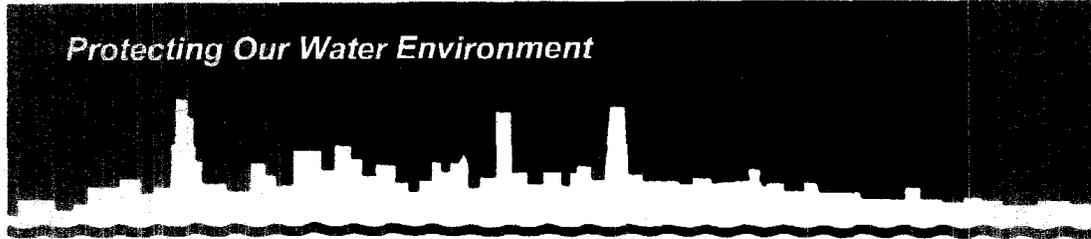


*Protecting Our Water Environment*



*Metropolitan Water Reclamation District of Greater Chicago*

***RESEARCH AND DEVELOPMENT  
DEPARTMENT***

***REPORT NO. 04-14***

***PRELIMINARY CALIBRATION OF A MODEL FOR SIMULATION OF  
WATER QUALITY DURING UNSTEADY FLOW IN THE CHICAGO  
WATERWAY SYSTEM AND APPLICATION TO PROPOSED  
CHANGES TO NAVIGATION MAKE-UP DIVERSION PROCEDURES***

***Prepared By***

***Institute for Urban Environmental Risk Management  
Marquette University, Milwaukee Wisconsin***

***September 2004***

**Metropolitan Water Reclamation District of Greater Chicago**  
100 East Erie Street Chicago, IL 60611-2803 (312) 751-5600

**PRELIMINARY CALIBRATION OF A MODEL FOR SIMULATION OF  
WATER QUALITY DURING UNSTEADY FLOW IN THE CHICAGO  
WATERWAY SYSTEM AND APPLICATION TO PROPOSED  
CHANGES TO NAVIGATION MAKE-UP DIVERSION PROCEDURES**

**Prepared By**

**Institute for Urban Environmental Risk Management  
Marquette University, Milwaukee Wisconsin**

**August 2004**

**Research and Development Department  
Richard Lanyon, Director**

**September 2004**

**Institute for Urban Environmental Risk Management**

**Marquette University, Milwaukee WI 53201-1881**

---

TECHNICAL REPORT # 15

PRELIMINARY CALIBRATION OF A MODEL FOR SIMULATION OF  
WATER QUALITY DURING UNSTEADY FLOW IN THE CHICAGO  
WATERWAY SYSTEM AND APPLICATION TO PROPOSED  
CHANGES TO NAVIGATION MAKE-UP DIVERSION PROCEDURES

SUBMITTED TO

The Metropolitan Water Reclamation District of Greater Chicago

Emre ALP, M.S.

Department of Civil and Environmental Engineering

Charles S. MELCHING, Ph.D, P.E.

Department of Civil and Environmental Engineering

Milwaukee, Wisconsin

August 2004

# TABLE OF CONTENTS

|  |           |
|--|-----------|
| TABLE OF CONTENTS.....   | i         |
| LIST OF FIGURES.....   | iv        |
| LIST OF TABLES.....  | x         |
| <b><u>CHAPTER 1 – INTRODUCTION</u></b> .....   | <b>1</b>  |
| <b><u>CHAPTER 2 - HYDRAULIC MODEL VERIFICATION</u></b> .....                               | <b>5</b>  |
| <u>2.1 INTRODUCTION</u> .....  | 5         |
| <u>2.2 HYDRAULIC DATA USED FOR THE MODEL INPUT</u> .....                                   | 6         |
| <u>2.2.1 Measured Inflows, Outflows, and Water-Surface Elevations</u> .....                | 6         |
| <u>2.2.2 Estimation of Flow for Ungaged Tributaries and Combined Sewer Overflows</u> ..... | 7         |
| <u>2.2.3 Summary of Boundary Conditions and Tributary Inflows</u> .....                    | 9         |
| <u>2.3 CHANNEL GEOMETRY AND ROUGHNESS COEFFICIENT</u> .....                                | 13        |
| <u>2.4 MODEL VERIFICATION LOCATIONS</u> .....  | 14        |
| <u>2.5 FLOW BALANCE</u> .....  | 14        |
| <u>2.6 RESULTS OF THE HYDRAULIC VERIFICATION</u> .....                                     | 18        |
| <b><u>CHAPTER 3 – CALIBRATION OF THE WATER QUALITY MODEL</u></b> .....                     | <b>26</b> |
| <u>3.1 THE DUFLOW WATER-QUALITY MODEL</u> .....  | 26        |
| <u>3.2 WATER-QUALITY INPUT DATA</u> .....  | 28        |
| <u>3.2.1 SEPA stations</u> .....   | 28        |
| <u>3.2.2 In-Stream Aeration Stations</u> .....   | 34        |
| <u>3.2.3 Water Reclamation Plants</u> .....  | 38        |

