Impact of Annual Average Discretionary Diversion on Water Quality in the Chicago Area Waterway System

Report Prepared for the Metropolitan Water Reclamation District of Greater Chicago

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Chapter 1 – INTRODUCTION

1.1 Background

The City of Chicago, Illinois, is located at the southern end of Lake Michigan, the fifth largest freshwater lake in the world (by surface area) that serves as the water supply for Chicago and surrounding communities. In the 1800s, Chicago built a network of combined sewers to drain stormwater and wastewater from the city to the Chicago River and then to Lake Michigan. During large storms the polluted combined sewer flows would extend far enough into Lake Michigan that they would enter the water supply intakes for Chicago. This contributed to very high levels of death by typhoid fever in Chicago, peaking at more than 170 per 100,000 residents in 1891 (Hill, 2000).

In 1889, the Sanitary District of Chicago (later known as the Metropolitan Sanitary District of Greater Chicago [MSD] and now known as the Metropolitan Water Reclamation District of Greater Chicago [MWRDGC]) was formed by the State of Illinois, and charged with building a canal that would carry flow from the polluted Chicago River away from Lake Michiganthrough the low continental divide west of Chicago to the Des Plaines River, Illinois River, and ultimately the Mississippi River (Lanyon, 2012). In 1892 construction began and in 1900 the Chicago Sanitary and Ship Canal (CSSC) was opened to reverse the flow of the Chicago River, thus, diverting the wastewater and combined sewer overflows from Chicago away from Lake Michigan and toward the Mississippi River. Two additional channels were later opened to improve water quality in the Chicago area: (1) the North Shore Channel(NSC, completed 1910) to flush water of poor quality from theNorth Branch Chicago River (NBCR) and (2) the Calumet-Sag Channel (completed 1922) to divert the Calumet River away from Lake Michigan. The lower portion of the NBCR, South Branch Chicago River (SBCR), Chicago River main stem, Calumet River, and Little Calumet River (north) also have been widened, deepened, and straightened to efficiently carry treated wastewater away from Lake Michigan.

The system of constructed and altered waterways described previously is known as the Chicago Area Waterway System (CAWS). In total, the CAWS is a 76.3 mi branching network of navigable waterways controlled by hydraulic structures in which the majority of flow is treated sewage effluent and there are periods of substantial combined sewer overflows (CSOs). The dominant uses of the CAWS are conveyance of treated municipal wastewater, commercial navigation, and flood control. The CAWS receives pollutant loads from 3 of the largest wastewater treatment plants in the world, nearly 240 gravity CSOs, 3 CSO pumping stations, eleven tributary streams or drainage areas, and direct diversions from Lake Michigan. The water quality in the CAWS also is affected by the operation of five Sidestream Elevated Pool Aeration (SEPA) stations and two in-stream aeration stations (IASs). The Calumet River and Chicago River systems are shown in Figure 1.1.

The operation of the CAWS has been a great public health success for the Chicago area (Hill, 2000; Lanyon, 2012), but the CAWS has been a source of intense litigation between Illinois and the Great Lakes states. In 1901, the MSD was authorized by the Secretary of War to divert 4,167 cfs for dilution of pollution and navigational purposes in addition to pumpage for domestic water supply. In 1908 and again in 1913, the United States (at the urging of the other Great Lakes states) brought actions to enjoin the MSD from diverting more than the 4,167 cfs previously authorized in 1901. The two actions were consolidated, and the Supreme Court entered a Decree on January 5, 1925, allowing the Secretary of War to issue diversion permits. In March 1925, a permit was issued to divert 8,500 cfs in addition to pumpage for domestic water supply, which was about the average diversion then being used.

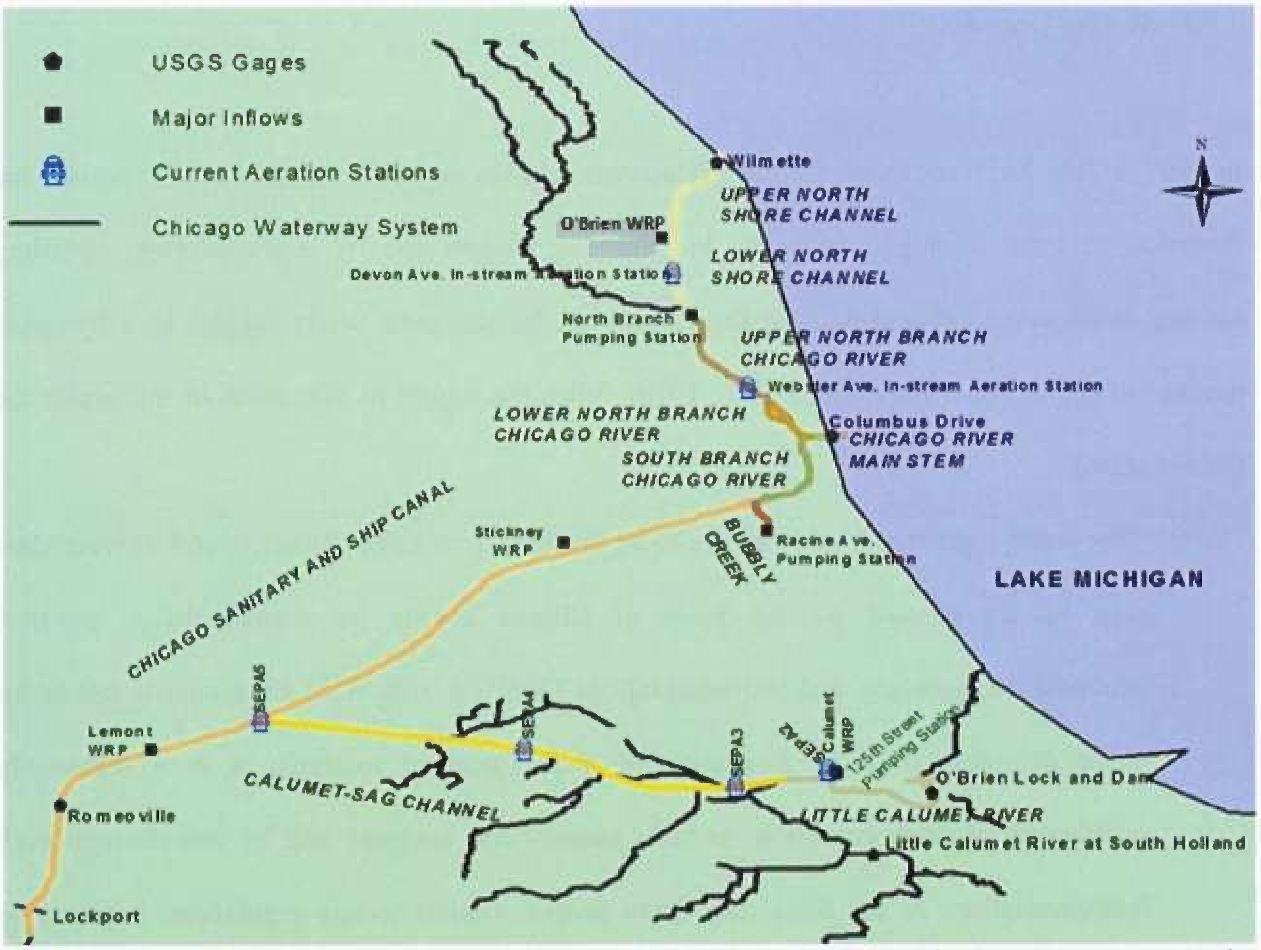


Figure 0.1. Schematic diagram of the Calumet and the Chicago River Systems (note: the upstream U.S. Geological Survey gages compose the upstream boundaries of the simulation model)

In 1922, 1925, and 1926, several Great Lakes states filed similar original actions in the U.S. Supreme Court seeking to restrict diversion at Chicago. A Special Master, appointed by the

Court to hear the combined suits, found the 1925 permit to be valid and recommended dismissal of the action. The Supreme Court reversed his findings and instructed the Special Master to determine the steps necessary for Illinois and the MSD to reduce diversion. Consequently, a 1930 Supreme Court Decree reduced allowable diversion (in addition to pumpage for domestic water supply) in three steps: 6,500 cfs after July 1, 1930; 5,000 cfs after December 30, 1935; and 1,500 cfs after December 31, 1938.

In 1967, a U.S. Supreme Court Decree (Wisconsin v. Illinois, 388 U.S. 426 (1967)) limited the diversion of Lake Michigan water by the State of Illinois and its municipalities, including sewage and sewage effluent derived from pumpage for domestic water supply, to a five-year average of 3,200 cfs, effective March 1, 1970. With the regard to allocation of this water the Decree stated:

> "The water permitted by this decree to be diverted from Lake Michigan and its watershed may be apportioned by the State of Illinois among its municipalities, political subdivisions, agencies, and instrumentalities [388 U.S. 426, 428] for domestic use or for direct diversion into the Sanitary and Ship Canal to maintain it in a reasonably satisfactory sanitary condition, in such manner and amounts and by and through such instrumentalities as the State may deem proper, subject to any regulations imposed by Congress in the interests of navigation or pollution control."

In 1977, the Illinois Department of Transportation-Division of Water Resources (IDOT-DWR, 1977) apportioned 320 cfs of Lake Michigan water for discretionary dilution for maintenance of water quality in the CAWS for 1979 and 1980. This amount was determined through a combination of modeling results obtained by Harza Engineering Company (Harza, 1976b) and the MSD (1976) as described in Section 1.2. IDOT-DWR (1980) then extended the 320 cfs limit for application for 1981 to 1999 and reduced the limit to 101 cfs for 2000 to 2020. The 101 cfs is representative of conditions with a system of 9 instream aeration stations and the Tunnel and Reservoir Plan (TARP) Phase I (i.e. the tunnels) operational as determined by Harza (1976b) and modified as per IDOT-DWR (1977).

In 2000, the Illinois Department of Natural Resources-Office of Water Resources (IDNR-OWR, 2000) set the limit for discretionary diversion to 270 cfs for Water Years (WYs) 2000 to 2014 (note: the water year is the period from October 1 to September 30 with the year designated by the closing date). IDNR-OWR (2000) then set the limit for discretionary diversion to 101 cfs for WYs 2015 to 2020. In changing the standard for WY 2000 from 101 cfs as per IDOT-DWR (1980), IDNR-OWR (2000) stated "The allocation for discretionary dilution will be increased from 101 cfs to 270 cfs until 2015 when the Tunnel and Reservoir Plan (TARP) is expected to be completed." IDNR-OWR (2000) further noted "If circumstances such as the completion of TARP or problems with significant exceedances of water quality standards occur, a proceeding for modification may need to occur." In Paragraph 14.610 on "Future Modifications," IDOT-DWR (1980) states:

> "Section 820.310 of the Rules provides that any entity may request a modification at any time. Section 820.310 (b) provides that modifications will be based on changes in circumstances … notification from IEPA that completion of pollution abatement facilities or a change in water quality standards prompts a hearing so that the Department can consider a change."

In 2007, the Illinois Pollution Control Board (IPCB) began considering Rule R08-9 proposed by the Illinois Environmental Protection Agency (IEPA, 2007) for an upgrading of the water quality standards for the CAWS.The IPCB divided Rule R08-9 into 4 subdockets: 1) Subdocket A dealt with the issues related to recreational use designations, 2) Subdocket B addressed issues relating to disinfection and whether or not disinfection may or may not be necessary to meet those use designations, 3) Subdocket C addresses the issues related to aquatic life use designations, and 4) Subdocket D addresses the issues dealing with water quality standards and criteria that are necessary to meet the aquatic life use designations (IPCB, 2014). On February 21, 2014, the IPCB added Subdocket E to Rule R08-9 to examine issues surrounding the South Fork of the South Branch of the Chicago River (commonly known as Bubbly Creek). The maintenance of adequate dissolved oxygen (DO) concentrations in the CAWS is the focus of the use of discretionary diversion flows. Thus, Subdockets C and D of Rule R08-9 are directly related to the discretionary diversion flows. Subdocket C was published by the IPCB (2014) on February 6, 2014, while Subdocket D isbeing finalized by the IPCB. Because the TARP will not be completed by WY 2015 and the State is changing water quality standards it is proper that a change in the discretionary diversion limit for WY 2015 and beyond should be considered.

1.2 Previous Water-Quality Modeling Studies of the CAWS

There have been several studies involving simulation of the water quality in the CAWS and the Upper Illinois River in the past. The earliest model was developed by the MWDRGC in the early 1970s to evaluate the effluent discharge standards being developed by the IPCB for the three major Water Reclamation Plants (WRPs)—O'Brien, Stickney, and Calumet—discharging to the CAWS. This model was anextension of the classical Streeter-Phelps model (Streeter and Phelps, 1925) to account for benthal demand (i.e. Sediment Oxygen Demand, SOD) (MSD, 1976). The benthic loadings were determined by calibration and considered in the model by two mechanisms: an areal average oxygen demand and a biochemical oxygen demand (BOD) contribution to the overlying water (MSD, 1976). The model was originally calibrated to the DO profiles from monthly averages for two time periods: April-May 1961 and August 1961.The District found that even using tertiary treatment at the WRPs the IPCB's 1973 DO standards for the CAWS could not be met, and so they proposed an alternative approach of intermediate tertiary treatment augmented by instream aeration in exchange for less stringent DO standards in the discharge permits for the WRPs (MSD, 1976; Macaitis et al., 1975). This extended Streeter-Phelps model then was recalibrated and verified for conditions in 1973 and applied to determine the appropriate levels of discretionary diversion to meet the IPCB's 1977 DO standards for the CAWS for flow conditions in 1980 for the case of the intermediate tertiary treatment and instream aeration operational (MSD, 1976). The Streeter-Phelps model is a steady-state model that is unable to consider flow variations in the CAWS. Thus, to determine the annual discretionary diversion requirement the model was run four times for flows and temperatures representative of the different seasons of the year and the seasonal amounts of discretionary diversion were adjusted and combined to obtain the annual total. The adjustment to the seasonal values was applied to account for only the dry weather flow days because the MWRDGC does not take discretionary diversion during wet weather.

In the mid-1970s, the Illinois Department of Transportation, Division of Water Resources contracted with Harza Engineering Company to develop a water-quality model of the CAWS to have an independent evaluation of the discretionary diversion needed to meet the IPCB's 1977 DO standards for the CAWS (Harza, 1976a). Harza applied the QUAL-II model (Water Resources Engineers, 1974) and in this model, as was the case for the MWRDGC's extended Streeter-Phelps model, the primary factors affecting DO in the CAWS were taken as carbonaceous BOD (CBOD) and benthic demand (SOD). In both studies the nitrogenous BOD was considered to be negligible in the CAWS and more of a problem for the Upper Illinois River. DO data from 1971, 1973, and 1974 were used to calibrate the QUAL-II model.In evaluating the need for discretionary diversion the Harza study considered the case of the intermediate tertiary treatment and instream aeration operational, and then the cases of Phase I (the tunnels) of TARP and Phase II (the reservoirs) of TARP completed. These evaluations were done for the case of the 7-day, 10-year low flows in the CAWS. As was the case in the MWRDGC model, temperature was not modeled, but rather input reach by reach using actual temperature data for the CAWS. The QUAL-II model is a steady-state model that is unable to consider flow variations in the CAWS. Thus, to determine the annual discretionary diversion requirement the model was run four times for flows and temperatures representative of the different seasons of the year and the seasonal amounts of discretionary diversion were adjusted and combined to obtain the annual total. the adjustment to the seasonal values was applied to account for only the dry weather flow days because the MWRDGC does not take discretionary diversion during wet weather.

In the late-1970s, the Illinois Department of Transportation, Division of Water Resources contracted with Keifer Engineering to evaluate all aspects of the Lake Michigan Diversion (IDOT-DWR, 1980). As part of this study, Keifer also applied QUAL-II to have another independent evaluation of the discretionary diversion needed to meet the IPCB's 1977 DO standards for the CAWS (Keifer, 1980). Keifer's application of the QUAL-II model was similar to that done by Harza, i.e. the primary factors affecting DO in the CAWS were taken as CBOD and benthic demand (SOD) and the nitrogenous BOD was considered to be negligible in the CAWS. Keifer calibrated their QUAL-II model to data from July 5, 1977, and June 20, 1978. Keifer (1980) then evaluated the discretionary diversion needed to meet the IPCB's 1977 DO standards for a variety of combinations of aeration stations and existing conditions (for 1980), TARP Phase I completed, TARP Phase I plus advanced waste treatment, and TARP Phase II plus advanced waste treatment. The Keifer (1980) model results indicated that 50 cfs of discretionary diversion would be sufficient to meet the IPCB's 1977 DO standards for the CAWS for the case of TARP Phase I completed and the instream aeration stations installed.

IDOT-DWR (1977) then determined the allowable discretionary diversion for 1980 as 320 cfs through a combination of the results obtained from the Harza (1976b) and MWRDGC (MSD, 1976) models. IDOT-DWR (1977) also determined that the demand for discretionary diversion will decrease to 101 cfs after the completion of TARP Phase I on the basis of the results obtained from the Harza (1976b) model. IDOT-DWR (1980, p. 55) rejected the results of the Keifer study noting:

> "The Department believes that it would not be prudent to limit discretionary dilution to 50 cfs after the year 2000. Too many of the assumptions and values contained in the modeling may be changed as additional pollution abatement facilities come on line and new data is generated."

Thus, IDOT-DWR (1980) reverted to the results of their 1977 allocation of discretionary diversion, stating "the Department believes that allocations of 101 cfs for discretionary dilution in 2000, 2010 and 2020 reflects a reasonable balance between the available alternatives." In Chapter 5, a discussion of the assumptions in the Harza (1976a, b) model is presented to evaluate the differences in performance for annual total discretionary diversion amounts of 101 and 270 cfs (and values in between) determined using a model that takes into account the performance of the actual pollution abatement facilities installed between 1977 and the present and the new data collected during this period.

Other major studies have included the study done in response to Section 208 of the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) by Hydrocomp, Inc. (1979a and b) for the Northeastern Illinois Planning Commission (Hey et al., 1980) and a modeling study done by Camp, Dresser & McKee (CDM, 1992) for the MWRDGC. CDM (1992) used QUAL2EU (Brown and Barnwell, 1987) to simulate dissolved oxygen (DO) on the Chicago Waterway and Upper Illinois River. This QUAL2EU model was used by the MWRDGC throughout the 1990s for water-quality management in the CAWS.

By 1998 the MWRDGC knew they would 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 CAWS, the development of total maximum daily load allocations, among other issues (Lanyon and Melching, 2001). Thus, in August 1998 they installed a network of 20 continuous DO and temperature measurement sondes throughout the CAWS (mainly on the Chicago River system).

In July 2001 an additional 12 measurement sondes were added to the Calumet River system. From 1998 to the present the number of sondes in the network has increased and decreased such that 13 were still active in 2011 and 32 were active for all or part of WY 2003. These sondes provide hourly temperature and DO data that could be used to calibrate and verify a new water-quality model for the CAWS. Because of the dynamic nature of the CAWS the available QUAL2EU model was considered inadequate to evaluate the previously mentioned management issues and their impact on water quality in the CAWS. A model capable of simulating hydraulics and water-quality processes under unsteady-flow conditions was needed to assist the MWRDGC in water-quality management and planning decision making processes.

In 2000, a number of models were available for simulation of water quality under unsteady-flow conditions. Some models had been developed by U.S. government agencies, for example, the Water-Quality Analysis and Simulation Program Version 5 (WASP5, Ambrose et al., 1993), developed by the U.S. Environmental Protection Agency (USEPA) and the Branched Lagrangian Transport Model (BLTM, Jobson and Schoellhamer, 1987; Jobson, 1997), developed by the U.S. Geological Survey (USGS). The water-quality capabilities of these models are quite robust. However, the hydrodynamic portions of these models were less efficient in 2000. The hydrodynamic model suggested for coupling with WASP5 had a history of not performing well for one-dimensional unsteady flows in river systems. BLTM requires the development of a separate hydrodynamic model for the river system, and the computed stages and velocities must be transformed from the hydrodynamic-model output to the water-quality model input.

The DUFLOW Model (DUFLOW, 2000) was jointly developed in The Netherlands by the Rijkswaterstaat, International Institute for Hydraulic and Environmental Engineering of the Delft

University of Technology, STOWA (Dutch acronym for the Foundation for Applied Water Management Research), and the Agricultural University of Wageningen. DUFLOW was considered a reasonable alternative to WASP (in fact, it included an option to use the WASP4 (Ambrose et al., 1988) routines to compute water-quality in the water column) and BLTM. DUFLOW has been applied with great success to several European river systems (e.g., Manache and Melching, 2004). In the study of Manache and Melching (2004), DUFLOW was found to be computationally robust with few computational failures encountered over thousands of runs. It allows several options for the simulation of water quality in stream systems, including allowing the user to add relations for the simulation of additional water-quality properties or constituents not originally included in the preprogrammed DUFLOW options. Finally, DUFLOW's compatibility with Geographical Information Systems (GIS) facilitated representation and display of the river system, its compatibility with Microsoft Windows facilitated ease of use and the import and export of input and results to and from Microsoft Excel, and its relatively low license cost made it affordable for many applications. Given these capabilities and advantages, DUFLOW was selected for modeling of the CAWS, and the MWRDGC entered into an agreement with Marquette University in 2000 to adapt the DUFLOW model for simulation of the hydraulics and water-quality processes of the CAWS. In the first several years of the adaptation of the DUFLOW model for the CAWS the MWRDGC convened an ad-hoc committee of representatives from government agencies in Illinois—USEPA, Region 5; U.S. Army Corps of Engineers, Chicago District (USACE); USGS, Illinois District; Illinois Department of Natural Resources-Office of Water Resources (IDNR-OWR); and IEPA—to keep these agencies informed of and to get their input on the development of the model.

To simulate water quality in the CAWS the DUFLOW water-quality simulation option that adds the DiToro and Fitzpatrick (1993) sediment flux model to the WASP4 (Ambrose et al., 1988) model of constituent interactions in the water column is applied. DUFLOW distinguishes among transported material that flows with water, bottom materials that are not transported with the water flow, and pore water in bottom materials that are not transported but that can be subject to similar water-quality interactions to those for the water column. Flow movement and constituent transport and transformation are simulated within DUFLOW and constituent transport is defined by advection and dispersion. The flow simulation in DUFLOW is based on the one-dimensional(1-D) partial differential equations that describe unsteady flow in open channels (de Saint-Venant equations). These equations are the mathematical translation of the laws of conservation of mass and momentum.

Marquette University has successfully applied the DUFLOW water-quality model to the CAWS for several purposes: i) Alp and Melching (2004) used the DUFLOW model to investigate the possible effects of a change in navigational water level requirements and the navigation make-up diversion of water from Lake Michigan during storm events on water-quality in the CAWS, ii) Neugebauer and Melching (2005) developed a method to verify the calibrated DUFLOW model under uncertain storm loads, iii) Manache and Melching (2005) applied the DUFLOW model to simulate fecal coliform concentrations in the CAWS under unsteady flow conditions; iv) Alp and Melching (2006) evaluated the effectiveness of flow augmentation, supplemental aeration, and CSO treatment acting individually to improve DO conditions in the CAWS; v) Melching et al. (2010, 2013) developed integrated strategies that combined flow augmentation and supplemental aeration in the CAWS so that the simulated DO concentrations equaled or exceeded various proposedDO standards for the CAWS; and vi)Melching and Liang (2013) applied the DUFLOW model to simulate the effects of ecological/hydrological separation of the Great Lakes and Mississippi River watersheds in the CAWS on water quality in the CAWS and loads to Lake Michigan as part of the USACE Great Lakes and Mississippi River Interbasin Study (GLMRIS).

The hydraulic component of the DUFLOW (2000) unsteady-flow model for the CAWS was calibrated and verified by Marquette University in 2003. The ability of the model to simulate unsteady flow conditions was demonstrated by comparing the simulation results to measured data for eight different periods between August 1, 1998 and July 31, 1999 (Shrestha and Melching, 2003). The DUFLOW water-quality model was calibrated and verified (Alp and Melching, 2006; Neugebauer and Melching, 2005) for the periods of July 12 to November 9, 2001 and May 1 to September 23, 2002, respectively. After these initial calibrations and verifications, the DUFLOW hydraulic and water-quality models were calibrated and verified in more detail for the full 2001 and 2003 WYs by Melching et al. (2010).

1.3 Project Objective and Scope

In the original allocation of water diverted from Lake Michigan for discretionary dilution of pollution in the CAWS, IDOT-DWR (1977) found "an analysis of dissolved oxygen levels to be an adequate indicator of water quality." In this study, the DUFLOW model of the CAWS, described in Section 1.2 and detailed in Chapter 2, is applied to determine the percentage of time with simulated DO concentrations equaling or exceeding the DO standards for the CAWS proposed by the IEPA to the IPCB in 2007(as modified in Subdocket C (IPCB, 2014), see

Chapter 4). Specifically a representative year will be evaluated for the cases of (a) the current conditions, (b) the Thornton Reservoir operational (in 2015), and (c) the Thornton and McCook Stage 1 reservoirs operational (in 2017).The system-wide percentage of time with simulated DO concentrations equaling or exceeding the DO standards proposed by the IEPAis evaluated for "optimal" allocations of average annual discretionary diversion amounts of 270 and 101 cfs, i.e. the current and proposed future (WY 2015) annual limits, respectively, for the representative year. Several annual average diversion amounts between 101 and 270 cfs also will be evaluated to inform the discussion between the IDNR-OWR, MWRDGC, and other interested parties regarding the appropriate annual discretionary diversion limit during the period of transition from no reservoirs being operational (i.e. current conditions) to two reservoirs being operational.

1.4 Selection of Representative Year for Evaluation of Discretionary Diversion Requirements

Representative "wet", "dry", and "normal" years were selected in order to be sure that the water-quality effects of the hydrological separation of the Great Lakes and Mississippi River basins in the CAWS could be determined over a reasonable range of hydrologic conditions as part of GLMRIS (Melching and Liang, 2013). These years were selected from the water yearsbetween 1997 and 2010 because hourly WRP flows are no longer available prior to WY 1997. Also, the continuous temperature and DO monitors on the CAWS first began collecting data in August 1998. Thus, in order to verify the model performance for the selected years and make adjustments, if necessary, Water Years 1999 to 2010 were potential candidate years in the GLMRIS modeling study (Melching and Liang, 2013).

The representative "wet", "dry", and "normal" years for the GLMRIS study were selected as WY 2008, WY 2003, and WY 2001, respectively. Because there is no representative flow data for the CSO drainage area to the CAWS, precipitation data and CSO pump station operation data (from 1993 to 2012, i.e. 20 years) were used to select the representative "wet", "dry", and "normal" years (Melching and Liang, 2013). To give a long-term perspective, precipitation data from the National Weather Service for O'Hare Airport (since WY 1963) and Midway Airport (since WY 1951) were considered through WY 2012. To give an area-wide perspective the average precipitation measured at the 25 precipitation gages spread over the CSO drainage area in Cook County established by the USACE and operated by the Illinois State Water Survey (ISWS) for use in the Lake Michigan Diversion Accounting (since WY 1990) were also considered through WY 2012.

For this study of the optimal allocation of discretionary diversion of water from Lake Michigan for water quality improvement in the CAWS only one year could be fully evaluated due to time limitations. The representative "dry" year, WY 2003, from the GLMRIS study was selected for evaluation of the optimal withdrawal of discretionary diversion flows from Lake Michigan. The goal of selecting representative years in the GLMRIS study was to be in the top (or bottom) quartile of years, but not being the wettest or driest year. WY 2003 ranks as the fifth smallest CSO volume at the pumping stations among 20 years (lower 25%) and it ranks in the lower 16% of years in terms of precipitation at O'Hare Airport and Midway Airport and the lower 10% for the ISWS network (i.e. third smallest).

The original annual limits on discretionary diversion (IDOT-DWR, 1977, 1980) relied on the Harza (1976a, b) modeling of the CAWS in which the 7-day, 10-year low flow conditions were applied. Thus, a focus on drier periods has precedence in discretionary diversion evaluations. Further, in actual operations, dry years have required more discretionary diversion to maintain adequate water-quality conditions than wetter years. This is because drier years tend to be warmer which stresses the DO resources of the CAWS and at the same time the tributary flows are lower providing less water to mix with the treated wastewater discharged to the CAWS.The lower flows also result in slower moving water that is more subject to the impact of SOD and the longer residence time of pollutants in the various river reaches yields greater DO consumption in these reaches. For example, WY 2005 was probably the driest year in the last 60 years (Melching and Liang, 2013) and it required the third highest discretionary diversion (284.69cfs) during the period of 1998 to 2010. WY 2003 required the second highest discretionary diversion (290.81cfs) during the period of 1998 to 2010.Further, considering the rainfall data at Midway and O'Hare airports, WY 2003 might be around the 6^{th} driest year in the last 60 years conforming to the 10-year low flow concept. Thus, selection of the representative "dry" year from the GLMRIS study (WY 2003) for evaluating the percentage of time withsimlated DO concentrations equaling or exceeding the DO standards for various amounts of discretionary diversion is consistent with the original determination of the discretionary diversion limits that considered the 7-day, 10-year low flow.

Whereas WY 2003 represents an approximation of the 10-year "dry year" and, thus, presents a rigorous test of the need for discretionary diversion to maintain water quality it does not compose a "worst-case" scenario that might overestimate the need for discretionary diversion.

Selection of WY 2005, the driest year in the last 60 years, would represent a "worst case" for maintaining adequate water quality during dry weather periods.

If maintaining the CAWS "in a reasonably satisfactory sanitary condition" as per the 1980 U.S. Supreme Court Decree is defined as DO concentrations greater than or equal to the DO standards at a high percentage of time at all locations throughout the CAWS, then performance during wet weather periods also becomes important. In the original determination of the maximum allowable allocation of discretionary diversion (IDOT-DWR, 1977, 1980) only dry weather periods were considered because the MWRDGC only withdrew discretionary diversion on dry weather days because of concern that this might compound flooding and promote flow reversals to Lake Michigan. The MWRDGC still follows this practice of not withdrawing discretionary diversion during wet weather, however, with the TARP tunnels now completed the definition of wet weather has changed with smaller storms not affecting diversion withdrawals. This is consistent with the assumptions of Harza (1976a, b) and IDOT-DWR (1977) that combined sewer overflow events will no longer restrict the use of discretionary diversion after the completion of Phase I of TARP.Considering recovery of low DO concentrations after wet weather, even a "normal" runoff year like WY 2001, would likely require more discretionary diversion than WY 2003 just as WY 2001 required more aeration resources than WY 2003 in the Use Attainability Analysis reported in Melching et al. (2010, 2013). Thus, WY 2003 provides a rigorous test of the need for discretionary diversion, but it does not represent an overly conservative estimate of the needed discretionary diversion.

1.5 Report Organization

In Chapter 2, the verification of the hydraulic and water-quality (i.e. DO) simulation ability of the DUFLOW model of the CAWS for WY 2003 is summarized from information contained in Melching et al. (2010). In the consideration of current and future hydraulic and water quality conditions applied to the hydrologic and wastewater flows of WY 2003, changes in temperature will result because of the closure of the Fisk and Crawford power plants and of Units 1 and 2 of the Will County Power Plant and CSO flows will change as the Thornton and McCook Stage 1 reservoirs become operational in 2015 and 2017, respectively. These flow and temperature changes are summarized in Chapter 3. The DO standards applied to the CAWS in this study, the definition of system-wide performance relative to these standards, and the procedure for the optimal allocation of discretionary diversion are described in Chapter 4. The results of this study and a discussion of the causes for the substantial differences in the system-wide performance found in this study compared to the original modeling of the CAWS done by the MSD (1976) and Harza (1976a, b) are presented in Chapter 5. Finally, the conclusions of this study are presented in Chapter 6.

Chapter 2 – MODEL VERIFICATION

The equations used in the DUFLOW model to simulate DO, ammonium, nitrate/nitrite, organic nitrogen, CBOD, total phosphorus, and chlorophyll a are given in DUFLOW (2000) and are not repeated here. The assumptions regarding the concentrations of these constituents in the inflows to the CAWS from Lake Michigan, tributary streams and rivers, and combined sewer overflows are described in Melching et al. (2010) and Neugebauer and Melching (2005) and are summarized in this chapter. The assumptions regarding the DO loads from theIASs andSEPA stations are described in Melching et al. (2010) and Alp and Melching (2004) and are summarized in this chapter. The calibration and verification quality of the DUFLOW model in the simulation of flow hydraulics and DO, CBOD, ammonium, nitrate/nitrite, chlorophyll a, and sediment oxygen demand for WYs 2001 and 2003 are presented in Melching et al. (2010) and for WY 2008 are presented in Melching and Liang (2013). The verification of the DUFLOW model for simulation of flow hydraulics and DO concentrations for WY 2003 are presented in this chapter to demonstrate the accuracy and usefulness of the model for WY 2003 before applying it to evaluate the optimal allocation of discretionary diversion presented in Chapter 5.

2.1 Hydraulic Model Input, Assumptions, and Verification

The DUFLOW unsteady-flow model for the CAWS was calibrated and verified by the Institute for Urban Environmental Risk Management, Marquette University in 2003. The ability of the model to simulate unsteady flow conditions was demonstrated by comparing the simulation results to measured data 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 USGS, and using daily flow data collected by the USGS near the Chicago River Controlling Works (CRCW) and O'Brien Lock and Dam upstream boundaries.

The previously calibrated hydraulic model of Shrestha and Melching (2003) has been verified for many periods: July 12 to November 9, 2001 by Alp and Melching (2006), May 1 to September 24, 2002 by Neugebauer and Melching (2005), WYs 2001 and 2003 by Melching et al. (2010), and WY 2008 by Melching and Liang (2013). In this chapter the verification for WY 2003 is documented. Also in this chapter the inputs and assumptions used in the DUFLOW model for WY 2003 are documented in the following sections.

2.1.1 Temporal and Spatial Distribution of CSO Inputs

In the earliest applications of the DUFLOW Model of the CAWS (e.g., Shrestha and Melching, 2003; Neugebauer and Melching, 2005; Alp and Melching, 2006) the inflows from gravity CSOs were estimated as follows. During storm events, the measured and estimated (for ungaged tributaries) inflows were insufficient for simulated water-surface elevations at Romeoville to match the measured water-surface elevations when flow at Romeoville was the downstream boundary condition. If the simulated water-surface elevation is substantially below the observed value, the hydraulic model is artificially dewatering the CAWS in order to match the observed flow at Romeoville indicating that the CAWS is receiving insufficient inflow without considering the gravity CSOs. Thus, gravity CSO volume (starting with the volume imbalance between measured outflows at Romeoville and measured and estimated inflows) was added until reasonable water-surface elevations were simulated at Romeoville. This gravity CSO volume was added at the representative CSO inflow locations on a per area basis at the time of operation of the Racine Avenue Pumping Station.

The estimated gravity CSO volumes yielded excellent hydraulic results for all periods considered (Shrestha and Melching, 2003; Neugebauer and Melching, 2005; Alp and Melching, 2006). However, the percentage of impervious area varies substantially throughout the CAWS watershed and the rainfall varies substantially throughout the CAWS watershed and among events. Thus, the runoff and related pollutant loads must vary throughout the CAWS watershed on more than a per area basis, and the time distribution of CSO flows is not uniform and may be longer or shorter than the operation hours of the Racine Avenue Pumping Station. Thus, simulations of flows, loads, and water-quality conditions could potentially be improved if the CSO discharges could be reliably modeled. Thus, CTE (2007) suggested that "The certainty in CSO and pump station volumes could be improved through the development of a collection system model." and "Identifying locations where CSO discharges are more frequent is the first step to improve the CSO volume input in the model."

Currently the rated pump capacities and pump on-and-off times are used to develop an hourly time series of pumping station flows. The estimated accuracy of calculating pump station discharges with this methodology is 1 or 2 percent of the exact volume from on-and-off times and rated pump capacities. A collection system model is unlikely to improve the certainty of estimating actual pump station volumes because of the various rules that are used to operate each station and hydraulic losses that occur during discharge.

Theuse of the results from a collection system model did improve the spatial and temporal distribution of the estimated gravity CSOs. For the purposes of the design of TARP the USACE developed a series of models to simulate the surface and subsurface runoff in the TARP drainage area (which includes the CAWS watershed); the flows in the major interceptors; the distribution of the flows to the WRPs or potentially to gravity CSO outfalls or TARP drop shafts; and the flows in the TARP tunnels. These models are run by the USACE for each water year in support of the Lake Michigan Diversion Accounting. The gravity CSOs simulated by these models during the months in which water from the CAWS flowed to Lake Michigan at Wilmette and/or the Chicago River Controlling Works were obtained by Marquette University from the UASCE for 1990 through 2002 as part of the project "Evaluation of Procedures to Prevent Flow Reversals to Lake Michigan from the Chicago Waterway System" for the MWRDGC (Alp and Melching, 2008). Evaluations for events in 2001 and 2002 of simulated water-surface elevations in the CAWS for the case of gravity CSO flows from the USACE models and pumping station flows from the operation records have yielded reasonable results throughout the CAWS in comparison to the results for the original input to the DUFLOW Model of the CAWS (Alp and Melching, 2008). Hence simulated gravity CSO flows obtained from the USACE are used in the DUFLOW simulations to identify an optimal allocation of discretionary diversion from Lake Michigan as they were used to determine an integrated strategy for DO improvement in the CAWS (Melching et al., 2010, 2013) and to determine the water-quality effects of hydrologic separation of the Great Lakes and Mississippi River basins (Melching and Liang, 2013). Detailed discussion of the USACE models (a combination of the Hydrological Simulation Program-Fortran, Special Contributing Area Loading Program, and Tunnel Network Model) is given in Espey et al. (2004).

2.1.2 Representative Gravity CSO Locations

There are nearly 240 gravity CSOs in the modeled portion of the CAWS watershed. Since it is difficult to introduce all CSO locations in the modeling, in the DUFLOW model of the CAWS, 43 representative CSO locations were identified and flow distribution was done on the basis of the drainage areas for each of these locations. Table 2.1 lists the locations of each of the representative CSOs. On the NSC, the representative CSO locations are the actual TARP drop shaft locations (with some minor aggregation) denoted by the prefix MDS (Mainstream Drop Shaft). The non-CSO flows in the NSC above the O'Brien WRP are very low, thus, if the CSO locations are aggregated the CSO flows will dominate the upstream flows and lead to an overestimation of the discretionary diversion needed to meet the DO standards. Melching et al. (2010, 2013) used 19gravity CSO locations (shown in Figure 2.1) to represent the 24 TARP drop shaftsdischarging into the NSC the CSO flows were determinedfor these locations using the results of the USACE models.

Table 2.1. Locations of the 43 representative combined sewer overflow (CSO) locations in the DUFLOW model of the Chicago Area Waterway System

CSO Number	River Mile relative to Lockport*	Waterway
MDS 115-116	49.6	North Shore Channel
MDS 114	49.2	North Shore Channel
MDS 112	49.0	North Shore Channel
MDS 111	48.7	North Shore Channel
MDS 110	48.5	North Shore Channel
MDS 108-109	48.1	North Shore Channel
MDS 106-107	47.5	North Shore Channel
MDS 105	47.2	North Shore Channel
MDS 104	46.5	North Shore Channel
MDS 103	46.3	North Shore Channel
MDS 102	46.1	North Shore Channel
MDS 101-100-99	45.6	North Shore Channel
MDS 98	44.8	North Shore Channel
MDS 97	44.5	North Shore Channel
MDS 96	44.1	North Shore Channel
MDS 95	43.5	North Shore Channel
MDS 94	43.3	North Shore Channel
MDS 93	43.0	North Shore Channel
MDS 92	42.6	North Shore Channel
CSO 5	40.0	North Branch Chicago River
CSO 6	39.0	North Branch Chicago River
CSO 7	38.0	North Branch Chicago River
CSO 8	36.0	North Branch Chicago River
CSO 9	35.0	North Branch Chicago River
CSO 10	35.0	Chicago River Main Stem
CSO 11	34.0	South Branch Chicago River
CSO 12	32.0	South Branch Chicago River
CSO 13	30.0	Chicago Sanitary and Ship Canal
CSO 14	29.0	Chicago Sanitary and Ship Canal
CSO 15	27.0	Chicago Sanitary and Ship Canal
CSO 16	26.0	Chicago Sanitary and Ship Canal
CSO 17	25.0	Chicago Sanitary and Ship Canal
CSO 18	21.0	Chicago Sanitary and Ship Canal
CSO 19	25.0	Calumet-Sag Channel
CSO 20	27.0	Calumet-Sag Channel
CSO 21	28.0	Little Calumet River (north)
CSO 22	30.0	Little Calumet River (north)
CSO 23	31.0	Little Calumet River (north)
CSO 24	34.0	Little Calumet River (north)
CSO 25	35.0	Little Calumet River (north)
CSO 26	31.0	Little Calumet River (south)
CSO 27	32.0	Little Calumet River (south)
CSO 28	35.0	Little Calumet River (south)

*River miles for the Chicago Area Waterway System often are described relative to the confluence of the Illinois River with the Mississippi River at Grafton, Ill., in this case the River Mile for the Lockport Lock and Powerhouse is 291, and all the values can have 291 added to them to give river miles relative to the mouth of the Illinois River.

