Wisconsin Railroad	DO	Little Calumet River (North)	31.6
Indiana Avenue	WQ	Little Calumet River (North)	31.4
Halsted Street	DO, WQ	Little Calumet River (North)	29.1
Ashland Avenue	WQ	Calumet-Sag Channel	28.1
Division Street	DO	Calumet-Sag Channel	27.6
Kedzie Avenue	DO	Calumet-Sag Channel	26.1
Cicero Avenue	DO, WQ	Calumet-Sag Channel	24
Harlem Avenue	DO	Calumet-Sag Channel	20.5
Southwest Highway	DO	Calumet-Sag Channel	19.7
104th Street	DO	Calumet-Sag Channel	16.3
Route 83	DO, WQ	Calumet-Sag Channel	13.3

*DO = Continuous (hourly) dissolved oxygen and temperature data; **WQ = Monthly grab sample water quality measurements coefficient plays an important role at some locations. For these sites different dispersion coefficients were used for high flow and low flow periods.

Calibrated Parameter Values

The values of the diffuse exchange rate coefficient, E_{dif}, BOD water column oxidation rate (k_{bod}), nitrification rate constant (k_{nit}), and high flow and low flow dispersion coefficients, D, determined by calibration are listed in Table 6 for each reach. For all other model coefficients and parameters, default values given in EUTROF2 were used.

Table 6 - Reach calibration parameters used in the DUFLOW water-quality model for April 1 to May 4, 2002

Reach Name	Waterway	River Mile from Lockport	Kbod (day^{-1})	Knit (day^{-1})	Edif (m^2/day)	D (m^2/s)
C1	North Shore Channel	50-46	(0.15 ; 0.20)*	(0.4 ; 0.8)*	0.0200	15
C2.1	North Shore Channel	46-42.6	(0.15 ; 0.20)	(0.4 ; 0.8)	0.0000	15
C2.2	North Branch	42.6-37	(0.15 ; 0.20)	(0.4 ; 1.0)	0.0020	(15 ; 1000)**
C3	North Branch	37-35.5	(0.15 ; 0.20)	(0.4 ; 1.1)	0.0020	15
C4	North Branch	35.5-34.5	(0.15 ; 0.20)	0.15	0.0020	15
C5	Main Stem	34.5-36	0.035	0.3	0.0200	1
C6	South Branch	34.5-31	0.0001	0.0001	0.0000	15
C7	CSSC	31-25	0.1	0.09	0.0020	(15 ; 1000)
C8	CSSC	25-17	0.1	0.09	0.0000	(60 ; 1000)
C9	CSSC	17-12.5	0.01	0.1	0.0000	(15 ; 2000 ; 1000)
C15	CSSC	12.5-8	0.01	0.1	0.0000	50
C16	CSSC	8-5.1	0.01	0.1	0.0000	50
C11	Little Calumet (N)	35.5-30.5	0.05	0.1	0.0002	15
C12	Little Calumet (N)	30.5-28.5	0.05	0.1	0.0200	15
C13	Calumet-Sag	28.5-19	0.005	0.005	0.0000	15
C14	Calumet-Sag	19-12.5	0.005	0.005	0.0000	10

*Numbers in the brackets indicate that two rate constants are used for a reach for different time periods: (April 1 to April 15; April 16 to May 4)

** Numbers in the brackets indicate that different dispersion coefficients were used for high flow and low flow periods

Calibration Results

Biochemical Oxygen Demand, Ammonia, and Nitrate

DUFLOW computes the concentration changes in space and time of BOD, organic nitrogen, ammonia, nitrite, nitrate, total inorganic phosphorus, total organic phosphorus, suspended solids, and algal biomass species. The MWRDGC collects monthly samples of BOD, total Kjeldahl nitrogen, organic nitrogen, ammonia nitrogen, nitrite plus nitrate, total phosphorus, soluble phosphorus, and total suspended solids among many other constituents (e.g., Abedin et al., 1999) at 21 locations in the study area (Table 5). Thus, only one measured value of these constituents was available for the study period, which is insufficient to evaluate the simulation accuracy of the model. Thus, historical data were evaluated at each of the 21 locations to try to identify periods for which water-quality conditions at each location were similar to that of the study period.

Once the periods of consistent data were determined, the mean, median, standard deviation, maximum, and minimum were determined for each constituent at each location. The calibration of BOD, ammonia, and nitrate proceeded by examining the agreement between the mean of simulated concentrations and the long-term mean of measured BOD, ammonia, and nitrate concentrations. Adjustments were made to the BOD decay rate and nitrification rate constants to calibrate the model. The simulated values of each constituent at each location were graphically compared to the mean and one standard deviation confidence bounds determined from the measured values as shown in Figures 5 and 6 for ammonia and BOD, respectively, to try to determine if the model was yielding unusually high or low concentrations, and if so, to determine a cause for these concentrations. As shown in Figures 5 and 6 simulated hourly ammonia and BOD concentrations generally are inside the one standard deviation confidence bounds for most of the simulation period except for storm periods. During storm periods BOD and ammonia concentrations increase and can reach values higher than the upper confidence bound. The monthly samples are predominantly taken during low flow, and, thus, concentrations above the upper confidence bound were expected because of high pollution loads coming from CSOs during storms. Further, BOD samples have only been collected since 2001, and, thus, the standard deviation of the measured values is not as broad as that for ammonia, which has been collected since 1997. The calibrated simulation results did not yield any unusually high or low constituent concentrations.