|  |     |
|--|-----|
| <u>3.2.4 Tributaries</u> .....   | 42  |
| <u>3.2.4.1 Dry Weather Concentrations</u> .....  | 42  |
| <u>3.2.4.2 Wet Weather Concentrations</u> .....  | 44  |
| <u>3.2.5 Combined Sewer Overflows</u> .....  | 45  |
| <u>3.2.6 Boundaries</u> .....  | 46  |
| <b><u>3.3 INITIAL CONDITIONS</u></b> .....   | 52  |
| <b><u>3.4 CALIBRATION OF THE WATER-QUALITY MODEL</u></b> .....   | 53  |
| <b><u>3.5 CALIBRATION RESULTS</u></b> .....  | 64  |
| <u>3.5.1 Biochemical Oxygen Demand, Ammonia, Nitrate and Chlorophyll-a</u> .....   | 64  |
| <u>3.5.2 Dissolved Oxygen Concentration</u> .....  | 75  |
| <u>3.5.2.1 North Branch Chicago River</u> .....  | 75  |
| <u>3.5.2.2 South Branch Chicago River and Chicago Sanitary and Ship Channel</u><br><u>(CSSC)</u> .....                           | 81  |
| <u>3.5.2.3 Calumet-Sag Channel</u> .....   | 88  |
| <u>3.5.2.4 Boundaries (North Shore Channel, Chicago River Main Stem, Little</u><br><u>Calumet River (North and South))</u> ..... | 91  |
| <b><u>CHAPTER 4 - SCENARIO RESULTS</u></b> .....   | 102 |
| <b><u>CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS</u></b> .....  | 116 |
| <b><u>REFERENCES CITED</u></b> .....   | 119 |
| <b><u>APPENDIX-A EUTROPHICATION MODEL EUTROF2</u></b> .....  | 122 |
| <b><u>APPENDIX-B DAILY DO LOADS FROM SEPA AND AERATION STATIONS</u></b><br>.....   | 128 |

APPENDIX-C INITIAL CONDITIONS ..... 129

APPENDIX-D DIFFERENCE DISSOLVED OXYGEN CONCENTRATION  
BETWEEN THE SCENARIO WHERE WATER-SURFACE ELEVATIONS ARE  
HELD AT OR ABOVE -2FT CITY OF CHICAGO DATUM AT THE  
LAKEFRONT AND THE SCENARIO WHERE MEASURED WATER SURFACE  
ELEVATIONS AT THE LAKEFRONT ARE USED..... 133

## LIST OF FIGURES

|   |    |
|---|----|
| <u>Figure 1.1. Schematic diagram of the Calumet and the Chicago River Systems</u> .....   | 3  |
| <u>Figure 2.1. Locations of the 28 representative combined sewer overflows (CSOs) used in this study</u> .....  | 11 |
| <u>Figure 2.2. Comparison of the summation of all measured or estimated (except combined sewer overflows) inflows (Total) and the measured outflow at Romeoville</u> .....  | 16 |
| <u>Figure 2.3. Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for April 1- May 4, 2002</u> ..... | 21 |
| <u>Figure 2.4. Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at new locations on the Chicago Waterway System for April 1- May 4, 2002</u> .....       | 23 |
| <u>Figure 2.5 The comparison of measured and simulated average daily flows at the boundaries</u> .....  | 25 |
| <u>Figure 3.1 Effect of upstream Dissolved Oxygen (DO) saturation on downstream DO absorption with one blower in operation at Devon Avenue</u> .....  | 34 |
| <u>Figure 3.2 Effect of upstream Dissolved Oxygen (DO) saturation on downstream DO absorption with two blowers in operation at Devon Avenue</u> .....   | 35 |
| <u>Figure 3.3 Effect of upstream Dissolved Oxygen (DO) saturation on downstream DO absorption with three blowers in operation at Devon Avenue</u> .....   | 35 |
| <u>Figure 3.4. Stickney Water Reclamation Plant daily effluent concentrations for April 1- May 5, 2002</u> .....  | 39 |