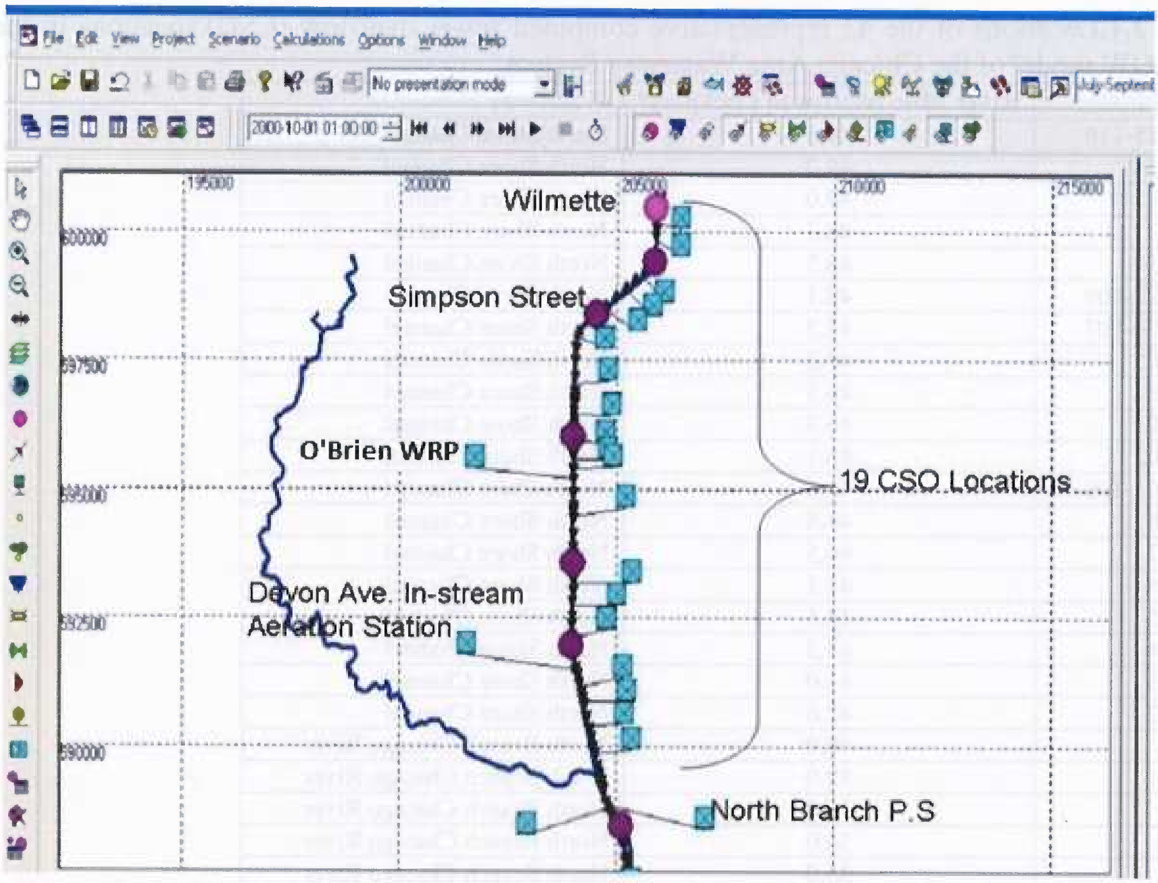


Figure 2.1. Location of the 19 representative gravity CSOs on the upper North Shore Channel in the DUFLOW model

In other areas of the CAWS the CSO flows are not as dominant and the representative CSO locations involve larger aggregations of TARP drop shafts.

2.1.3 Hydraulic Data Used for Model Input

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

Measured inflows, outflows, and water-surface elevations

The hydraulic and hydrologic data available for the CAWS have been compiled from different agencies. In WY 2003 the USGS operated discharge and stage gages at three primary locations where water is diverted from Lake Michigan into the CAWS. These locations are:

i) The Chicago River main stem at Columbus Drive (near CRCW)

ii) The CalumetRiver at the O'Brien Lock and Dam

iii)The North Shore Channel at Maple Avenue (near the Wilmette Pumping Station, referred to as Wilmette throughout the remainder of the report)

The data from the Chicago River main stem at Columbus Drive, the Calumet River at the O'Brien Lock and Dam, and the North Shore Channel at Maple Avenue gages are used as the primary upstream flow versus time (on a 15-minutes basis) boundary conditions for the unsteady-flow water-quality model in the model verification for WY 2003. In order to determine the optimal allocations of discretionary diversion the daily discretionary diversion flows estimated by the MWRDGC were subtracted from each 15-min flow value estimated by the USGS for WY 2003. The boundary flows then were increased to reflect different allocations of discretionary diversion as described in Chapter 4.

Elevation versus time data (on an hourly basis) from the MWRDGC gage on the CSSC at the Lockport Controlling Works (CW) 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 model. Two tributaries to the Calumet-Sag Channel are gaged by the USGS, Tinley Creek near Palos Park and Midlothian

Creek at Oak Forest, and these flows are input to the model. The USGS gage on the GrandCalumetRiver at Hohman Avenue at Hammond, Ind. is used to obtain the flow input from the Grand Calumet River, which is a tributary to the Little Calumet River (north). Flow on the NBCR is measured just upstream of its confluence with the NSC at the USGS gage at Albany Avenue and is input to the model.

There also are inflows coming from MWRDGC facilities. Hourly flow data are available from the MWRDGC for the treated effluent discharged to the CAWS by each of the four WRPs—O'Brien, Stickney, Calumet, and Lemont. Hourly flows were input to the model for the first three WRPs; whereas daily flows were used at Lemont. In addition, hourly flows discharged to the CAWS at three CSO pumping stations—North Branch, Racine Avenue, and 125th Street—were estimated from operating logs of these stations (described in Section 2.1.1). The boundary conditions and tributary inflows for the DUFLOW model of the CAWS are summarized in Section 2.1.4.

Estimation of flow for ungaged tributaries and combined sewer overflow pump stations

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). In the original hydraulic calibration, flows on Midlothian Creek were used to estimate flows fromungaged tributaries on an area-ratio basis. The drainage area ratios for the ungaged tributaries compared to the Midlothian Creek drainage area are listed in Table 2.2. The U.S. Army Corps of Engineers (2001) has estimated the land cover distribution in percent for the "ungaged" Calumet-Sag (including Midlothian and Tinley Creeks) and lower Des Plaines watersheds as follows.

Watershed	Impervious	Grassland	Forest
Ungaged Calumet-Sag	35.8	58.7	5.5
Ungaged lower Des Plaines	30.1	40.3	29.6

Because of the relatively small variation in the distribution of pervious and impervious land cover in the ungaged watersheds the area-ratio method results in estimates with sufficient accuracy for the purposes of this study.

Table 2.2. Calculation of ungaged tributaries and watersheds

Stream Ungaged	Ratio with Midlothian*
Mill Creek West	0.55
Stony Creek West	1.086
Cal-Sag Watershed East	0.246
Navajo Creek	0.137
Stony Creek East	0.486
UngagedDes Plaines Watershed	0.703
Calumet Union Drainage Ditch	1.168
Cal-Sag Watershed West	0.991

*The gaged Midlothian Creek drainage area is 12.6 mi^2, but these ratios are computed to the total Midlothian Creek drainage area of 20 mi^2. The total flow for both Midlothian and Tinley Creeks was determined by area ratio of the total drainage area to the gaged drainage area, 12.6 mi^2 and 11.2 mi^2 for Midlothian and Tinley Creeks, respectively.

Hourly flows from all 3 pumping stations were estimated from pump operation records of on and off times and the rated capacity of the various pumps and then input to the model. Daily average discharges from the 3 pumping stations are shown in Figure 2.2 for October 1, 2002 to September 30, 2003 (i.e. WY 2003).

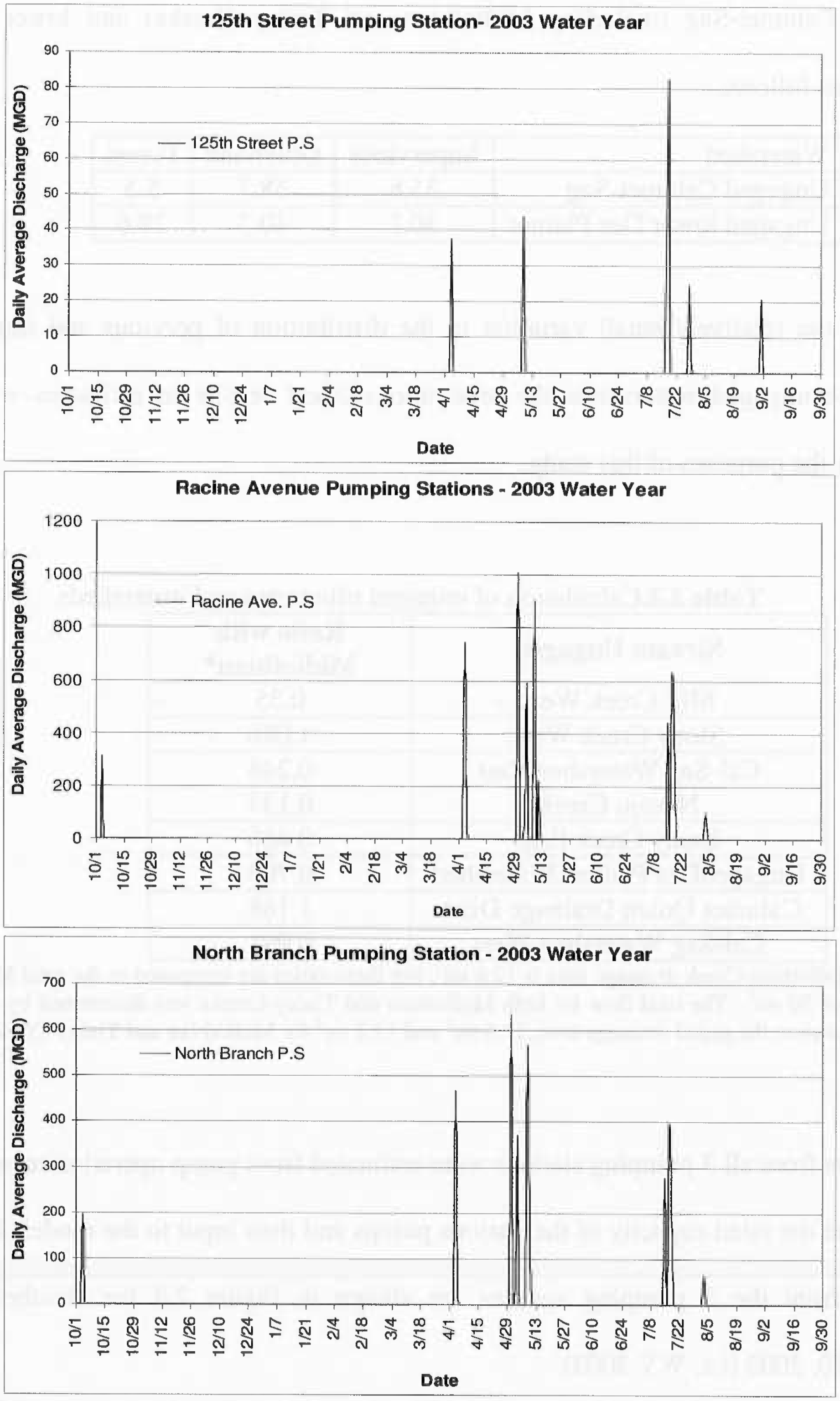


Figure 2.2. Daily average discharges from the North Branch, Racine Avenue, and 125th Street Pumping Stations for October 1, 2002 to September 30, 2003 (Water Year 2003)

2.1.4 Summary of Boundary Conditions and Tributary Inflows

Boundary and initial conditions for the hydraulic and water-quality verification period were set by data collected by the USGS at the three lake front control structures, by the MWRDGC data at the Lockport Controlling Works, and by the USGS for the tributary flows. Data collected by the MWRDGC for the discharges from different WRPs also were used.

Boundary Locations:

a. Chicago River at Columbus Drive
b. NorthShore Channel at Wilmette (Maple Avenue)
c. CalumetRiver at O'Brien Lock and Dam
d. Little Calumet River (south) at South Holland (Cottage Grove Avenue)
e. CSSC at the Lockport Controlling Works (downstream boundary)

The major flows into CAWS have been identified as follows:

a. O'Brien Water Reclamation Plant
b. Stickney Water Reclamation Plant
c. Calumet Water Reclamation Plant

and the minor flows into the CAWS are from:

a. North Branch Chicago River at Albany Avenue
b. Racine Avenue Pumping Station
c. North Branch Pumping Station
d. 125th Street Pumping Station
e. Lemont Water Reclamation Plant

f. Tinley Creek+Navajo Creek (i.e. Navajo Creek estimated based on area ratio with Midlothian Creek and added with nearby Tinley Creek)

g. Midlothian Creek

h. GrandCalumetRiver

i. Mill+Stony Creek (west)*

j. Stony Creek (east)*

k. Des PlainesRiver Basin*

l. Calumet Union Drainage Ditch*

m. Cal-Sag Watershed West*

n. 43 representative CSO locations

* These flows were estimated based on Midlothian Creek flows

In 1995, the USGS did an evaluation of direct groundwater inflows to the CAWS downstream from the USGS streamflow gages on the basis of test boring data and piezometric water levels near the waterways. The U.S. Army Corps of Engineers (1996) summarized the USGS results and determined a total groundwater inflow of 4 cubic feet per second (cfs). Therefore, the effects of direct groundwater inflow to the CAWS was not directly considered in the water balance for the DUFLOW model. However, for tributary areas draining directly to the CAWS, groundwater inflows are considered as part of the area ratio estimate of flows from these areas.

2.1.5 Channel Geometry and Roughness Coefficient

The channel geometry is represented as a series of 197 measured cross sections in the calibrated hydraulic model. The DUFLOW model uses Chezy's roughness coefficient, C, to calculate hydraulic resistance. The calibrated C values, which vary between 6 and 60 were used in this study, and the equivalent Manning's n values range from 0.022 to 0.165. Complete details on the calibrated values of Chezy's C and the equivalent Manning's n value are listed in Table 4.2 of Shrestha and Melching (2003).

2.1.6 Model Verification Locations

Although flow in the various branches of the CAWS is not measured, water-surface elevation recorded at different locations was used for calibration and verification of the model. The water-surface elevations recorded on the NSC at Wilmette; on the NBCR at Lawrence Avenue; on the CSSC at Western Avenue, Willow Springs Road, and Sag Junction by the MWRDGC and at Romeoville by the USGS; on the Calumet-Sag Channel at Southwest Highway by the MWRDGC; and on the Chicago River main stem at Columbus Drive by the USGS were used for model verification. Daily flows recorded by the USGS for the CSSC at Romeoville also were used for model verification.

2.1.7 Flow Balance

The inflow to the CAWS is comprised of flows from tributaries, WRPs, pumping stations, CSOs, and from Lake Michigan at the controlling structures. All the inflows to the system are measured as flow at Romeoville. 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. Daily average simulated gravity CSO flows obtained from the Corps as explained in Section 2.1.1 are shown in Figure 2.3. Comparison of the summation of all inflows to the system and outflow at Romeoville are shown in Figure 2.4. All inflows to the system and flow at Romeoville for the period of October 1, 2002 to September 30, 2003 (WY 2003) are listed in Table 2.3. Over the full study period the inflows (except CSOs) were 2.8% higher than the flow at Romeoville for WY 2003, respectively. The flow balance indicated that inflows to the CAWS are slightly overestimated.

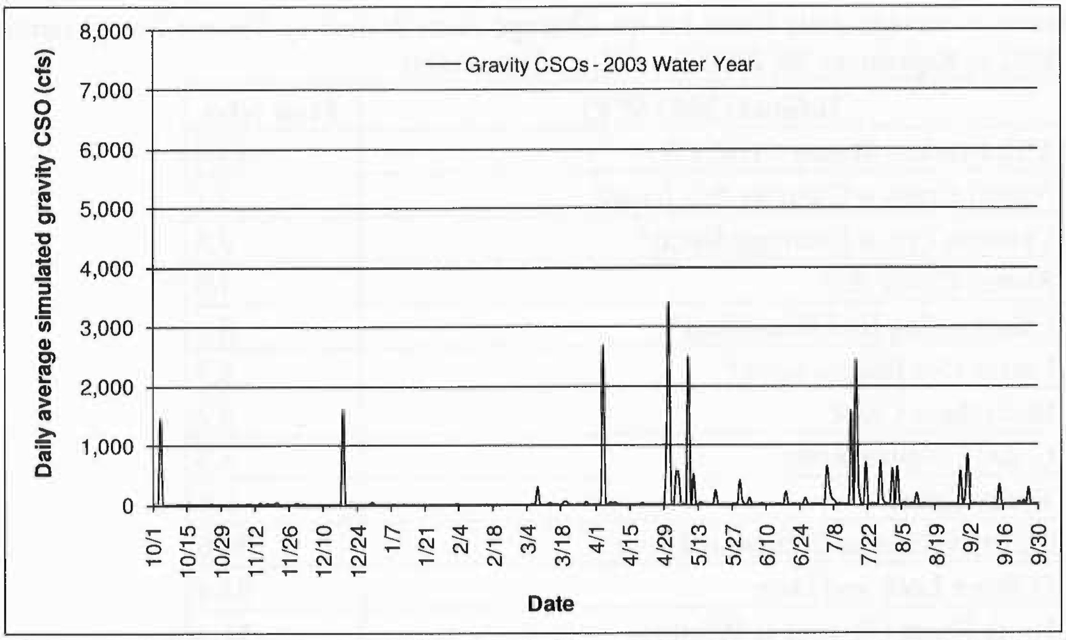


Figure 2.3. Daily average simulated gravity combined sewer overflow (CSO) flows obtained from the U.S. Army Corps of Engineers models for October 1, 2002 to September 30, 2003 (i.e. Water Year 2003)

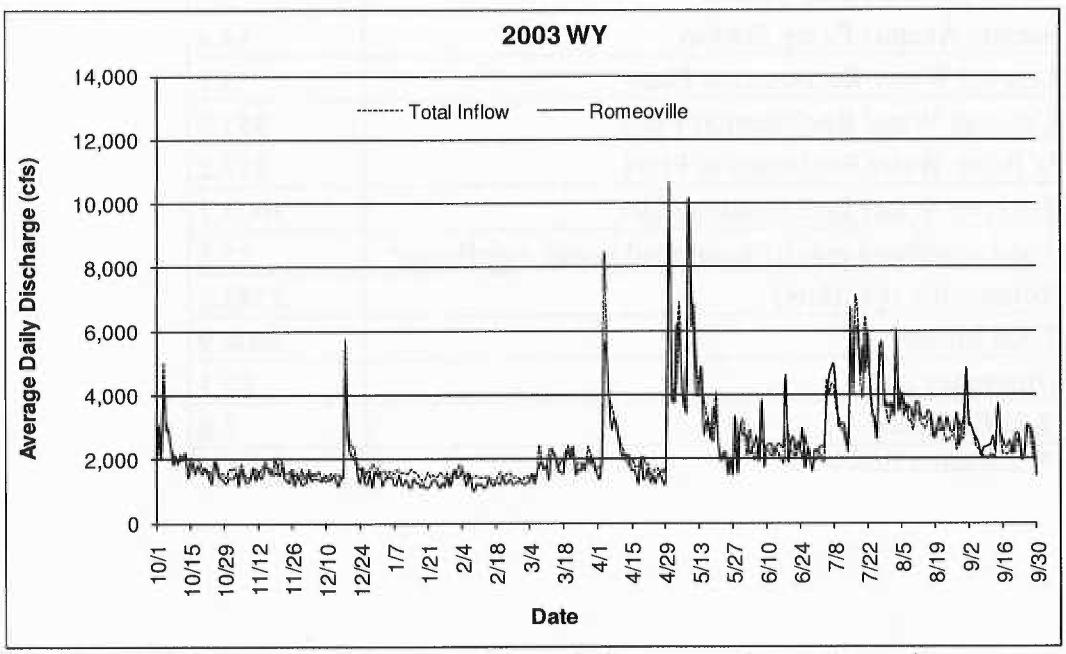


Figure 2.4. Comparison of the summation of all measured or estimated (except gravity combined sewer overflows) inflows (Total) and the measured outflow at Romeoville for October 1, 2002 to September 30, 2003 (i.e. Water Year 2003)

Table 2.3. Balance of average daily flows for the Chicago Area Waterway System for the period of October 1, 2002 to September 30, 2003 (i.e. Water Year 2003)

Inflows (2003 WY)	**Flow (cfs)**
Mill Creek + Stoney Creek (W)*	13.4
Narajo Creek + Calumet-Sag basin*	3.1
Calumet Union Drainage Ditch*	9.5
Stoney Creek (E)*	4.0
Calumet-Sag End Watershed*	8.1
Lower Des Plaines basin*	5.7
Midlothian Creek	8.2
Grand Calumet River	8.5
Tinley Creek	9.1
Chicago River at Columbus Drive	138.6
O'Brien Lock and Dam	95.4
North Shore Channel at Wilmette	51.3
Little Calumet River at South Holland	144.9
North Branch Chicago River at Albany Avenue	90.0
125th Street Pump Station	1.0
North Branch Pump Station	6.1
Racine Avenue Pump Station	14.4
Lemont Water Reclamation Plant	3.1
Calumet Water Reclamation Plant	353.8
O'Brien Water Reclamation Plant	357.2
Stickney Water Reclamation Plant	1005.7
Total simulated gravity combined sewer overflows*	75.8
Romeoville (Outflow)	2342.2
Total Inflow	2406.9
Difference (cfs)	64.7
% Difference	2.8

*Estimated flows

2.1.8 Results of the Hydraulic Verification

The comparison of measured and simulated water-surface elevations at various locations used in the model verification is shown in Figure 2.5 for WY 2003. Statistical analysis listed in Table 2.4 shows that the difference between the measured and simulated stages are below 5% relative to the depth (where depth is measured relative to the thalweg of the channel) of the water for 100% of the simulation periods for all locations except for Wilmette, Lawrence Avenue, and Southwest Highway. The simulated water-surface elevations were within 5% of the measured values with respect to the depth at these locations 65-93% of the time for WY 2003. As can be seen in Figure 2.5, there is a constant almost 1 ft difference between the measured and simulated water-surface elevations between October 2002 and January 2003 on the NBCR at Lawrence Avenue. The fact that this difference diminishes after January 2003 suggests that measured water-surface elevations at Lawrence Avenue between October 2002 and January 2003 are suspicious. Similarly, unusually high water-surface elevation values between January and March 2003 on Cal-Sag Channel at Southwest Highway are suspicious and result in a low correlation coefficient for WY 2003.

As listed in Table 2.4, high percentages of small errors and the high correlation coefficients (0.64-0.91 not including Lawrence Avenue and Southwest Highway) indicate an excellent hydraulic verification of the model. Further, data were not available at Southwest Highway and Lawrence Avenue during the original hydraulic calibration. Thus, the results at Southwest Highway (93% of errors within 5% of the depth) and Lawrence Avenue provide a more stringent verification of the model's accuracy than do the stage comparisons at locations used in the model calibration. Similar hydraulic verification results have been obtained for all other periods evaluated. Since the calibrated model can predict stages throughout the CAWS with high accuracy, this model can be safely used for the water-quality simulation once the water-quality simulation routines are properly calibrated.

Table 2.4. Correlation coefficient and percentage of the hourly water-surface elevations for which the error in simulated versus measured water-surface elevations relative to the depth of flow (measured from the thalweg of the channel) is less than the specified percentage for October 1, 2002 to September 30, 2003 (i.e. Water Year 2003)

		Percentage		
Location	**Correlation Coefficient**	**<±2% of D**	**<±5% of D**	**<±10% of D**
Wilmette (NSC)	0.82	16	78	98
CRCW (Chicago River Main Stem)	0.77	95	100	100
O'Brien Lock and Dam (CalumetRiver)	0.64	98	100	100
Lawrence Avenue (NBCR)	0.42	18	65	97
Western Avenue (CSSC)	0.77	97	100	100
Willow Springs (CSSC)	0.81	100	100	100
Southwest Highway (Cal-Sag Channel)	0.47	67	93	96
Calumet-Sag Junction	0.84	98	100	100
Romeoville (CSSC)	0.91	97	100	100

The comparison of measured and simulated average daily flows on the CSSC at Romeoville is shown in Figure 2.6. The simulated average flow rate at Romeoville is 2,441.5 cfs for WY 2003. The measured and simulated flows show very close agreement and the overall difference between the simulated and measured daily discharges at Romeoville is 4.2% for WY 2003.

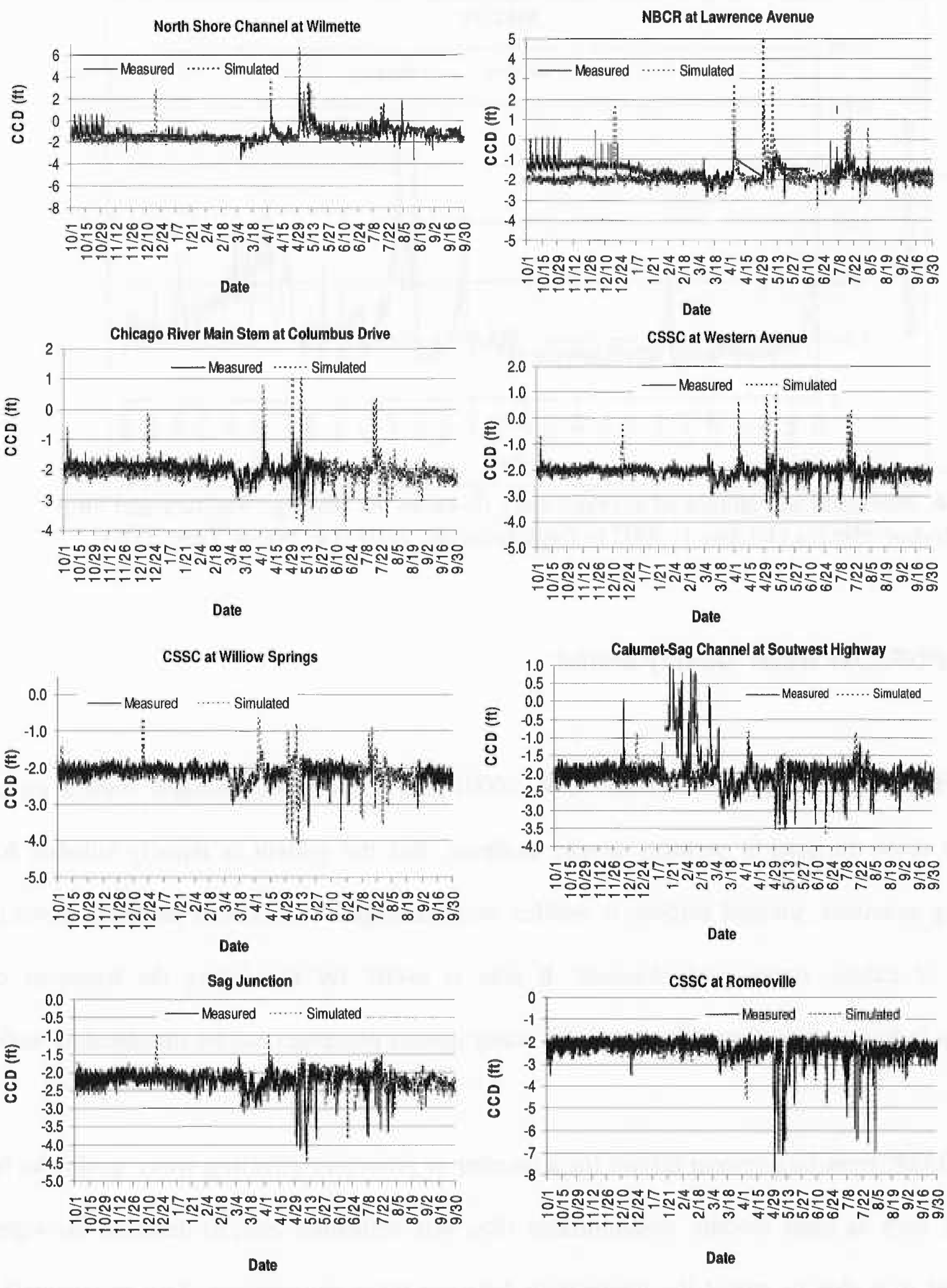


Figure 2.5. Measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Area Waterway System for October 1, 2002 to September 30, 2003 (i.e. Water Year 2003)

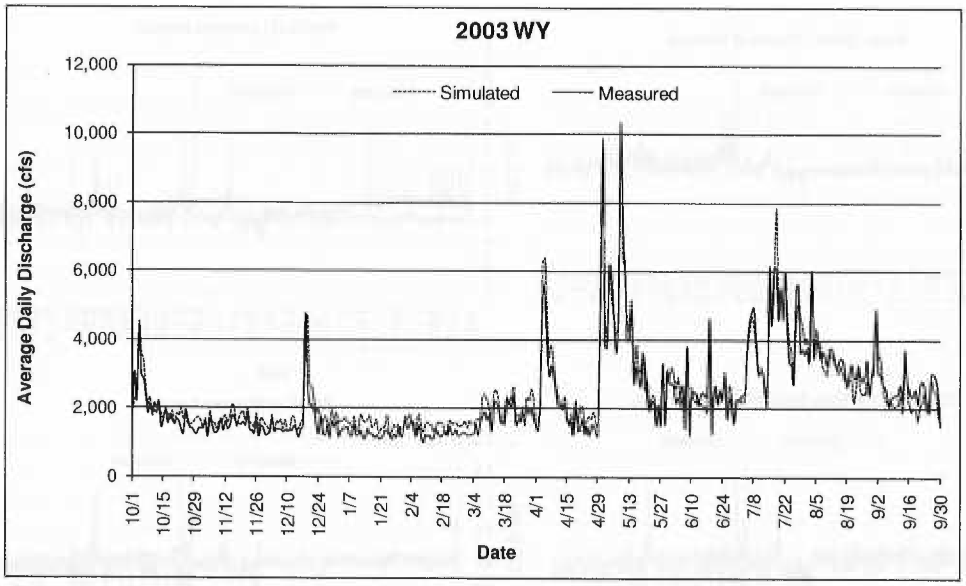


Figure 2.6. Measured and simulated average daily flows on the Chicago Sanitary and Ship Canalat Romeoville for October 1, 2002 to September 30, 2003 (i.e. Water Year 2003)

2.2 The DUFLOW Water-Quality Model

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

The DUFLOW modeling system 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 DO using the same formulations as applied in the USEPA 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 this study, EUTROF2 was selected as the appropriate unsteady-flow water-quality model for the CAWS. Details of the EUTROF2 model can be found in Alp and Melching (2004) and Neugebauer and Melching (2005). The complete EUTROF2 model is given in Appendix A of Melching et al. (2010).

2.2.1 Water-Quality Input Data

The water quality in the modeled portion of the CAWS is affected by the operation of four SEPA stations and two IASs (shown in Figure 1.1). The CAWS receives pollutant loads from four WRPs, nearly 240 CSOs (condensed to 43 representative locations to facilitate the modeling as previously described), direct diversions from Lake Michigan, and eleven tributary streams or drainage areas. The effects of nonpoint source pollution are included in the CSO and tributary flow pollutant loads. 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 CAWS.

<u>SEPA stations</u>

Because the CAWS was constructed to convey treated municipal wastewater and provide for commercial navigation and flood control, the system has low in-stream velocities. DO concentrations in the CAWS, therefore, have been low compared to other rivers in Illinois. In

1984, the MWRDGC issued a feasibility report on a new concept of artificial aeration referred to as SEPA. The SEPA concept involves pumping a portion of the water from the stream into an elevated pool. Water is then aerated by flowing over a cascade or waterfall, 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. The locations of the SEPA stations are listed in Table 2.5. Comparing the locations of the SEPA stations with those of the proposed aeration stations evaluated by MSD (1976) and Harza (1976a, b): SEPA 2 is around 1 mile from the proposed Indiana Avenue station, SEPA 3 is within 2 miles of the proposed Crawford Avenue station, and SEPA 4 is at the same location as the proposed Harlem Avenue station.

Table 2.5. Locations of Sidestream Elevated Pool Aeration (SEPA) stations in the modeled portion of the Chicago Area Waterway System

SEPA STATION #	Location	River Mile* from Lockport
2	127th Street	30.3
3	Blue Island	27
4	Worth (Harlem Avenue)	20.7
5	Sag Junction	12.3

*River miles for the Chicago Area Waterway System often are described relative to the confluence of the Illinois River with the Mississippi River at Grafton, Ill., in this case the River Mile for Lockport is 291, and all of the values can have 291 added to them to give river mile values relative to the mouth of the Illinois River.

Two previously conducted studies (Butts et al., 1999 and 2000) were used to examine the efficiency of and calculate DO load from the SEPA stations. Summaries of these studies and the estimation of DO loads from SEPA stations are explained in detail in Alp and Melching (2004). The procedure explained in Alp and Melching (2004) was followed to estimate the DO loads from the SEPA stations for WY 2003.

In the water-quality modeling, the DO load from the SEPA stations was calculated using the following formula:

$$\text{OXYGEN LOAD} = Q_P \times \alpha \times (C_{SAT} - C_{UPSTREAM}) \text{ in g/s}$$

where:

Q_P	=	Flow through the SEPA station, m^3/s
	=	Number of Pumps Operating x Pump Capacity
C_{SAT}	=	Saturation concentration of DO, mg/L, (determined from continuous in-stream temperature data)
$C_{UPSTREAM}$	=	DO concentration (mg/L) upstream of SEPA station from continuous in-stream monitoring data (for calibration) or modeling results (for assessment of the optimal allocation of discretionary diversion)
α	=	Fraction of saturation achieved = f(number of pumps in operation), from Butts et al. (1999)

These hourly DO loads were directly input to the CAWS 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.

In-Stream Aeration Stations

Among the 6 aeration stations proposed for the Chicago River system in the 1970s and evaluated in Macaitis et al. (1975), MSD (1976), and Harza (1976a, b) only two diffused aeration stations were built. In 1979, the Devon Avenue station was completed on the NSC. A second aeration station was constructed at Webster Avenue on the NBCR and became operational 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 DO loads from the in-stream aeration stations. The details of the estimation of the DO loads from in-stream aeration stations are given in Alp and Melching (2004).

Blower operation hours were provided by the MWRDGC. The following equation is used to calculate hourly DO load for input to the model:

$$Load = \%DO_{increase} \times DO_{upstream} \times Q/100$$

where:

Load = Oxygen load from the in-stream aeration station (g/s)

$\%DO_{increase}$ = Percent DO increase downstream of the aeration station (determined from the equations in Polls et al. (1982))

$DO_{upstream}$ = Measured DO concentration upstream of the aeration station (mg/L)

Q = Discharge at the aeration station (m^3/s)

For model calibration, the discharge and DO concentration upstream of Devon Avenue were calculated using a mass balance approach. The O'BrienWRP and NSC 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 to define the upstream conditions for the Webster Avenue aeration station calculations. For the evaluation of optimal allocation of discretionary diversion to improve the percentage of time with simulated DO concentrations equaling or exceeding the DO standards, simulated discharge and DO concentrations upstream from the in-stream aeration stations are used.

Water Reclamation Plants

Four point sources potentially affect the DO in the CAWS: the O'BrienWRP, Stickney WRP, Calumet WRP, and Lemont WRP. Measured daily concentrations were used in the model for the four WRPs. The summation of the discharges from the O'Brien, Stickney, and Calumet WRPs has the greatest contribution of loads to the CAWS. Daily measured concentration from these 3 WRPs are shown in Figures 2.7-2.9, respectively. In these figures and throughout the report the constituent abbreviations are as follows: DO = dissolved oxygen, CBOD5 (figures) $CBOD_5$ (text) = 5-day carbonaceous biochemical oxygen demand, TSS = total suspended solids, TKN = total Kjeldahl nitrogen as nitrogen, NH4-N (figures) NH_4-N (text) = ammonium as nitrogen, Org-N = organic nitrogen as nitrogen, NO3-N (figures) NO_3-N (text) = nitrate as nitrogen, NO2+NO3 = nitrite plus nitrate as nitrogen, P-Tot = total phosphorus, Sol-P = soluble phosphorus, Org-P = organic phosphorus, In-P = inorganic phosphorus, and Chll-a = chlorophyll a. The load from the Citgo Petroleum outfall was not considered in this study because of intermitten water-quality data available for this discharge and the insignificant amount of flow and pollutant load contributed by this discharger.

Tributaries

Long-term average values are used for the concentrations for the tributaries. All water-quality data used were collected as a part of the MWRDGC monthly waterway sampling program. A limited amount of event mean concentration data are available on the Little Calumet River (south) at Ashland Avenue (8 events) and the North Branch Chicago River at Albany Avenue (9 events) in the summer and fall 2001 (see Alp and Melching, 2006). These data were believed to be insufficient to describe storm flows for all events and all tributaries for WY 2003. Thus, in order to be consistent throughout the simulation period of WY 2003 and use the same kinetic parameters, long-term average in-stream concentrations were used for both wet and dry periods.

Average concentrations for Calendar Years 2000-2004 for the Little Calumet River at South Holland were calculated using a mass balance approach and data from the Little Calumet River at Wentworth Avenue (upstream from the South Holland gage) and at Ashland Avenue (downstream from the South Holland gage) and Thorn Creek at 170th Street (upstream from the South Holland gage). Results are listed in Table 2.6, where NO_2+NO_3-N represents nitrite plus nitrate as nitrogen and P-Sol represents soluble phosphorus.