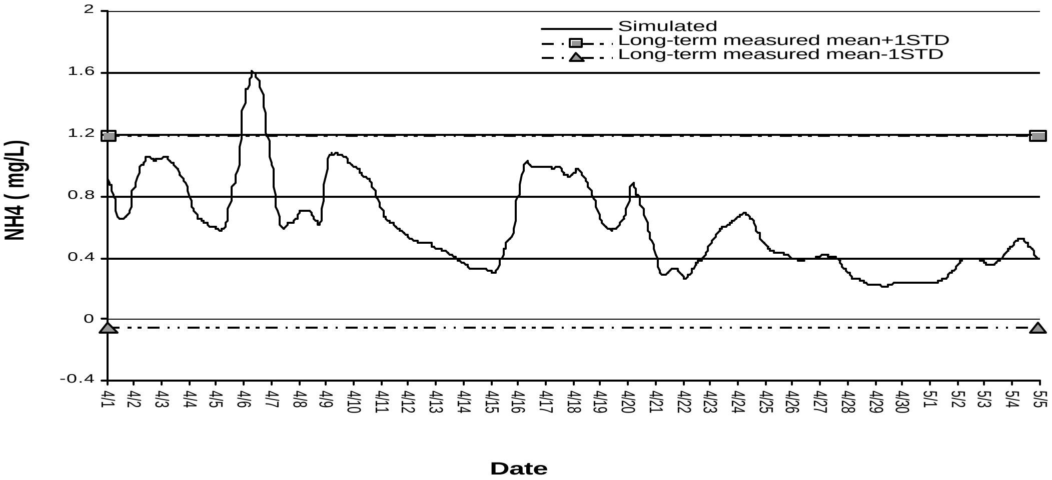


Figure 5 - Comparison of long term measured mean plus or minus one standard deviation, and simulated hourly ammonia (NH4) concentrations on the Chicago Sanitary and Ship Canal at Harlem Avenue.

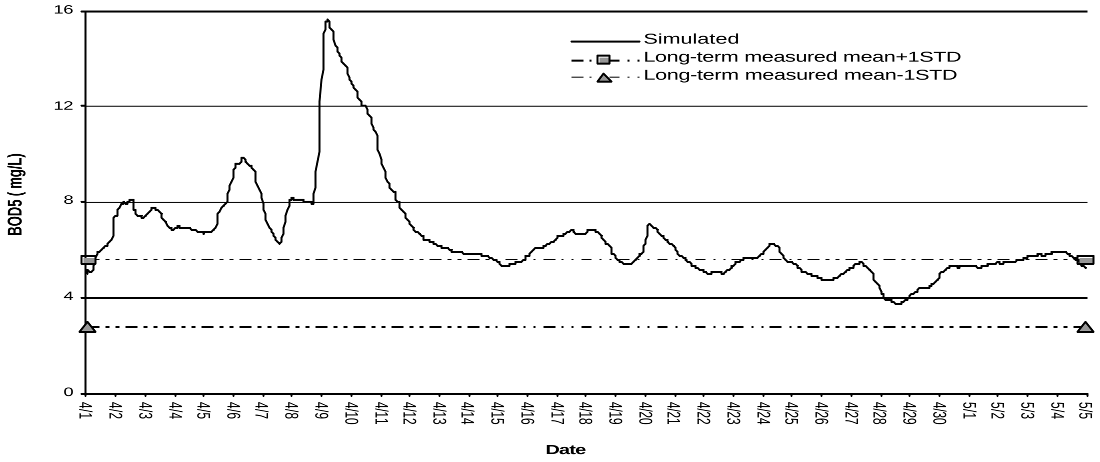


Figure 6 - Comparison of long term measured mean plus or minus one standard deviation, and simulated hourly biochemical oxygen demand (BOD5) concentrations on the Chicago Sanitary and Ship Canal at Harlem Avenue.

Dissolved Oxygen Concentration

Simulated DO concentrations were compared with hourly measured DO concentrations at 27 locations for the period of April 1 to May 4, 2002 (Alp and Melching, 2004). Results are presented in 4 categories: North Branch Chicago River, South Branch Chicago River and Chicago Sanitary and Ship Canal, Calumet-Sag Channel, and boundary conditions (this includes DO monitoring sites on the North Shore Channel, Chicago River main stem, and Little Calumet River (North) upstream of the Calumet WRP). Only representative results are presented here. Results for all sites are given in Alp and Melching (2004).

North Branch Chicago River

Dissolved oxygen concentrations on the North Branch Chicago River were calibrated starting from upstream to downstream locations. This section of the CWS is divided into 3 reaches and the following continuous DO stations represent each reach: i) Addison Street and Fullerton Avenue, ii) Division Street, and iii) Kinzie Street

The Addison Street DO monitoring site is the first station at which the combined effects of the North Branch Chicago River flow, North Side WRP flow, and Devon Avenue aeration station are observed. Significant DO fluctuations within very short time intervals are the main characteristics of this location (Figure 7). Almost all fluctuations were a result of operation of the Devon Avenue aeration station. Flow at Addison Street is dominated by North Side WRP flow during dry weather periods, whereas during storm periods, flow on the North Branch Chicago River at Albany Avenue has a significant effect on Addison Street flow. For this reason, wet weather DO concentrations were calculated using a mass balance for the North Branch Chicago River at Albany Avenue for April 10-11 and May 3, 2002. Since the Devon Avenue aeration station was in operation less than 2 hrs on April 10-11 and on May 3, the effect of the aeration station on DO concentrations is insignificant and mass balance results are reliable enough to use as input to the water-quality model. For the other days (dry weather period), long-term average DO values were used for the North Branch at Albany Avenue. Figure 7 shows good agreement between the simulated and measured DO concentrations at Addison Street. The successfully simulated storm period (April 8-14) DO concentrations show that accurate wet weather DO concentrations were used.