|   |    |
|---|----|
| <u>Figure 3.5. North Side Water Reclamation Plant daily effluent concentrations for April 1-</u>          |    |
| <u>May 5, 2002</u> .....  | 40 |
| <u>Figure 3.6. Calumet Water Reclamation Plant daily effluent concentrations for April 1-May 5, 2002</u>  | 41 |
| <u>Figure 3.7. Monthly mean concentrations for the Chicago River Main Stem at Lake Shore</u>              |    |
| <u>Drive for 1997-2002 taken as representative of the boundary condition at Columbus</u>                  |    |
| <u>Drive 0.3 mi downstream</u> .....  | 49 |
| <u>Figure 3.8. Monthly mean concentrations for the North Shore Channel at Central Avenue</u>              |    |
| <u>for 1990-2002</u> .....  | 50 |
| <u>Figure 3.9. Monthly mean concentrations for the Calumet River at 130<sup>th</sup> Street for 1990-</u> |    |
| <u>2002</u> .....   | 51 |
| <u>Figure 3.10. Chicago Waterway System reaches</u> .....   | 54 |
| <u>Figure 3.11. Temperature variation on the North Shore Channel, North Branch Chicago</u>                |    |
| <u>River, South Branch Chicago River, and Chicago Sanitary and Ship Canal</u> .....                       | 57 |
| <u>Figure 3.12. Temperature variation on the Calumet River, Little Calumet River (North),</u>             |    |
| <u>and Calumet-Sag Channel</u> .....  | 57 |
| <u>Figure 3.13 Temperature profile at Division Street on North Branch Chicago River</u> .....             | 59 |
| <u>Figure 3.14. Comparison of long term measured mean plus or minus one standard</u>                      |    |
| <u>deviation, and simulated hourly ammonia nitrogen (NH<sub>4</sub>-N) concentrations at</u>              |    |
| <u>different locations in the Chicago Waterway System</u> .....   | 67 |
| <u>Figure 3.15. Comparison of long term measured mean plus or minus one standard</u>                      |    |
| <u>deviation, and simulated hourly biochemical oxygen demand (BOD<sub>5</sub>)</u>                        |    |
| <u>concentrations at different locations in the Chicago Waterway System</u> .....                         | 68 |

Figure 3.16. Comparison of long-term measured mean (plus or minus one standard deviation), simulated mean, and measured biochemical oxygen demand (BOD) concentrations in the Chicago Waterway System for April 1-May 4, 2002 ..... 70

Figure 3.17 Comparison of long-term measured mean (plus or minus one standard deviation), simulated mean, and measured ammonia nitrogen (NH<sub>4</sub>-N) concentrations in the Chicago Waterway System for April 1-May 4, 2002 ..... 71

Figure 3.18. Comparison of long-term measured mean (plus or minus one standard deviation), simulated mean, and measured nitrate nitrogen (NO<sub>3</sub>-N) concentrations in the Chicago Waterway System for April 1-May 4, 2002 ..... 72

Figure 3.19 Comparison of simulated mean and measured chlorophyll-a concentrations in the Chicago Waterway System for April 1-May 4, 2002 ..... 74

Figure 3.20 Comparison of simulated mean and measured chlorophyll-a concentrations in the Calumet River System with the SEPA stations providing chlorophyll-a loads for April 1-May 4, 2002 ..... 74

Figure 3.21. Flow comparison: North Branch Chicago River at Albany Avenue and at Addison Street and Upstream of the North Branch-North Shore Channel Junction for the period of April 1- May 4, 2002 ..... 77

Figure 3.22. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Addison Street and Fullerton Avenue on the North Branch Chicago River ..... 78

Figure 3.23. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Division Street on the North Branch Chicago River ..... 80

|   |    |
|---|----|
| <u>Figure 3.24. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Kinzie Street on the North Branch Chicago River</u> .....        | 81 |
| <u>Figure 3.25. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Jackson Boulevard on the South Branch Chicago River</u> .....    | 83 |
| <u>Figure 3.26. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Cicero Avenue on the Chicago Sanitary and Ship Canal</u> .....   | 84 |
| <u>Figure 3.27. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at the Baltimore and Ohio Railroad on the Chicago Sanitary Ship</u> |    |
| <u>Canal</u> .....  | 85 |
| <u>Figure 3.28. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Route 83 on the Chicago Sanitary and Ship Canal</u> .....        | 86 |
| <u>Figure 3.29. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at River Mile 11.6 on the Chicago Sanitary and Ship Canal</u> ..... | 87 |
| <u>Figure 3.30. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Romeoville on the Chicago Sanitary and Ship Canal</u> .....      | 88 |
| <u>Figure 3.31. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Halsted Street on the Little Calumet River (North)</u> .....     | 90 |
| <u>Figure 3.32. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Division Street, Kedzie Avenue, and Cicero Avenue on the</u>     |    |
| <u>Calumet-Sag Channel</u> .....  | 93 |
| <u>Figure 3.33. Comparison of measured and simulated dissolved oxygen (DO)</u>        |    |
| <u>concentrations at Harlem Avenue and Southwest Highway on the Calumet-Sag</u>       |    |
| <u>Channel</u> .....  | 94 |