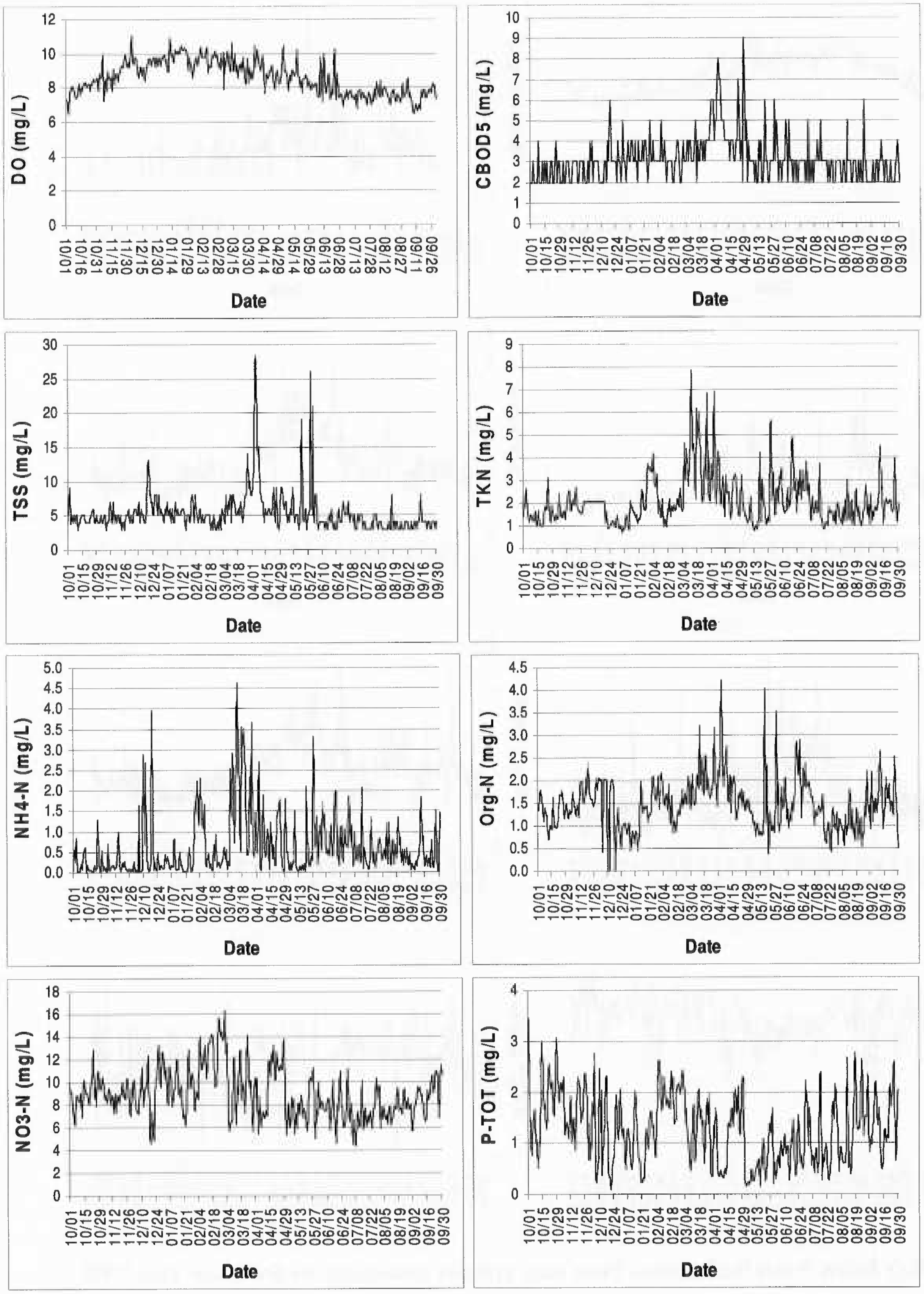


Figure 2.7. Stickney Water Reclamation Plant daily effluent concentrations for Water Year 2003

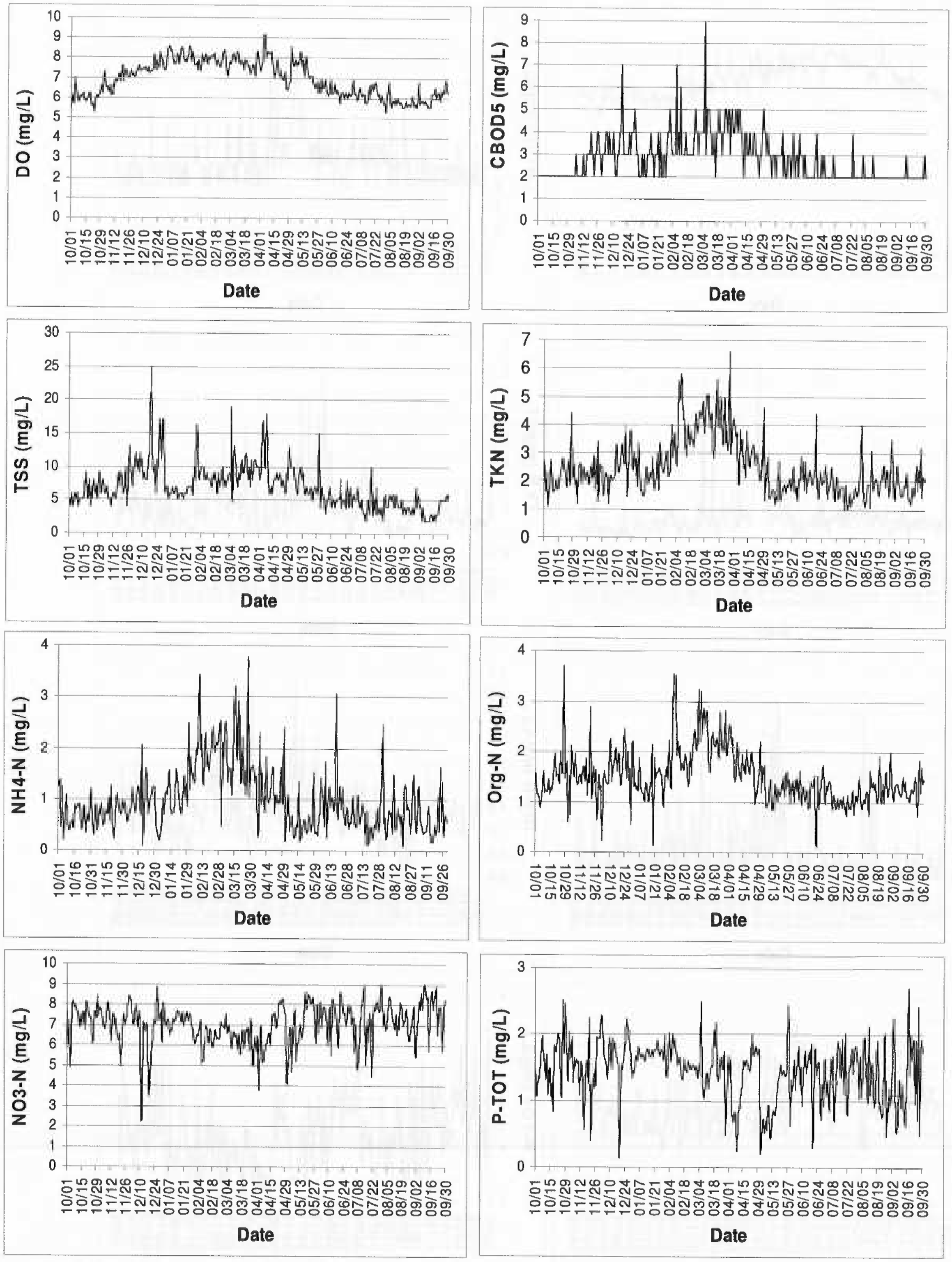


Figure2.8. O'Brien Water Reclamation Plant daily effluent concentrations for Water Year 2003

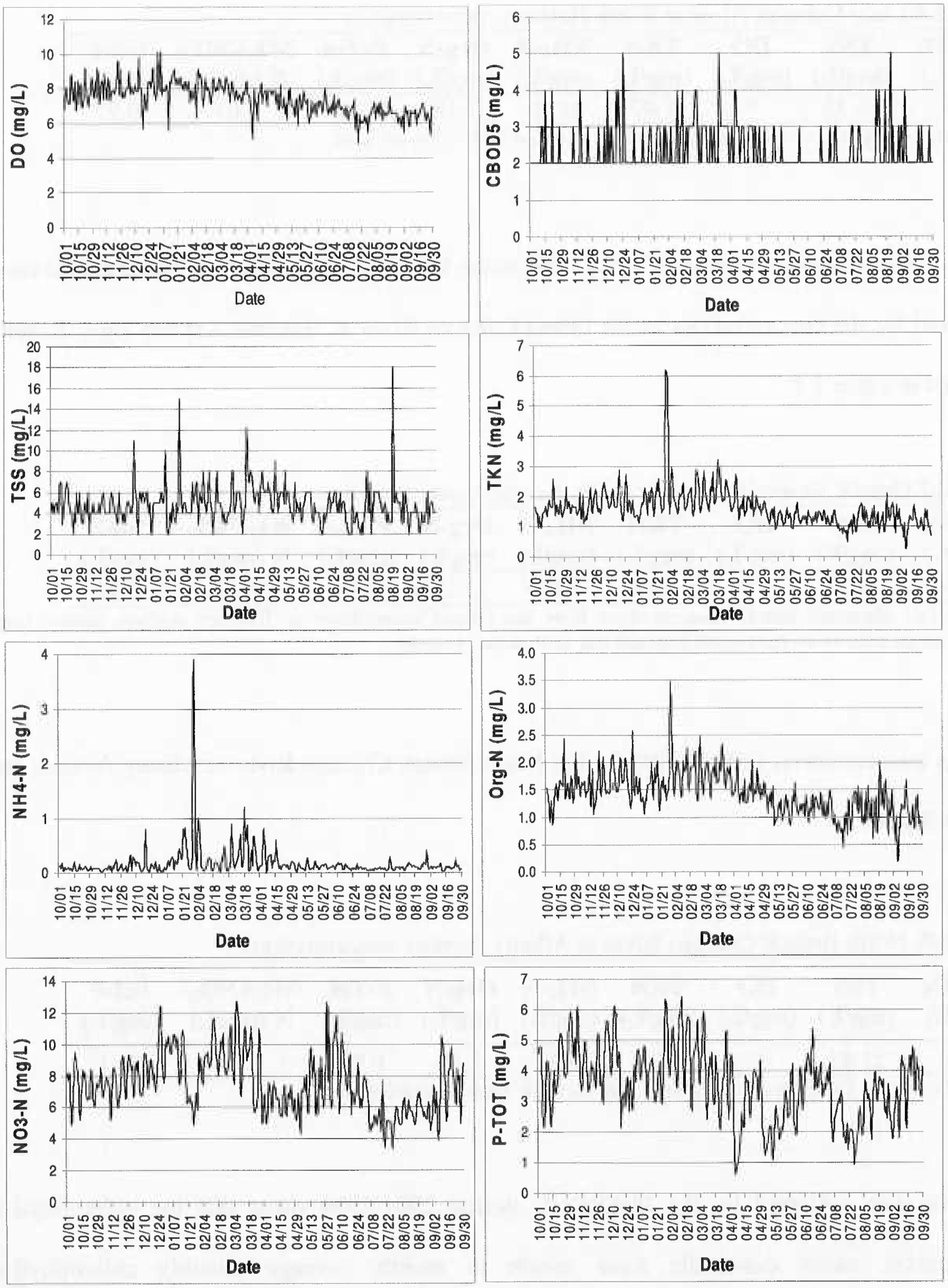


Figure 2.9. Calumet Water Reclamation Plant daily effluent concentrations for Water Year 2003

Table 2.6. Little Calumet River at South Holland concentrations

$CBOD_5$ (mg/L)	TSS (mg/L)	DO (mg/L)	TKN (mg/L)	NH_4-N (mg/L)	Org-N (mg/L)	P-Tot (mg/L)	NO_2+NO_3-N (mg/L)	Sol-P (mg/L)
3.15	36.15	*	1.47	0.28	1.18	1.40	5.07	0.97

* Monthly average DO concentrations measured between 2000-2004 are used

Concentrations measured between 1990-2004 at the Grand Calumet River at Burnham Avenue were used for the concentrations at the Grand Calumet River at Hohman Avenue gage. Results are listed in Table 2.7.

Table 2.7. GrandCalumetRiver at Hohman Avenue concentrations

$CBOD_5$ (mg/L)	TSS (mg/L)	DO (mg/L)	TKN (mg/L)	NH_4-N (mg/L)	Org-N (mg/L)	P-Tot (mg/L)	NO_2+NO_3-N (mg/L)	Sol-P (mg/L)
6.69	34.97	***	4.33	2.01	2.32	0.74	7.73	0.22

*** For DO measured hourly concentrations from the GrandCalumetRiver at Torrence Avenue station were assigned to the inflows on the GrandCalumetRiver at Hohman Avenue

Average concentrations (2000-2004) for the North Branch Chicago River at Albany Avenue are listed in Table 2.8.

Table 2.8. North Branch Chicago River at Albany Avenue concentrations

$CBOD_5$ (mg/L)	TSS (mg/L)	DO (mg/L)	TKN (mg/L)	NH_4-N (mg/L)	Org-N (mg/L)	P-Tot (mg/L)	NO_2+NO_3-N (mg/L)	Sol-P (mg/L)
4.79	21.41	*	1.38	0.28	1.10	0.93	4.20	0.81

* Monthly average DO concentrations measured between 2000-2004 are used

Since the data collected by the MWRDGC during 2001-2004 show that the chlorophyll-a concentration varies drastically from month to month, average monthly chlorophyll-a concentrations were calculated for the Little Calumet River at South Holland and measured concentrations were used at the North Branch Chicago River at Albany Avenue and Grand Calumet River at Burnham Avenue. The chlorophyll-a concentration, in micrograms per liter (μg/L), for the Little Calumet River at South Holland was computed using the same mass balance approach applied for the other constituents. The monthly chlorophyll-a concentrations used in the modeling are listed in Table 2.9.

Table 2.9. North Branch Chicago River at Albany Avenue, Little Calumet River at South Holland, and Grand Calumet River at Burnham Avenue chlorophyll-a concentrations based on data from 2001-2004

	North Branch Chicago River at Albany Avenue (μg/L)	**Little Calumet at South Holland (μg/L)**	**GrandCalumetRiver at Burnham Avenue (μg/L)**
October	10.8	3.5	9.4
November	7.7	10.2	21.1
December	8.0	2.1	15.0
January	7.8	12.2	9.1
February	26.6	10.6	96.3
March	19.6	18.9	132.0
April	58.8	16.1	4.5
May	22.1	6.0	17.8
June	24.5	8.9	24.6
July	13.8	9.6	24.0
August	11.1	11.3	12.6
September	9.6	4.9	50.4

Concentrations for other tributaries are based on the Little Calumet River concentrations because all of the other gaged and ungaged tributaries are on the southern portion of the Chicago metropolitan area and were assumed to be similar to the Little Calumet River drainage basin.

Combined Sewer Overflows

There are nearly 240 CSO locations discharging to the modeled portion of the CAWS and they are represented by 43 CSO locations in the model (see Table 2.1). In addition to CSO locations there are 3 CSO pumping stations. Table 2.10 lists the historic event mean concentrations (EMCs) calculated based on measurements done by the MWRDGC for each pumping station. AverageEMCs for eachpump station then were calculated using the data in Table 2.10 for the North Branch Pumping Station and 125th Street Pumping Station and are listed in Table 2.11. As explained in Alp (2006), because of lack of data, the Racine Avenue Pumping Station EMCs were determined by regression equations based on discharge and EMC. As historic data are available for $CBOD_5$, TSS, and NH_4-N at the Racine Avenue Pumping Station, these values were used in the regression analysis. For other constituents (NO_3-N, P-Tot, TKN, and DO) historic North Branch Pumping Station EMCs were used at the Racine Avenue Pumping Station. For each constituent, EMCs were regressed against the total CSO volume. After that, Racine Avenue Pumping Station CSO volume data were used to estimate EMC as listed in Table 2.11.

The EMCs for the North Branch Pumping Station in Table 2.11 were applied to all gravity CSOs discharging to the North Shore Channel and North Branch Chicago River. The EMCs for the Racine Avenue Pumping Station in Table 2.11 were applied to all gravity CSOs discharging to the Chicago River main stem, South Branch Chicago River, and CSSC. Finally, the EMCs for the 125th Street Pumping Station in Table 2.11 were applied to all gravity CSOs discharging to the Little Calumet River and Calumet-Sag Channel. The reasonableness of this approach was statistically demonstrated in Neugebauer and Melching (2005).

Table 2.10. Measured event mean concentrations for combined sewer overflow pumping stations

	DO (mg/L)	$CBOD_5$* (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	Org-N (mg/L)	Org-P** (mg/L)	In-P** (mg/L)	TSS (mg/L)
North Branch Pumping Station								
08/02/01	5.8	27.3	1.8	1.5	5.7	0.4	0.6	92.3
08/09/01	2.4	71.4	3.2	0.7	14.2	2.6	0.1	263.0
09/20/01	4.2	20.8	1.8	0.5	5.4	0.8	0.3	83.1
09/23/01	4.0	42.3	5.8	0.3	6.5	1.1	0.6	87.1
10/13/01	4.0	30.2	1.8	0.6	3.8	0.5	0.5	52.2
10/23/01	6.7	42.4	2.2	0.6	5.4	1.1	0.1	107.5
04/7-9/02	-	34.3	3.8	0.7	4.4	0.7	0.9	62.5
Racine Avenue Pumping Station								
07/20/95	-	76.8	3.1	-	-	-	-	-
08/15/95	-	32.4	1.8	-	-	-	-	-
11/10/95	-	8.9	0.6	-	-	-	-	-
07/17/96	-	15.8	0.4	0.8	-	-	-	113.4
07/18/97	-	54.7	-	-	-	-	-	887.5
04/22/99	-	49.1	-	-	-	-	-	232.1
06/01/99	-	120.5	-	-	-	-	-	1405.5
12/4/99	-	36.9	-	-	-	-	-	179.2
04/7-9/02	-	38.0	-	-	-	-	-	182.0
125th Street Pumping Station								
11/10/95	-	68.0	1.2	-	-	-	-	-
07/17/96	-	27.1	-	-	-	-	-	99.0
08/16/97	-	27.1	-	-	-	-	-	26.2
04/23/99	-	21.0	-	-	-	-	-	153.0
04/22/99	-	26.3	-	-	-	-	-	77.8
06/01/99	-	17.7	-	-	-	-	-	101.8
08/02/01	4.3	24.4	1.2	1.5	4.3	0.7	1.3	86.0
08/25/01	4.3	12.6	0.9	1.8	3.0	0.5	0.0	68.3
10/13/01	-	8.4	0.3	1.7	2.4	0.3	0.1	41.4
04/7-9/02	-	24.0	1.6	2.2	4.6	0.2	3.8	30.0

*$CBOD_5$ was not measured for the Racine Avenue Pumping Station. This concentration was estimated as proportional to the measured BOD_5 concentration. The ratio of BOD_5 to $CBOD_5$ for the North Branch Pumping Station ($CBOD_5 = 0.65 \cdot BOD_5$) was used to estimate $CBOD_5$ at the Racine Avenue Pumping Station.
**Organic and inorganic phosphorous concentrations were calculated based on measured total phosphorous and suspended solids concentrations from the following equations: $P_{ORGANIC} = 0.7 * 0.025 * SS$
$P_{INORGANIC} = P_{TOTAL} - P_{ORGANIC}$.

Table 2.11. The mean values of the event meanconcentrations in milligrams per liter for pumping stations discharging to the Chicago Area Waterway System

	Constituent	Average
North Branch Pumping Station	DO	4.0
	$CBOD_5$	35.4
	NH_4-N	2.9
	NO_3-N	0.7
	Org-N	6.1
	Org-P	1.0
	In-P	0.4
	TSS	102
Racine Avenue Pumping Station	DO	6.9
	$CBOD_5$	51.2
	NH_4-N	1.6
	NO_3-N	0.8
	Org-N	4.1
	Org-P	0.2
	In-P	0.7
	TSS	825
125th Street Pumping Station	DO	4.3
	$CBOD_5$	25.7
	NH_4-N	1.0
	NO_3-N	1.8
	Org-N	3.6
	Org-P	0.4
	In-P	1.3
	TSS	76

2.2.2 Initial Conditions

To start the computations, initial values for water-surface elevation and discharge, and all state variables (concentrations) are required by the DUFLOW model. Initial conditions are introduced for each DUFLOW point, i.e. each node (water quality and DO monitoring sites) or schematization points (discharge points). As stated in the DUFLOW manual (DUFLOW, 2000), the values can be based on historical measurements, obtained from former computations, or from a first reasonable guess.

Starting from upstream boundaries, initial conditions for discharge (1st measurement of the simulation period) were introduced at each node by adding the cumulative flow as tributaries or treatment facilities discharge to the CAWS. Water-surface elevation data provided by the MWRDGC (Southwest Highway, Western Avenue, Willow Springs Road, Sag Junction, and Lockport Controlling Works) and the USGS (Romeoville and upstream boundaries) were used to set initial conditions for water-surface elevation at each node by linear interpolation. Initial conditions for the water-quality constituents were introduced based on the water-quality measurements provided by the MWRDGC at several sampling locations. For simulated DO concentrations the errors resulting from the assumed initial conditions are eliminated within a few hours. Default DUFLOW EUTROF2 sediment concentrations were used as initial conditions. Initial conditions, calculation nodes, and sections are provided in Appendix C of Melching et al. (2010).

2.2.3 Calibration of the Water-Quality Model

In Melching et al. (2010), the preliminarily calibrated DUFLOW model (Alp and Melching, 2006) was adapted and improved to be used in the simulations of the Integrated Strategies to meet the proposed DO standards for the CAWS. The improved DUFLOW water-quality model was first calibrated for WY 2001 and verified for WY 2003.A total of 18 reaches are used in the current modeling study. Within these reaches computational nodes have been placed at intervals equal to or less than 1,640 ft (500 m) (Figure 2.10).

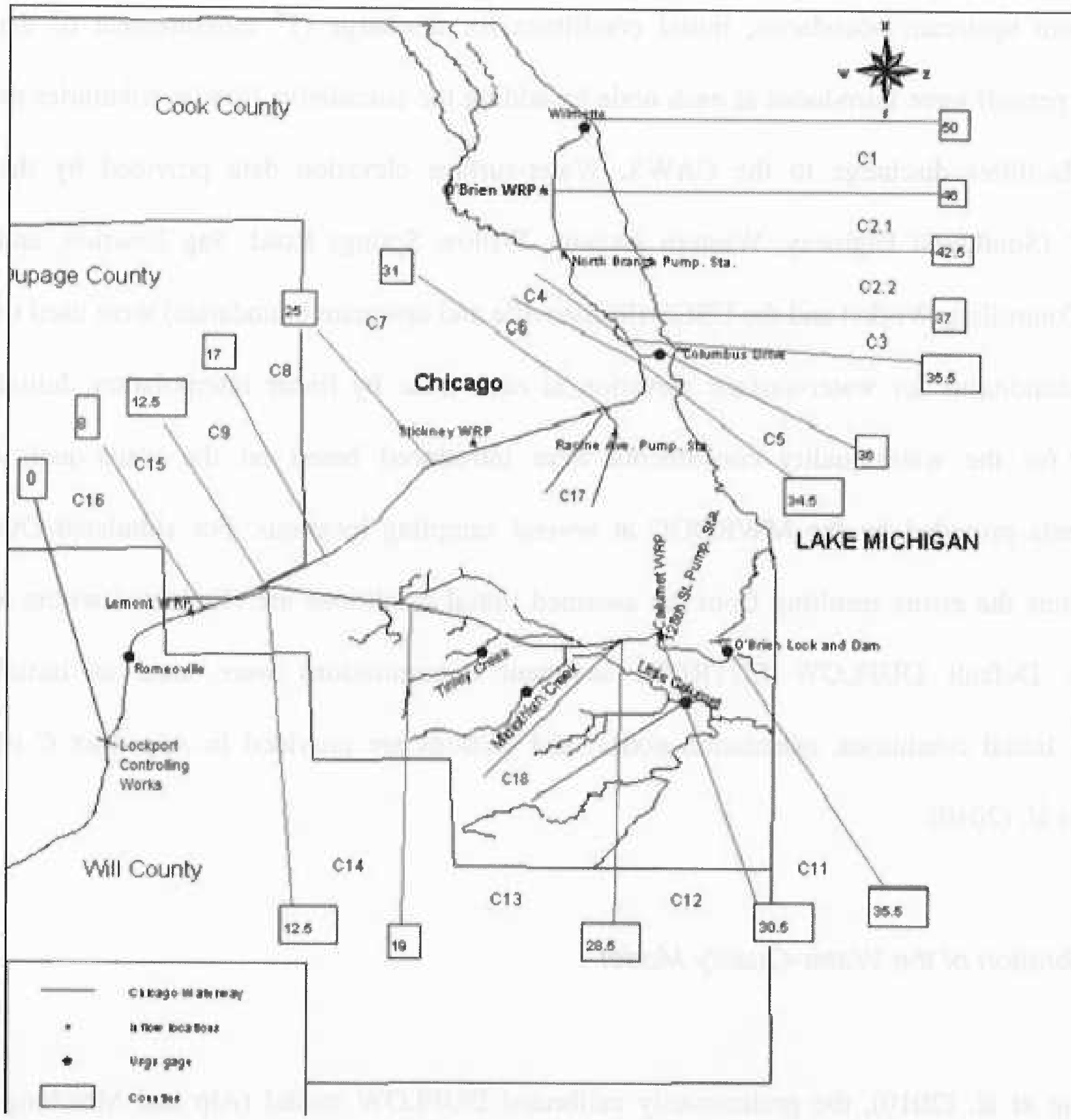


Figure 2.10. Chicago Area Waterway System reaches. The numbers in boxes are the river miles from the Chicago Sanitary and Ship Canal at Lockport Lock and Dam (note: the Little Calumet River (south) is the 18th reach; also the major Inflow Locations are denoted by stars and the USGS gages are denoted by pentagons)

<u>In-Stream Water-Quality Data</u>

The water-quality model was calibrated using monthly grab sample data at 19 locations and hourly DO concentration data at 25 locations in the CAWS collected by the MWRDGC. The locations of water quality and DO sampling stations are listed in Table 2.12. The model was run with a 15-min. time step and a one-hour output time step for WY 2003.

Temperature (^oC)

Temperature is one of the key variables because it affects reaction kinetics and the DO saturation concentration. The rate constant at a reference temperature of 20°C is multiplied by a coefficient, determining the change per °C difference from the reference temperature. In order to eliminate the bias that might result from usage of a constant temperature, hourly measured temperature values were introduced at each continuous monitoring location (node in the model). Therefore, temperature varies spatially and temporally in the water-quality model. For calibration and verification measured hourly temperatures were used, but for evaluation of optimal allocation of discretionary diversion computed daily temperatures were used on the SBCR and CSSC to reflect the closure of the Fisk and Crawford power plants and Units 1 and 2 of the Will County Power Plant as described in Section 3.3.

Model Parameters

The following parameters were set as space dependent (i.e. reach variable): Diffusive exchange rate constant for sediment (E_{dif}); nitrification rate constant (K_{nit}); $CBOD_5$ decay rate (K_{BOD}); dispersion (D); and the algal maximum growth (μ_{max}), die-off (k_{die}), and respiration rates (k_{res}). All other parameters had system wide values.

Table 2.12. Locations of the continuous monitoring and ambient water-quality sampling stations of the Metropolitan Water Reclamation District of Greater Chicago in the modeled portion of the Chicago Area Waterway System used for calibration and verification

Station Location	Data Available	Waterway	River Mile*
Central Street	WQ	NorthShore Channel	49.4
Simpson Street	DO	NorthShore Channel	48.5
Main Street	DO	NorthShore Channel	46.7
Oakton Street	WQ	NorthShore Channel	46
Touhy Avenue	WQ	NorthShore Channel	45.2
Foster Avenue	WQ	NorthShore Channel	44
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
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
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	DO	Little Calumet River (south)	30.3
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 Avenue	DO	Calumet-Sag Channel	16.3
Route 83	DO, WQ	Calumet-Sag Channel	13.3
Interstate 55 (I-55)	DO	Bubbly Creek	29.4

Notes: DO = Continuous (hourly) dissolved oxygen and temperature data; WQ= Monthly grab sample water quality data
* River miles for the Chicago Waterway System often are described relative to the confluence of the Illinois River with the Mississippi River at Grafton, Ill., in this case the River Mile for Lockport is 291, and all of the values can have 291 added to them to give river mile values relative to the mouth of the Illinois River.

Diffusive exchange rate constant, $E_{dif,}$ (m^2/day): Oxygen demand by benthic sediments and organisms has historically represented a large fraction of oxygen consumption in the CAWS (CDM, 1992). 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:

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

where:

SOD = Sediment Oxygen Demand (g/m^2-d)

E_{dif} = Diffusive exchange rate constant (m^2/d)

HB = Depth of sediment top layer (m)

$O2_w$ = Water column DO concentration (mg/L)

$O2_B$ = DO concentration in the pore water in the sediment bed (mg/L)

A default initial value for $O2_B$ was used and then the value of $O2_B$ was computed over time throughout the simulation on the basis of the DO balance for the sediments, which is dominated by the E_{dif} values that have been calibrated to match, on average, the SOD values measured by the MWRDGC at 18 locations in the CAWS in 2001 (see Melching et al. (2010) and Section 5.2.2).

$CBOD_5$ water column oxidation rate and nitrification rate constant (day^{-1}): $CBOD_5$ decay and nitrification constants (k_{BOD} and k_{nit}) play important roles in water-quality models. Different values were determined for different reaches by calibration. Since the values of k_{BOD} and k_{nit} were determined in model calibration, it should be noted that the calibrated values have limited physical significance. That is, the rate constants were adjusted to fit measured bulk water quality data, and, thus, account for multiple processes that may affect the concentration of the individual water-quality constituents. Thus, one cannot automatically assume that a reach with a higher rate constant has more biological activity. That is, nitrification, CBOD decay, reaeration, SOD, algal activities, and hydraulic characteristics, such as diffusion, dispersion, and advection are some of the processes that have incremental effects on bulk water quality concentrations in the CAWS. Since the constants that are related to these processes were not measured in the CAWS, the rate constants in the DUFLOW model were adjusted to match the measured concentrations. Furthermore, there are other processes that were not considered in the calibration process and default values were assumed to represent the parameters affecting these processes. Therefore, there is a chance that effects of some processes are embedded in different parameters during the calibration process.

Dispersion, D, (m^2/s): The model requires entering a dispersion coefficient 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. In this study, the dispersion coefficienthas been calibrated based on the flow characteristics of a given reach in the CAWS and the effects of dispersion on the DO in the CAWS.

Reaeration-rate coefficient, k_{aer}: In DUFLOW the reaeration-rate coefficient is automatically calculated by the model using the O'Connor-Dobbins (1958) formula:

$$k=3.94*V^{0.5}/H^{1.5}$$

where k= reaeration-rate coefficient, d^{-1}

V = Velocity, m/s

H = Water depth, m

A modified O'Connor-Dobbins formula also was used to compute the reaeration-rate coefficient in the MSD (1976) application of the extended Streeter-Phelps model to the CAWS.

Algal Simulation Parameters: Algal maximum growth rate (μ_{max}), die-off rate (k_{die}), settling rate, and respiration rate (k_{res}) are the algal rate parameters used in the EUTROF2 routines of the DUFLOW model. In general, algal growth is limited by the availability of nutrients and light, and also is affected by temperature. The availability of light energy is limited by 1) the clarity of the water, which is a function of the sediment load and algal self-shading, 2) the presence of canopy cover over the waterway, and 3) the depth of the water. Algae also typically need low velocity flows and low turbulence to grow in a water body. Light intensity is related to incoming solar radiation, and, thus, hourly solar radiation data from Argonne National Laboratory was used as an input for the simulation. As previously explained temperature also varies spatially and temporally in the water-quality model. A default settling rate value was used in the calibration process.

Calibrated Model Parameters: The values of the diffusive exchange rate coefficient (E_{dif}), $CBOD_5$ water column oxidation rate (k_{bod}), nitrification rate constant (k_{nit}), dispersion coefficient (D), and algal parameters determined by calibration are listed in Table 2.13 for each reach. For all other model coefficients and parameters, default values given in EUTROF2 were used (see Appendix A in Melching et al. (2010)).

Table 2.13. Reach variable calibration parameters used in the DUFLOW water-quality model for Water Year 2003

Reach Name	Waterway	River Mile from Lockport	K_{bod} (day^{-1})	K_{nit} (day^{-1})	E_{dif} (m^2/day)	D (m^2/s)	μ_{max}	k_{die}	k_{res}
C1	NorthShore Channel	50-46	0.15	1.2	0.014	25	1	0.05*	0.1*
C2.1	NorthShore Channel	46-42.6	0.1	1.2	0.002	50	1	0.05*	0.1*
C2.2	North Branch	42.6-37	0.1	1.2	0.002	60	1	0.05*	0.1*
C3	North Branch	37-35.5	0.01	0.01	0.001	60	1	0.05*	0.1*
C4	North Branch	35.5-34.5	0.01	0.01	0.001	60	1	0.05*	0.1*
C5	Main Stem	34.5-36	0.01	0.01	0.0002*	10	1	0.05*	0.1*
C6	South Branch	34.5-31	0.1	1	0.005	60	1	0.05*	0.1*
C7	CSSC	31-25	0.15	1	0.004	1000	1	0.05*	0.1*
C8	CSSC	25-17	0.01	0.01	0	60	1	0.05*	0.1*
C9	CSSC	17-12.5	0.01	0.05	0	60	1	0.05*	0.1*
C15	CSSC	12.5-8	0.05	0.05	0	50	1	0.05*	0.1*
C16	CSSC	8-2.2	0.05	0.05	0	50	1	0.05*	0.1*
C11	Calumet and Little Calumet (N)	35.5-30.5	0.10	0.5	0.002**	15	1	0.2	0.1*
C12	Little Calumet (N)	30.5-28.5	0.1	0.5	0.004	15	1.5	0.2	0.1*
C13	Calumet-Sag	28.5-19	0.1	0.5	0.004	15	1.5	0.2	0.1*
C14	Calumet-Sag	19-12.5	0.1	0.5	0.004	10	1	0.2	0.1*
C17	Bubbly Creek		0.15	1.2	0.012	150	1	0.05*	0.1*
C18	Little Calumet (S)		0.035	0.3	0.002	15	1	0.05*	0.1*

* Default value (see Appendix A)

** Within Reach C11 the portion from O'Brien Lock and Dam to the junction with the GrandCalumetRiver has an E_{dif} value of 0.0002, which is the default value.

The typical ranges of parameter values from the water quality modeling literature for the parameters in Table 2.13 except for E_{dif} and D are listed as follows:

Parameter	Minimum	Maximum	Source
K_{bod} (day^{-1})	0.02	3.2	Brown and Barnwell (1987)
K_{nit} (day^{-1})*	0.1	1.0	Brown and Barnwell (1987)
μ_{max}	1.0	5.0	DUFLOW (2000)
k_{die}	0.0	0.3	DUFLOW (2000)
k_{res}	0.05	0.2	DUFLOW (2000)

*The ranges for QUAL2EU (Brown and Barnwell, 1987) are not strictly appropriate for DUFLOW because QUAL2EU considers the transformation of ammonia to nitrite to nitrate whereas in DUFLOW ammonia transforms directly to nitrate.

For Salt Creek in western Cook County and Eastern Du Page County, Illinois, in laboratory 20-day "bottle" measurements of CBOD indicated that K_{bod} ranged between 0.113 and 0.159 day^{-1} (Melching and Chang, 1996). Thus, the values applied in the DUFLOW model of the CAWS are generally within the ranges reported in the water-quality modeling literature.

Brown and Barnwell (1987) reported a value of D for the CSSC of 3 m^2/s and a range of D values from 4.6 to 1,480 m^2/s for rivers in the U.S. The values used in this study are higher than those found in the previous study considered in Brown and Barnwell (1987), but still within a reasonable range. The high value of 1,000 m^2/s in reach C7 reflects the intense mixing caused by discharge from the Racine Avenue Pumping Station.

Finally, no range information for E_{dif} is included in the DUFLOW (2000) user's manual, and, thus, comparisons to other studies cannot be done.

2.2.4 Water Quality Verification Results

Calibration of the DUFLOW water quality model was conducted in a step-wise fashion in Melching et al. (2010). First, the simulated $CBOD_5$, ammonium, nitrate, and chlorophyll-a concentrations were compared with ranges of historic measurements. Then, simulated and measured hourly DO concentrations were compared at the 25 DO measurement locations. Finally simulated SOD values are compared with the SOD values measured in 2001. The calibration primarily focused on WY 2001 because this was the year for which CSO EMCs were measured, and, thus, the most complete data on pollutant loads to the CAWS were available.

The verification of the DUFLOW water quality model was primarily focused on WY 2003 in Melching et al. (2010) and later Melching and Liang (2013) provided additional verification for WY 2008. Because IDOT-DWR (1977) found “an analysis of dissolved oxygen levels to be an adequate indicator of water quality” the verification results for DO simulation for WY 2003 are presented in the following sections.

Simulated DO concentrations were compared with hourly measured DO concentrations at 25 locations for WY 2003. Results are presented in 4 categories: NBCR, SBCR and CSSC, Calumet-Sag Channel, and boundaries (this includes DO monitoring sites on the NSC, Chicago River main stem, and Little Calumet River (north) upstream of the Calumet WRP).

In the following subsections, the quality of the DO simulations for WY 2003 is listed by season and over the entire year. For the locations in the Chicago River main stem (Michigan Avenue and Clark Street) and nearby locations on the NBCR (Kinzie Street) and SBCR (Jackson Boulevard) the differences in simulated and measured concentrations are particularly large for winter periods. Bi-directional/stratified flow occurs in the Chicago River main stem during periods without discretionary diversion (late October to early May), particularly in winter. Research suggests that this may be caused by the use of salt for road de-icing, which could lead to an increase in salinity in the NBCR (Jackson et al., 2008). Garcia et al. (2007) reported the results of monitoring for bi-directional flow resulting from density currents in and near the Chicago River main stem during the period from November 20, 2003 to February 1, 2004. They found that during the observation period 28 density current events occurred lasting a total of 77% of the time. Sixteen of these events were generated by underflows from the NBCR and 12 of these events were generated by overflows from the NBCR. Further, Jackson et al. (2008) noted that the underflow events were driven by differences in salinity and overflows were driven by differences in temperature. Finally, Garcia et al. (2007) noted that the plunge point for the density currents can be upstream of Grand Avenue (which is upstream of Kinzie Street) and that the overflow events may propagate into the SBCR. Garcia et al. (2006) noted that the greater the density difference, the farther upstream on the NBCR the plunging point is observed.

The DUFLOW model is a one-dimensional model that assumes complete mixing over a cross section, and as such it cannot simulate the details of the stratified flow. However, the DO concentrations obtained by simulation in the winter (and also in the late fall and early spring) reflect the total pollution load in the cross section whereas the DO measurement sondes typically are located 3 ft below the water surface (Polls, 2002) and the measured DO concentrations primarily reflect the surface layer which has higher DO concentrations than the bottom layer because of the contact with the atmosphere. Thus, the poor agreement between the measured and simulated DO concentrations in the winter (and other times with stratified flows) in and near the Chicago River main stem are a result of the physics of flows in the CAWS. It is also interesting to note that the extended Streeter-Phelps model used by the MWRDGC (MSD, 1976) to simulate DO in the CAWS underestimated the measured DO concentrations by 1.02 mg/L on average for winter 1973 conditions. Thus, the bi-directional flow effects on water-quality grab samples may have also been present in 1973 and affected the verification of the extended Streeter-Phelps model.

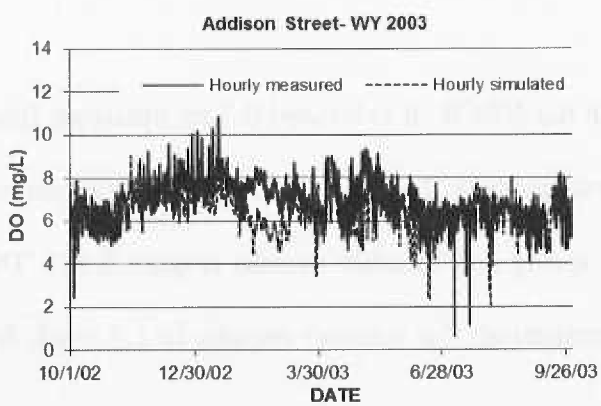
2.2.4.1 North Branch Chicago River

Simulation of DO concentrations on the NBCR was calibrated starting from upstream to downstream locations. This section of the CAWS is divided into 3 reaches and the following continuous DO monitoring stations represent each reach: i) Addison Street and Fullerton Avenue, ii) Division Street, and iii) Kinzie Street. A statistical comparison between seasonally averaged hourly simulated and measured DO concentrations is listed in Table 2.14, where fall is defined as September-November, winter is defined as December-February, spring is defined as March-May, and summer is defined as June-August. In all cases, the average percent error is less than 10 % indicating unbiased estimates of DO concentrations are obtained throughout these reaches.