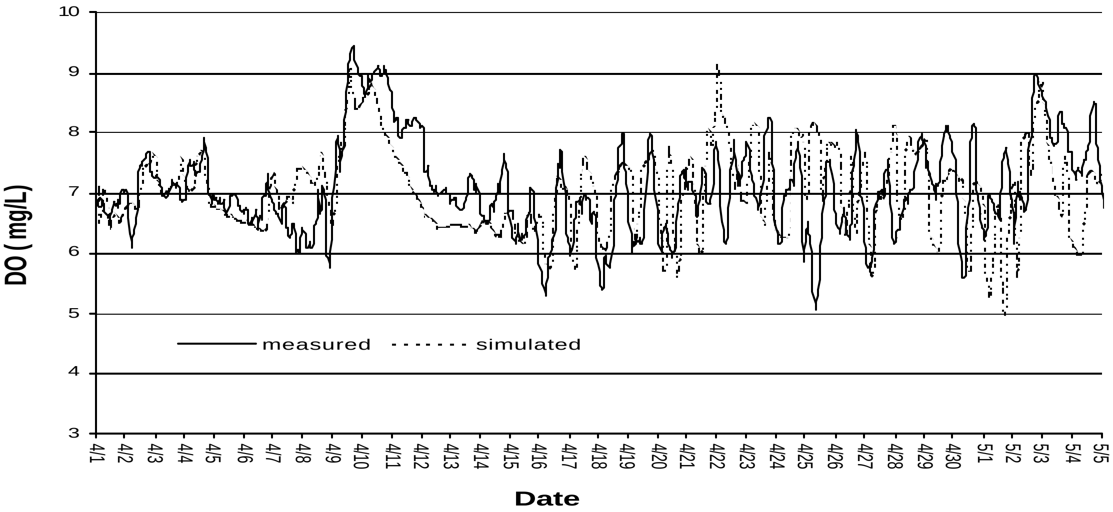


Figure 7 - Comparison of measured and simulated dissolved oxygen (DO) concentrations at Addison Street on the North Branch Chicago River

Kinzie Street is the last DO station on the North Branch Chicago River. It is located 0.2 mi upstream from North Branch Chicago River junction with the Chicago River main stem and South Branch. Like all the other North Branch DO stations, significant DO fluctuations are observed at this station (Figure 8). The measured and simulated DO concentrations have good agreement (Figure 8). Although there are some differences, the general trends of measured DO concentrations were successfully simulated.

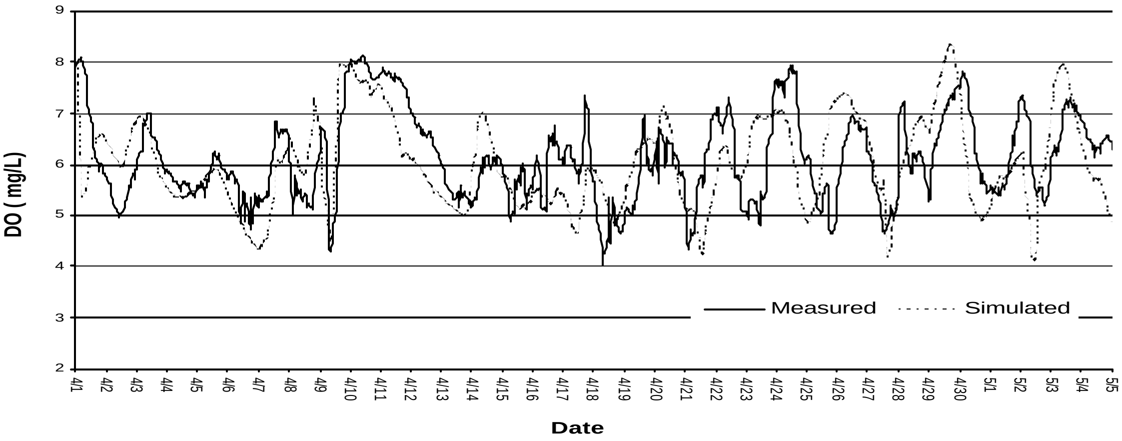


Figure 8 - Comparison of measured and simulated dissolved oxygen (DO) concentrations at Kinzie Street on the North Branch Chicago River

South Branch Chicago River and Chicago Sanitary and Ship Channel (CSSC)
Since all locations are linked to each other, the approach of first calibrating upstream locations did not work in the South Branch and CSSC section of the river system. This section is divided into 5 reaches and the following DO stations represent each reach: i) Jackson Boulevard, ii) Cicero Avenue, iii) Baltimore and Ohio Railroad, iv) Route 83, and v) River Mile 11.6 and Romeoville.

The Baltimore and Ohio Railroad (B&O RR) is located downstream of the Stickney WRP. Therefore, the effect of the Stickney WRP is very obvious at this location. The DO concentrations go down to 4 mg/L from 7 mg/L from April 21-25 (Figure 9). The simulated DO concentrations agree well with measured DO concentrations for all periods except this April 21-25 period (Figure 9). There are four significant DO drops between April 21 and 25 that the model could not simulate. The flow balance (Figure 3) indicates storm runoff beginning on April 19 and continuing through April 23, thus, the low DO concentrations occurring between April 21 and 25 could be the result of localized CSOs. Similar results were not seen on the North Shore Channel during this period because rainfall data collected by the Illinois State Water Survey (Westcott, 2003) indicated heavier rainfall in the southern part than in the northern part of the study area. The model could not match the low DO concentrations during this period because CSO inputs were not applied during this period. The simulated and measured water-surface elevation at Romeoville showed good agreement during this storm period, thus, no independent means of estimating CSO volume was possible.