|  |     |
|--|-----|
| <u>Figure 3.34. Comparison of measured and simulated dissolved oxygen (DO)</u><br><u>concentrations at Route 83 on the Calumet-Sag Channel</u> .....   | 94  |
| <u>Figure 3.35. Comparison of simulated and measured dissolved oxygen (DO)</u><br><u>concentrations at Linden, Simpson, and Main Streets on the North Shore Channel</u>  | 95  |
| <u>Figure 3.36. Comparison of measured and simulated dissolved oxygen (DO)</u><br><u>concentrations at Clark Street and Michigan Avenue on the Chicago River Main</u><br><u>Stem</u> .....   | 97  |
| <u>Figure 3.37. Comparison of measured dissolved oxygen (DO) concentrations on the</u><br><u>Chicago River at the Chicago River Controlling Works (CRCW) and Clark Street</u><br><u>and on the North Branch Chicago River at Kinzie Street</u> .....   | 97  |
| <u>Figure 3.38 Comparison of measured and simulated dissolved oxygen (DO)</u><br><u>concentrations at Ashland Avenue on the Little Calumet River (South)</u> .....   | 98  |
| <u>Figure 3.39. Comparison of measured and simulated dissolved oxygen (DO) concentrations</u><br><u>at O'Brien Lock and Dam on the Calumet River (with the measured concentrations at</u><br><u>130<sup>th</sup> Street used for comparison with the simulation results), and Conrail Railroad and</u><br><u>the Central and Wisconsin Railroad both on the Little Calumet River (North)</u> ..... | 99  |
| <u>Figure 3.40. Comparison of measured and saturation dissolved oxygen (DO)</u><br><u>concentrations on the Calumet River at 130<sup>th</sup> Street, on the Little Calumet River</u><br><u>(North) at Conrail Railroad and at the Central and Wisconsin Railroad</u> .....  | 101 |
| <u>Figure 4.1. Water-surface elevations relative to the City of Chicago Datum at the</u><br><u>upstream boundaries to the DUFLOW model of the Chicago Waterway System</u> .  | 103 |
| <u>Figure 4.2 Comparison of flows at the lake front controlling structures simulated with the</u><br><u>measured water-surface elevations (calibrated model) and the water-surface</u>   |     |

elevations held at -2 ft City of Chicago Datum (scenario = -2ft) for April 7-9, 2002  
..... 106

Figure 4.3. Comparison of flows at the lake front controlling structures simulated with  
the measured water-surface elevations (calibrated model) and the water-surface  
elevations held at -2 ft City of Chicago Datum (scenario = -2ft) for May 1-3, 2002  
..... 107

Figure 4.4 Comparison of water-surface elevations on the Chicago Sanitary and Ship  
Canal simulated with the measured water-surface elevations (calibrated model) and  
the water surface elevations held at -2 ft City of Chicago Datum (Scenario = -2ft)  
..... 110

Figure 4.5 Comparison of the water-surface elevations of the North Branch Chicago  
River and Calumet-Sag Channel simulated with measured water-surface elevations  
(calibrated model) and the water-surface elevations held at -2 ft City of Chicago  
Datum (scenario = -2ft)..... 111