Table 2.14. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the North Branch Chicago River, Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

Season	Addison Street			Fullerton Avenue			Division Street			Kinzie Street		
	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. Mg/L	Sim. mg/L	error mg/L
Fall	6.4	6.4	0.0	5.8	6.1	0.3	6.3	6.2	-0.1	5.8	6.1	0.3
Winter	7.7	6.7	-1.1	7.1	5.9	-1.2	7.4	5.6	-1.7	7.3	5.5	-1.8
Spring	7.1	6.5	-0.7	6.0	5.8	-0.1	6.4	5.8	-0.6	6.2	5.6	-0.6
Summer	6.3	5.9	-0.4	4.8	5.6	0.8	5.7	6.4	0.7	4.9	6.2	1.3
Overall Average	6.9	6.4		5.9	5.8		6.4	6.0		6.0	5.8	
Error	-0.5			-0.1			-0.4			-0.2		
% Error	-7.8			-0.9			-6.6			-3.1		

The Addison Street DO monitoring site is the first station at which the combined effects of the upper NBCR flow, O'BrienWRP flow, and the Devon Avenue in-stream aeration station are observed. Figure 2.11 shows good agreement between the simulated and measured DO concentrations especially at both Addison Street and Fullerton Avenue. The average percent error in the simulated hourly average DO concentrations is -7.8% at Addison Street in WY 2003. The general trend of DO concentration fluctuations throughout the simulation period is well captured at Fullerton Avenue. The highest error between the seasonally averaged values of the simulated and the measured DO concentrations are observed for winter months. The model tends to underestimate the DO concentrations in winter months with seasonally averaged errors of -1.1 and -1.2 mg/L for WY 2003 for Addison Street and Fullerton Avenue, respectively. The seasonally averaged error for summer in which the lowest DO concentrations are measured is less than 0.8 mg/L for both locations.



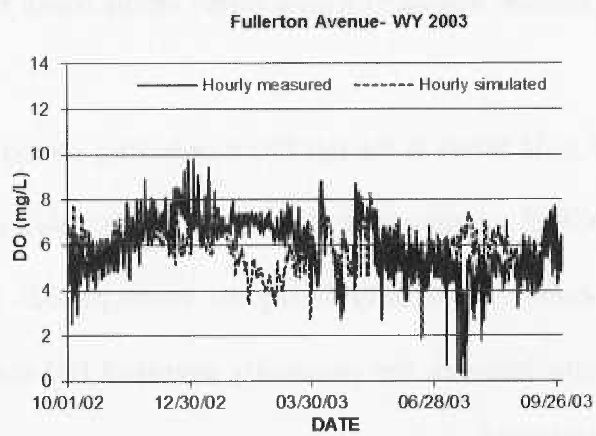


Figure 2.11. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Addison Street and Fullerton Avenue on the North Branch Chicago River for Water Year 2003

Division Street is the first DO monitoring station downstream from the Webster Avenue IAS. The Webster Avenue IAS causes a significant DO increase at downstream locations. Comparison of simulated and measured DO concentrations at Division Street is shown in Figure 2.12.Measured and simulated DO concentrations at Division Street (Figure 2.12) are in close agreement for most of the simulation period except for winter months in 2003. The overall average simulated and measured hourly DO concentrations are 6.4 mg/L and 6.0 mg/L, respectively, and the overall average error is less than 6.6 % for WY 2003.

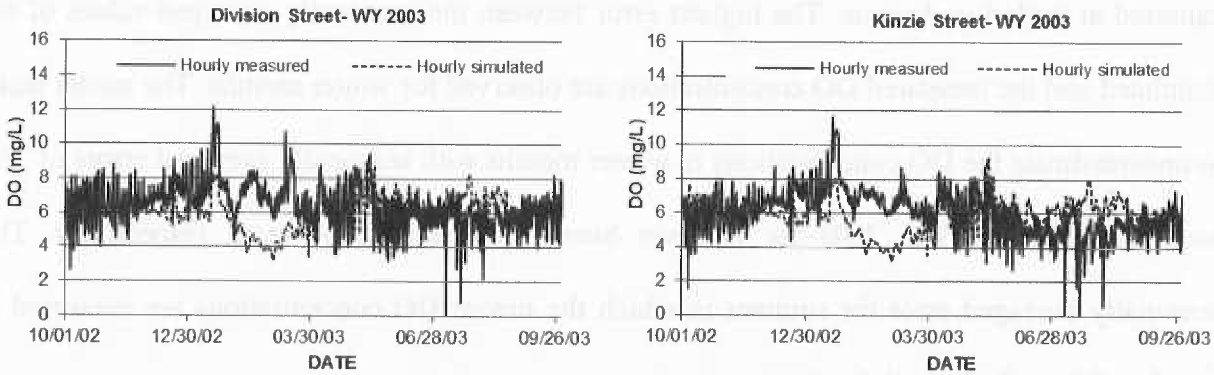


Figure 2.12. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Division Streetand Kinzie Street on the North Branch Chicago River for Water Year 2003

Kinzie Street is the last DO monitoring station on the NBCR. It is located 0.2 mi upstream from NBCR junction with the Chicago River main stem and SBCR. Very low DO concentrations are observed especially during the storm periods in spring and summer months (Figure 2.12). The error between the seasonally averaged DO concentrations for summer months is 1.3 mg/L for WY 2003.

2.2.4.2 South Branch Chicago River and Chicago Sanitary and Ship Canal

Since all locations are linked to each other, the approach of first calibrating upstream locations did not work in the SBCR and CSSC section of the river system. This section is divided into 6 reaches and the following DO monitoring stations represent each reach: i) Jackson Boulevard, ii) Cicero Avenue, iii) Baltimore and Ohio Railroad, iv) Route 83, v) River Mile 11.6, and vi)

Romeoville. A statistical comparison between seasonally averaged simulated and measured hourly DO concentrations for all locations upstream of the junction with the Calumet-Sag Channel is listed in Table 2.15. In all cases the average percent error is less than 13% indicating unbiased estimates of DO concentrations are obtained throughout these reaches.

Table 2.15. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the South Branch Chicago River and Chicago Sanitary and Ship Canal, Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

	Jackson Boulevard			**Cicero Avenue**			**Baltimore and Ohio RR**			**Route 83**		
Season	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	Error mg/L
Fall	6.4	5.9	-0.5	5.1	5.2	0.1	6.3	6.0	-0.3	5.5	5.9	0.4
Winter	7.1	5.1	-2.1	6.4	5.5	-0.9	8.1	6.7	-1.4	7.6	6.8	-0.8
Spring	6.2	5.0	-1.2	4.9	3.8	-1.1	6.6	5.4	-1.2	5.2	5.5	0.2
Summer	6.0	6.5	0.5	4.3	4.7	0.3	5.5	5.5	0.1	3.7	5.4	1.7
Overall Average	6.4	5.6		5.2	4.8		6.6	5.9		5.5	5.9	
Error	-0.8			-0.4			-0.7			0.4		
% Error	-12.7			-7.6			-10.7			7.3		

Jackson Boulevard is located just downstream of the junction of the NBCR, SBCR, and Chicago River main stem. Simulated and measured DO concentrations are shown in Figure 2.13. The simulated DO concentrations follow the general trend of the measured DO concentrations very well. The lowest DO concentrations are observed in the summer months and the average errors in simulated seasonally averaged hourly DO concentrations for the summer of 2003 is 0.5 mg/L. The model tends, by design, to underestimate measured DO concentrations during significant storm events.That is, throughout the calibration process it was aimed to matchhourly measured and simulated DO concentrations as much aspossible. On the other hand, as Harremoes et al. (1996)mentioned,it is almost impossible to match all the measured hourly data ifthere are a large number of data to be fitted to. It was particularlyhard to match measured DO concentrations over the entire simulationperiod at certain locations that are dominated by CSO flows,such as the NSC. Thus, model calibration wasdone manually via a conservative approach, in which the goal wasto better match the lower DO concentrations resulting from CSOsand produce similar probability of exceedence for different DOconcentrations. Using this approach, the simulations of anymanagement alternative (such as discretionary diversion) that can bring simulated DO concentrations todesired levels can also work well in the actual situation.In particular, the target of the discretionary diversion allocations to bring the water-quality conditions to desired levels requires solutions for the periods where very low DO concentrations are observed. Hence, because the model tends to underestimate DO concentrations during storm-affected periods, if the model results indicate a discretionary diversion allocation can bring simulated DO concentrations to a target level, actual DO concentrations would be expected to be equal to or greater than the simulated DO concentrations.

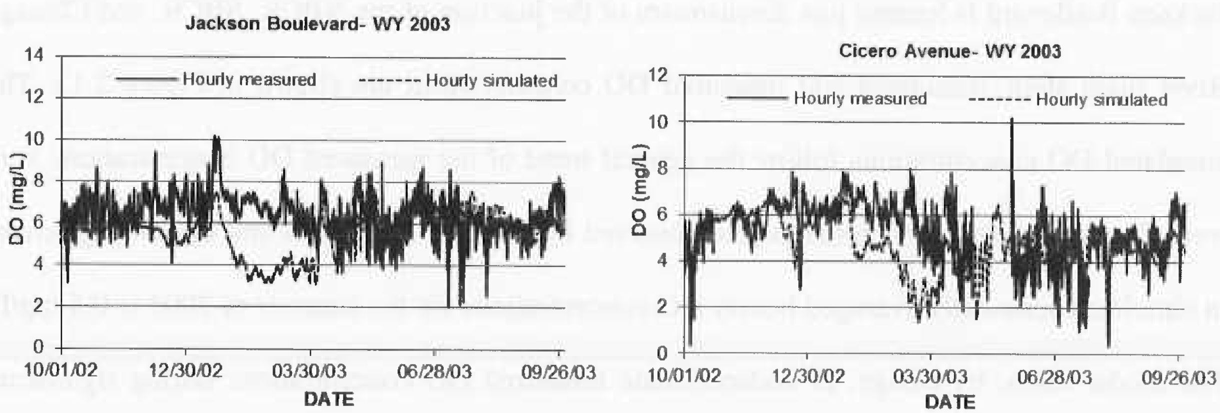


Figure 2.13. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Jackson Boulevard on the South Branch Chicago River and Cicero Avenue on the Chicago Sanitary and Ship Canal for Water Year 2003

Cicero Avenue is located between the Racine Avenue Pump Station and the Stickney WRP and it is possible to see the effect of both of these point sources on DO concentrations at this station (Figure 2.13). Most of the time flow from the Stickney WRP is greater than the flows from upstream of the plant. The hydraulic simulation results have found that because of the generally low flow gradient throughout the CAWS, the flow leaving the Stickney WRPmay flow both ways (upstream and downstream) when leaving the plant. The complexity of the hydraulic behavior of the CAWS makes this station one of the most difficult locations to calibrate. The average percent error in seasonally averaged hourly DO concentrations is less than 10% for WY 2003. Measured and simulated DO concentrations at Cicero Avenue have very close agreement for most of the periods where extremely low DO concentrations are observed, especially the July-August period, and the average error in seasonally averaged hourly DO concentrations for summer months is 0.3 mg/L for WY 2003.

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 average measured hourly DO concentration at B&O RR in summer months is 1.2 mg/L higher for WY 2003 than that at Cicero Avenue. The DO concentrations fluctuate between 4-10 mg/L and go down to 2 mg/L during significant storms (Figure 2.14). The simulated DO concentrations agree well with measured DO concentrations and the average percent error is less than 10 %. The model captured low DO concentrations during most of the storms.

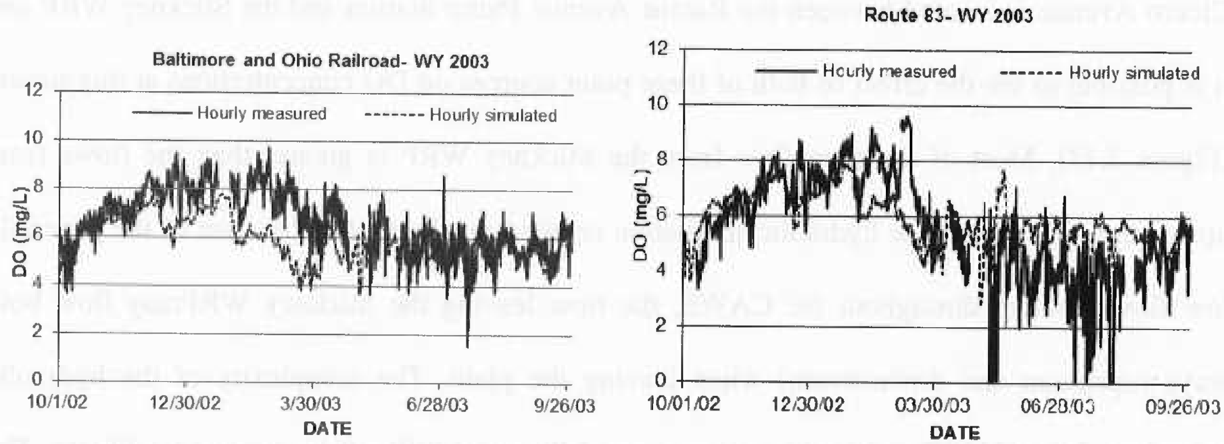


Figure 2.14. Comparison of measured and simulated dissolved oxygen (DO) concentrations at the Baltimore and Ohio Railroad and Route 83 on the Chicago Sanitary Ship Canal for Water Year 2003

The last DO measurement location on the CSSC upstream from the junction with the Calumet-Sag Channel is Route 83. The comparison of simulated and measured DO concentrations is shown in Figure 2.14. The average error between measured and simulated hourly DO concentrations for summer months in WY 2003 is 1.7 mg/L. The measured DO concentrations at Route 83 for the summer of WY 2003 seem inconsistent and prone to low values. Jennifer Wasik of the MWRDGC (2010, written communication) indicated that the Route 83 location is problematic because no bridge is available to which the DO monitor may be attached, so the monitor is attached to the shore by a chain and then suspended in the water of the CSSC. The monitor sometimes is buried by sediment after storm events (such as occurred in early May 2003) and takes inaccurate readings. The problem is corrected by a Quality Assurance/Quality Control program that requires retrieval and replacement of a DO monitoring probe every week. Thus, model calibration should not rely on the questionable measured DO concentrations. The simulated and measured DO concentrations at this location were in general agreement, as shown in Figure 2.14, since the questionable DO concentrations represent only a small portion of the measured data. Like the other DO monitoring locations on the CSSC, the model successfully matched the low DO concentrations during the major storm events in the summer.

River Mile 11.6 is located 0.8 mi downstream from the Calumet-Sag Channel junction with the CSSC. The comparison between the measured and simulated DO concentrations shows good agreement during most of the storm events (Figure 2.15) with an overall average percent error of 1.0% for the average hourly DO concentrations (Table 2.16).

Table 2.16. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the Chicago Sanitary and Ship Canal, Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

Season	River Mile 11.6 Meas. mg/L	Sim. mg/L	error mg/L	Romeoville Meas. mg/L	Sim. mg/L	error mg/L
Fall	5.8	6.0	0.3	5.4	5.9	0.4
Winter	8.0	7.1	-0.8	7.9	7.1	-0.8
Spring	6.0	6.0	0.0	5.6	5.8	0.2
Summer	4.6	5.5	0.8	4.1	5.3	1.2
Overall Average	6.1	6.1		5.8	6.0	
Error	0.1			0.3		
% Error	1.0			4.4		

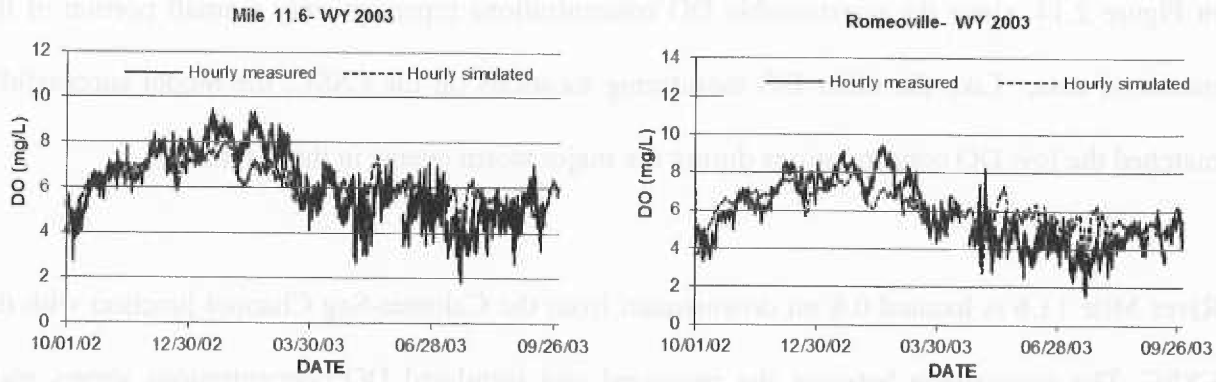


Figure 2.15. Comparison of measured and simulated dissolved oxygen (DO) concentrations at River Mile 11.6 and Romeoville Road on the Chicago Sanitary and Ship Canal for Water Year 2003

Romeoville is the most downstream point of comparison for the water-quality model. As can be seen from Figure 2.15, the simulated and measured DO concentrations are generally in good agreement and the average percent error in the average hourly DO concentrations is less than 5%. The difference between the overall average simulated and measured hourly DO concentrations for summer months is 1.2 mg/L for WY 2003 (Table 2.16).

2.2.4.3 Calumet-Sag Channel

In this section simulation results for locations between the Calumet WRP and the Calumet-Sag Channel junction with the CSSC are presented. This section is divided into 3 reaches and the following DOmonitoring stations represent each reach: i) Halsted Street, ii) Division Street, Kedzie Avenue, Cicero Avenue, Harlem Avenue, and Southwest Highway, and iii) 104th Avenue and Route 83. A statistical comparison between seasonally averaged simulated and measured hourly DO concentrations is listed in Tables 2.17 and 2.18.With the exception of 104th Avenue and Route 83, in all cases the average percent error is less than 10% for WY 2003. These results indicate that unbiased estimates of DO concentrations are obtained throughout these reaches.

Table 2.17. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the Calumet-Sag Channel and Little Calumet River (north) downstream from the Calumet Water Reclamation Plant, Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

	Halsted Street			**Division Street**			**Kedzie Avenue**			**Cicero Avenue**		
Season	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L
Fall	7.2	6.8	-0.4	6.7	6.7	0.0	7.2	6.7	-0.5	7.1	6.5	-0.6
Winter	8.2	8.4	0.2	8.8	8.5	-0.2	8.9	8.4	-0.5	8.9	8.3	-0.6
Spring	7.4	7.3	-0.1	7.2	7.3	0.2	7.6	7.6	0.0	7.6	7.4	-0.2
Summer	6.4	5.8	-0.6	5.8	5.6	-0.2	6.7	5.8	-0.8	6.2	5.6	-0.6
Overall Average	7.3	7.1		7.1	7.1		7.6	7.1		7.5	6.9	
Error	-0.2			0.0			-0.5			-0.5		
% Error	-3.3			-0.6			-6.1			-6.8		

Table 2.18. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the Calumet-Sag Channel downstream from the Calumet Water Reclamation Plant, Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

	Harlem Avenue			**Southwest Highway**			**104th Avenue**			**Route 83**		
Season	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L
Fall	7.0	6.5	-0.5	7.2	6.5	-0.7	7.1	6.3	-0.8	6.9	6.3	-0.7
Winter	9.1	8.2	-0.9	8.9	8.2	-0.7	9.7	8.2	-1.4	9.1	8.1	-1.0
Spring	7.6	7.6	0.0	7.7	7.5	-0.2	8.0	7.3	-0.7	7.5	7.1	-0.5
Summer	6.5	5.7	-0.8	6.3	5.6	-0.7	6.5	5.5	-1.1	6.8	5.4	-1.5
Overall Average	7.6	7.0		7.5	7.0		7.8	6.8		7.6	6.7	
Error	-0.5			-0.6			-1.0			-0.9		
% Error	-7.3			-7.7			-12.5			-11.9		

Halsted Street is located downstream of the Calumet WRP. The simulated DO concentrations follow the general trend of the measured DO concentrations as shown in Figure 2.16 with very close agreement in October through March The average percent error in the average hourly DO concentrations is less than 5%, and the difference between the overall average simulated and measured hourly DO concentrations in summer months is less than 0.6 mg/L.

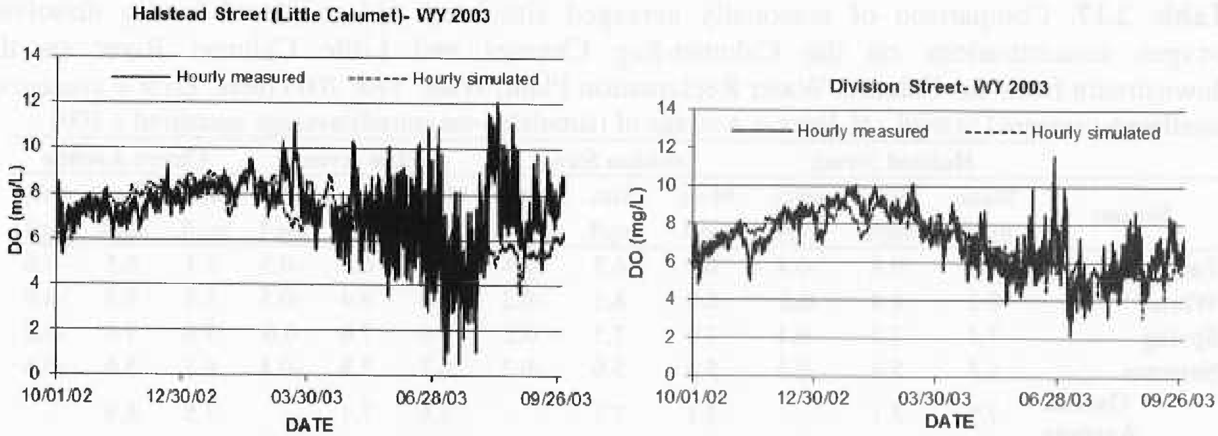


Figure 2.16. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Halsted Street on the Little Calumet River (north)and Division Street on the Calumet-Sag Channel for Water Year 2003

The comparisons of simulated and measured DO concentrations have very good agreement between Division Street and Southwest Highway. The results are shown in Figures 2.16 and 2.17. The average and percent errors in the average hourly DO concentrations are less than or equal to 0.6 mg/L and 7.7% at all locations for WY 2003. In general, comparison of the simulated and measured hourly DO concentrations for WY 2003 indicates strong agreement.

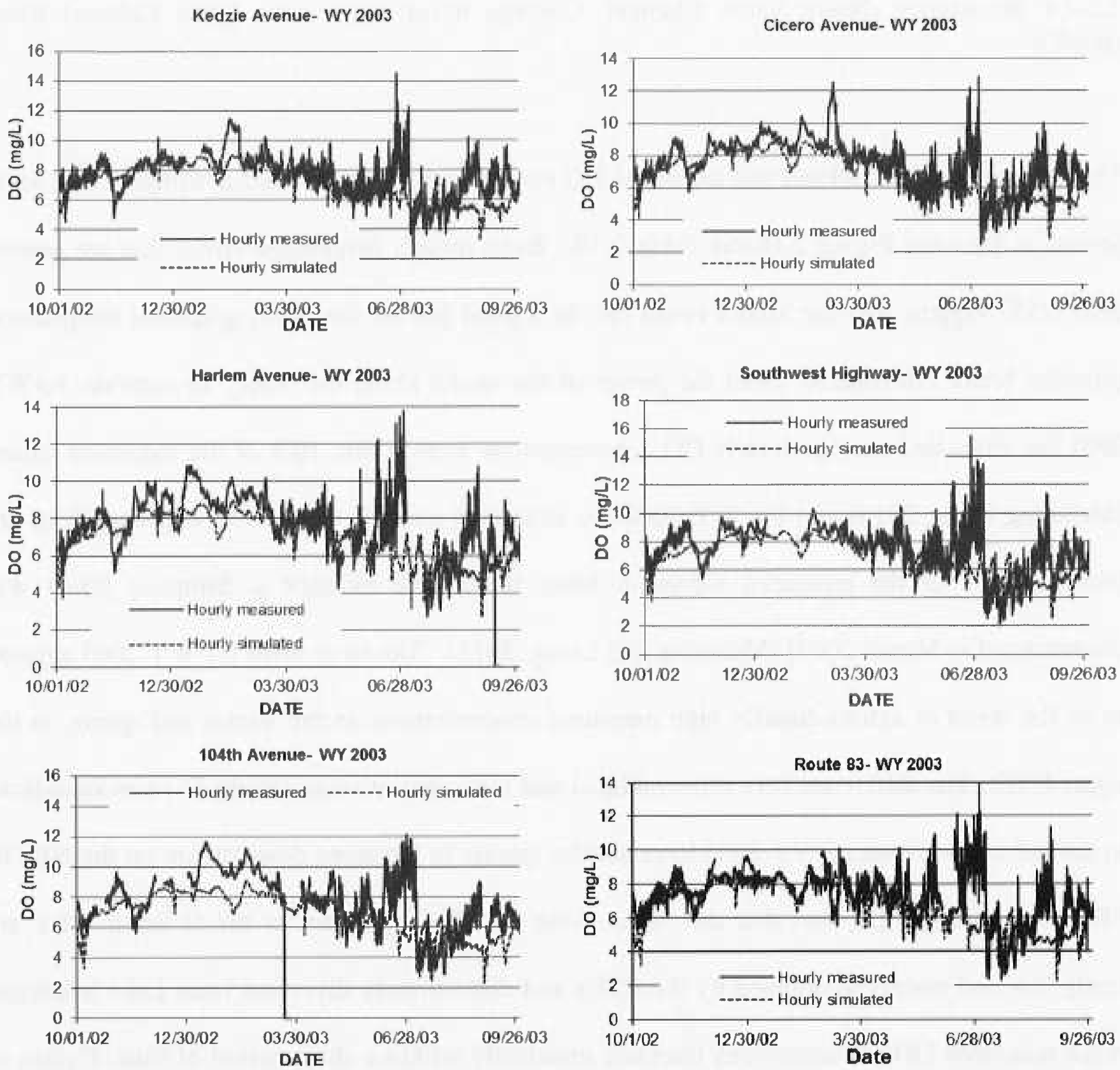


Figure 2.17. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Kedzie Avenue, Cicero Avenue, Harlem Avenue, Southwest Highway, 104th Avenue, and Route 83 on the Calumet-Sag Channel for Water Year 2003

The last DO stations on the Calumet-Sag Channel are 104th Avenue and Route 83. Just like other Calumet-Sag Channel locations, measured values were successfully simulated with the model (Figure 2.17). The average and percent errors in the average hourly DO concentrations are less than or equal to 1.0 mg/L and 12.5%, respectively.

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

The comparison of simulated and measured DO concentrations on the NSC at Simpson and Main Streets is shownin Figure 2.18and Table 2.19. Even though percentage errors that are greater than -25% suggest that the model could not do a good job on the NSC, graphical comparison provides better information about the power of the model along the NSC. In contrast, forWY 2001 the simulated average hourly DO concentrations were within 10% of the measured values (Melching et al., 2010) and for WY 2008 the simulated average hourly DO concentrations are within 11.1% of the measured values at Main Street [the monitor at Simpson Street was discontinued in March 2004] (Melching and Liang, 2013). The large error for WY 2003 appears to be the result of extraordinarily high measured concentrations in the winter and spring on the upper NSC. The difference between simulated and measured average hourly DO concentrations in the fall and summer of WY 2003 have similar quality to locations downstream on the NBCR, SBCR, and CSSC. The fact that the flows along the NSC upstream of the O'Brien WRP are really low and mainly dominated by the CSOs and discretionary diversion from Lake Michigan make measured DO concentrations fluctuate drastically within a short period of time. Cycles of extremely low and very high concentrations are the main characteristics of the DO concentration in the NSC above the O'BrienWRP during WY 2003. It is hard to attribute these fluctuations to algal activities since chlorophyll-a concentrations were low during WY 2003. It is obvious that discretionary diversion of water from Lake Michigan can bring DO concentrations almost to saturation. Whereas when there is no flow from the lake, DO concentrations can quickly go down to extremely low concentrations. The hydraulic features of the NSC and SOD play an important role in DO changes along the upper NSC. Thus, the calibration strategy along the NSC was to simulate low DO concentrations accurately and to follow the general trend of the measured DO concentration as much as possible. As shown inFigure 2.18, the model successfully predicted extremely low DO concentrations and follows the general DO trend along the NSC upstream from the O'BrienWRP.

Table 2.19. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the North Shore Channel, Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

	Simpson Street			Main Street		
Season	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L
Fall	7.4	7.1	-0.3	8.3	6.5	-1.8
Winter	13.1	6.4	-6.8	13.3	6.3	-7.0
Spring	8.0	4.0	-4.0	8.4	4.6	-3.8
Summer	5.4	6.8	1.3	6.2	6.1	-0.2
Overall Average	8.5	6.0		9.0	5.9	
Error	-2.4			-3.2		
% Error	-28.6			-35.2		

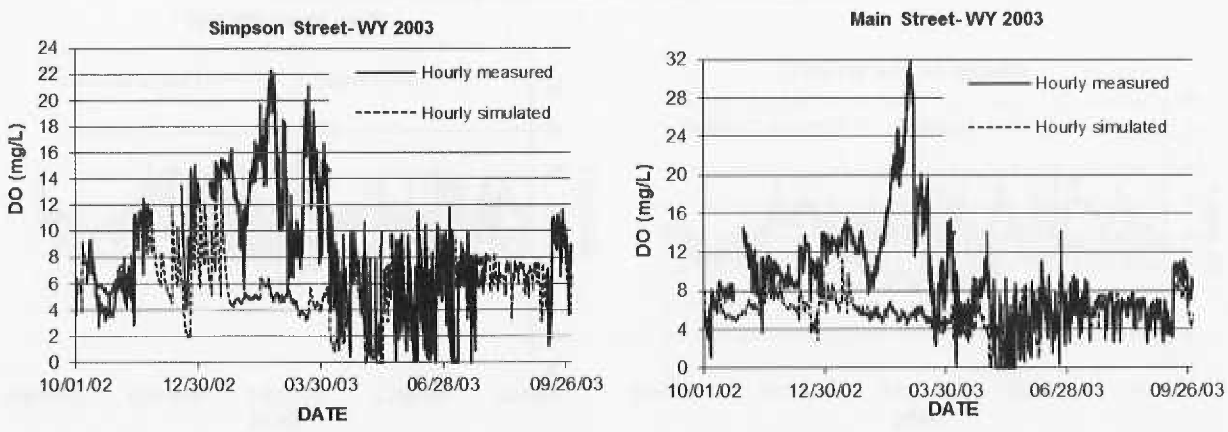


Figure 2.18. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Simpson Street and Main Street on the North Shore Channel for Water Year 2003

The Chicago River main stem results are shown in Figure 2.19. A statistical comparison between daily average simulated and measured DO concentrations is listed in Table 2.20. Big differences between the simulated and the measured DO concentrations are obvious mainly in the winter months most likely because of stratified flows as previously discussed. On the other hand, the model successfully simulated DO concentrations in summer months in which low DO concentrations are frequently observed. The average error in hourly DO concentrations in summer months of 2003 is just -0.3 mg/L at both Michigan Avenue and Clark Street.

Table 2.20. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the Chicago River Main Stem, Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

Season	Michigan Avenue Meas. mg/L	Michigan Avenue Sim. mg/L	Michigan Avenue error mg/L	Clark Street Meas. mg/L	Clark Street Sim. mg/L	Clark Street error mg/L
Fall	8.6	7.4	-1.2	8.1	6.8	-1.2
Winter	8.9	6.6	-2.3	7.7	5.9	-1.8
Spring	8.8	6.4	-2.4	7.8	5.8	-1.9
Summer	8.4	8.1	-0.3	8.1	7.8	-0.3
Overall Average	8.7	7.1		7.9	6.6	
Error	-1.6			-1.3		
% Error	-18.0			-16.7		

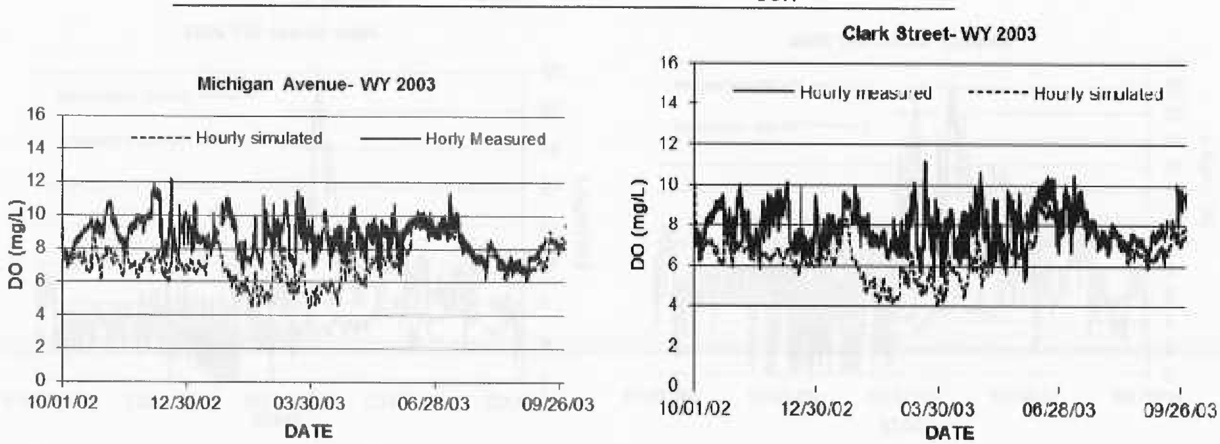


Figure 2.19. Comparison of measured and simulated dissolved oxygen (DO) concentrations on the Chicago River Main Stem at Clark Street and Michigan Avenue for Water Year 2003

The Little Calumet River (north) results are shown in Figure 2.20 and Table 2.21. The average error of average hourly DO concentrations for the summer of 2003 vary between 0 and -0.6 mg/L. However, results for fall, winter, and spring of WY 2003 are much poorer on the Little Calumet River (north). As was the case for the NSC upstream of the O'Brien WRP, the reason for the poor results appears to be the result of extraordinarily high measured DO concentrations.

Table 2.21. Comparison of seasonally averaged simulated and measured hourly dissolved oxygen concentrations on the Little Calumet River (north)for Water Year 2003 [note: Error = average of simulated–measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100]

Season	Conrail Railroad			Central and Wisconsin Railroad		
	Meas. mg/L	Sim. mg/L	error mg/L	Meas. mg/L	Sim. mg/L	error mg/L
Fall	8.9	6.9	-2.0	9.1	6.9	-2.2
Winter	13.2	8.8	-4.4	13.2	8.7	-4.5
Spring	10.0	7.3	-2.7	10.7	7.3	-3.4
Summer	6.3	5.7	-0.6	5.8	5.7	0.0
Overall Average	9.6	7.2		9.7	7.2	
Error	-2.4			-2.5		
% Error	-25.2			-26.2		

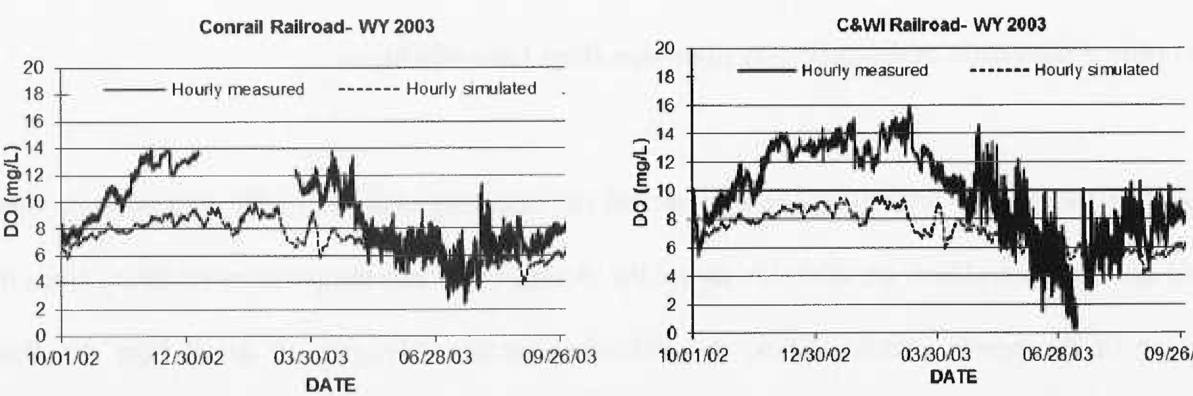


Figure 2.20. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Conrail Railroad and the Central and Wisconsin Railroad on the Little Calumet River (North)for Water Year 2003

Chapter 3 – FLOW AND TEMPERATURE CHANGES FOR THE CURRENT AND FUTURE DRAINAGE SYSTEMS EVALUATED

Whereas the DUFLOW model of the CAWS was tested and verified for the actual flow, treatment plant effluent load, and temperature conditions in WYs 2001 and 2003 in Melching et al. (2010)[results for WY 2003 are reproduced in Chapter 2] and in WYs 2001 and 2008 in Melching and Liang (2013), the evaluation of the optimal allocation of discretionary diversion must reflect current and expected future conditions. In particular, the phased completion of the TARP Reservoirs—Thornton Reservoir in 2015 and McCook Reservoir Stage 1 in 2017—will greatly affect the flows in the CAWS and the evaluation of the optimal allocation of discretionary diversion from Lake Michigan during the planning period for this study. Also, the changes in thermal power plant operations relative to the actual conditions in the representative study year, WY 2003, (i.e. the closure of the Fisk and Crawford power plants in 2012 and of the Will County Power Plant Units 1 and 2 in 2010) will affect water quality in the CAWS and, thus, the optimal allocation of discretionary diversion from Lake Michigan.

The changes in CSO inflows to the system and the resulting changes in the downstream water level boundary condition are complex as are the changes in water temperature resulting from the closure of the power plants. Thus, the following sections describe in detail how the flow, boundary condition, and temperature changes necessary to reflect the conditions during the planning period for this study were implemented in the DUFLOW simulations.

3.1 Combined Sewer Overflow and Water Reclamation Plant Flow Changes

Three CSO inflow conditions are considered in the evaluation of the optimal allocation of discretionary diversion: current CSOs, CSOs after the Thornton Reservoir becomes operational in 2015, and CSOs after the McCook Reservoir Stage 1 becomes operational in 2017. The determination of the CSO and WRP flows for these conditions are summarized in the following subsections.

3.1.1 Current Conditions

For the actual inflow conditions for WY 2003, estimates of the gravity CSO flows to the modeled portion of the CAWS were obtained from the series of models developed by the USACE, Chicago District, to simulate the flows in the TARP system. The Hydrological Simulation Program—Fortran (HSPF) is used to simulate surface and subsurface runoff from the drainage basin on the basis of precipitation measured by the network of 25 precipitation gages maintained by the ISWS as part of the accounting of flows diverted from the Lake Michigan watershed by the State of Illinois (see, for example, Westcott, 2002). The output flows from HSPF are input to the Special Contributing Area Loading Program (SCALP) which simulates the flows in the major interceptor sewers in the Chicago area. The output from the SCALP program is then input to the Tunnel Network (TNET) model, which determines which potential CSOs can enter the TARP system via the drop shafts and which will go directly to the CAWS as CSOs. A detailed discussion of the USACE models is given in Espey et al. (2004). The simulated CSO flows obtained from the USACE models then were aggregated to determine the total inflow to the CAWS from each of the 43 representative CSO locations (see Table 2.1). These aggregated CSO flows then were used to determine the optimal allocation of discretionary diversion for current conditions.

The flows from the CSO pumping stations—North Branch, Racine Avenue, and 125th Street—were determined from operational records and pump capacities. The hourly flows and daily mean constituent concentrations measured by the MWRDGC at each of the WRPs also were input to the model to simulate current conditions as described in Chapter 2.