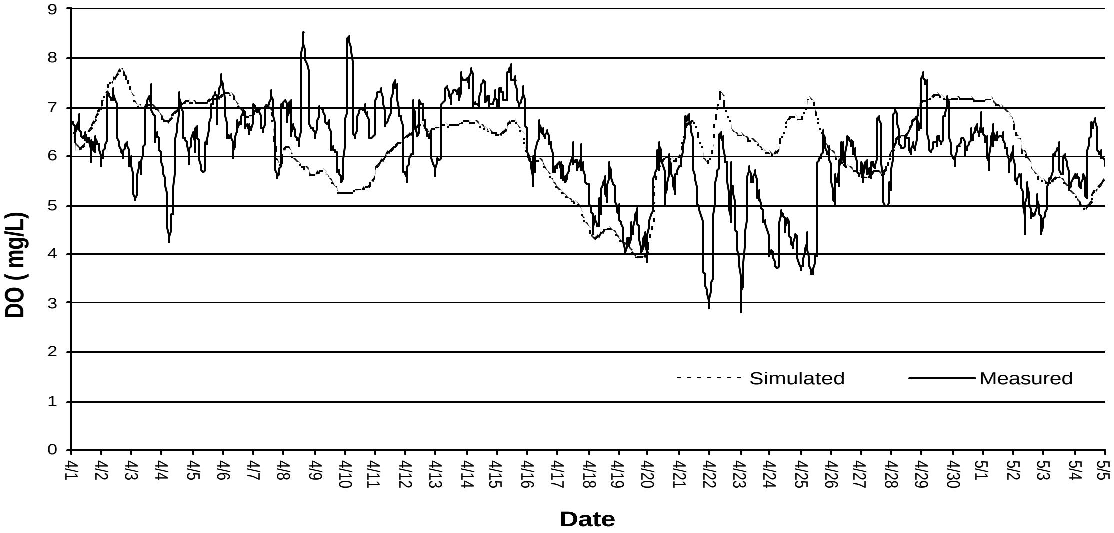


Figure 9 - Comparison of measured and simulated dissolved oxygen (DO) concentrations at the Baltimore and Ohio Railroad on the Chicago Sanitary Ship Canal

Romeoville is the downstream boundary condition for the water-quality model. The simulated and measured DO concentrations are generally in good agreement (Figure 10). From the B&O RR to Romeoville the sharp decrease in DO concentrations on April 23 was observed with the simulated DO concentrations higher than the measured concentrations. As discussed earlier, this probably resulted from CSO loads resulting from a storm event, which was not considered as input to the modeled system.

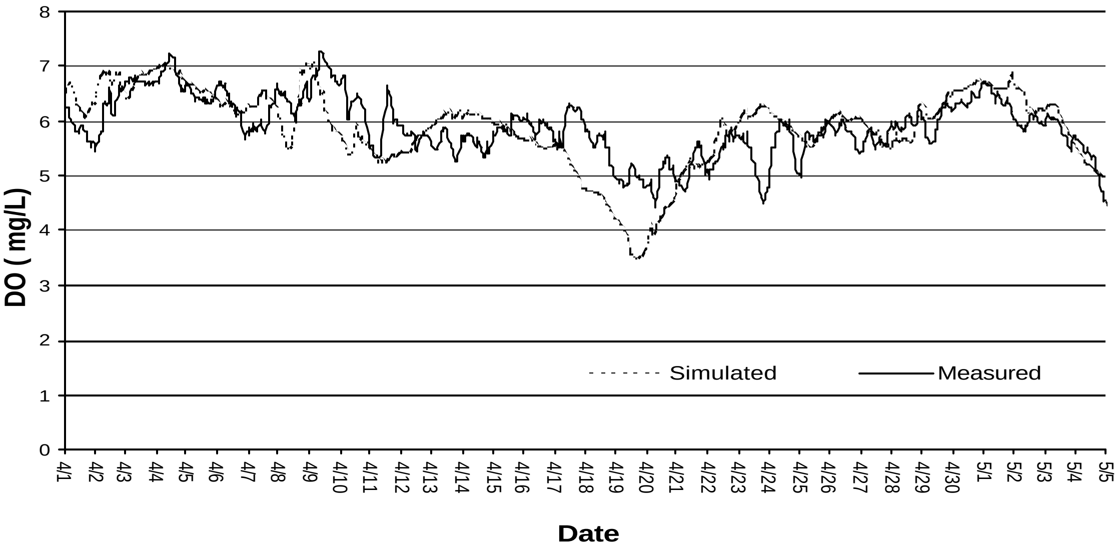


Figure 10 - Comparison of measured and simulated dissolved oxygen (DO) concentrations at Romeoville on the Chicago Sanitary and Ship Canal

Calumet-Sag Channel

This section includes locations between the Calumet WRP and the Calumet-Sag Channel Junction with the CSSC. This section is divided into 3 reaches and the following DO stations represent each reach: i) Halsted Street, ii) Division Street, Kedzie Avenue, Cicero Avenue, Harlem Avenue, and Southwest Highway, and iii) Route 83. The comparisons of simulated and measured DO concentrations have very good and very similar agreement between Division Street and Route 83 all stations on the Calumet-Sag Channel. For this reason only the results at Southwest Highway are presented here in Figure 11.

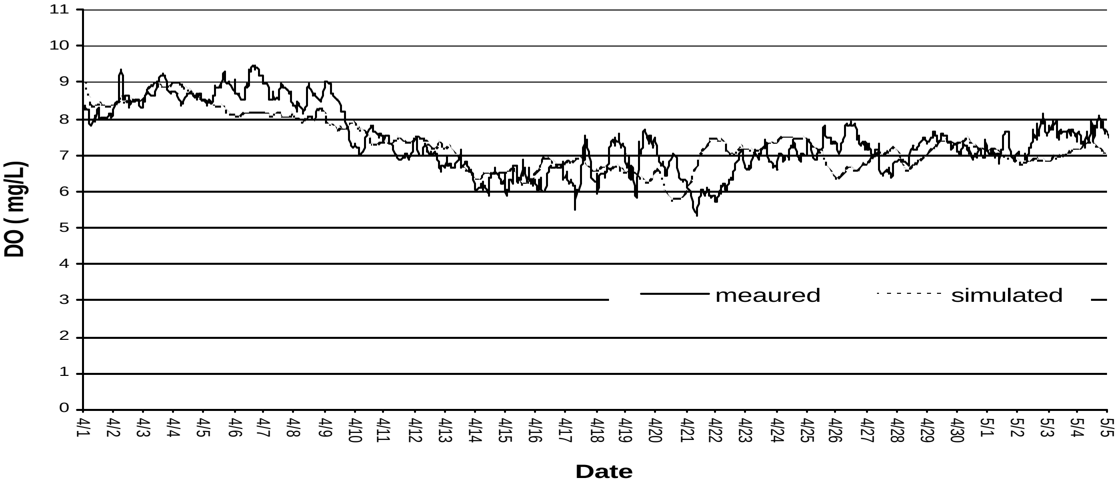


Figure 11 - Comparison of measured and simulated dissolved oxygen (DO) concentrations at Southwest Highway on the Calumet-Sag Channel

Boundaries (North Shore Channel, Chicago River main stem, Little Calumet River (North))

Although the model simulated DO concentrations without any major problems at most the locations throughout the CWS downstream from the WRPs, the same kind of success was not archived at the locations close to the boundary conditions and/or upstream from WRPs. Locations upstream of the WRPs and on the Chicago River main stem had very low flows during the study period. Poor DO simulations resulted at these locations because of the imbalance between inflows and outflows to the CWS in the modeling and the hydraulic complexities of the CWS.

The simulated inflow to the North Shore Channel from Lake Michigan is greater than the measured inflow from Lake Michigan. With the higher amount of Lake Michigan inflow in the simulation, the simulated DO concentrations tended to be higher than the measured DO concentrations on the North Shore Channel. The simulated inflow to the Chicago River main stem tended to be underestimated. Therefore, the simulated flows at Clark Street and Michigan Avenue have less Lake Michigan water than in the actual river, and DO concentrations were substantially underestimated. The amount of Lake Michigan water entering the CWS at O’Brien also tended to be underestimated, thus, decreasing the simulated DO concentrations on the Little Calumet River (North) upstream of the Calumet WRP.

Without a substantial improvement in the flow balance for the CWS, DO concentrations will be poorly simulated on the North Shore Channel, Chicago River main stem, and Little Calumet River (North) upstream of the Calumet WRP. Because of poor DO simulation results on these reaches estimated changes in DO resulting from a change in navigational water levels will not be reported for these reaches in the next section. For complete details on the calibration results for these reaches see Alp and Melching (2004).

SCENARIO RESULTS

The current Code of Federal Regulations (CFR) requires that the water-surface elevation at two lake front control structures (O’Brien and CRCW) must be kept greater than or equal to –2 ft (-0.610 m) relative to the City of Chicago Datum (CCD, 579.48 ft = 176.626 m above mean sea level). In anticipation of storms the MWRDGC often draws down the CWS to create storage space for the expected storm runoff. If the storm does not occur or is smaller than expected, the MWRDGC may have to withdraw water from Lake Michigan (“navigation make up water”) to restore the water-surface elevation at the lake front structures to –2 ft CCD. Because diversion of water from Lake Michigan is carefully regulated, the State of Illinois requested that the U.S. Army Corps of Engineers evaluate the effects of allowing water-surface elevations to go as low as –3 ft CCD during or after expected storm periods. The goal of the study would be to see if the benefits of the reduction of navigation make up water would outweigh any adverse impacts to water quality, navigation, and other uses/interests. If the adverse effects of reducing the minimum water-surface elevation to –3 ft CCD were found to be minimal, then a change in the CFR might be recommended.

In order to study the effects of the allowing water-surface elevations to be less than –2 ft CCD, the MWRDGC was allowed to drain the canal below –2 ft CCD for two storms during the April 1 to May 4, 2002, study period. The measured water-surface elevations at the lake front boundaries during the study period are shown in Figure 12.