3.1.2 Thornton Reservoir Operational (2015)

For the case of the Thornton Reservoir operational, the series of models developed for the MWRDGC by the University of Illinois (U of I) to simulate inflows to and flows through the Calumet TARP system (Cantone et al., 2011) were run to determine the CSO flows to the Calumet River system for the case of the Thornton Reservoir operational for the hydrologic conditions of the representative year, WY 2003. The U of I models indicated that no CSOs to the Calumet River system would have occurred in WY 2003 if the Thornton Reservoir had been operational. Thus, the flows for representative CSOs 19-28 (see Table 2.1) and for the 125th Street Pumping Station were set to zero to simulate the case of the Thornton Reservoir operational. The flows for representative CSOs 19-28 computed with the USACE models and for the 125th Street Pumping Station determined from operational records then were assumed to be input to the Thornton Reservoir to be pumped out and treated at the Calumet WRP when capacity is available. Figure 3.1 shows the sum of the CSOs to the Calumet River system under current (no reservoir) conditions and Thornton Reservoir operational conditions for WY 2003 as per the USACE and U of I models, respectively.

Several CSO locations are present on the Little Calumet River upstream of the USGS gage at South Holland whose flows will be affected by the operation of the Thornton Reservoir. For these locations the CSO flows from the USACE model run for current conditions (i.e. without the reservoir) were determined and summed. If the CSO flows were less than the measured flow at the South Holland gage, the CSO flows were subtracted from the 1 hr flows measured by the USGS to define the input at the boundary and the reduction in flows was considered an inflow to the Thornton Reservoir. If the CSO flows were greater than the measured flow at the South Holland gage the inflow at the boundary was set to zero, and the streamflow value was considered an inflow to the Thornton Reservoir.

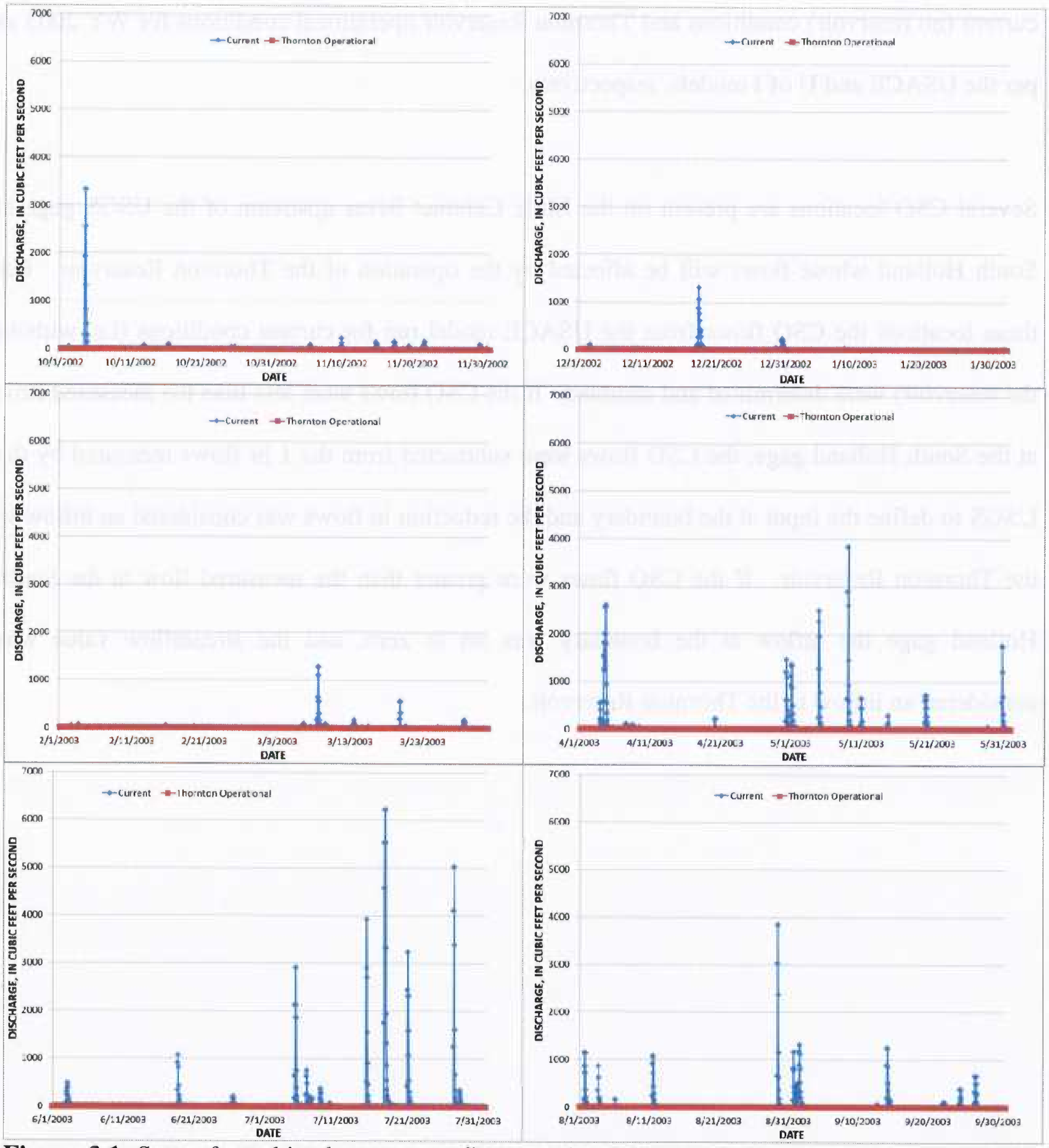


Figure 3.1. Sum of combined sewer overflows to the Calumet River system under current (no reservoir) conditions and Thornton Reservoir operational conditions for Water Year 2003.

As previously discussed the reduction in CSO inflows and boundary flows at South Holland with and without the Thornton Reservoir were summed to determine the inflow to the Thornton

Reservoir. This stored water is assumed to be pumped out from the reservoir as capacity is available at the Calumet WRP. Typically the pump out of the reservoir is started after the tunnels have been pumped out. The pump out of the tunnels is indicated in the flow record from the Calumet WRP by the periods when the WRP is discharging at or above its capacity (430 million gallons per day [mgd]). In actual operations flows above the capacity of the plant occur when the tunnels are being drained, but in this study the rate at which the reservoirs are drained is the difference between the actual inflows to the WRP and the WRP capacity. Figure 3.2 shows the storage in the Thornton Reservoir for operational conditions applied to WY 2003 and the effluent from the Calumet WRP for current (no reservoir) and Thornton Operational conditions for WY 2003.In the simulations it is assumed that the increased effluent flow has the same quality (i.e. constituent concentrations) as for the actual effluent on that day. That is, the WRP performance is assumed to be unaffected by the increased flow.

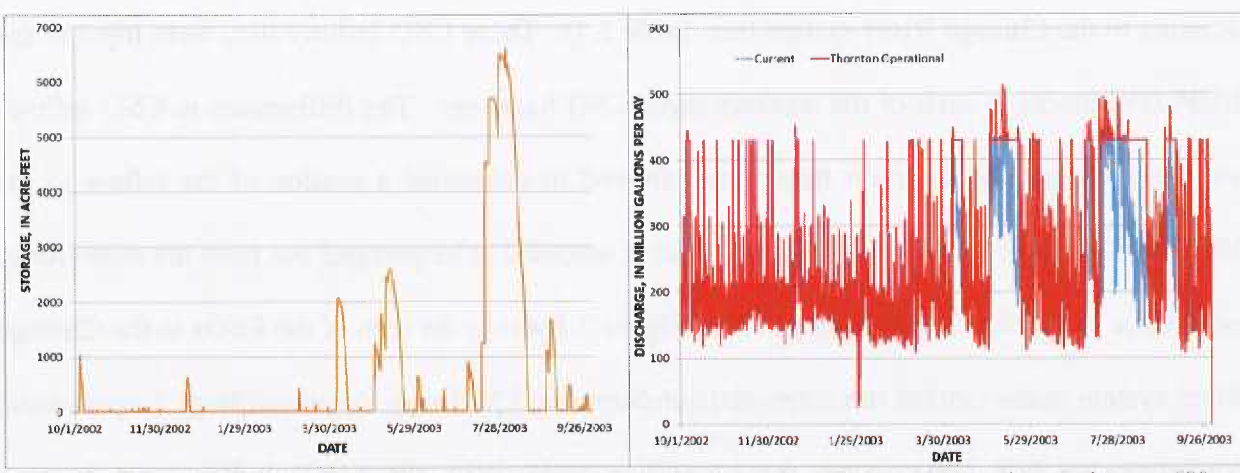


Figure 3.2. Storage in the Thornton Reservoir (left) and effluent from the Calumet Water Reclamation Plant for current (no reservoir) and Thornton Operational conditions (right) for Water Year 2003.

3.1.3 Thornton Reservoir and McCook Reservoir Stage 1 Operational (2017)

The flows from the CSOs and Calumet WRP to the Calumet River System are the same as for the case of only the Thornton Reservoir operational previously described. For the case of the McCook Reservoir Stage 1 operational, the changes in CSO, North Branch Chicago River at Albany Avenue boundary, and Stickney WRP flows are determined on the basis of the USACE models because the U of I models of the Mainstream and Des Plaines TARP tunnels and the McCook Reservoir were not completed at the time this study was done.

The USACE models were run for the hydrologic conditions of WY 2003 for the case of the McCook Reservoir Stage 1 in operation. The simulated CSO flows obtained from the USACE models for the case of the McCook Reservoir Stage 1 in operation then were aggregated to determine the total inflow to the CAWS from each of the 33 representative CSO locations draining to the Chicago River system (see Table 2.1). These CSO inflows then were input to the DUFLOW model at each of the representative CSO locations. The differences in CSO inflows with and without the reservoir then were summed to determine a portion of the inflow to the McCook Reservoir Stage 1. This stored water is assumed to be pumped out from the reservoir as capacity is available at the Stickney WRP. Figure 3.3 shows the sum of the CSOs to the Chicago River system under current (no reservoir) conditions and McCook Reservoir Stage 1 operational conditions for WY 2003 as per the USACE models. With the McCook Reservoir Stage 1 operational, May 5th, 9th, and 11th experience substantial CSO flows, and very small CSOs occur on May 1st and 10th indicating that the combined sewer flows on these dates fill the reservoir resulting in high CSO flows on the 5th, 9th, and 11th. Outside of May no CSOs occur with the McCook Reservoir Stage 1 in operation.

Several CSOs are present on the NBCR upstream of Albany Avenue whose flows will be affected by the operation of the McCook Reservoir Stage 1. For these locations the difference in the CSO flows from the USACE model runs with and without the reservoir was determined and summed for the CSO locations upstream of the USGS streamflow gage at Albany Avenue. If the difference was less than the measured flow, it was subtracted from the 1 hr flows measured by the USGS and the reduction was considered an inflow to the McCook Reservoir Stage 1. If the difference was greater than the measured flow at the Albany Avenue gage, the inflow at the boundary was set to zero, and the streamflow value was considered an inflow to the McCook Reservoir Stage 1.

Finally, the flows from the CSO pumping stations are affected by the operation of the McCook Reservoir Stage 1. For the North Branch and Racine Avenue pumping stations the percentage decrease in CSO flows for the areas tributary to these pumping stations were determined from the USACE models for the case of the McCook Reservoir Stage 1 operational relative to the case without the reservoir. The percentage reductions then were applied to the CSO flows for these pumping stations estimated from pump capacity and operations. The flow reductions at these pumping stations were considered inflows to the McCook Reservoir Stage 1.

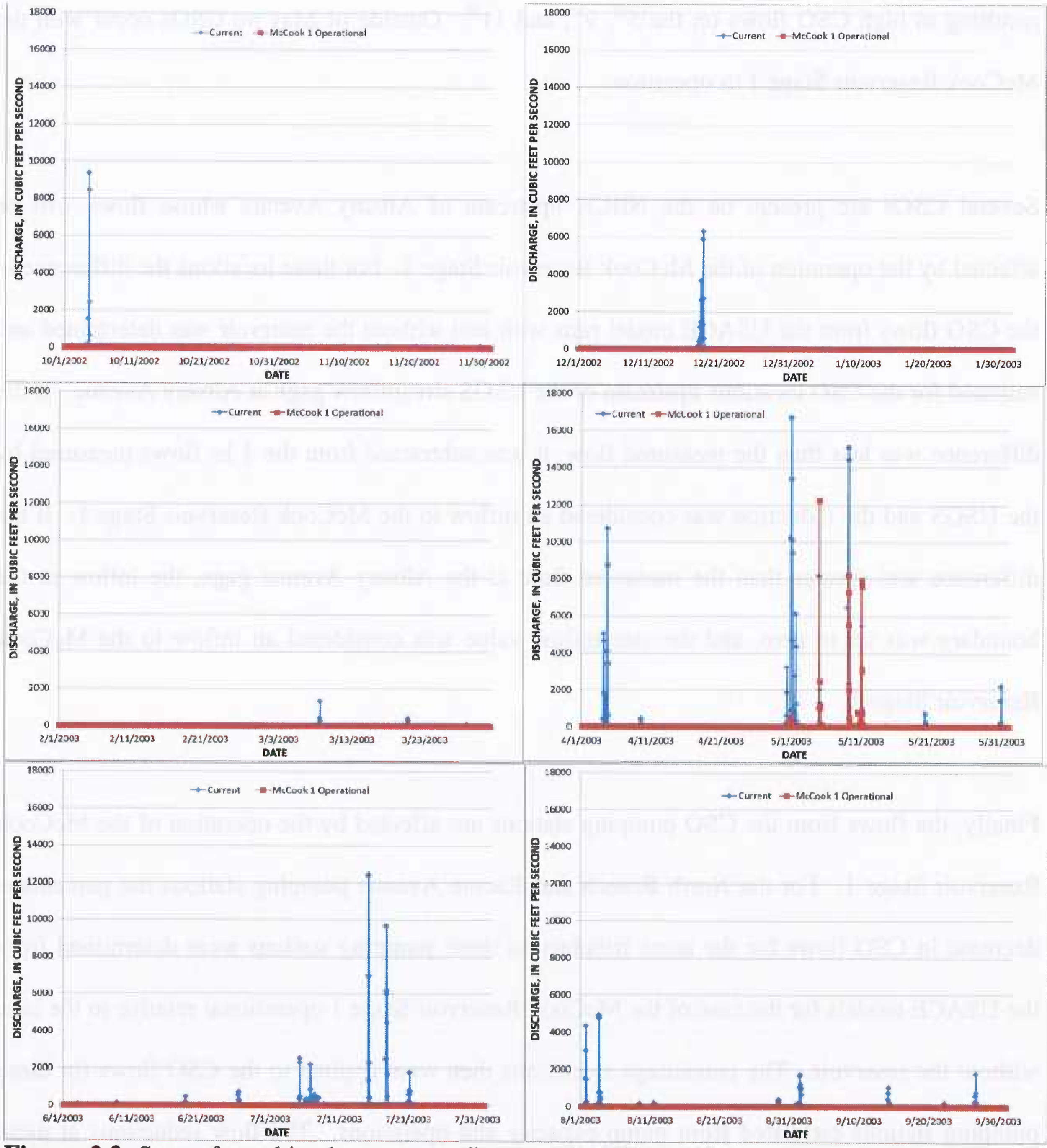


Figure 3.3. Sum of combined sewer overflows to the Chicago River system under current (no reservoir) conditions and McCook Reservoir Stage 1 operational conditions for Water Year 2003.

In total, the USACE models indicate that 83.6% of the gravity CSOs flowing into the Chicago River system in the DUFLOW model domain and 84.4% and 95.7% of the CSOs from the North Branch and Racine Avenue pumping stations, respectively, are captured by McCook Reservoir Stage 1 for WY 2003 (Melching and Liang, 2013). A similar evaluation of the performance of the Thornton Reservoir for WY 2003 using the USACE models found that 95.7% of the gravity CSOs flowing into the Calumet River system in the DUFLOW model domain and 96.8% of the CSOs from the 125th Street Pumping Stations are captured by the Thornton Reservoir (Melching and Liang, 2013). This indicates that the USACE models estimate a lower capture of CSOs by the reservoirs than are the U of I models. Thus, the post-reservoir case may need more discretionary diversion to improve simulated DO concentrations in the CAWS for this evaluation based on the USACE models than for a future evaluation considering the post-reservoir CSO flows estimated using the U of I models of the Mainstream and Des Plaines TARP tunnels and McCook Reservoir Stage 1.

As previously discussed the reductions in CSO inflows and boundary flows at Albany Avenue with and without the McCook Reservoir Stage 1 were summed to determine the inflow to the McCook Reservoir Stage 1. This stored water is assumed to be pumped out from the reservoir as capacity is available at the Stickney WRP. Typically the pump out of the reservoir is started after the tunnels have been pumped out. The pump out of the tunnels is indicated in the flow record from the WRPs by the periods when the WRP is discharging at or above its capacity (1200 mgd for the Stickney WRP). In actual operations, flows above the capacity of the plant occur when the tunnels are being drained, but in this study the rate at which the reservoirs are drained is the difference between the actual inflows to the WRP and the WRP capacity. Figure

3.4 shows the storage in the McCook Reservoir Stage 1 for operational conditions applied to WY 2003 and the effluent from the Stickney WRP for current (no reservoir) and McCook Stage 1 Operational conditions for WY 2003. In the simulations, it also is assumed that the increased effluent flow has the same quality (i.e. constituent concentrations) as for the actual effluent on that day. That is, the WRP performance is assumed to be unaffected by the increased flow. Similarly, the concentrations of pollutants in the CSOs are considered the same as for the actual conditions in WY 2003 (see Chapter 2). Thus, it is assumed that the reduction in "first flush effects" and subsequent reduction in the concentration of pollutants in the CSOs accomplished by the TARP tunnels adequately describes the capture of pollutants by the reservoirs.

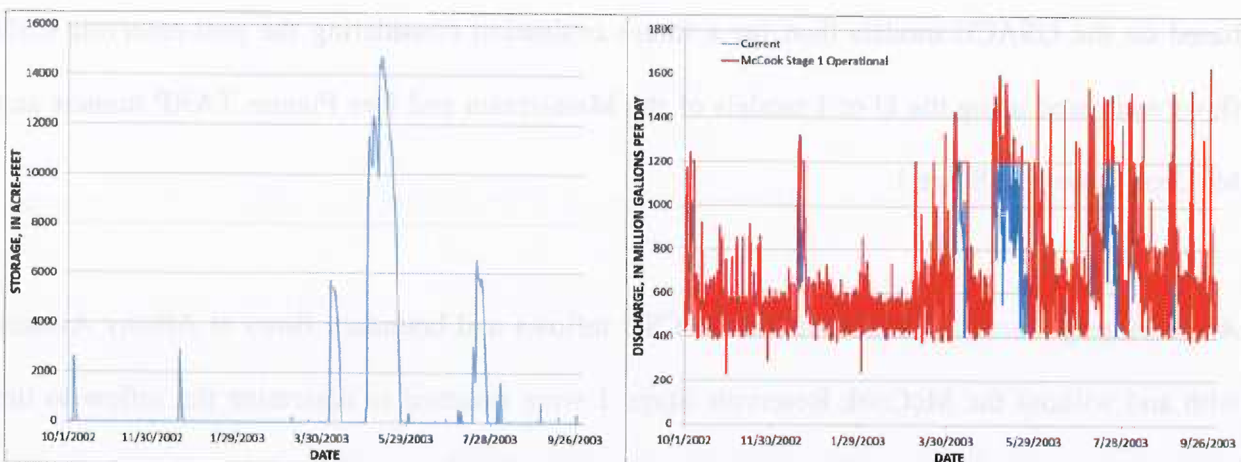


Figure 3.4. Storage in the McCook Reservoir Stage 1 (left) and effluent from the Stickney Water Reclamation Plant for current (no reservoir) and McCook Reservoir Stage 1 Operational conditions (right) for Water Year 2003.

3.2 Change in Downstream Boundary Water Levels

The downstream boundary condition for the calibrated and verified DUFLOW hydraulic model is the measured hourly water level at the Lockport Controlling Works. The changes in flows coming into the system for (a) the Thornton Reservoir operational case and (b) the Thornton Reservoir and McCook Reservoir Stage 1 operational case will affect the downstream water levels. Thus, an approach must be determined to appropriately modify the downstream water levels in response to the reduction in flows in the CAWS. Changes in low flows occur because of the changes in discretionary diversion evaluated in this study and changes in high flows occur because of the large changes in CSO flows described in Section 3.1. This section describes how these two changes were accounted for in the DUFLOW modeling of the evaluation of optimal allocations of discretionary diversion for cases (a) and (b).

In order to understand the relation between flow and water level (stage) at the downstream end of the CSSC, hourly flow data at the Romeoville and Lemont gages were obtained from the USGS and hourly water level (stage) data at the Lockport Controlling Works were obtained from the MWRDGC. Finally, operational data for the Lockport Powerhouse (number of turbines on and number of sluice gates open) and Lockport Controlling Works (number of gates open) were obtained from the MWRDGC. Flow and stage then were compared for the wide range of turbine, sluice gate, and controlling works gate operations. Low (dry weather) flows typically only pass through the turbines at the Lockport Powerhouse. Figure 3.5 shows the relation between flow at Romeoville or Lemont and stage at the Lockport Controlling Works for the cases of one and two turbines on at the Lockport Powerhouse and no sluice gates or controlling works gates open. From Figure 3.5 it is clear when only the turbines are operating a wide range of flows can pass through the lower reaches of the CSSC for the same water level (stage). Thus, the relatively small reductions (compared to the sum of the flows from the WRPs and tributary streams) in the dry weather flow resulting from the changes in discretionary diversion relative to the actual discretionary diversion in WY 2003 were assumed to not substantially affect the stages at the Lockport Controlling Works and the measured stages were used as the downstream boundary condition for the dry weather periods that experienced a change in discretionary diversion.

Properly characterizing the changes in stage at the downstream boundary resulting from the large reductions in storm flows reported in Section 3.1 is more complex. Figure 3.6 shows the relation between flow at Romeoville or Lemont and stage at the Lockport Controlling Works for the cases of one turbine on at the Lockport Powerhouse and various combinations of sluice gates and/or controlling works gates open (similar figures for two turbines on are shown in Addendum G of Melching and Liang (2013)). For the figures within Figure 3.6 it is clear that the flows passing through the lower CSSC are strongly related to the number of gates open. That is, a relatively narrow range of flows (range around 2000 to 3000 cfs) for a wide range in stages (range around 4 to 7 ft) for the different combinations of gate openings. Thus, flow through the lower CSSC is primarily a function the number of gates open and is less dependent on the downstream stage. Thus, if the change in the number of gates open resulting from the decrease in CSO flows because of the presence of the reservoirs can be reasonably determined, a good approximation of the change in the stage at the Lockport Controlling Works can be made and used for the revised downstream boundary condition.

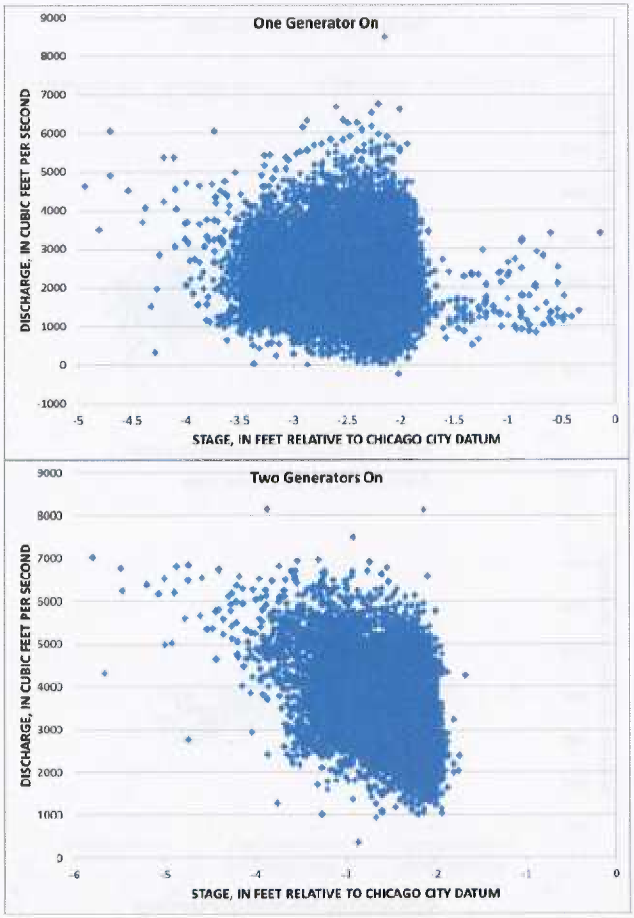


Figure 3.5. Relation between discharge at Romeoville or Lemont and stage at the Lockport Controlling Works for the cases of one generator (left) and two generators (right) on at the Lockport Powerhouse and no sluice gates or controlling works gates open.

Figure 3.7 shows the sum of all inflows to the CAWS for WY 2003 for the current (no reservoirs) and Thornton Reservoir operational conditions, and Figure 3.8 shows the sum of all inflows to the CAWS for WY 2003 for the current (no reservoirs) and Thornton Reservoir and McCook Reservoir Stage 1 operational conditions. It should be noted for the majority of the time the three conditions yield nearly identical total inflow values.

Figure 3.6. Relation between flow at Romeoville or Lemont and stage at the Lockport Controlling Works for the cases of one generator on at the Lockport Powerhouse and various numbers of powerhouse sluice gates and/or controlling works gates open.

Figure 3.6. (cont.) Relation between flow at Romeoville or Lemont and stage at the Lockport Controlling Works for the cases of one generator on at the Lockport Powerhouse and various numbers of powerhouse sluice gates and/or controlling works gates open.

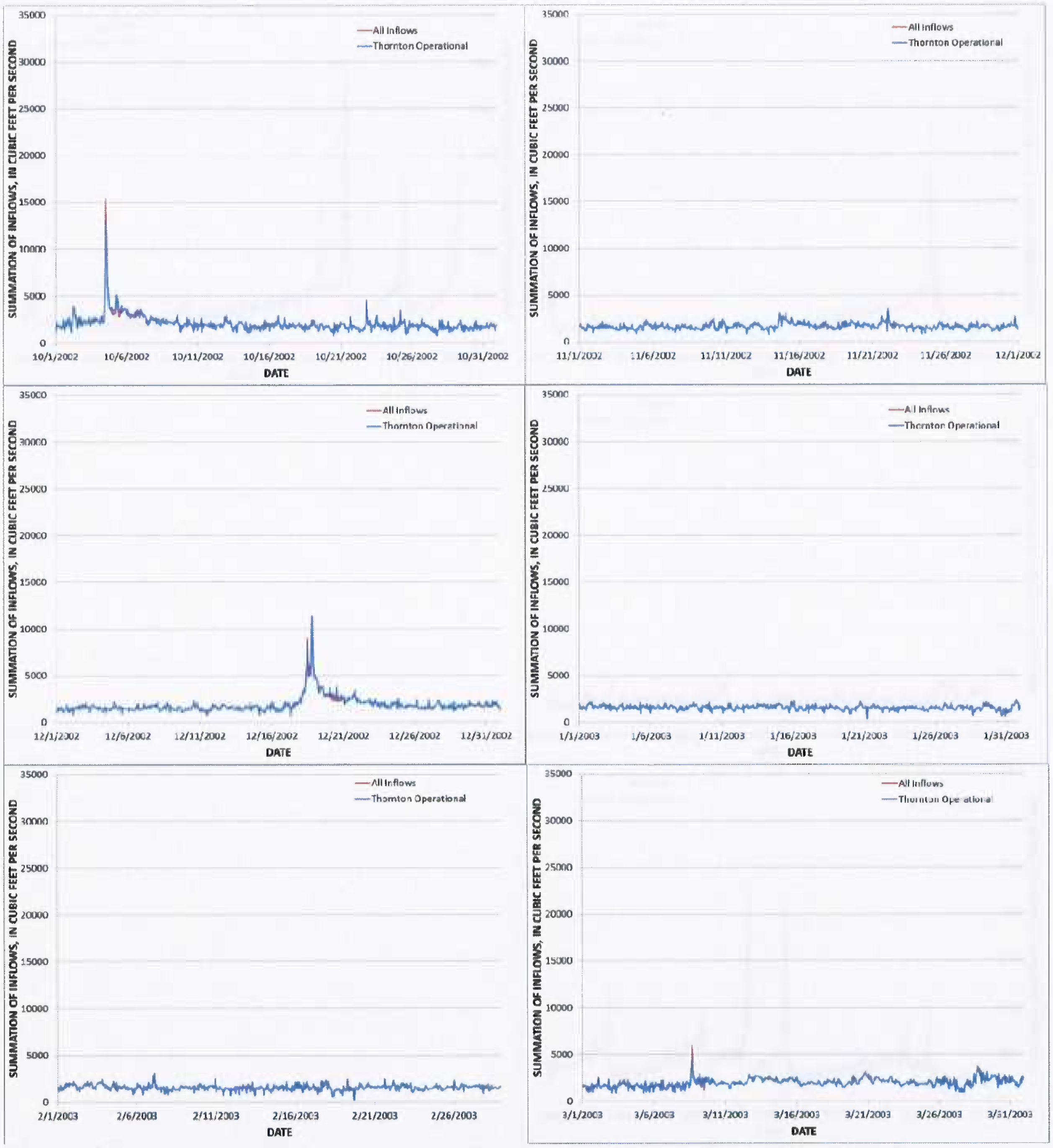


Figure 3.7. Comparison of the sum of inflows to the Chicago Area Waterway System for the Current and Thornton Reservoir operational conditions for Water Year 2003.

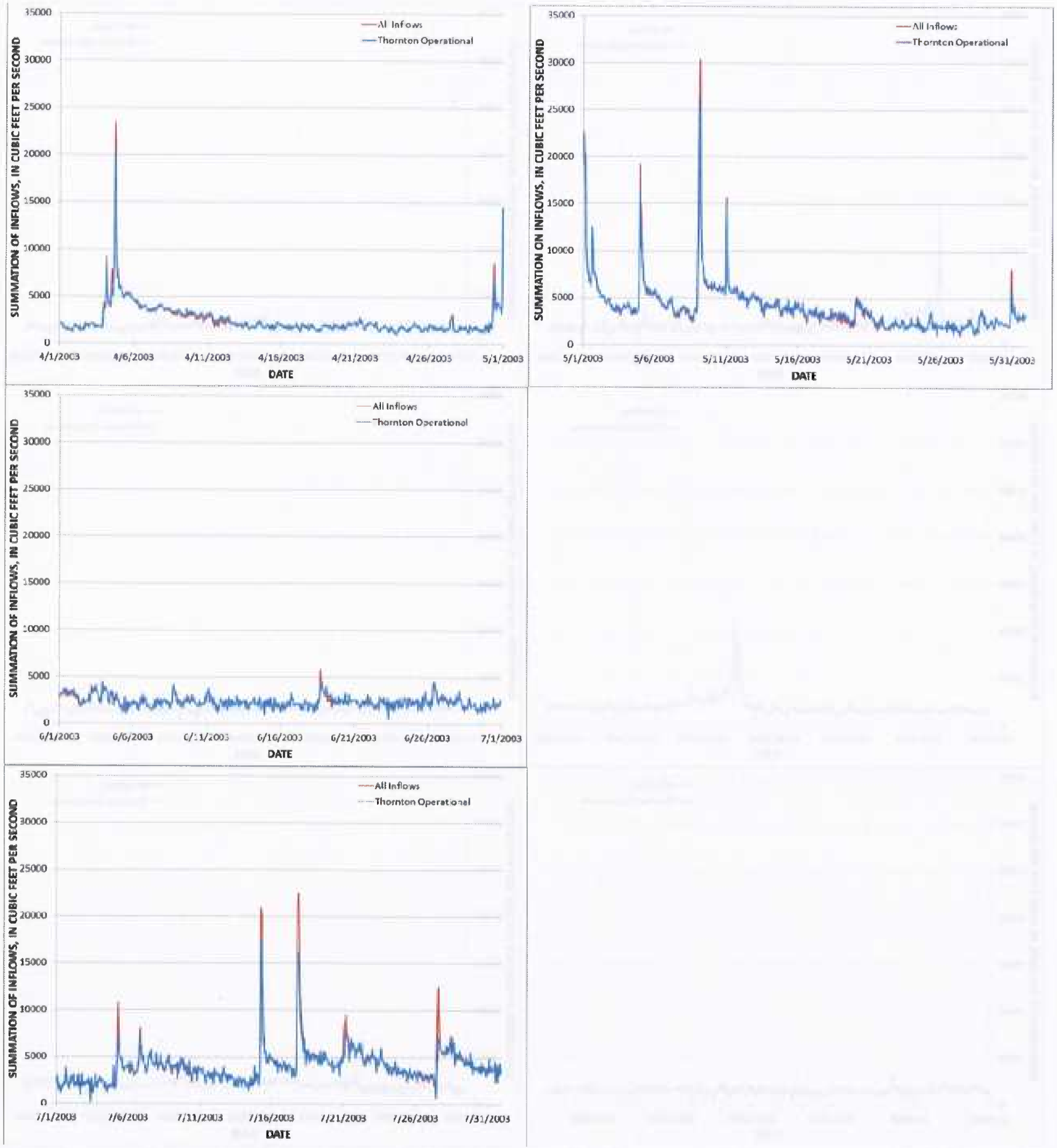


Figure 3.7. Comparison of the sum of inflows to the Chicago Area Waterway System for the Current and Thornton Reservoir operational conditions for Water Year 2003.

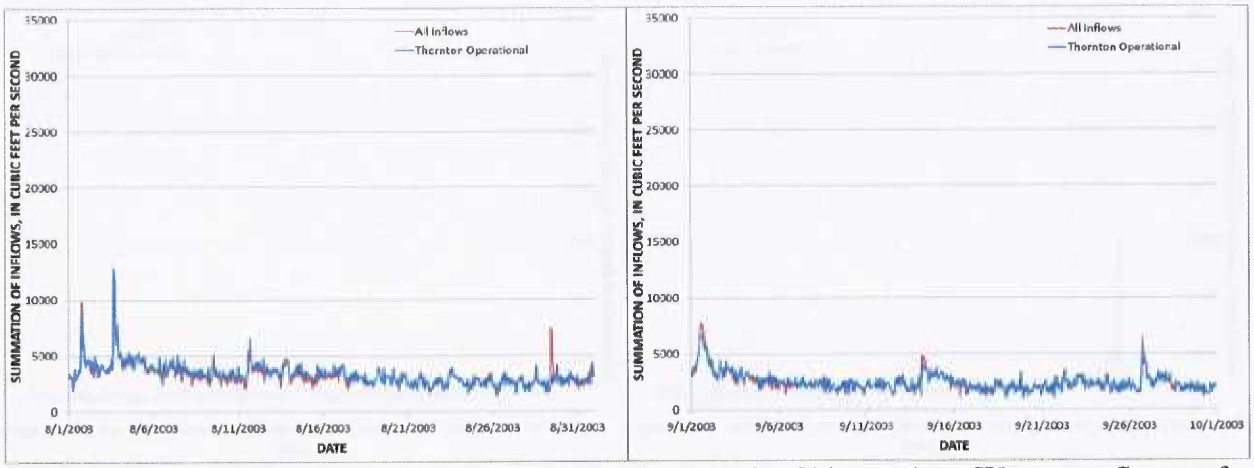


Figure 3.7. (cont.) Comparison of the sum of inflows to the Chicago Area Waterway System for the Current and Thornton Reservoir operational conditions for Water Year 2003.

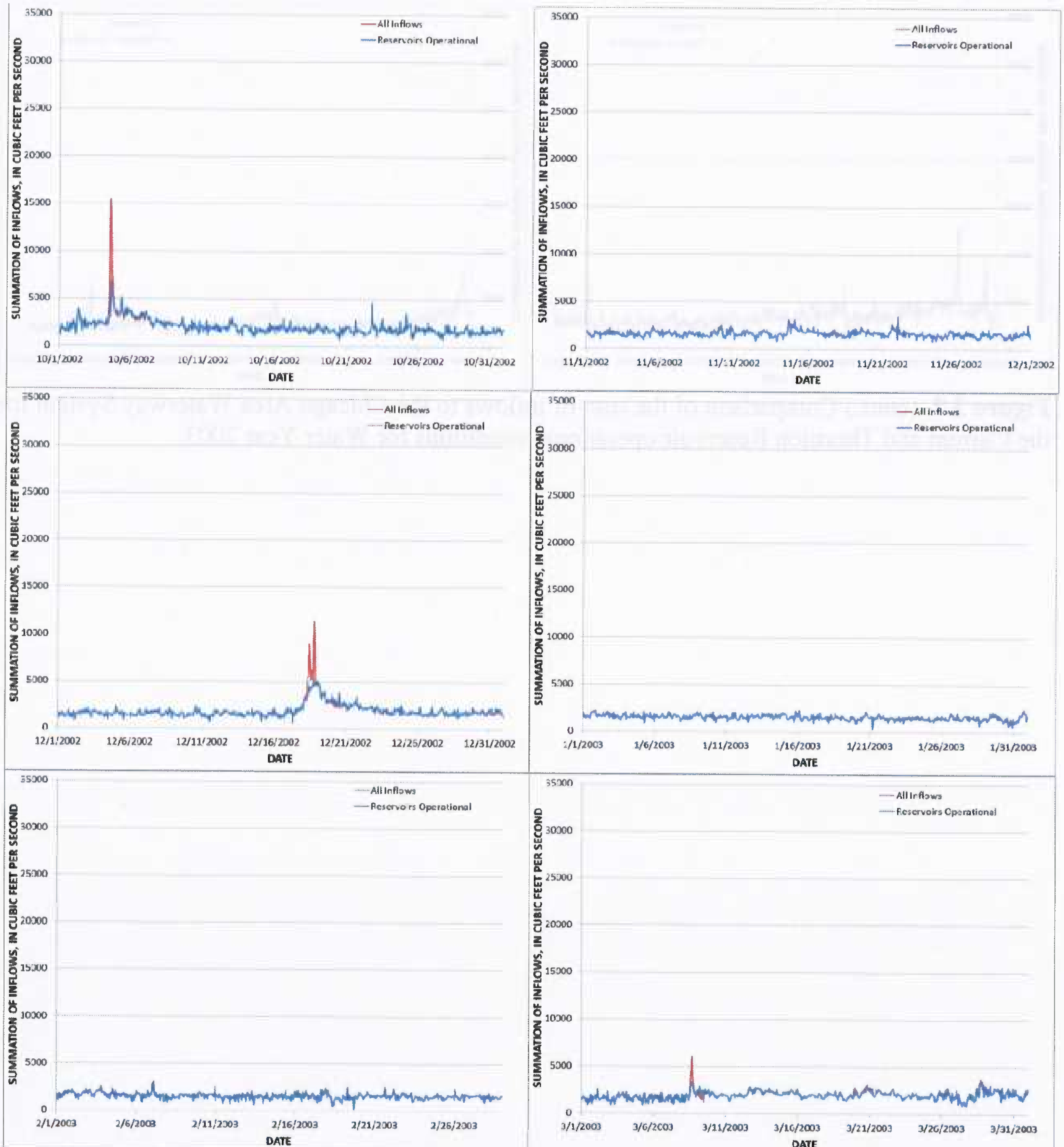
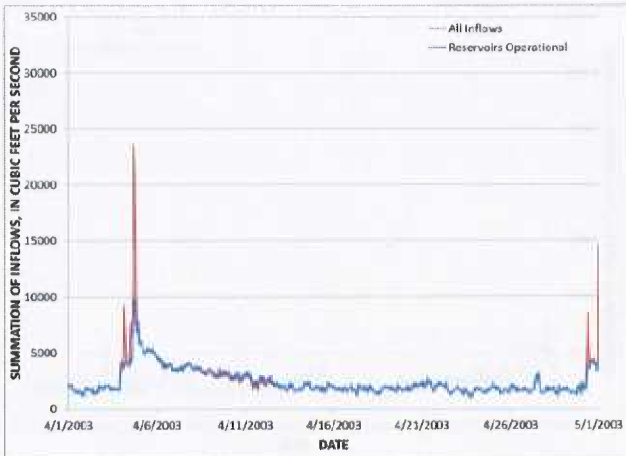


Figure 3.8. Comparison of the sum of inflows to the Chicago Area Waterway System for the Current and Thornton and McCook Stage 1 reservoirs operational conditions for Water Year 2003.