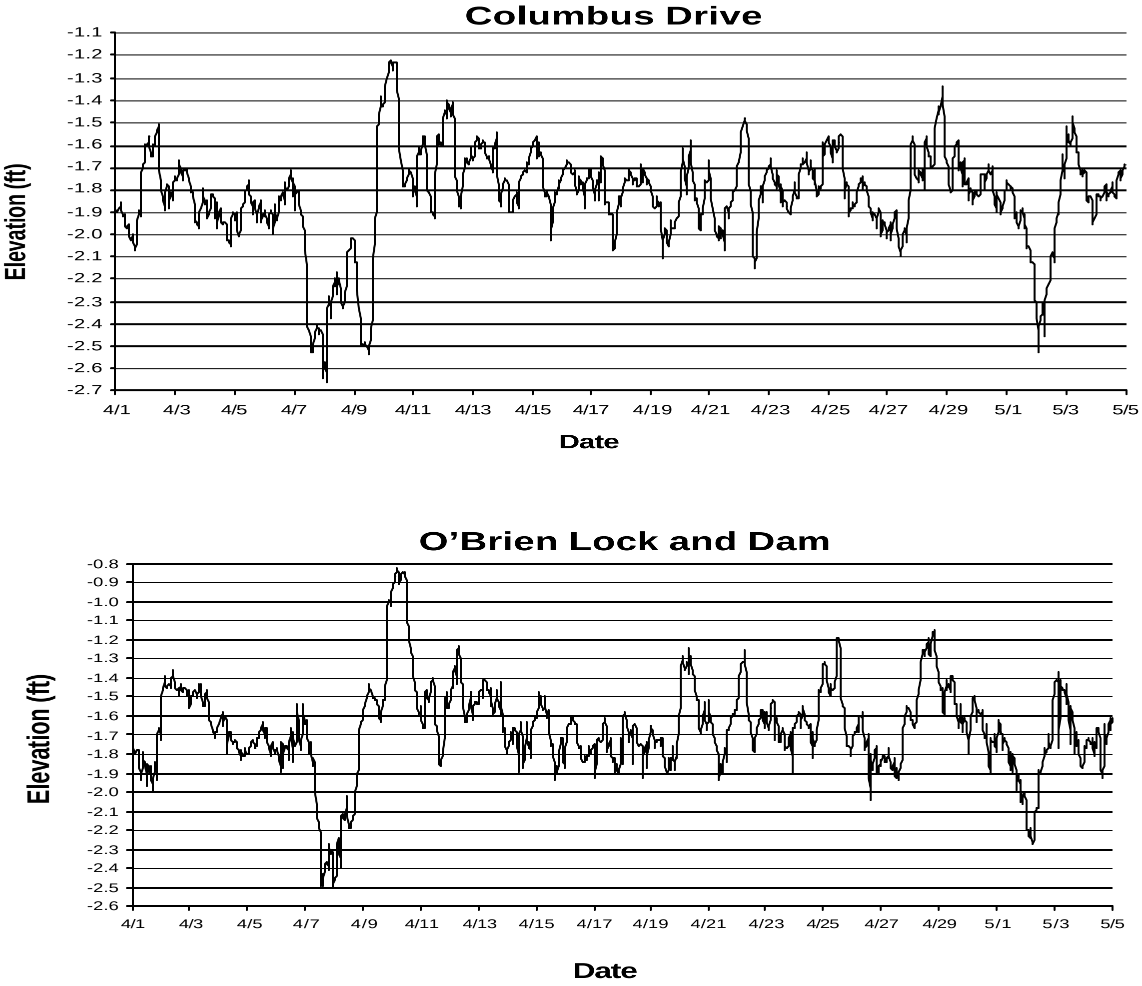


Figure 12 - Water-surface elevations at upstream boundaries to the DUFLOW model of the Chicago Waterway System

To simulate the effects of maintaining water-surface elevations at or greater than –2 ft CCD, the DUFLOW model was run setting the water-surface elevation to –2 ft CCD for those periods when actual water-surface elevations went below –2 ft CCD. The water-quality and hydraulic results of the two scenarios—(1) actual water-surface elevations at the boundaries and (2) water-surface elevations at the boundaries held to –2 ft CCD—then were compared to get an idea of the effect on flow and water quality of allowing water-surface elevations to be less than –2 ft CCD.

There are two significant limitations to this comparison. First, if the upstream boundary conditions were changed relative to the observed case, the observed downstream boundary condition also would change. Therefore, using the observed downstream boundary condition with the hypothetical upstream boundary conditions is incorrect. It was felt that downstream water-surface elevation would be less effected by the changed upstream conditions then would be the downstream flow. The flow must increase because of the increased system-wide slope resulting from higher water-surface elevations at the boundaries. However, the downstream water-surface elevation is more affected by the sluice gate and controlling works settings at Lockport than upstream conditions. Review of 8 large floods on the CWS from 1990 to 2001 showed a very similar pattern in water-surface elevation at Romeoville indicating the dominant effect of the sluice gate and controlling works settings at Lockport. Thus, in the comparison both simulations were done with identical downstream water-surface elevation boundary conditions.

Second, in the simulations the sluice gates would be open at both Lockport and CRCW and O'Brien. In real operations, if a storm failed to occur or was smaller than expected, the MWRDGC would close the sluice gates and controlling works at Lockport, and if this was not sufficient to maintain adequate water levels at the lake front, the lake front gates would be opened to bring in navigation make up water. Therefore, the scenario where –2 ft CCD is maintained while the gates at Lockport are fully open greatly overstates the amount of navigation make up water that would be withdrawn from the lake under similar actual operating conditions. Because the amount of water withdrawn is overstated the increase in DO concentration resulting from applying the –2 ft CCD limit also will be overstated. Thus, the results of the comparison presented in the following paragraphs are an upper bound on the positive effect on water quality of maintaining the –2 ft CCD regulation.

The changes in flow at the lake front controlling structures resulting from maintaining water-surface elevations at or above –2 ft CCD are listed in Table 7 for the April 7-9 and May 1-3 periods. The changes in flows for the April 7-9 period is shown in Figure 13.

Table 7 - Comparison of flows at the lake front controlling structures simulated with the measured water-surface elevations (calibrated model) and the water-surface elevations held at –2 ft City of Chicago Datum (scenario = -2ft)

		Columbus		**O'Brien**		**Wilmette**	
		Scenario=-2ft	**Calibrated Model**	**Scenario=-2ft**	**Calibrated Model**	**Scenario=-2ft**	**Calibrated Model**
April 7-9	Average (m^3/s)	16.3	-7.6	9.5	7.9	-3.1	-1.4
May 1-3	Average (m^3/s)	19.7	-4.1	12.8	13.4	1.0	2.0

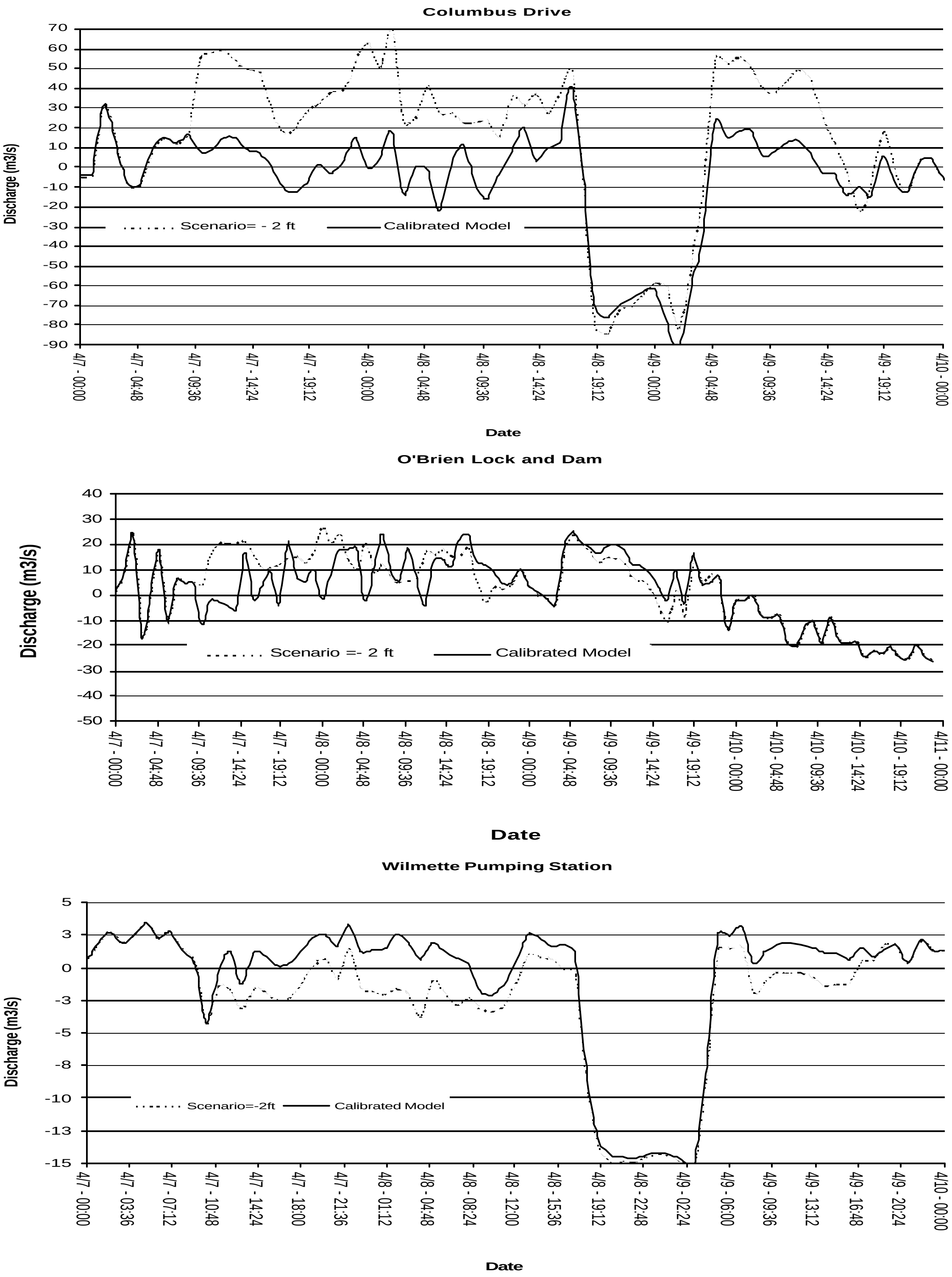


Figure 13 - Comparison of flows at the lake front controlling structures simulated with the measured water-surface elevations (calibrated model) and the water-surface elevations held at –2 ft City of Chicago Datum (scenario = -2ft) for April 7-9, 2002

For the April 7-9 storm, the flow increased 23.9 m^3/s at Columbus Drive and 1.6 m^3/s at O'Brien, and decreased 1.7 m^3/s at the Wilmette Pump Station for a total increase of 23.8 m^3/s (840.5 cfs) because of maintaining the –2 ft CCD water-surface elevation. The duration of the increase is only 63 hrs, and, thus, the total volume of increase is 5,400,000 m^3. For the May 1-3 storm, the flow increased 23.8 m^3/s at Columbus Drive and decreased 1.0 and 0.7 m^3/s at the Wilmette Pump Station and O'Brien, respectively, for a total increase of 22.1 m^3/s (780 cfs) because of maintaining the –2 ft CCD water-surface elevation. The duration of the increase is only 28 hrs, and, thus, the total volume of increase is 2,230,000 m^3.

Figure 14 shows the difference between DO concentrations simulated with water-surface elevations held at –2 ft CCD and with the measured water-surface elevations over the full study period at Romeoville (results for all locations are included in Alp and Melching (2004)). The results at Romeoville illustrate one the most interesting features of the scenario comparison. On the CSSC from the B&O RR to Romeoville, the increased water-surface elevation scenario initially results in lower DO concentrations at the beginning of the April 7-9 and May 1-3 storms. This results because the increased gradient from the lake front to Romeoville causes the poorer quality water discharged from CSOs during the storm to move downstream more quickly initially depressing the DO concentration. After this initial period the higher quality Lake Michigan water reaches these locations and the DO concentration increases relative to the simulation with the measured water-surface elevations at the lake front.

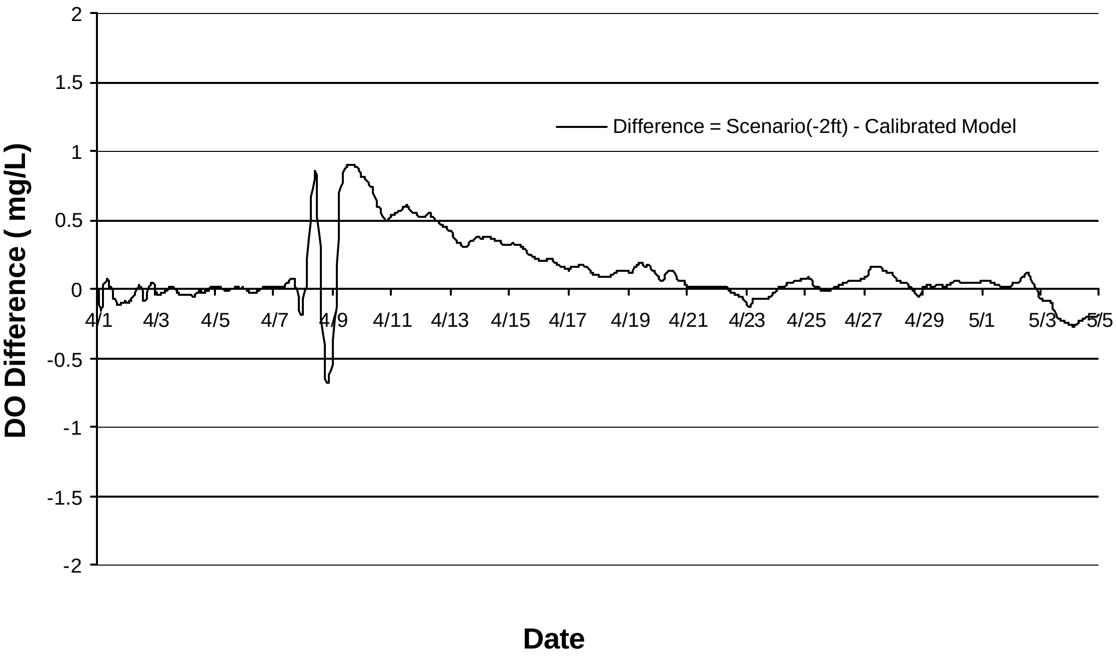


Figure 14 - Difference in dissolved oxygen (DO) concentration on the Chicago Sanitary and Ship Canal at Romeoville between the simulation holding water-surface elevations at the lake front at or above –2 ft City of Chicago Datum and the simulation using observed water-surface elevations at the lake front