All Inflows
Reservoirs Operational
SUMMATION OF INFLOWS, IN CUBIC FEET PER SECOND
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30000
25000
20000
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5/1/2003
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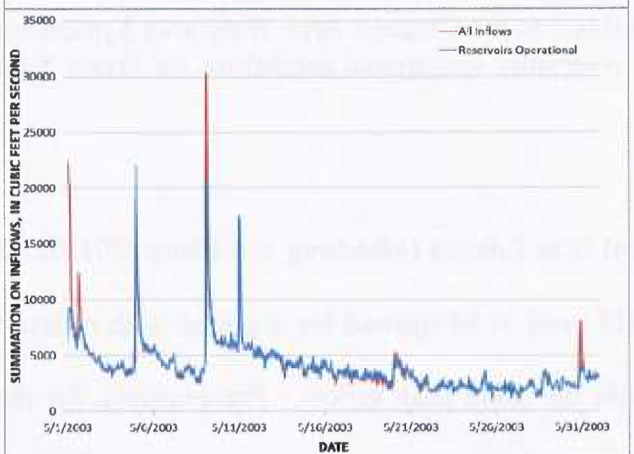
All Inflows
Reservoirs Operational
SUMMATION ON INFLOWS, IN CUBIC FEET PER SECOND
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20000
15000
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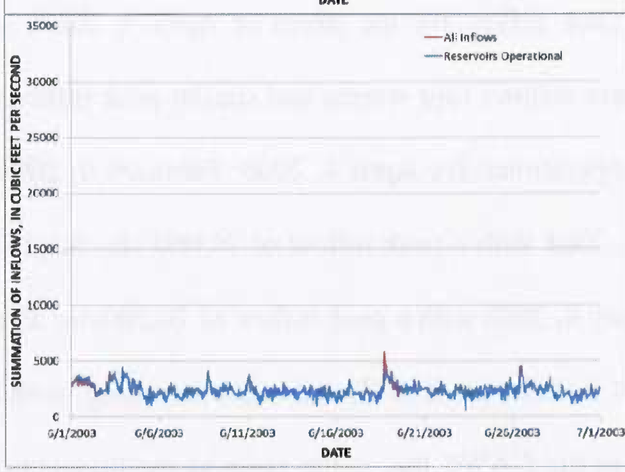
5/26/2003
5/31/2003
DATE


All Inflows
Reservoirs Operational
SUMMATION OF INFLOWS, IN CUBIC FEET PER SECOND
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15000
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7/1/2003
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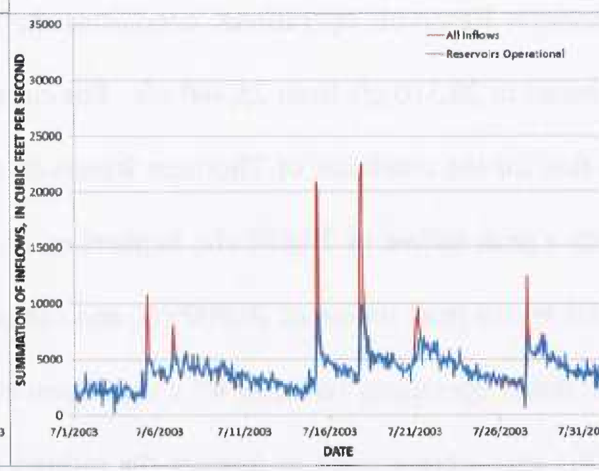
All Inflows
Reservoirs Operational
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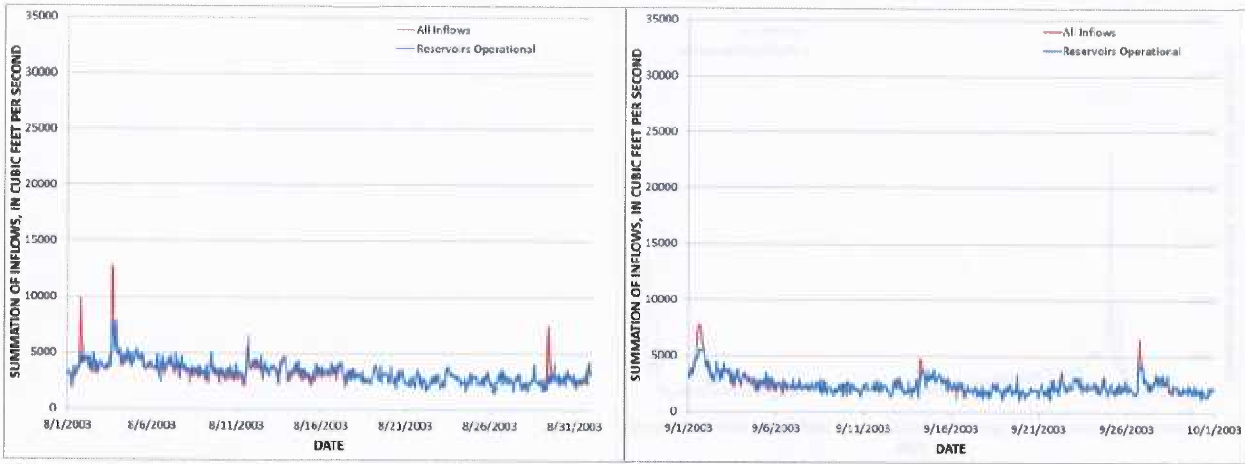


Figure 3.8. (cont.) Comparison of the sum of inflows to the Chicago Area Waterway System for the Current and Thornton and McCook Stage 1 reservoirs operational conditions for Water Year 2003.

The procedure for adjusting the stage at Lockport is as follows (Melching and Liang (2013)). It is assumed that a similar number of gates would need to be opened for a period with reduced CSO flows as for the case of a current flow with the same peak inflow. For example, for the Thornton Reservoir operational conditions the peak inflow for the storm of April 4, 2003, is reduced to 20,510 cfs from 23,460 cfs. For current inflows four storms had similar peak inflows to that for the condition of Thornton Reservoir operational for April 4, 2003: February 9, 2001 with a peak inflow of 20,670 cfs, September 21, 2001 with a peak inflow of 20,060 cfs, July15, 2003 with a peak inflow of 20,900 cfs, and January 8, 2008 with a peak inflow of 20,580cfs. For the actual operations on April 4th a maximum of 8 sluice gates (SG) and one controlling works (CW) gate were opened to manage the inflows to the CAWS this is the same as the maximum total number of gates opened on July 15, 2003 (6 SG, 3 CW) and less than the maximum total number of gates opened on February 9, 2001 (7 SG, 4 CW) and January 8, 2008 (6 SG, 5 CW). Only the event of September 21, 2001, required fewer gates open (8 SG) than the actual operations for April 4, 2003. Thus, by using the actual operations of September 21, 2001, as a model for the post-reservoir operations for April 4, 2003, essentially it is assumed that it would not be necessary to open the one controlling works gate and just pass the flows through the 8 sluice gates resulting in an increase in the downstream water level. For the actual operations on April 4, 2003, the water-surface elevation (stage) dropped to -6.53 ft relative to the Chicago City Datum (CCD), whereas for September 21, 2001, the lowest water-surface elevation (stage) was -5.53 ft CCD. Thus, it was decided to hold the lowest stage around -5.0 to -5.5ft CCD in the DUFLOW simulations for the Thornton Reservoir operational conditions. Figure 3.9 shows the measured and adjusted stages at the Lockport Controlling Works for the storm of April 4, 2003. Similar adjustments were applied to all storm events for the Thornton Reservoir operational and Thornton and McCook Stage 1 reservoirs operationalconditions for WY 2003.

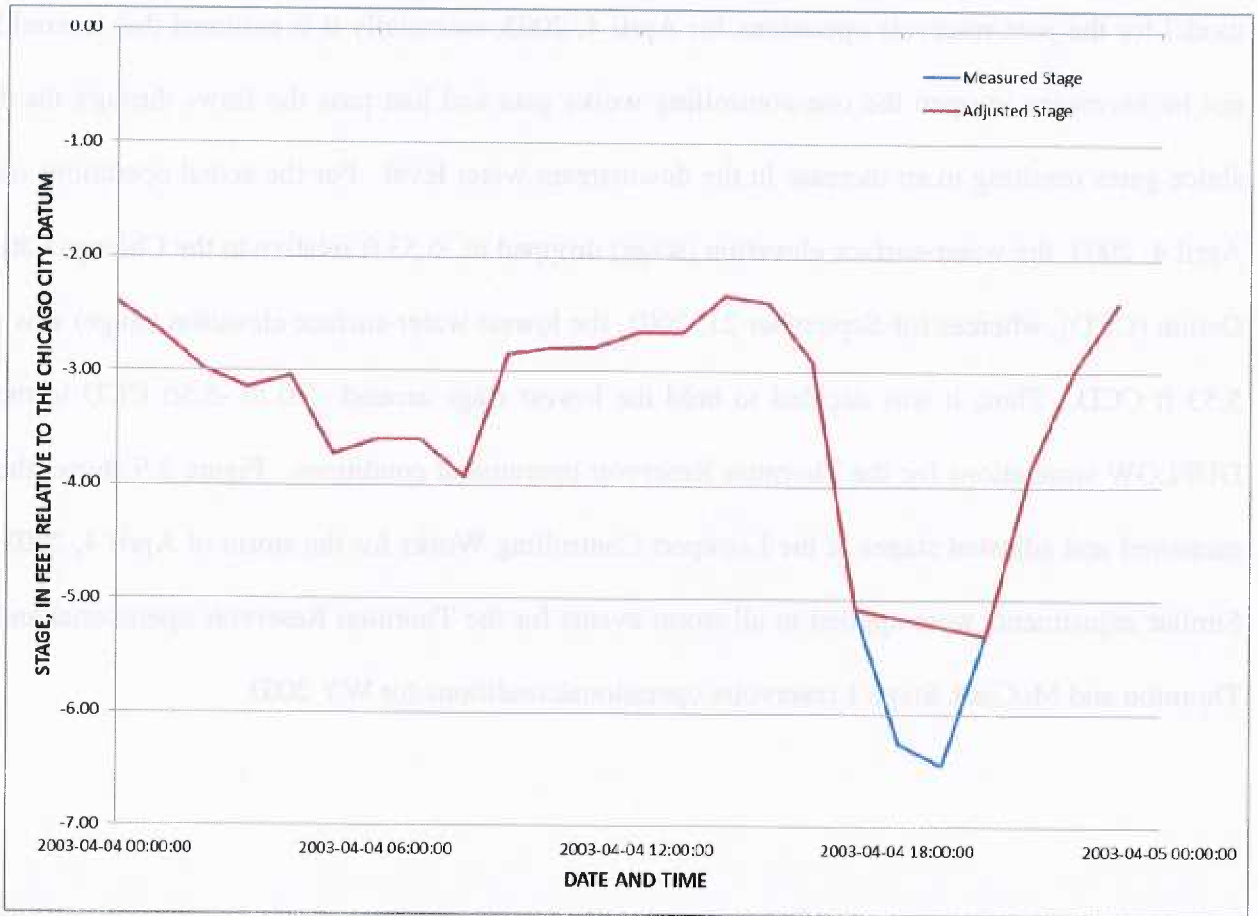


Figure 3.9. Measured stage and stage adjusted to account for the reduction in combined sewer overflows to the Chicago Area Waterway System for the Thornton Reservoir operational conditions for the storm of April 4, 2003.

The current and adjusted stages for the Thornton Reservoir operational and Thornton and McCook Stage 1 reservoirs operationalconditions for WY 2003 are shown in Figure 3.10 (note: when the three stages are identical only the value for the Thornton and McCook Stage 1 reservoirs operational is seen in the figure). Figure 3.11 shows the simulated flows at the Lockport Controlling Works for the current condition with the actual discretionary diversionversus Thornton Reservoir operational and Thornton and McCook Stage 1 reservoirs operationalconditions for the case of optimal allocations of 101 cfs of discretionary diversion for WY 2003Only the months for which there are substantial differences in the downstream boundary conditions at the Lockport Controlling Works are shown in Figures 3.10 and 3.11. The smoothness of the computed outflows in Figure 3.11 shows the reasonableness of the approximated downstream boundary conditions for the reservoirs operational conditions.

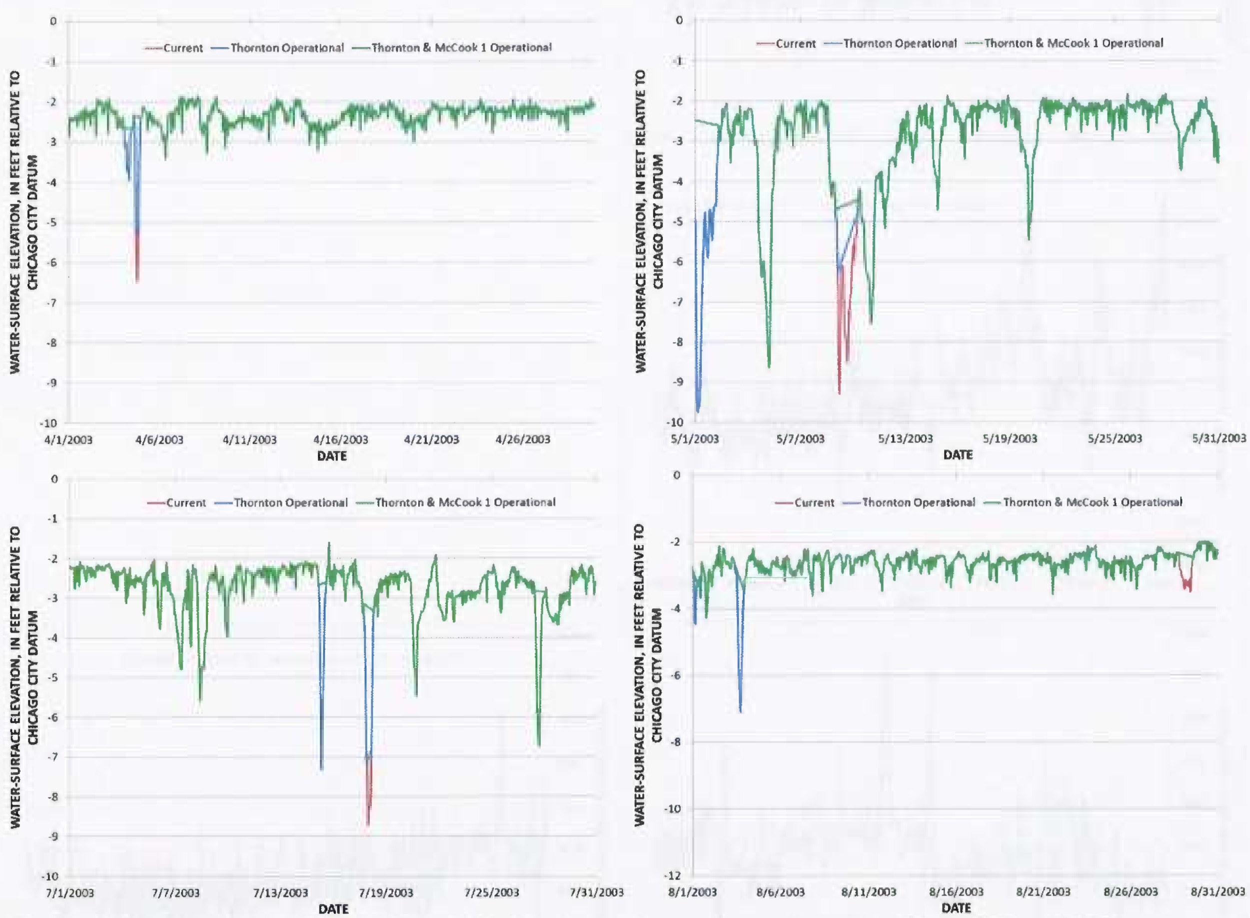


Figure 3.10. Lockport Controlling Works downstream boundary for Water Year 2003: measured (Current) water-surface elevations and water-surface elevations adjusted to reflect the reduction in combined sewer overflows to the Chicago Area Waterway System for Thornton Reservoir operational and Thornton and McCook Stage 1 reservoirs operational conditions.

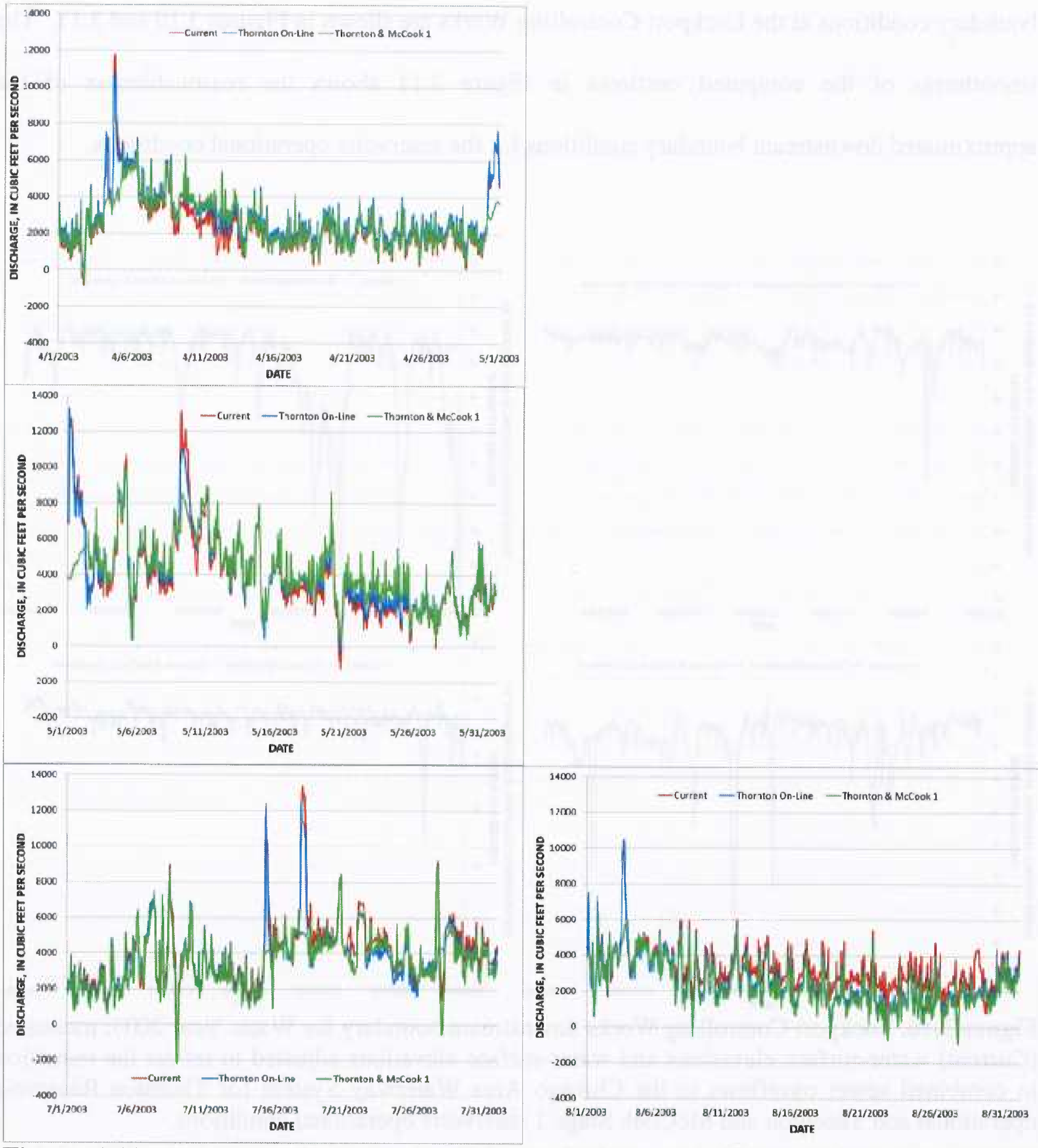


Figure 3.11. Computed flows in the Chicago Sanitary and Ship Canal at the Lockport Controlling Works for the current conditions with actual discretionary diversion and the Thornton Reservoir operational conditions and the Thornton and McCook Stage 1 reservoirs operational conditions both for the optimal allocation of 101 cfs of discretionary diversion for Water Year 2003.

3.3 Change in Temperature

Temperature has important effects on the simulation of water quality constituents related to DO. The rate coefficients that describe the relations between various constituents are affected by temperature, and the saturation concentration of DO in water is affected by temperature. The DUFLOW (2000) model does not include routines for simulating the heat balance and temperature of a river system. Thus, in the original DUFLOW model of the CAWS (Alp and Melching, 2006; Melching et al., 2010) measured hourly temperatures were input at 27 locations throughout the CAWS. These locations were selected on the basis of stations operational throughout the majority of the time periods that were the focus of the earlier studies (Alp and Melching, 2006; Melching et al., 2010): WYs 2001 and 2003 and May 1 to September 23, 2002. Thus, the Devon Avenue monitor that was discontinued in January 2001 and the Loomis Street monitor that was discontinued in January 2001 and re-activated in April 2003 were not included in the model.

The missing temperature records for WYs 2001 and 2003 were estimated by linear interpolation in time for shorter periods of missing record and by linear interpolation between neighboring monitors for longer periods of missing record. Since nearly all the monitors on the Calumet-Sag Channel and the Little Calumet River (north) were installed in July 2001, monthly average temperatures from later years were used for October 2000 through the monitor's installation date in July 2001.

Being able to use measured hourly temperatures at so many locations throughout the CAWS has contributed substantially to the reliability of the DUFLOW model of the CAWS in simulating DO and related constituents. However, measured temperature data cannot be used to evaluate the optimal allocation of discretionary diversion from Lake Michigan for water-quality improvement because the measured temperatures in WY 2003 do not reflect temperature conditions in the CAWS for the planning period to which the optimal allocation of discretionary diversion will apply. This is because of the closure of the Fisk and Crawford power plants in September 2012, and the retirement of the Will County Power Plant Units 1 and 2 at the end of 2010 (Julia Wozniak, Midwest Generation, written communication to Dave Wethington, USACE, May 30, 2012).

As part of the GLMRIS study linear regression and mass balance models were developed to estimate daily mean temperature at points downstream of the power plants reflecting periods when these plants had been shut down for maintenance (Melching and Liang, 2013). The Fisk Power Plant withdrew water from the SBCR and returned heated water to it between Jackson Boulevard and Loomis Street. The Crawford Power Plant withdrew water from the CSSC and returned heated water to it between Loomis Street and Cicero Avenue. Thus, as shown in Figure 3.12 the operations of these plants can have substantial effects on the downstream temperatures. Operational information on whether the various power generation units at the plants were "on" or "off" were obtained from Midwest Generation, and these were used to determine regression equations for periods when the plants were "off" that are representative of current conditions in the CAWS. In calendar years 2003 and 2004, April 1999, and November and December 2000, Units 1 and 2 at the Will County Power Plant were out of service. Thus, these periods were studied by Melching and Liang (2013) as they reflect the current temperature conditions, and the "on" and "off" conditions of Units 3 and 4 were evaluated.

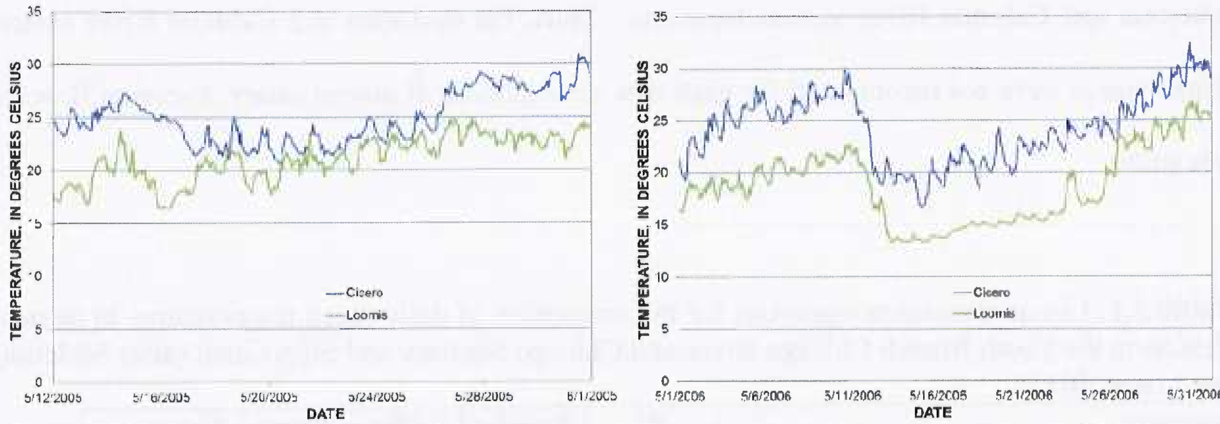


Figure 3.12. Examples of the effects of power unit outages at the Crawford and Fisk power plants: (left) Crawford unit 8 shut down May 16-26, 2005, and the downstream temperature at Cicero Avenue moves close to the upstream temperature at Loomis Street, (right) Fisk Power Plant shut down May 12-23, 2006, both downstream temperatures show a sudden decrease on the 12th and a sudden increase on the 23rd.

Table 3.1 lists the linear regression equations for daily mean temperatures and their coefficients of determination (R^2), standard errors, and numbers of days of observations used to derive these equations for locations along the SBCR and CSSC downstream from the now closed power plants. Measured hourly temperatures were used at all temperature input locations to the model upstream of and including Jackson Boulevard and at all locations in the Calumet River system, and the equations listed in Table 3.1 were used to estimate the daily mean temperatures downstream from the power plants for the condition of the power plants shut down. For the case of the temperatures at the Lockport Controlling Works the temperatures measured upstream and downstream of the Will County Power Plant were examined to determine the days when the power plant was not operational and the appropriate equations from Table 3.1 were applied.

Regression and mass balance equations were derived to estimate daily mean temperatures at all locations throughout the CAWS by Melching and Liang (2013), however, in the GLMRIS study it was found that changes in discretionary diversion had only minor effects on temperature at the upstream and Calumet River system locations. Thus, the upstream and Calumet River system temperatures were not recomputed for each new arrangement of discretionary diversion flows in this study.

Table 3.1. Linear regression equations for the estimation of daily mean temperatures in degrees Celsius in the South Branch Chicago River and Chicago Sanitary and Ship Canal (after Melching and Liang, 2013).

Equation	R^2	Standard Error, °C	Observations	Notes
Loomis = 1.03773 Jackson – 0.61924	0.98350	0.7232	208	Power off
Cicero = 1.07090 Loomis - 0.60431	0.92949	1.4387	578	Power off
B&O = 0.99092 MBST – 0.77847	0.94496	1.4161	1285	
Route 83 = 1.03427 B&O – 0.72886	0.99128	0.7784	3099	
RM 302.6 = 1.01137 MBCS – 0.34646	0.99804	0.2884	257	
Romeo = 1.01567 RM 302.6 – 0.38954	0.99694	0.3872	1754	
Lockport = 0.91825 Romeo + 4.01442	0.98265	0.9224	299	Power on
Lockport = 0.98837 Romeo + 1.25938	0.98397	0.6439	184	Power off

MBST = Mass balance of Cicero Avenue and Stickney WRP temperatures
MBCS = Mass balance of Route 83 (CSSC) and Route 83 (Calumet-Sag) temperatures

Chapter 4 – WATER QUALITY GOALS AND OPTIMAL DISCRETIONARY DIVERSION STRATEGY

4.1 Dissolved Oxygen Standards and System-wide Water Quality Goal

As a result of an Use Attainability Analysis (UAA) of the CAWS (CDM, 2007), the IEPA (2007) proposed two aquatic life use classes for the CAWS—Chicago Area Waterway System Aquatic Life Use A waters (CAWS A) and Chicago Area Waterway System and Brandon Pool Aquatic Life Use B waters (CAWS B)—to the IPCB. Recently the IPCB (2014), as Subdocket C of Rule 08-9, established three aquatic life uses relevant to the CAWS. The Chicago River maintains its designation as a General Use water. The designation of CAWS A water is applied to the North Shore Channel, North Branch Chicago River downstream from the confluence with the North Shore Channel, South Branch Chicago River, Calumet River, Little Calumet River (north), and Calumet-Sag Channel.The designation of CAWS B water is applied to the Chicago Sanitary and Ship Canal. The aquatic life use designation for Bubbly Creek (i.e. the South Fork of the South Branch Chicago River) remains "subject to the Board's secondary contact and indigenous aquatic life use standards under Part 302 Subpart D pursuant to Section 302.304 until specific use designation and water quality standards are adopted in Subdocket E" (IPCB, 2014). No further discussion or consideration of Bubbly Creek is made in this report.

For General Use waters the following DO concentration targets must be met or exceeded:

1) During the period of March through July,

    A. 5.0 mg/L at any time; and

B. 6.0 mg/L as a daily mean averaged over 7 days

2) During the period of August through February,

A. 3.5 mg/L at any time;

B. 4.0 mg/L as a daily minimum averaged over 7 days; and

C. 5.5 mg/L as a daily mean averaged over 30 days.

For the Chicago River main stem the long-term mean criteria, 1.B and 2.C, were the most restrictive criteria and were evaluated in the allocation of discretionary diversion in this study.

For CAWS A waters it has been proposed that the following DO concentration targets must be met or exceeded:

1) During the period of March through July, 5.0 mg/L at all times

2) During the period August through February

A. 4.0 mg/L as a daily minimum averaged over 7 days, and

B. 3.5 mg/L at all times

For CAWS B waters it has been proposed that the following DO concentration targets must be met or exceeded:

1) 4.0 mg/L as a daily minimum averaged over 7 days, and

2) 3.5 mg/L at all times

The modeling trials done by Melching et al. (2010) found that 3.5 mg/L at all times was more restrictive than 4.0 mg/L as a daily minimum averaged over 7 days, and, thus, only the absolute minimum DO standards were used for calculating percentage of time with simulated DO concentrations equaling or exceeding the DO standards in this study for the CAWS A and B waters.

In order to evaluate system-wide performance, the percentage of time withsimjulated DO concentrations equaling or exceeding the IPCB standards for the Chicago River main stem and the IEPA proposed DO standards for all other locations(together these are referred to as the DO standards in the remainder of this report unless otherwise specified) was computed for each of the DO monitoring locations listed in Table 2.12 (except I-55 on Bubbly Creek and Ashland Avenue on the Little Calumet River (south)). The water quality goal for this study then was set as maximizing the percentage of time with simulated DO concentrations equaling or exceeding the appropriate DO standards at the DO monitoring location with the lowest percentage throughout the CAWS. This goal was selected because relative to the implementation of water-quality regulations the performance for the entire CAWS is only as good as the lowest point, i.e. if the CAWS has DO concentrations below the DO standards at any point, then the CAWS as a system does not meet the standards.

4.2 Optimal Discretionary Diversion Strategy

4.2.1 "On Demand" Diversion

In order to consider the discretionary diversion necessary to maintain high percentages of time with simulated DO concentrations equaling or exceeding the DO standards in the CAWS a procedure for determining the time and place where discretionary diversion is needed that can be practically implemented must be developed. For periods of low DO concentrations at locations near the facilities where discretionary diversion can be taken—Wilmette, CRCW, and O'Brien Lock and Dam—discretionary diversion can be taken "On Demand." That is, when measured (in actual practice) or simulated (in this simulation-based evaluation) DO concentrations get within a tolerance level of the DO standard at a monitoring location a fixed amount of discretionary diversion is taken until the DO concentration again exceeds the standard plus the tolerance.

Melching (2013) demonstrated the effectiveness of this "On Demand" procedure for the NSC upstream of the O'Brien WRP. Initially the tolerance was set as 0.5 mg/L, but this was found through several DO simulation trials to be too conservative and the tolerance was reduced to 0.3 mg/L. That is, in August-February when the simulated DO concentration dropped below 3.8 mg/L or in March-July when the simulated DO concentration dropped below 5.3 mg/L the increased discretionary diversion would begin and it would end when the simulated DO concentrations exceeded these values in the original simulation.

Melching (2013) found that the majority of the dry weather periods on the NSC could be brought to simulated DO concentrations equaling or exceeding the DO standards by increasing the discretionary diversion once the simulated DO concentrations got within 0.3 mg/L of the DO standards (i.e. less than 3.8 mg/L in August-February, and less than 5.3 mg/L in March-July). However, there were 12 periods for which the increase in discretionary diversion needed to start 3-6 hours earlier than the onset of simulated low DO concentrations at the monitoring points (using a tolerance of 0.5 mg/L would not change this result). In these cases, the traveltime from Wilmette to Simpson Street and/or Main Street required the high DO Lake Michigan water to already be on the way to head off periods of low DO concentrations. This operation can be done in hindsight for a modeling study, but in practical operations some dry weather events might experience short periods of DO concentrations below the DO standards until the high DO Lake Michigan water can spread through the entire NSC.

4.2.2 Procedure for Downstream Locations

Table 4.1 lists the average travel time to various locations in the CAWS from Wilmette, CRCW, and O'Brien Lock and Dam. These average travel times were calculated from the flow velocities in the CAWS computed with the DUFLOW model for the period of July 1 to August 31, 2003. This period was chosen because it was a period with substantial discretionary diversion, which allows a reasonable estimate of travel times for periods with discretionary diversion in those reaches of the CAWS that do not convey treated effluent: i.e. the NSC upstream of the O'Brien WRP, Chicago River main stem, and Little Calumet River (north) upstream of the Calumet WRP. It seems reasonable that discretionary diversion can be taken "On Demand" based on low DO concentrations for locations within about 1 day travel time of the diversion locations: i.e. up to Main Street on the NSC, the entire Chicago River main stem, and up to Conrail Railroad on the Little Calumet River (north).

In order to develop an approach to achieve DO concentrations equaling or exceeding the DO standards at locations more than 1 day away from the diversion points, the periods during which the simulated DO concentrations were less than the DO standard plus the 0.3 mg/L tolerance (i.e. less than 3.8 mg/L in August to February and 5.3 mg/L for March to July) were determined for all DO monitoring locations for the case of no discretionary diversion at the Wilmette. Simpson Street was found to be below 3.8 mg/L from 16:00 on December 19 to 5:00 on December 24,

2002. This period could be handled "On Demand." Figure 4.1 shows the periods of simulated DO concentrations less than the standard plus 0.3 mg/L for all the DO monitoring locations for February to September 2003. In these figures the following values indicate periods of low DO: Simpson Street = 1, Main Street = 2, Foster Avenue = 3, Addison Street = 4, Fullerton Avenue = 5, Division Street = 6, and Kinzie Street = 7.

From Figure 4.1 it can be seen that for nearly all of March to August one or more locations on the NSC or NBCR had simulated DO concentrations less than the standard plus 0.3 mg/L.Therefore, a continuous discretionary diversion at Wilmette was applied throughout the month. The continuous discretionary diversion for each month was slowly increased until either the DO standards were equaled or exceeded at all times, or the periods of simulatedDO concentrations below the DO standards became so short that it was felt that it would be more efficient to obtain simulated DO concentrations equaling or exceeding the DO standards by changing operations at the Devon Avenue and/or Webster Avenue IASs than to take additional discretionary diversion (as discussed in Section 4.2.3).

For February, it was assumed that the brief periods with simulated DO concentrations less than 3.8 mg/L at downstream locations shown in Figure 4.1 could be made greater than or equal to the DO standards by changing the operations of the Devon Avenue and/or Webster Avenue IASs. Further, the simulations found that in order to achieve simulated DO concentrations equaling or exceeding the DO standards throughout March (when the standard increases to 5.0 mg/L) it was necessary to begin the discretionary diversion at 0:00 on February 25, 2003 to account for the travel time to Kinzie Street. This same February 25th start time was applied to discretionary diversion at CRCW needed to achieve simulated DO concentrations equaling or exceeding the DO standards on the SBCR.

Table 4.1. Average travel times in the Chicago Area Waterway System for the period July 1 to August 31, 2003.

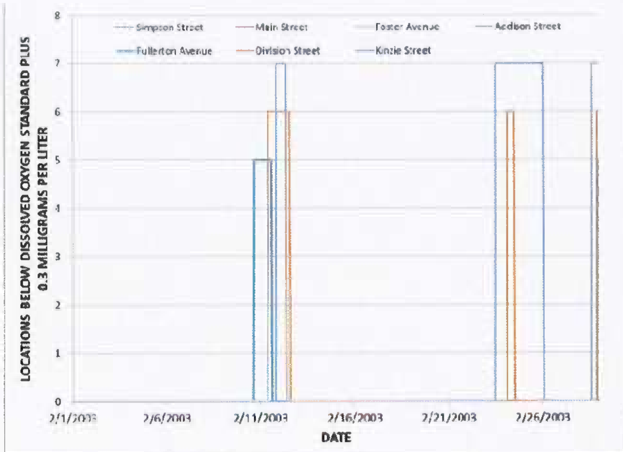
Location	Waterway	Travel Time
		from Wilmette (hr)
Simpson Street	North Shore Channel	11.1
Main Street	North Shore Channel	22.2
Addison Street	North Branch Chicago River	38.5
Fullerton Avenue	North Branch Chicago River	43.7
Division Street	North Branch Chicago River	58.5
Kinzie Street	North Branch Chicago River	71.7
Wolf Point*	North Branch Chicago River	75.8
		from CRCW (hr)
Clark Street	Chicago River main stem	17.0
Wolf Point*	Chicago River main stem	24.9
Jackson Boulevard	South Branch Chicago River	27.0
Loomis Street	South Branch Chicago River	43.2
Cicero Avenue	Chicago Sanitary and Ship Canal	74.5
Baltimore & Ohio Railroad	Chicago Sanitary and Ship Canal	94.1
Route 83	Chicago Sanitary and Ship Canal	117.0
Sag Junction	Chicago Sanitary and Ship Canal	118.5
River Mile 11.6	Chicago Sanitary and Ship Canal	120.0
Romeoville	Chicago Sanitary and Ship Canal	132.2
Lockport Controlling Works	Chicago Sanitary and Ship Canal	138.7
		from O'Brien Lock & Dam (hr)
Conrail Railroad	Little Calumet River (north)	24.5
Central & Wisconsin Railroad	Little Calumet River (north)	59.0
Halsted Street	Little Calumet River (north)	94.7
Calumet-Sag Channel begin	Little Calumet River (north)	97.6
Division Street	Calumet-Sag Channel	101.7
Kedzie Street	Calumet-Sag Channel	107.7
Cicero Avenue	Calumet-Sag Channel	116.7
Harlem Avenue	Calumet-Sag Channel	130.1
Southwest Highway	Calumet-Sag Channel	133.8
104^{th} Street	Calumet-Sag Channel	147.5
Route 83	Calumet-Sag Channel	161.9
Sag Junction	Calumet-Sag Channel	163.5

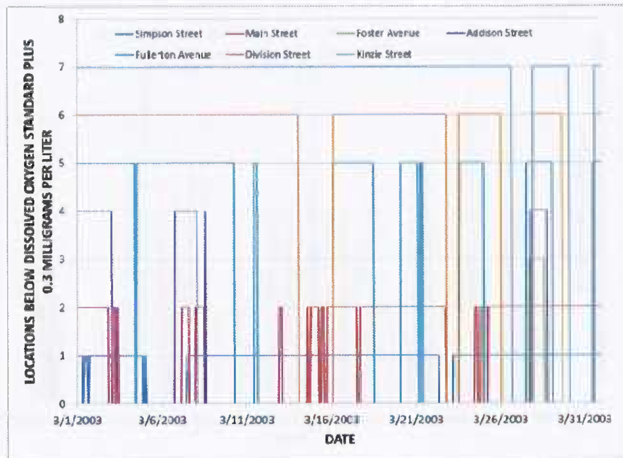
*Wolf Point is the junction of the North Branch, South Branch, and main stem of the Chicago River

For September, it was assumed that the brief periods with simulated DO concentrations less than 3.8 mg/L at downstream locations shown in Figure 4.1 could be made greater than or equal to the DO standards by changing the operations of the Devon Avenue and/or Webster Avenue IASs.