Table 8 lists the average change in DO concentration resulting for the April 7-9, 2002, storm comparing the simulation holding water-surface elevations at the lake front at or above –2 ft CCD with the simulation using the observed water-surface elevations. The sequence of DO concentration increases moving down the South Branch to the CSSC and Romeoville was completely expected. The highest increase in inflows from Lake Michigan is at CRCW and this inflow makes up a substantial portion of the flow at Jackson Boulevard. Thus, Jackson Boulevard has the largest DO concentration increase. The DO increase is reduced at Cicero Avenue because of the dilution effects of the Racine Avenue Pump Station flows, and the DO increase is further reduced downstream from the Stickney WRP (B&O RR to Romeoville) because of dilution.

Table 8 - Average change in dissolved oxygen concentration for the April 7-9 storm comparing the simulation holding water-surface elevations at the lake front at or above –2 ft City of Chicago Datum with the simulation using observed water-surface elevations at the lake front

Location	Average	River Mile	Water Course
Addison Street	0	40.3	North Branch Chicago River
Fullerton Avenue	0	38.4	North Branch Chicago River
Division Street	-0.1	36.3	North Branch Chicago River
Kinzie Street	-0.7	34.8	North Branch Chicago River
Jackson Boulevard	2	34	South Branch Chicago River
Cicero Avenue	1.2	26.3	Chicago Sanitary and Ship Canal
Baltimore and Ohio Railroad	0.5	21.3	Chicago Sanitary and Ship Canal
Route 83	0.4	13.1	Chicago Sanitary and Ship Canal
River Mile 11.6	0.4	11.6	Chicago Sanitary and Ship Canal
Romeoville	0.4	5.2	Chicago Sanitary and Ship Canal
Halsted Street	0.3	29.1	Little Calumet River (North)
Division Street	0.2	27.6	Calumet-Sag Channel
Kedzie Avenue	0.2	26.1	Calumet-Sag Channel
Cicero Avenue	0.2	24	Calumet-Sag Channel
Harlem Avenue	0.1	20.7	Calumet-Sag Channel
Southwest Highway	0.2	19.7	Calumet-Sag Channel
Route 83	0.2	13.3	Calumet-Sag Channel

The results of the scenario holding water-surface elevation at or above -2 ft CCD on the Little Calumet River (North)-Calumet-Sag Channel also were expected. Because the inflow at O'Brien was virtually unchanged the DO concentrations throughout the Little Calumet River (North) and Calumet-Sag Channel waterway experienced only minor changes.

The DO concentrations in the upper portion of the North Branch Chicago River were unchanged for the scenario holding water-surface elevation at or above -2 ft CCD. However, DO concentrations at Kinzie Street substantially decreased for the scenario holding water-surface elevation at or above -2 ft CCD. This resulted because the higher water-surface elevations on the Chicago River main stem effectively formed a hydraulic block to flows from the North Branch holding poor quality water in the downstream reaches of the North Branch for a longer time than when the water-surface elevations were allowed to go below -2 ft CCD.

CONCLUSIONS

An unsteady water-quality model for the Chicago Waterway System (CWS) has been calibrated to assist water-quality management and planning decision making. An extensive set of flow, stage, and water-quality data have been used for verification of the previously calibrated hydraulic model and for calibration of the unsteady-flow water-quality model for the CWS for the period of April 1 to May 4, 2002. Hydraulic verification of the previously calibrated hydraulic model (Shrestha and Melching, 2003) was done. Water-surface elevation data at two new stations were used to test the power of the model, and it was observed that the model could predict water levels at all locations with a high accuracy (one to two percent error relative to depth).

Except for locations close to the boundaries (i.e. upstream of WRPs), the simulated DO concentrations agreed well with the observed concentrations. The calibration results showed that reaction rate constants are low during the simulation period and most of the variations in DO result from hydraulic behavior of the system. This result is similar to previous experience with QUAL2EU applied to the CWS (CDM, 1992).

Simulated concentrations of other constituents such as BOD, ammonia, nitrate, among others were compared to the mean and one standard deviation confidence bounds of historic data in order to detect and correct any unusual simulated concentrations. The simulated mean BOD, ammonia, and nitrate concentrations are close to the measured mean concentrations and most of the simulated values are within ± 1 standard deviation of the mean of the long-term measured values.

The model then was applied to evaluate the effect of a change in navigational water levels on the water quality in the CWS. In order to reduce diversions from Lake Michigan allowing water surface elevations at the lake front down to –3 ft CCD during or after a storm is being evaluated (relative to the current requirement to maintain water-surface elevations at or above –2 ft CCD). On April 7-9 and May 1-2, 2002, the MWRDGC was allowed to draw the water-surface elevation at CRCW and O'Brien below –2 ft CCD to determine effects on navigation, water quality, and other features. In order to examine the effect of the intake of navigation makeup water at CRCW and O'Brien on water-quality in the CWS, water-surface elevations below –2 ft CCD at the boundaries were set to –2 ft and DO concentrations were simulated and compared to the results of simulation using measured water-surface elevations at CRCW and O'Brien. Results showed that dissolved oxygen concentrations increased on average by 0.4 mg/L at Romeoville because of navigation make up water at Columbus Drive in the April 7-9 storm event.

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