The brief periods of simulated DO concentrations less than 3.8 mg/L at Simpson Street could be brought into compliance with discretionary diversion "On Demand."DO loads from the Devon Avenue IAS also were maximized effectively by turning on more blowers for periods with simulated DO concentrations less than 5.5 mg/L at downstream locations, such as Fullerton Avenue, in order to reduce the need for discretionary diversion in May and July.

Downstream from CRCW, Loomis Street is the location with the longest periods of simulated DO concentrations less thanthe DO standards. For the case of no discretionary diversion the percentage of time with simulated DO concentrations less than the DO standard plus 0.3 mg/L at Loomis Street by month is: March = 100%, April = 100%, May = 66.94%, June = 93.06%, July = 100%, August = 99.19%, and September = 57.64%. Therefore, a continuous discretionary diversion at CRCW was applied throughout the month. The continuous discretionary diversion for each month was slowly increased until either simulated DO concentrations equaled or exceeded the DO standards at all times, or the discretionary diversion limit (101 or 270 cfs) was reached. Note: in all the increases of discretionary diversion at CRCW or Wilmette values were increased by tens or fives of cubic feet per second not unrealistic fractions of cubic feet per second flows.


Simpson Street
Main Street
Foster Avenue
Addison Street
Fullerton Avenue
Division Street
Kinzie Street
LOCATIONS BELOW DISSOLVED OXYGEN STANDARD PLUS 0.3 MILLIGRAMS PER LITER
2/6/2003
2/11/2003
2/16/2003
2/21/2003
2/26/2003
DATE


Simpson Street
Main Street
Foster Avenue
Addison Street
Fullerton Avenue
Division Street
Kinzie Street
LOCATIONS BELOW DISSOLVED OXYGEN STANDARD PLUS 0.3 MILLIGRAMS PER LITER
3/1/2003
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3/16/2003
3/21/2003
3/26/2003
3/31/2003
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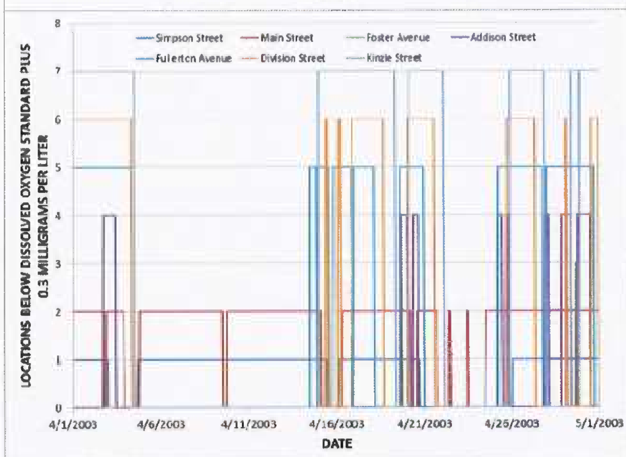
Simpson Street
Main Street
Foster Avenue
Addison Street
Fullerton Avenue
Division Street
Kinzie Street
LOCATIONS BELOW DISSOLVED OXYGEN STANDARD PLUS 0.3 MILLIGRAMS PER LITER
4/1/2003
4/6/2003
4/11/2003
4/16/2003
4/21/2003
4/26/2003
5/1/2003
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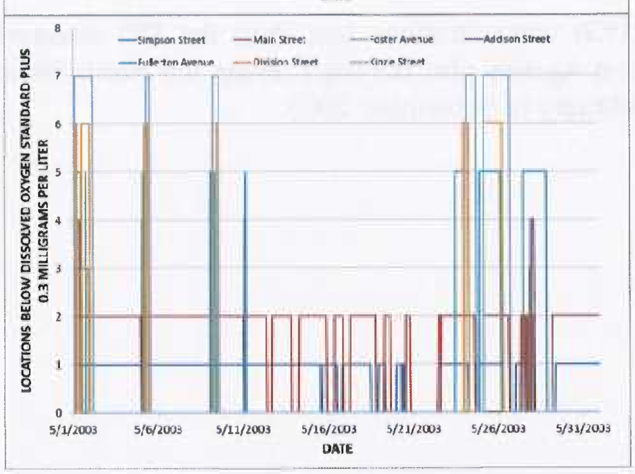
Simpson Street
Main Street
Foster Avenue
Addison Street
LOCATIONS BELOW DISSOLVED OXYGEN STANDARD PLUS 0.3 MILLIGRAMS PER LITER
5/1/2003
5/6/2003
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5/16/2003
5/21/2003
5/26/2003
5/31/2003
DATE

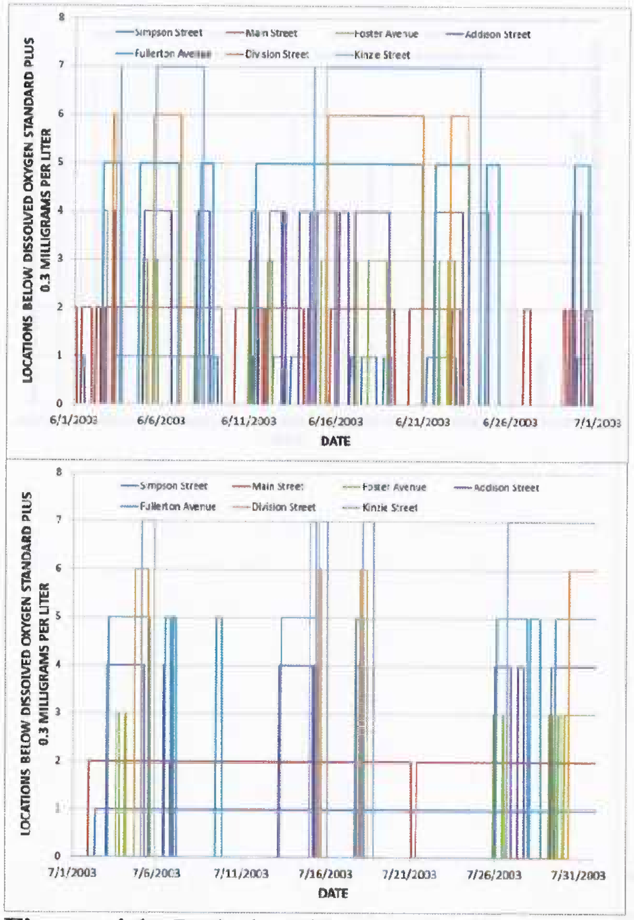

Figure 4.1. Periods with dissolved oxygen (DO) concentrations less than the DO standard proposed by the Illinois Environmental Protection Agency plus 0.3 mg/L along the North Shore Channel and North Branch Chicago River for February to September 2003.

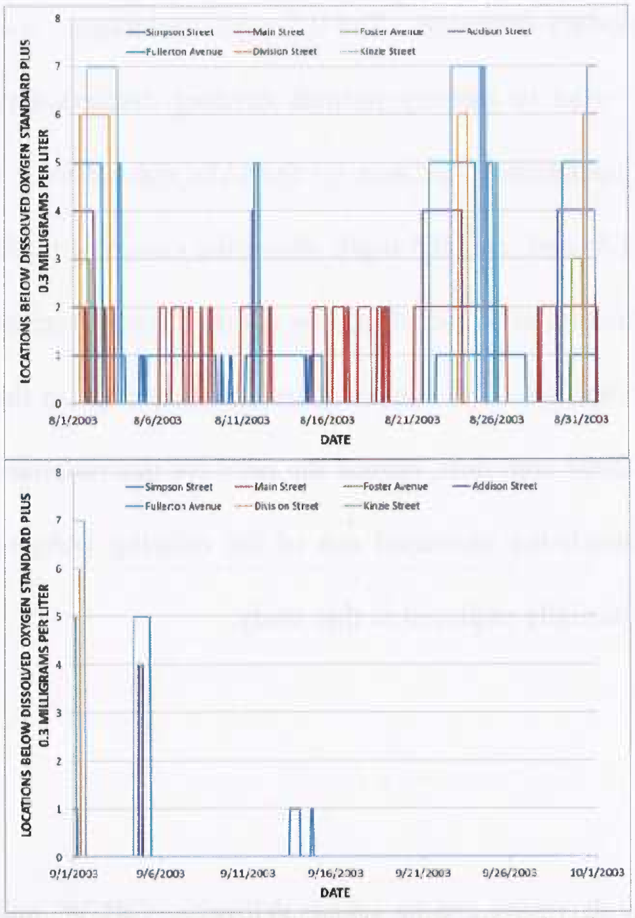

Figure 4.1. (cont.) Periods with dissolved oxygen (DO) concentrations less than the DO standard proposed by the Illinois Environmental Protection Agency plus 0.3 mg/L along the North Shore Channel and North Branch Chicago River for February to September 2003.

4.2.3 Change in Instream Aeration Station Operations

Initially all the simulations were done assuming the actual operations of the IAS and SEPA stations. Then as the increased discretionary diversion resulted in simulated DO concentrations greater than or equal to the DO standards at nearly all times it was decided to change the IAS and SEPA operations to maximize the oxygen load during periods when the simulated DO concentration was less than the DO standard plus 0.5 mg/L. This was done to see if IAS and SEPA operations could be used to make simulated DO concentrations greater than or equal to the

DO standards without taking additional discretionary diversion. The 0.5 mg/L "tolerance" was used as opposed to the 0.3 mg/L "tolerance" used to identify periods needing discretionary diversion in order to be consistent with current operational guidance for the IASs that calls for 3 blowers on when DO concentrations go under 4.5 mg/L (i.e. 0.5 mg/L above the current 4 mg/L standard). As noted in the previous section, increases in blower operations at the Devon Avenue and/or Webster Avenue were used to improve simulated DO concentrations downstream on the NBCR in February, May, July, and September 2003 and, thus, reduce the need for discretionary diversion in these months. Through this approach the increased use of the existing IASs to reduce the need for discretionary diversion was partially explored in this study.

4.2.4 Division of Discretionary Diversion

There are three locations at which discretionary diversion can be taken: Wilmette, CRCW, and O'Brien Lock and Dam. Thus, a strategy must be determined to apportion the discretionary diversion among these locations. For the case of no discretionary diversion and existing CSO flows, the point on the Little Calumet River (north) and Calumet-Sag Channel with the lowest percentage of time with simulated DO concentrations equaling of exceeding the DO standards was Route 83 with a value of 95.4%. On the NSC the point with the lowest percentage was Simpson Street with a value of 68.1%, and on the SBCR the point with the lowest percentage for the entire CAWS was Loomis Street with a value of 46.9%. For the case of no discretionary diversionand the Thornton and McCook Stage 1 reservoirs operational, these minimum percentages become: Little Calumet River (north) at Conrail Railroad = 98.0%, NSC at Simpson Street = 70.9%, and SBCR at Loomis Street = 60.1%. Thus, it is obvious that all the discretionary diversion should be concentrated at Wilmette and CRCW until the simulated DO concentrations at monitoring locations downstream from these points achieve percentages of time with simulated DO concentrations equaling or exceeding the DO standards equal to those along the Calumet River system.

The initial strategy to distribute the discretionary diversion was to take enough discretionary diversion at Wilmette to achieve a target level of the percentage of time with simulated DO concentrations equaling or exceeding the DO standards (say 90% or 95%) along the NSC and NBCR and then target all the remaining discretionary diversion to CRCW to try to achieve a high percentage of time with simulated DO concentrations equaling or exceeding the DO standards at Loomis Street. It was reasoned that higher DO concentrations at Loomis Street could be most effectively achieved by taking water at CRCW because of the shorter distance to Loomis Street. However, it was found that taking higher discretionary diversion at Wilmette also effectively improved simulated DO concentrations at Loomis Street, and, thus, discretionary diversion allocations that achieved simulated DO concentrations equaling or exceeding the DO standards at nearly all times (for dry weather for the current conditions case, and for all flows for the Thornton and McCook Stage 1 reservoirs operational case) along the NSC and NBCR were determined and then additional discretionary diversion was taken at CRCW.

Chapter 5 DISCRETIONARY DIVERSION ALLOCATION RESULTS

The initial evaluation of the optimal allocation of discretionary diversion was to determine the system-wide percentage of time with simulated DO concentrations equaling or exceeding the DO standards for the case of annual maximum discretionary diversions of 270 and 101 cfs for current inflow conditions. Then the optimal allocation was determined for the case of an annual maximum discretionary diversion of 101 cfs for the case of the Thornton and McCook Stage 1 reservoirs operational. The optimal allocation for the case of the Thornton Reservoir operational is identical to that for current inflow conditions because the operations of the Thornton Reservoir do not affect the percentage of time with simulated DO concentrations equaling or exceeding the DO standards at Loomis Street, which is the critical point for system-wide performance. Upon determining the percentage of time with simulated DO concentrations equaling or exceeding the DO standards for these discretionary diversion amounts the annual maximum discretionary diversion for the current conditions was varied between 101 and 270 cfs to determine the discretionary diversion amount needed to achieve target levels of the percentage of time with simulated DO concentrations equaling or exceeding the DO standards, such as 90%. Also for the case of the Thornton and McCook Stage 1 reservoirs operational the discretionary diversion amount was gradually increased to determine the discretionary diversion needed to achieve target levels of the percentage of time with simulated DO concentrations equaling or exceeding the DO standards, such as 90% and 95%, and to determine the maximum percentage possible for the case of the current discretionary diversion limit of 270 cfs.

This chapter presents the optimal allocations for the case of current inflows and inflow with the Thornton and McCook Stage 1 reservoirs operational for various amounts of annual discretionary diversion between 101 and 270 cfs. The chapter also discusses the conceptual differences in the assumptions and application of the Harza (1976a, b) QUAL-II model of the CAWS used to determine the original discretionary diversion limits and the DUFLOW model of the CAWS used in this study to explain why the original discretionary diversion limits for TARP Phase I operational yield a relatively low percentage of time with simulated DO concentrations equaling or exceeding the DO standards.

5.1 Optimal Allocations of Discretionary Diversion

5.1.1 Current Inflow Conditions

The "optimal" allocation of discretionary diversion at Wilmette for current inflow conditions was designed to maximize the percentage of time with simulated DO concentrations equaling or exceeding the DO standards during dry weather along the NSC and NBCR. Taking a total discretionary diversion at Wilmette averaged over the year of 63.30 cfsand slightly adjusting IAS operations resulted in percentages of time with simulated DO concentrations equaling or exceeding the DO standards greater than or equal to 99% over the entire year at all monitoring locations along the NSC and NBCR. Figure 5.1 shows the optimal discretionary diversion at Wilmette with the short spikes ofhigh discretionary diversion in April, May, and September representing the "On Demand" withdrawal of discretionary diversion to improve simulated DO concentrations at Simpson Street and/or Main Street. The remainder of the available discretionary diversion (i.e. 270 or 101 cfs) then wastaken at CRCW to maximize the percentage of time with simulated DO concentrations greater than the DO standards at Loomis Street. Figure 5.2 shows the optimal discretionary diversion at CRCW for the 101 and 270 cfs discretionary diversion limits.The maximum system-wide performance that could be attained under current conditions for 270 cfs and 101 cfs of discretionary diversion was 95.8% and 66.8%, respectively, with Loomis Street as the critical point. Figure 5.3 shows the simulated DO concentrations at Loomis Street for the cases of no discretionary diversion and 101 and 270 cfsof discretionary diversion.

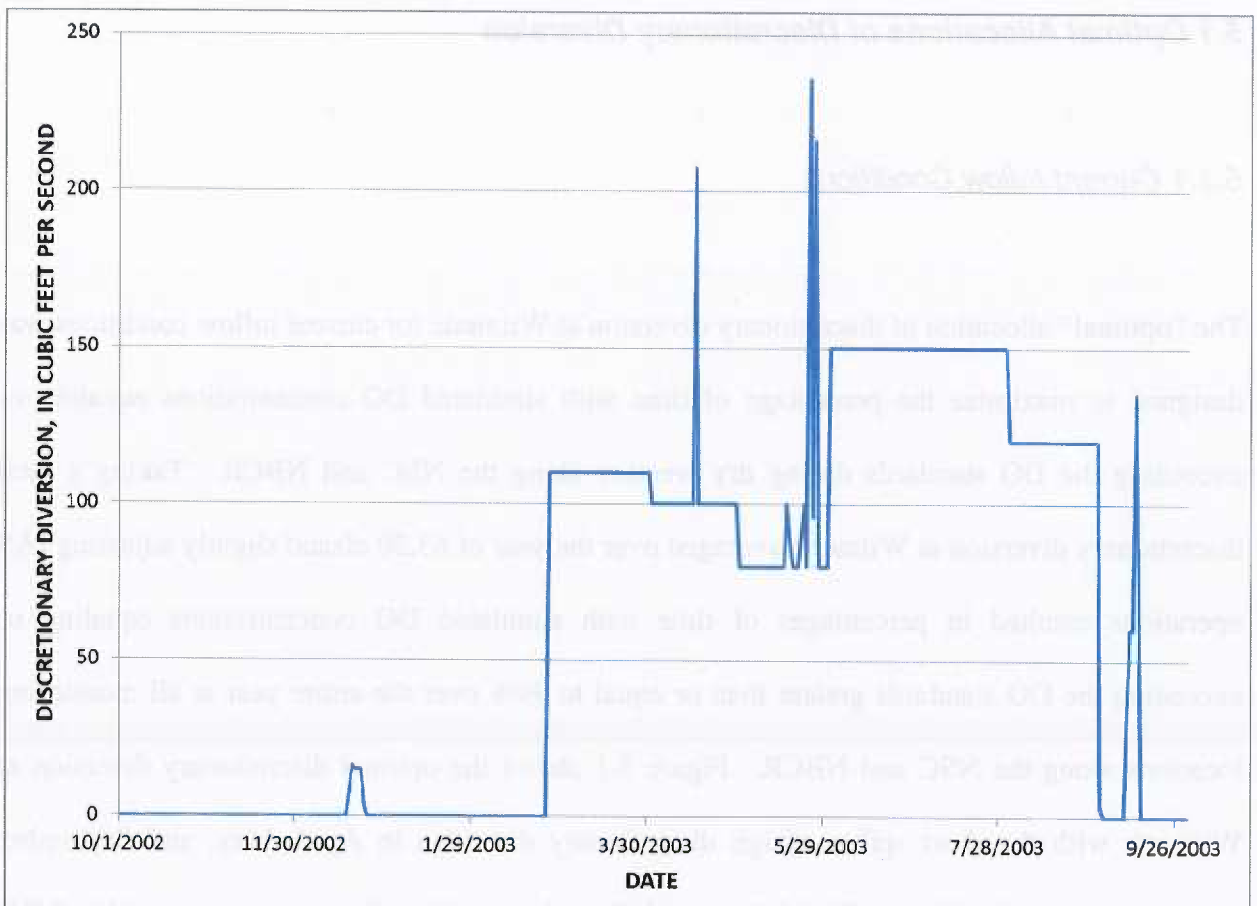

Figure 5.1. Optimal discretionary diversion at the Wilmette Pumping Station for Water Year 2003 for the case of current inflows.

For the case of 270 cfs, it should be noted that the minimum percentage of time with simulated DO concentrations equaling or exceeding the DO standards on the Calumet River system increased to 97.0% (at Route 83) compared to a minimum of 95.4% for the case of no discretionary diversion even though no discretionary diversion was taken at the O'Brien Lock and Dam for either case. At Route 83 on the Calumet-Sag Channel,the improvement in simulated DO concentrations on the nearby CSSC is the most likely cause of increased simulated DO concentrations at Route 83.

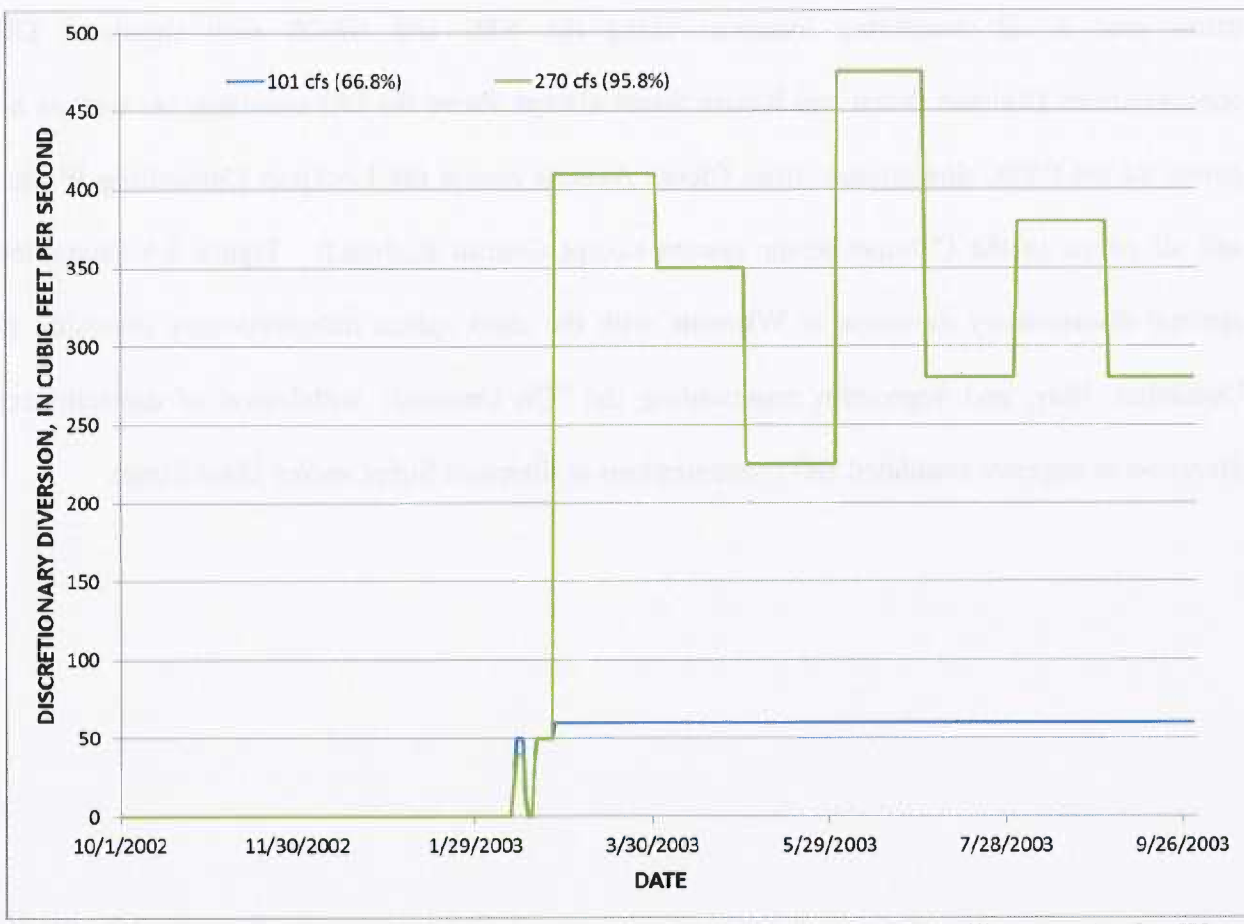

Figure 5.2. Optimal discretionary diversion at the Chicago River Controlling Works for Water Year 2003 for the case of current inflows.

5.1.2 Thornton and McCook Stage 1 Reservoirs Operational

The "optimal" allocation of discretionary diversion at Wilmette for the inflow conditions with the reservoirs operational was designed to maximize the percentage of time with simulated DO concentrations equaling or exceeding the DO standards throughout WY 2003 along the NSC and NBCR. Taking a total discretionary diversion at Wilmette averaged over the year of70.60cfs and slightly adjusting IAS operations resulted in a percentage of time with simulated DO concentrations equaling or exceeding the DO standards greater than or equal to 99.7% over the entire year at all monitoring locations along the NSC and NBCR with simulated DO concentrations Division Street and Kinzie Street always above the DO standards (as well as all points on the CSSC downstream from Cicero Avenue except the Lockport Controlling Works, and all points in the Calumet River system except Conrail Railroad). Figure 5.4 shows the optimal discretionary diversion at Wilmette with the short spikes ofdiscretionary diversion in December, May, and September representing the "On Demand" withdrawal of discretionary diversion to improve simulated DO concentrations at Simpson Street and/or Main Street.

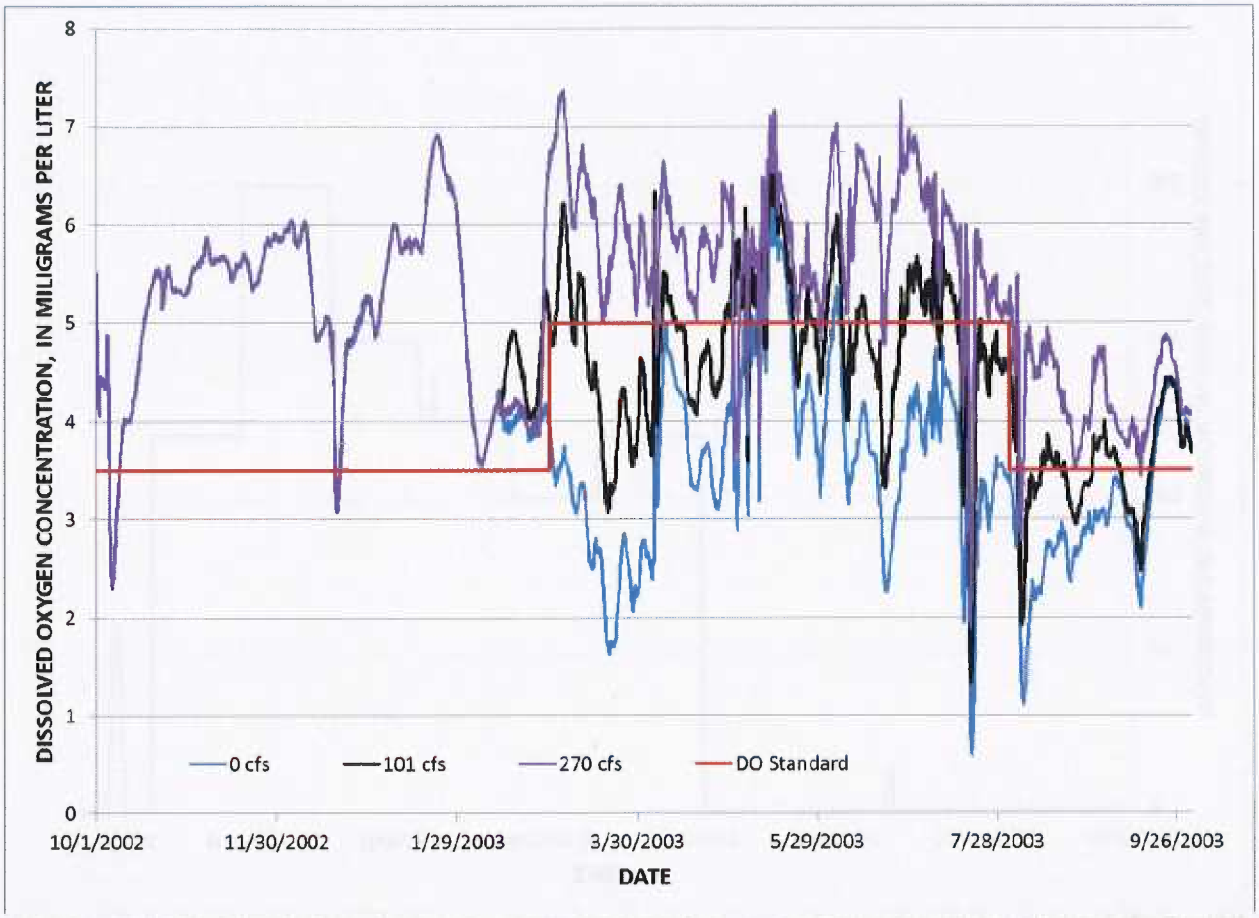

Figure 5.3 Simulated dissolved oxygen concentration at Loomis Street on the South Branch Chicago River for discretionary diversion levels of 0, 101, and 270 cfs for Water Year 2003 for the case of current inflows.

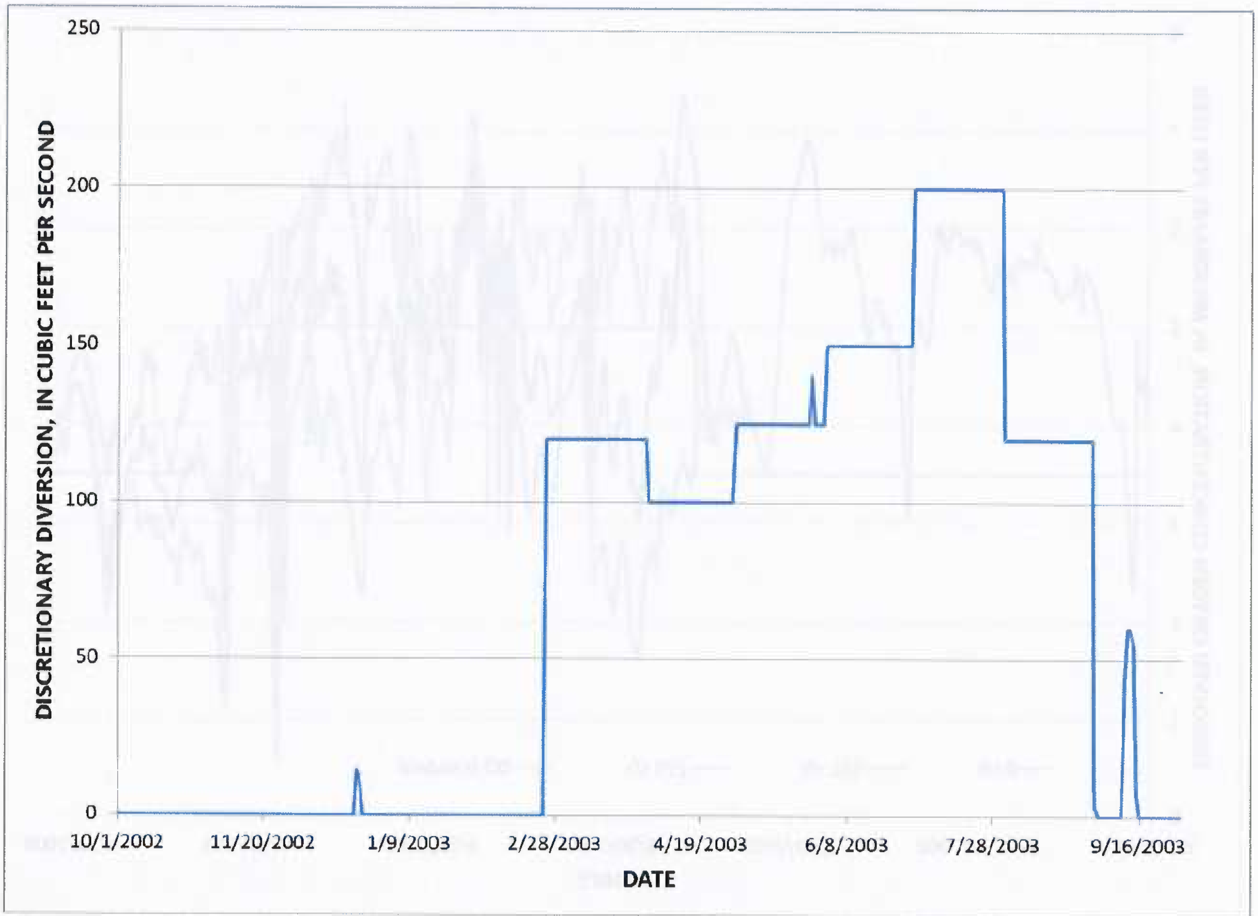

Figure 5.4. Optimal discretionary diversion at the Wilmette Pumping Station for Water Year 2003 for the case of Thornton and McCook Stage 1 reservoirs operational and a 101 cfs limit on discretionary diversion.

The optimal allocation of discretionary diversion at CRCW for the case of Thornton and McCook Stage 1 reservoirs operational and a 101 cfs limit is 50 cfs starting at 0:00 on February 25th and ending at 24:00 on September 30th. The combination of this discretionary diversion at CRCW with the allocation at Wilmette shown in Figure 5.4 and some small adjustments in the IAS operations results in a system-wide performance of 81.5% (with Loomis Street as the critical location). Figure 5.5 shows the simulated DO concentrations at Loomis Street for the cases of no discretionary diversion and 101 cfs of discretionary diversion.

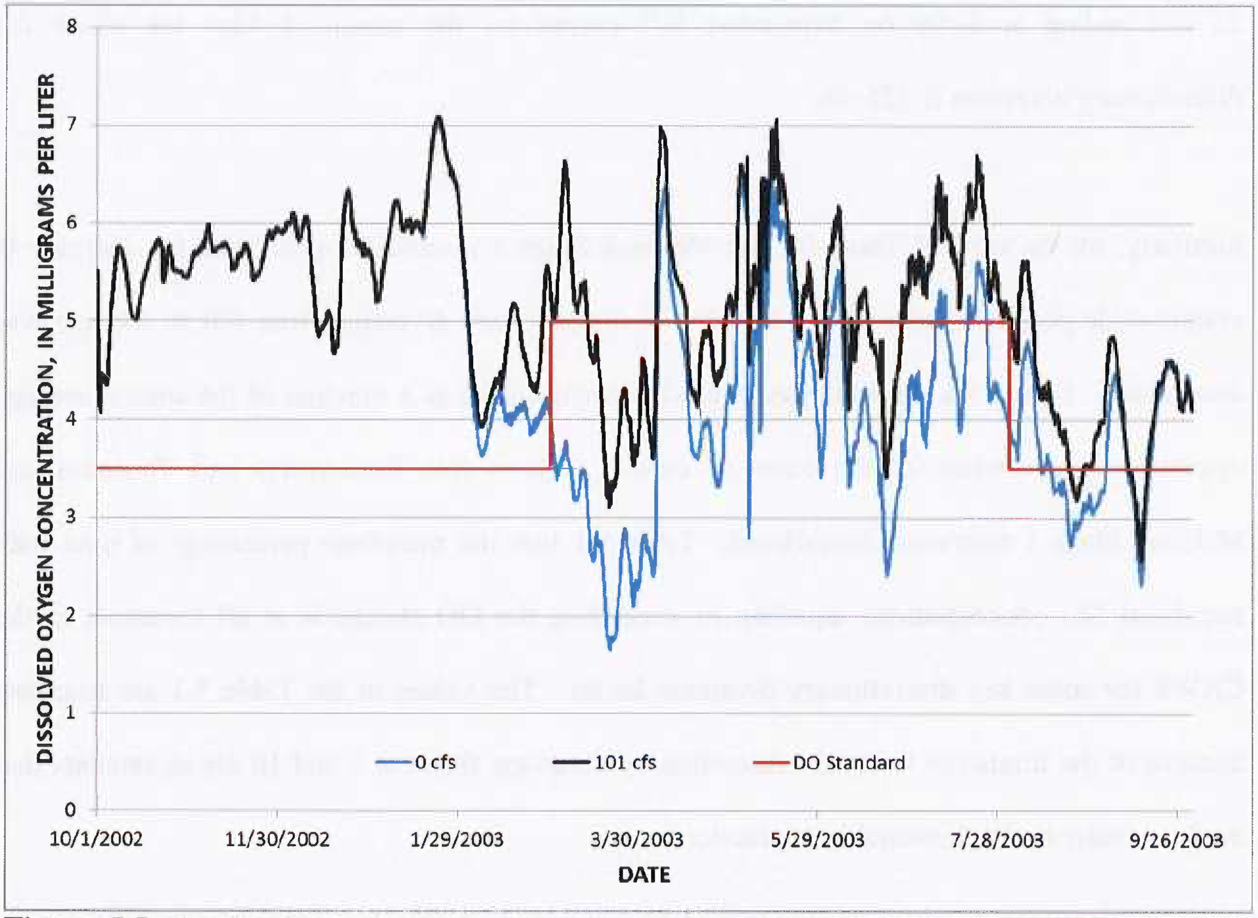

Figure 5.5 Simulated dissolved oxygen concentration at Loomis Street on the South Branch Chicago River for discretionary diversion levels of 0 and 101 cfs for Water Year 2003 for the case of Thornton and McCook Stage 1 reservoirs operational.

5.1.3 System-wide Performance for Intermediate Levels of Discretionary Diversion

To inform the discussion regarding the appropriate amount of annual discretionary diversion required to maintain the CAWS "in a reasonably satisfactory sanitary condition," intermediate levels of discretionary diversion between 101 and 270 cfs were examined for the case of current inflows. It was found that an annual average discretionary diversion of 211.9 cfs could yield a system-wide performance of 90.1%. For this case the discretionary diversion allocation for Wilmette is as shown in Figure 5.4 and that at CRCW is 250 cfs starting at 0:00 on February

25th and ending at 24:00 on September 30th except for the month of May for which the discretionary diversion is 225 cfs.

Similarly, for the case of Thornton and McCook Stage 1 reservoirs operational the increase in system-wide performance with the increase in discretionary diversion from 101 to 270 cfs was determined. Figure 5.6 shows the system-wide performance as a function of the annual average discretionary diversion for the cases of current inflows (No Reservoirs) and Thornton and McCook Stage 1 reservoirs operational. Table 5.1 lists the minimum percentage of time with simulated DO concentrations equaling or exceeding the DO standards at all locations in the CAWS for some key discretionary diversion levels. The values in the Table 5.1 are fractions because of the limitation to set the discretionary diversion flows at 5 and 10 cfs increments that might actually be implementable in practice.

Table 5.1. System-wide minimum percentage of time with simulated dissolved oxygen concentrations equaling or exceeding the dissolved oxygen standards proposed by the Illinois Environmental Protection Agency for key annual average discretionary diversion amounts for the cases of current inflows and Thornton and McCook Stage 1 reservoirs operational for Water Year 2003.

Discretionary Diversion (cfs)	Current Inflows	Thornton and McCook Stage 1 operational
101	66.8	81.5
165	80.1	90.3
206	89.5	95.1
211.9	90.1	95.7
270	95.8	99.9

Loomis Street was the critical location for system-wide performance for the case of Thornton and McCook Stage 1 reservoirs operational through an annual average discretionary diversion amount of around 235 cfs. At this point Conrail Railroad becomes the critical location and discretionary diversion needs to be taken at O'Brien Lock and Dam in the month of July 2003 as shown in Figure 5.7. The discretionary flows of 600 cfs in late July are needed to counteract storm flows and loads originating upstream from South Holland on the Little Calumet River (south) that begin on July 17th and rise as high as 1600 cfs. As the discretionary diversion increases from 235 to 270 cfs Conrail Railroad and Loomis Street alternate as the critical location until a total of 51 hours at 8 locations that have simulated DO concentrations lower than the DO standards: Simpson Street – 3 hr, Main Street – 7 hr, Foster Avenue – 2 hr, Addison Street – 2 hr, Fullerton Avenue – 10 hr, Loomis Street – 12 hr, Lockport Controlling Works – 5 hr, and Conrail Railroad – 10 hr. In total, 160.60, 90.76, and 18.63 cfs of discretionary diversion are taken at CRCW, Wilmette, and O'Brien Lock and Dam, respectively. It is interesting to note that even for the case of TARP Phase II partially complete, the DO standards cannot be equaled or exceeded at all locations in the CAWS for WY 2003 even with 270 cfs of discretionary diversion.

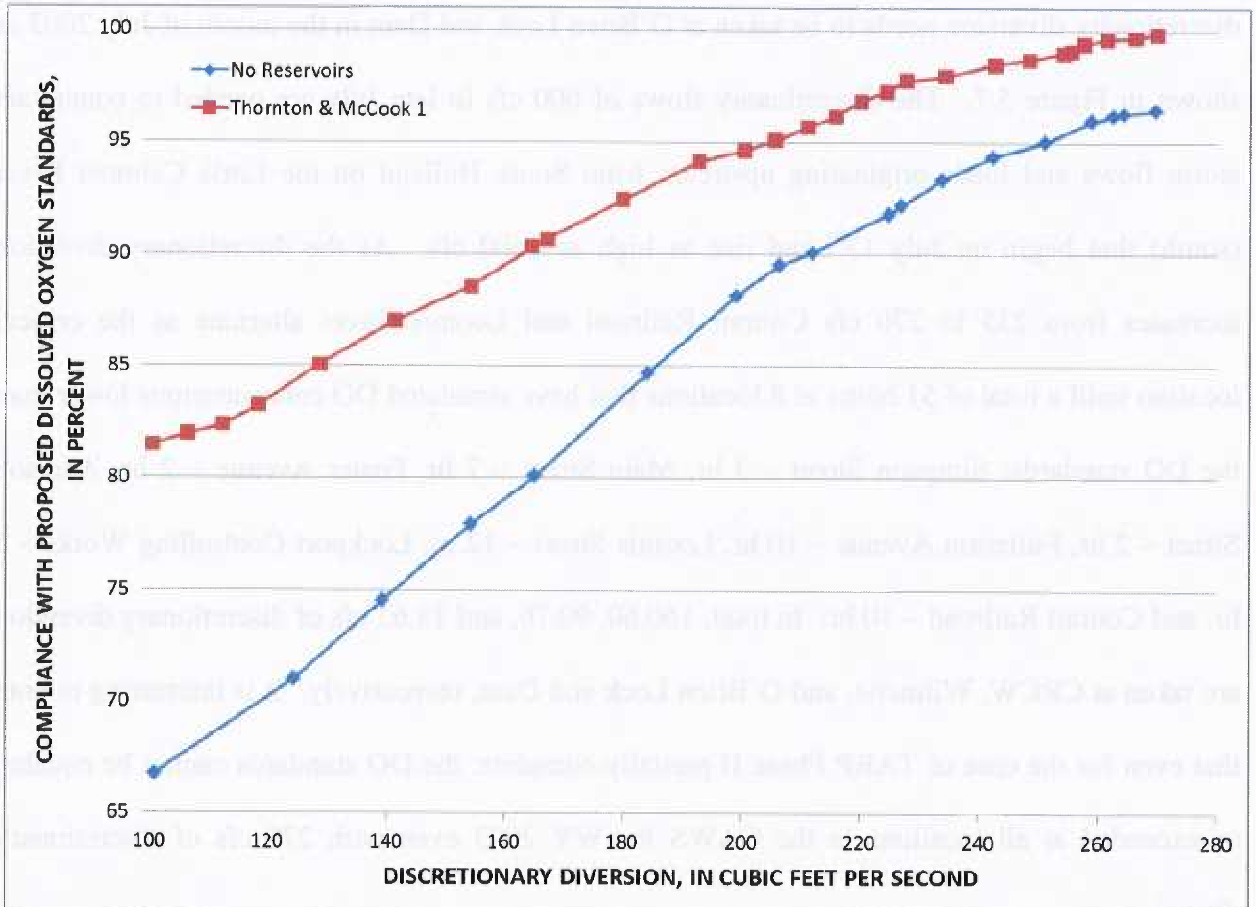

Figure 5.6. System-wide minimum percentage of time with simulated dissolved oxygen concentration equaling or exceeding the dissolved oxygen standards proposed by the Illinois Environmental Protection Agency for Water Year 2003 for the cases of current inflows (No Reservoirs) and Thornton and McCook Stage 1 reservoirs operational.

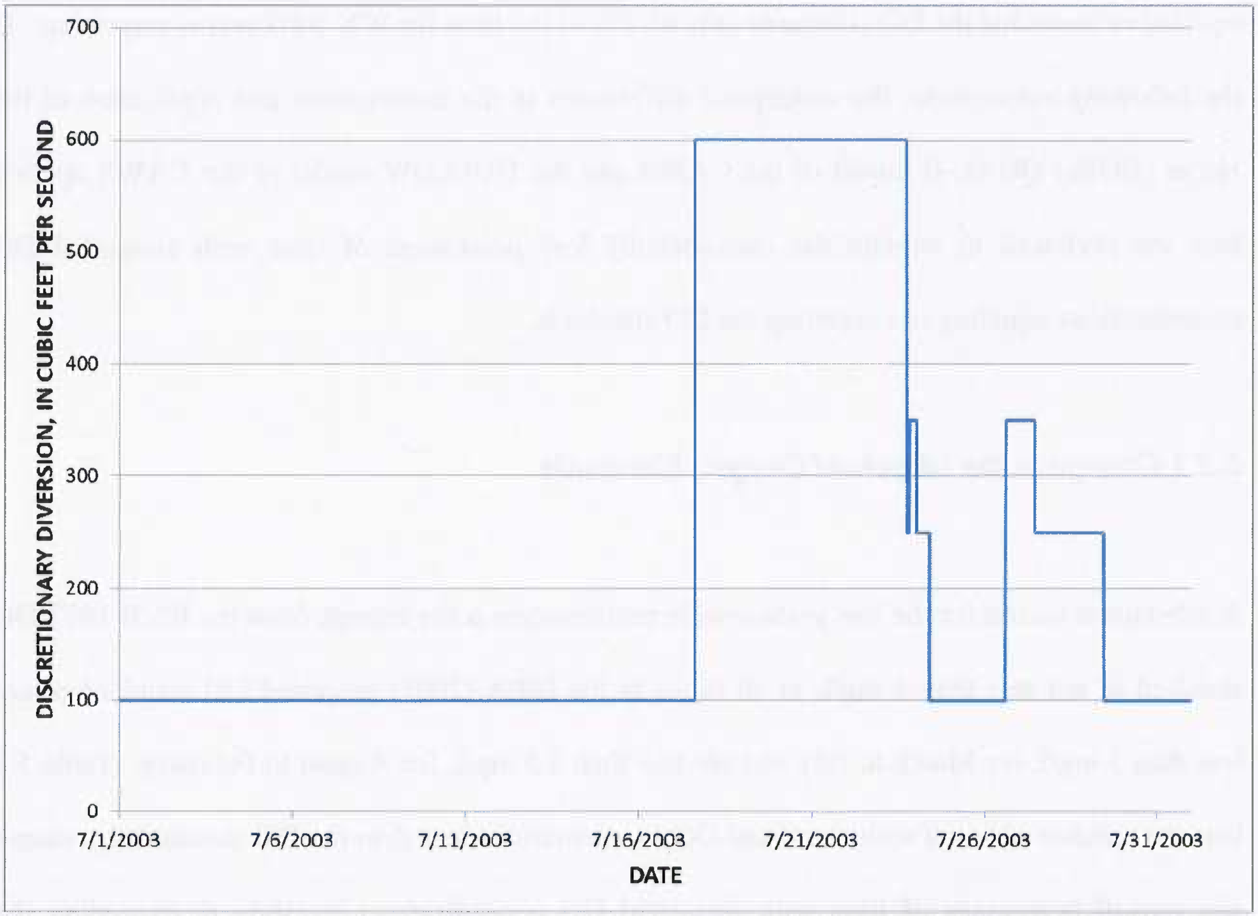

Figure 5.7. Discretionary diversion at the O'Brien Lock and Dam for July 2003 for the case of Thornton and McCook Stage 1 reservoirs operational and 270 cfs of total discretionary diversion.

5.2 Differences in Performance and Concepts Between Original QUAL-II and DUFLOW Modeling of the CAWS

According to the IDOT-DWR (1977) analysis of the QUAL-II modeling results obtained by Harza (1976b) 101 cfs of discretionary diversion should have been sufficient to yield DO concentrations that would equal or exceed the IPCB 1977 DO standards for the CAWS for the case of TARP Phase I fully operational and a system of 9 aeration stations constructed. By WY 2003, TARP Phase I was nearly complete and a system of 7 aeration stations had been constructed in the CAWS, thus, the result that the simulated DO concentration at Loomis Street equaled or exceeded the DO standards only 66.8% of the time for WY 2003 seems surprising. In the following subsections, the conceptual differences in the assumptions and application of the Harza (1976a) QUAL-II model of the CAWS and the DUFLOW model of the CAWS applied here are reviewed to explain the unexpectedly low percentage of time with simulated DO concentrations equaling or exceeding the DO standards.

5.2.1 Change in the Dissolved Oxygen Standards

A substantial reason for the low system-wide performance is the change from the IPCB 1977 DO standard of not less than 4 mg/L at all times to the IEPA (2007) proposed DO standard of not less than 5 mg/L for March to July and not less than 3.5 mg/L for August to February. Table 5.2 lists the number of hours with simulated DO concentrations less than the DO standards by month and overall percentage of time with simulated DO concentrations equaling or exceeding the IEPA (2007) proposed DO standard and the IPCB 1977 DO standard for the optimal allocation of 101 cfs for WY 2003. In this comparison, no changes in the operations at the Devon Avenue and Webster Avenue IASs to improve simulated DO concentrations on the NBCR have been applied, hence the difference in overall percentage of time with simulated DO concentrations equaling or exceeding the IEPA (2007) proposed DO standards reported earlier (66.8%) and that reported in the Table 5.2 (62.9%). The changes in the operations of the Devon Avenue and Webster Avenue IASs would be different to maximize the percentage of time with simulated DO concentrations equaling or exceeding the IPCB 1977 DO standards on the NBCR than those used to maximize the percentage of time with simulated DO concentrations equaling or exceeding the IEPA (2007) proposed DO standards. Thus, because it is desired to evaluate the effectiveness of the discretionary diversion in yielding simulated DO concentrations that equal or exceed the DO standards proposed by the IEPA it was felt that comparing results for the actual operations of the aeration stations would give a clearer indication of the effects of the change in DO standards on system-wide performance.

Table 5.2. Number of hours with simulated dissolved oxygen (DO) concentrations below and the overall percentage of DO concentrations equaling or exceeding the DO standards proposed by the Illinois Environmental Protection Agency (IEPA) in 2007 and the 1977 DO standards of the Illinois Pollution Control Board (IPCB) at Loomis Street for the optimal allocation of 101 cfs of discretionary diversion.

Month	IEPA (2007)	IPCB (1977)
October	80	133
November	0	0
December	35	60
January	0	0
February	0	311
March	744	257
April	538	87
May	356	59
June	405	94
July	424	86
August	418	693
September	249	535
Total	3249	2315
Percent Equaling or Exceeding	62.9	73.6

In Table 5.2 substantial decreases in the number of hours with simulated DO concentrations below the DO standards can be seen for March to July as the DO standard changes from 5 to 4 mg/L, similarly substantial increases in the number of hours can be seen in August-February as the DO standard changes from 3.5 to 4 mg/L. Overall the percentage of time with simulated DO concentrations equaling or exceeding the DO standards decreases 10.7 points with the change in DO standards. Therefore, about 10 percentage points of the low level of system-wide performance can be attributed to the change in DO standards.

5.2.2 Sediment Oxygen Demand (SOD)

The calibration of SOD (or benthic oxygen demand) and the adjustment of SOD to reflect the reductions in pollutant loadings with TARP Phase I operational involve major assumptions that greatly affect the reliability of the Harza (1976a, b) QUAL-II modeling and the reliability of the 101 cfs discretionary diversion limit. Harza (1976a, p. III-6) states "Since benthic oxygen demand has not been separately measured, the benthic component of the model was determined following calibration of the model to the existing DO levels in the waterways." Harza (1976a, b) does not include any detailed information (statistics on or figures showing the comparison of simulated and measured DO concentrations) on the quality of the DO calibration. Exhibits 3-5 of Harza (1976a) show the computed DO profiles for various reaches of the CAWS for different seasons simulated for existing conditions (i.e. TARP and aeration stations not operational). If it is assumed that these profiles reflect the actual DO data used to calibrate the models some key characteristics of the calibration can be surmised. Figure 5.8 shows Exhibit 4a from Harza (1976a) that shows the DO profile along the SBCR and CSSC for existing summer conditions. From this it can be seen that anoxic conditions existed along the majority of these waterways in the summer including the region around Loomis Street (RM 321.9 in Figure 5.8). Thus, in the calibration of the SOD rate in the SBCR the rate probably was gradually increased until zero DO was achieved in the SBCR. However, this minimum level of the SOD rate necessary to achieve zero DO is not necessarily a good reflection of the true SOD rate. Using a much higher SOD rate would also achieve "calibration to measured DO concentrations," i.e. a DO concentration of zero, but the two different SOD rates would result in substantially different projections of the amount of discretionary diversion needed to yield high percentages of time with DO concentrations that equal or exceed the DO standards or of the response of the system to the installation of water quality mitigation measures, such as aeration stations or WRP improvements. Figure 5.9 shows Figure 2 of Harza (1976b) in which the results of the Harza (1976a, b) QUAL-II and MSD (1976) extended Streeter-Phelps models of the CAWS are compared for the SBCR and CSSC for the case of the aeration stations operational. Harza (1976b) states "Harza's benthic demand in this reach would have to be increased by more than 100 percent to match the MSDGC result." The DO profile obtained with the MSD (1976) model for these waterways are more in line with actual DO measurements made with the MWRDGC's continuous DO monitors (for the case of TARP Phase I nearly operational and 7 aeration stations operational) than is the DO profile obtained with the Harza model. Thus, the true SOD rate may have been double (or more) that used in Harza (1976a, b).

Harza (1976a) reasoned that the reduction in CSO loads because of the operation of TARP Phase I and TARP Phase II would have a substantial effect on the SOD rates in the CAWS. For the case of TARP Phase II operational Harza (1976a, p. IV-2) stated "It is expected that with combined sewer overflows virtually eliminated, the benthic deposits will stabilize and cease to exert an oxygen demand on the overlying waters." Thus, they assumed that the SOD rate would decrease to zero for the case of TARP Phase II operational. This is a highly unrealistic assumption because it implies that for streams not receiving CSO loads there should be no SOD, which certainly is not the case in nature.

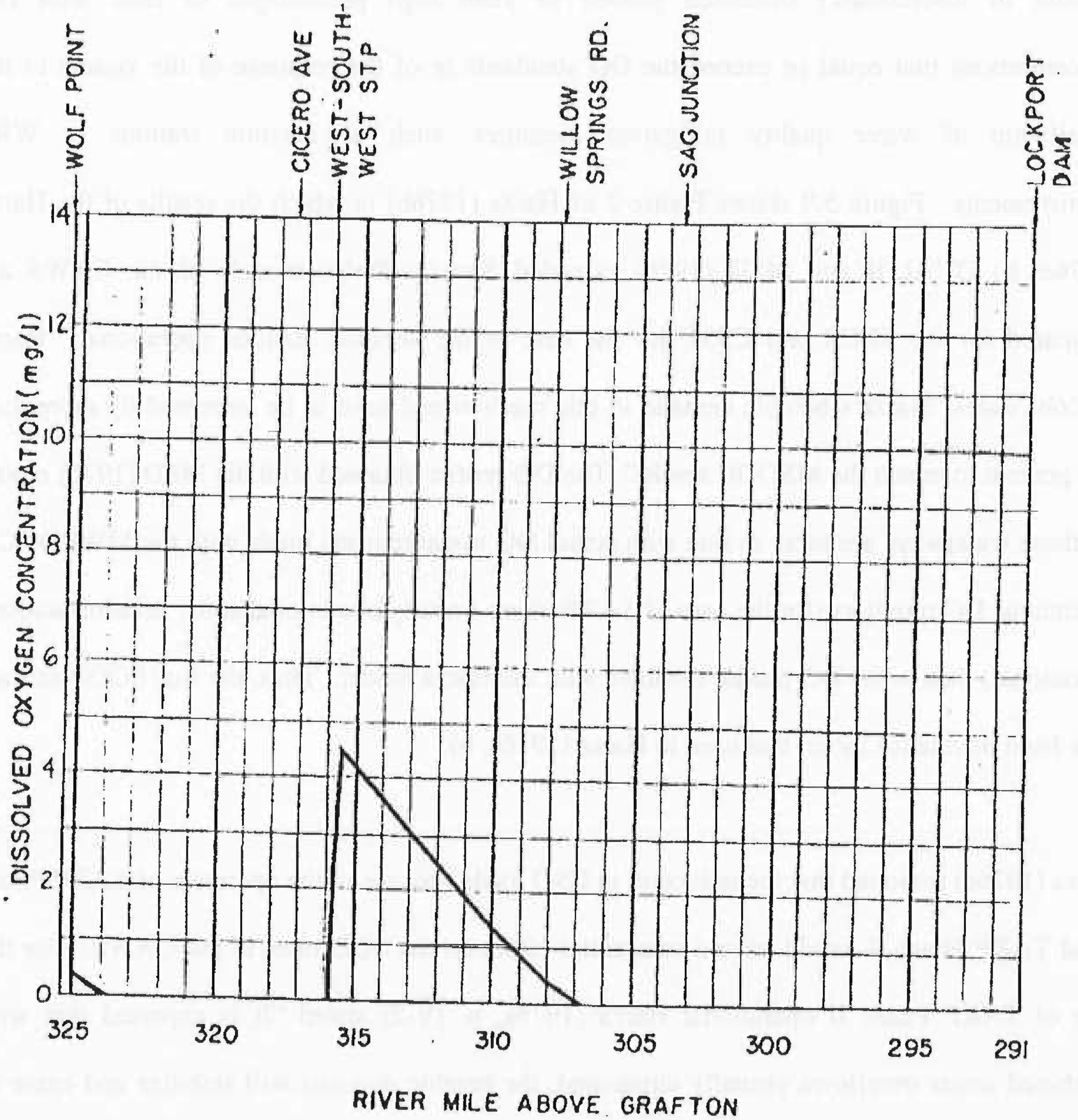

Figure 5.8. Dissolved oxygen profile along the South Branch Chicago River and Chicago Sanitary and Ship Canal for existing summer conditions in the mid-1970s computed with the QUAL-II model of the Chicago Area Waterway System developed by Harza (1976a) [Exhibit 4a of Harza (1976a)]

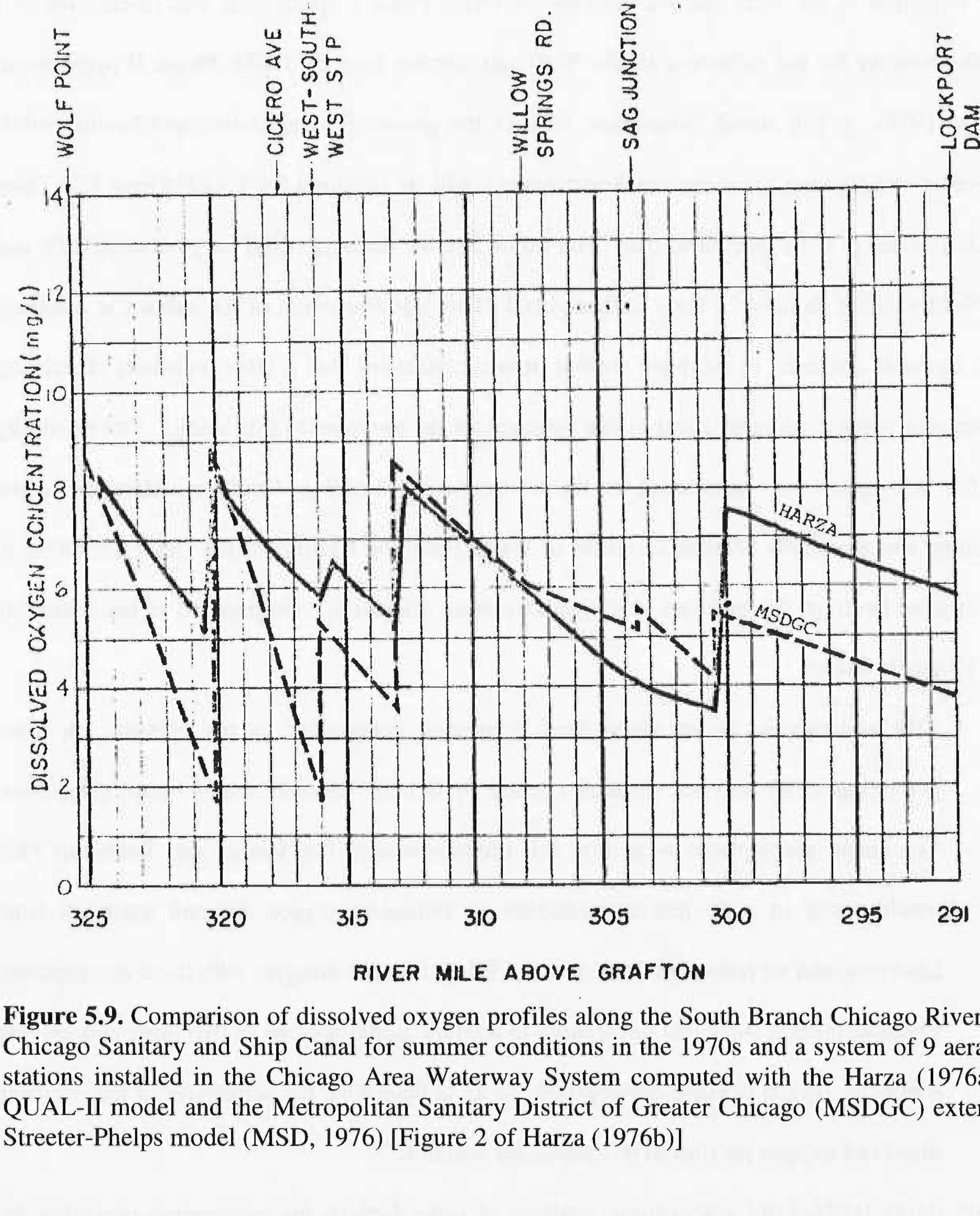

Figure 5.9. Comparison of dissolved oxygen profiles along the South Branch Chicago River and Chicago Sanitary and Ship Canal for summer conditions in the 1970s and a system of 9 aeration stations installed in the Chicago Area Waterway System computed with the Harza (1976a, b) QUAL-II model and the Metropolitan Sanitary District of Greater Chicago (MSDGC) extended Streeter-Phelps model (MSD, 1976) [Figure 2 of Harza (1976b)]

The reduction in the SOD rate for the case of TARP Phase I operational was determined in a similar way as for the reduction in the SOD rate for the case of TARP Phase II operational. Harza (1976a, p. I-9) stated "More than 85% of the grease, floating debris and benthal solids presently overflowing from the combined sewers will be captured by TARP Phase I." Thus, Harza (1976a, p. II-6) speculated that "The future benthic demand could vary between 20% and 100% of existing demand." They further stated "Through discussion of the subject at meetings with agencies involved in the prior studies, it was concluded that a 50% reduction of existing values represents a reasonable and usable estimate for the purposes of this study." The reliability of this assumption was questioned in the testimony of Daniel J. Goodwin, Manager of the Planning and Standards Section, Division of Water Pollution Control, IEPA (May 27, 1976) in the original hearings on the Lake Michigan Diversion allocation. On page 18 of his testimony Mr. Goodwin stated:

> "The assumptions about which there is greatest uncertainty, in my opinion, are those pertaining to the oxygen demand exerted by benthic deposits under future conditions. The stated assumptions were that full implementation the Tunnel and Reservoir Plan would result in a 50 percent reduction in sediment oxygen demand upstream from Lockport, and no reduction downstream. While I do not disagree with these assumptions, I believe there is sufficient uncertainty to warrant modelling one or two other conceivable sediment oxygen demand assumptions, so as to determine the sensitivity of the resulting dissolved oxygen profiles to this particular variable."

While Harza (1976a) did a sensitivity analysis of some factors, the assumption regarding the reduction in the SOD rate was not the subject of this sensitivity analysis.

Little information on the reduction of SOD rates in response to reductions in loads of BOD and suspended solids is available in the literature. Melching and Smith (2010) determined the changes in calibrated SOD rates resulting from changes in CBOD loads to the East Branch Du Page River, in Du Page County, Ill., between 1983 and 1997. In July and August 1983 diurnal water quality data were collected on this river for the verification and calibration, respectively, of a QUAL-II (Water Resources Engineers, 1974) model for use in water-quality planning (Freeman et al., 1986). In June 1997, diurnal water quality data were collected on this river for the calibration of a QUAL2E model (Brown and Barnwell, 1987) for use in a Total Maximum Daily Load (TMDL) allocation (CH2M-Hill, 2004). In between 1983 and 1997 major improvements were made at the Glenbard, Downers Grove, Du Page County-Woodbridge-Valley Green, Bolingbrook #1, and Citizen's Utility #2 wastewater treatment plants such that the CBOD load to the downstream end of the East Branch Du Page River was more than 90% lower in 1997 than in 1983. Melching and Smith (2010) calibrated and verified a QUAL2E model (Brown and Barnwell, 1987) for the August 1983 and July 1983 data using identical parameters as for the QUAL-II model of Freeman et al. (1986) where appropriate. Melching and Smith (2010) also calibrated a QUAL2E model for the June 1997 data keeping the same parameters as for the 1983 model except for the SOD rate. Over the lower 8.7 miles of the river the more than 90% reduction in CBOD load resulted in a reach-averaged reduction in the SOD rates around 64%. Thus, there was not a one-to-one proportionality between the reductions in CBOD loads and SOD rates.

Macaitis (1975) and MSD (1976) reported that the BOD loads from the CSOs were between about 45 and 50% of the total BOD loads to the CAWS with the WRPs accounting for approximately the other half of the BOD loads for the pre-TARP conditions. Thus, if it is assumed that TARP Phase I captures 85% of the BOD load from CSOs, this may only result in a 40% reduction in the total BOD load. From the experience of the East Branch Du Page River, a 40% reduction in the total BOD load might only result in a 30% reduction in the SOD rate.

In the DUFLOW model of the CAWS the computed SOD rates were calibrated against point measurements made in 2001 by the MWRDGC as detailed in Table 3.28 of Melching et al. (2010). In DUFLOW (2000) the SOD is computed using the DiToro and Fitzpatrick (1993) sediment flux model. This sediment flux model distinguishes among transported material that flows with water, bottom materials that are not transported with the water flow, and pore water in bottom materials that are not transported but that can be subject to similar water-quality interactions to those for the water column. In DUFLOW (2000), the SOD rate is simulated as a diffusive exchange of oxygen between the water column and the active (top) sediment layer (which has its own CBOD, DO, nutrients, etc. in the pore water). In DUFLOW the SOD rate changes with time as sediment is eroded and deposited and the quality of the sediment pore water and the overlying water change over time.

Figure 5.10 shows the SOD rates computed with DUFLOW for the current inflows (i.e. No Reservoirs) and Thornton and McCook Stage 1 reservoirs operational at 104th Street on the Calumet-Sag Channel for WY 2003. 104th Street was chosen because it is near the downstream end of the Calumet-Sag Channel, and, thus, the change in the SOD rate at this location reflects the reduction resulting from the end of CSO flows to the Calumet River system. The SOD rate for the Thornton and McCook Stage 1 reservoirs operational ranges from 18.2% higher to 46.5%

lower than that for current inflow conditions with a mean of 16.4% lower and a median of 14.8% lower. It may be appropriate to speculate that the true reduction in SOD rate resulting from the reduction in CSOs can be better estimated by considering the results for September so that the changes have had nearly one year to stabilize. Over the month of September the reduction in the SOD rate ranges from 12.3% to 41.7% with a mean of 31.3% and a median of 31.0%. Of course, this 30% reduction represents the case for TARP Phase II complete for the waterway under consideration, and it is clear that there is still a substantial SOD rate with TARP Phase II complete. The reductions in the SOD rate at the upstream end of the Calumet River system are smaller than those at 104th Street and other points on the downstream end of the Calumet-Sag Channel.

Changes in SOD rates along the Chicago River system are much smaller than those for the Calumet River system because the Chicago River system receives CSO flows for a case with hydrologic conditions identical to WY 2003 and the McCook Reservoir Stage 1 operational, and it receives treated effluents from the O'Brien and Stickney WRPs. Figure 5.11 shows the SOD rates computed with DUFLOW for the current inflows (i.e. No Reservoirs) and Thornton and McCook Stage 1 reservoirs operational at Kinzie Street on the NBCR and at Cicero Avenue on the CSSC.

Figure 5.10. Sediment oxygen demand rates at 104th Avenue on the Calumet-Sag Channel computed for the hydrologic conditions of Water Year 2003 for the cases of current inflows (No Reservoirs) and the Thornton and McCook Stage 1 reservoirs operational.

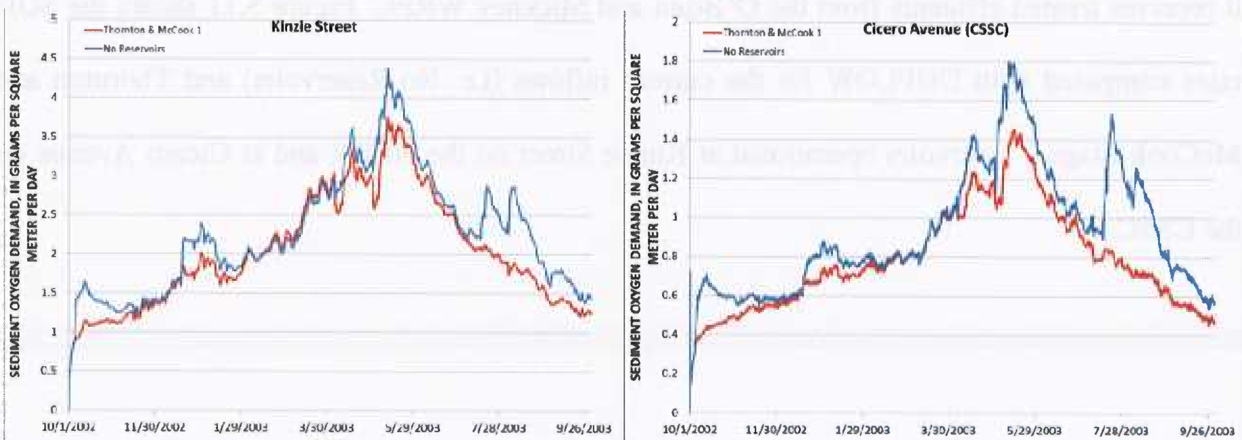

Figure 5.11. Sediment oxygen demand rates at Kinzie Street on the North Branch Chicago River and Cicero Avenue on the Chicago Sanitary and Ship Canal computed for the hydrologic conditions of Water Year 2003 for the cases of current inflows (No Reservoirs) and the Thornton and McCook Stage 1 reservoirs operational.

In summary, the originally calibrated SOD rates for the Harza (1976a, b) QUAL-II model of the CAWS may be one half (or even lower) of the true SOD rates for the CAWS in the mid-1970s. These low SOD rates then were reduced by 50% when evaluating the reduction in loading to the CAWS because of the operations of TARP Phase I (Harza, 1976a, b). However, a 30% reductionmight have been more appropriate considering the reduction in the overall BOD loading to the CAWS, the experience of SOD rate reduction in the East Branch Du Page River determined fromMelching and Smith (2010), and the DUFLOW simulation of SOD rates for the Calumet-Sag Channel in this study. This leads to a potentially large underestimate of SOD rates after TARP Phase I is completed, which, in turn, leads to a substantial underestimate of the discretionary diversion needed to meet the IPCB 1977 DO standards.

5.2.3 Nitrogeneous Oxygen Demand

In the development of the extended Streeter-Phelps model of the CAWS the MSD (1976) reasoned that oxygen demand resulting from the transformation of ammonium to nitrate (i.e. nitrification) was insignificant in the CAWS because:

1) Lake Michigan diversion water has a negligible ammonia concentration and as a consequence, ammonia oxidizing organisms are not introduced into the waterways in significant populations by diversion.
2) The benthic material is largely in an anaerobic state.

3) Chlorine residuals are introduced into the waterways with treatment plant effluents. While these residuals dissipate rapidly, nitrifying organism kills near plant outfalls are likely.

4) The growth time required to generate significant ammonia oxidizing organisms is on the order of five days. Travel times with the waterway system are generally less than five days.

Harza (1976a, p. II-6) adopted a similar assumption stating "Nitrification of ammonia does not occur in the waterway above Lockport."

IDOT-DWR (1980, p. 54-55, Paragraph (14.356)) noted that "IEPA felt that it could not be assumed that nitrification would not occur above Lockport after construction of TARP and improvements in MSD's sewage treatment abilities. If nitrification does occur above Lockport, the modeled oxygen demand could be too low." IEPA's 1980 concern would seem to relate to item 2 above that with TARP and other improvements operational, the benthic material would now be in an aerobic state and also to the fact that carbonaceous waste would no longer dominate the CAWS and block the growth of *nitrosomonas* and *nitrobacter* bacteria needed to break down ammonium and nitrite, respectively. Further, in 1984 the MWRDGC discontinued chlorine disinfection at the major WRPs so item 3 is no longer an issue. Finally, as shown in Table 4.1 travel times greater than 5 days are common in the CAWS, so item 4 is not issue, especially since massive bacteria growth to consume CBOD is less of an issue with TARP Phase I and other WRP improvements now operational.

As noted by IEPA the ignorance of nitrification in the CAWS above Lockport resulted in too low an oxygen demand for the case of TARP Phase I operational, and, thus, an underestimation of the discretionary diversion needed to meet the IPCB 1977 DO standards. The inclusion of the nitrogeneous oxygen demand in the DUFLOW model of the CAWS contributes to the need for higher levels of discretionary diversion found in this study.

5.2.4 Aeration Stations

In the Harza (1976a, b) modeling of the CAWS for the case of TARP Phase I and a system of 9 aeration stations operational used to determine the 101 cfs limit on discretionary diversion, 4 aeration stations—between Randolph and Washington streets on the SBCR and at Western Avenue, Summit-Lyons Road, and the Lemont WRP on the CSSC—that weren't constructed were considered. Only the aeration station between Randolph and Washington streets on the SBCR would affect the percentage of time with simulated DO concentrations equaling or exceeding the DO standards at Loomis Street. The fact that this station was not built also contributes to the low percentage of time with simulated DO concentrations equaling or exceeding the DO standards at Loomis Street. However, Melching et al. (2010, 2013) found that in order to obtain simulated DO concentrations greater than or equal to the CAWS B DO standards throughout the SBCR for WY 2003 two new aeration stations would be needed on the SBCR in addition to 5 new aeration stations on the NSC and NBCR. Most likely many more aeration stations would be needed to obtain simulated DO concentrations that meet the more stringent CAWS A DO standards at Loomis Street. Thus, the fact that one proposed station on the SBCR was not built would seem to be a far smaller reason for the low percentage of time with simulated DO concentrations equaling or exceeding the DO standards at Loomis Street than the three causes discussed in the previous subsections.

Chapter 6 CONCLUSIONS

The DUFLOW model has been calibrated and verified for the simulation of DO and related constituents for WYs 2001, 2003, and 2008. This model was applied to determine the optimal allocation of discretionary diversion in the CAWS and the percentage of time with simulated DO concentrations equaling of exceeding the IEPA (2007) proposed DO standards that can be attained in the CAWS for various amounts of discretionary diversion ranging between 270 cfs (the currently allowed annual maximum) and 101 cfs (the annual maximum scheduled to take effect in WY 2015). The inflows to the DUFLOW model for WY 2003 were used to evaluate the relation between percentage of time with simulated DO concentrations equaling or exceeding the DO standards and the amount of discretionary diversion in the CAWS for the case of current inflows and the Thornton and McCook Stage 1 reservoirs operational (i.e. the condition beginning in 2017). The condition with only the Thornton Reservoir operational (i.e. the condition beginning in 2015) was not evaluated in detail because the critical location for system-wide performance is Loomis Street on the South Branch Chicago River which is not substantially affected by the changes in CSO flows resulting from the operation of the Thornton Reservoir.

The current gravity CSO flows for WY 2003 to the CAWS were obtained from the USACE models of the CSO drainage areas, major interceptor sewers, and TARP tunnels. These flows were decreased as per the results of the U of I models of the Calumet TARP tunnels for the case of Thornton Reservoirs operational and the USACE models of the Mainstream TARP tunnels for the case of the McCook Reservoir Stage 1 operational. The reductions in CSO flows then were stored in the reservoirs and pumped out to the Stickney and Calumet WRPs and treated at these plants as capacity was available. The downstream stage boundary condition also was modified to account for the reduction in the CSO flows. Finally, the water temperatures in the CAWS were adjusted to account for the closure of the Fisk and Crawford power plants and of Units 1 and 2 of the Will County Power Plant.

For the current conditions, discretionary diversion limits of 101 and 270 cfs were found to yield system-wide performances of 66.8% and 95.8%, respectively, and a discretionary diversion of 211.9 cfs was found to yield a system-wide performance of 90.1% when applying an optimization strategy to the discretionary diversion for the hydrologic inflow conditions of WY 2003. For the case of the Thornton and McCook Stage 1 reservoirs operational, discretionary diversion limits of 101 and 270 cfs were found to yield system-wide performances of 81.5% and 99.9%, respectively, and discretionary diversion limits of 165 cfs and 206cfs were found to yield system-wide performances of 90.3% and 95.1%, respectively, when applying an optimization strategy to the discretionary diversion for the hydrologic inflow conditions of WY 2003.

The original discretionary diversion limits of 320 cfs and 101 cfs, were determined from the Harza (1976a, b) QUAL-II modeling of the CAWS for the case of the 7-day, 10-year low flow. The use of the 7-day, 10-year low flow is appropriate for a steady-state model such as QUAL-II, but the 7-day, 10-year low flow does not really have a meaning when applying an unsteady-state model like DUFLOW that considers the fluctuations in flows and pollutant loads throughout the year. WY 2003 represents an approximation of the 10-year "dry year" and, thus, presents a rigorous test of the need for discretionary diversion to maintain water quality that is consistent with the 7-day, 10-year low flow concept, but it does not compose a "worst-case" scenario that might overestimate the need for discretionary diversion. Under current conditions, on the other hand, the overall percentage of time with simulated DO concentrations equaling or exceeding the DO standards would be lower for wetter years as discretionary diversion can only shorten the duration of low DO concentrations following a CSO event, it cannot mitigate the short term heavy pollutant load resulting from a CSO event. Therefore, if DO concentrations equaling or exceeding the DO standards 90% of the timeare sought under current conditions it might be wise to add in a 10% or 15% safety factor to the discretionary diversion allowance, thus, the total should be on the order of 230 to 240 cfs. For the case of the Thornton and McCook Stage 1 reservoirs operational the CSO events have less importance, even for wetter years, and the 165 cfs limit might be a reasonable level of discretionary diversion. However, it is important to keep in mind that the optimal allocation done here was done in a modeling environment in which the diversion amounts could be determined through trial and error procedures. In practice, water-quality managers will seek to minimize error (i.e. periods with DO concentrations less than theDO standards), thus, the actual practical rules for taking discretionary diversion will seek to use more water to ensure DO concentrations that equal or exceed the DO standards are obtained. Thus, even higher discretionary diversion, such as the current discretionary diversion limit of 270 cfs for the case of current inflows or 200 cfs for the case Thornton and McCook Stage 1 reservoirs operational, might be appropriate for actual operations that maximize the percentage of time with DO concentrations equaling or exceeding the DO standards in a practically, implementable way.

The results of this study indicate that much higher amounts of discretionary diversion are needed to maintain water quality in the CAWS for the case of TARP Phase I operational and a system of aeration stations constructed and operational than was estimated using the QUAL-II model developed by Harza (1976a, b). Three important features of the changes in the model concepts and application primarily have contributed to this larger requirement for discretionary diversion: (1) the change from the IPCB 1977 DO standards to the IEPA (2007) proposed DO standards, (2) the underestimation of the SOD rates in the CAWS during the mid-1970s and the subsequent overestimation in the reduction in the SOD rates due to the operation of TARP Phase I, and (3) the ignorance of the nitrogeneous oxygen demand in the CAWS in the original QUAL-II modeling. The importance of the first issue above is clear. The assumptions related to the second and third issues above had been questioned by the IEPA at the time the original allocation for discretionary diversion was made. Therefore, the original discretionary diversion limits were set on the basis of questionable assumptions and now the CAWS faces new DO standards, and, thus, it seems appropriate to re-examine the scheduled changes in the discretionary diversion limit and to let the results of this evaluation inform this re-examination.

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