## LIST OF TABLES

|   |    |
|---|----|
| <u>Table 2.1. Calculation of ungaged tributaries and watersheds .....</u>   | 8  |
| <u>Table 2.2. Drainage areas of each of the 28 representative combined sewer overflow<br/>(CSO) locations.....</u>  | 12 |
| <u>Table 2.3. Balance of average daily flows for the Chicago Waterway System for the<br/>period of April 1 to May 4, 2002 .....</u>   | 17 |
| <u>Table 2.4. Percentage of the hourly water-surface elevations for which the error in<br/>simulated versus measured values relative to the depth of flow (measured from the<br/>thalweg of the channel) is less than the specified percentage.....</u> | 19 |
| <u>Table 2.5. Comparison of simulated and measured water-surface elevations relative to CCD,<br/>April 1-May 4, 2002.....</u>   | 20 |
| <u>Table 2.6 Comparison of average simulated and measured flow at the boundaries.....</u>   | 24 |
| <u>Table 3.1 Locations of Sidestream Elevated Pool Aeration (SEPA) stations.....</u>  | 29 |
| <u>Table 3.2 Mean of Manually Measured Dissolved Oxygen (DO) and Temperature Values<br/>for Vertically Averaged Intake and Outfall Values for Different Pump Operations at<br/>the Sidestream Elevated Pool Aeration Stations.....</u>                  | 29 |
| <u>Table 3.3 Mean of Manually Measured Dissolved Oxygen (DO) and Temperature Values<br/>for Vertically Averaged Intake and Outfall Values for Different Seasons at the<br/>Sidestream Elevated Pool Aeration (SEPA) stations.....</u>                   | 30 |
| <u>Table 3.4 Mean Dissolved Oxygen (DO) Values and Percent Saturation at the Sidestream<br/>Elevated Pool Aeration (SEPA) stations 3, 4, and 5 for Different Seasons and Pump<br/>Operations.....</u>   | 31 |

|   |    |
|---|----|
| <u>Table 3.5 Fraction of dissolved oxygen saturation achieved by the Sidestream Elevated Pool Aeration (SEPA) stations with different pump operations.....</u>  | 32 |
| <u>Table 3.6 Engineering Design Features of the Sidestream Elevated Pool Aeration (SEPA) stations.....</u>  | 32 |
| <u>Table 3.7. Little Calumet River at South Holland dry-weather concentrations.....</u>   | 42 |
| <u>Table 3.8. Grand Calumet River at Hohman Avenue dry-weather concentrations.....</u>  | 43 |
| <u>Table 3.9. North Branch Chicago River at Albany Avenue dry-weather concentrations.....</u>   | 43 |
| <u>Table 3.10 North Branch Chicago River at Albany Avenue and Little Calumet at South Holland chlorophyll-a concentrations.....</u>   | 43 |
| <u>Table 3.11. Event mean concentrations measured at the Little Calumet River at Ashland Avenue.....</u>  | 44 |
| <u>Table 3.12. Event mean concentrations measured at the North Branch Chicago River at Albany Avenue.....</u>   | 44 |
| <u>Table 3.13. Concentrations measured at the North Branch Pumping Station in April 2002.....</u>   | 46 |
| <u>Table 3.14. Concentrations measured at the Racine Avenue Pumping Station in April 2002.....</u>  | 46 |
| <u>Table 3.15. Concentrations measured at the 125<sup>th</sup> Street Pumping Station in April 2002.....</u>  | 46 |
| <u>Table 3.16. Mean concentrations at the water-quality model boundaries for 1990-2002.....</u>   | 48 |
| <u>Table 3.17. 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 Waterway System used for calibration.....</u> | 56 |

|  |     |
|--|-----|
| <u>Table 3.18 Reach calibration parameters used in the DUFLOW water-quality model for April 1 to May 4, 2002</u> .....   | 62  |
| <u>Table 3.19 Reach calibration parameters used in the QUAL2EU water-quality model developed by Camp, Dresser &amp; McKee (CDM, 1992) for October 1990</u> .....   | 63  |
| <u>Table 3.20 Comparison of daily average simulated and measured dissolved oxygen concentrations on North Branch Chicago River, April 1-May 4, 2002</u> .....  | 76  |
| <u>Table 3.21 Comparison of daily average simulated and measured dissolved oxygen concentrations on South Branch Chicago River and Chicago Sanitary and Ship Channel, April 1-May 4, 2002</u> .....  | 82  |
| <u>Table 3.22 Comparison of daily average simulated and measured dissolved oxygen concentrations on Calumet-Sag and Little Calumet (North, downstream from Calumet WRP), April 1-May 4, 2002</u> .....   | 89  |
| <u>Table 4.1. Comparison of flows at the lake front controlling structures simulated with the measured water-surface elevations (calibrated model) and the water-surface elevations held at -2 ft City of Chicago Datum (scenario = -2ft)</u> .....  | 106 |
| <u>Table 4.2 Average change in DO concentration in milligrams per liter over the period affected by the April 7-9 and May 1-3 storms comparing the simulation holding water-surface elevations at the lake front at or above -2 ft City of Chicago Datum with the simulation using observed water-surface elevations at the lake front</u> ..... | 114 |

## Chapter 1 – INTRODUCTION

The Chicago Waterway System (CWS) is composed of the Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag Channel, North Shore Channel, lower portion of the North Branch Chicago River, South Branch Chicago River, Chicago River Main Stem, and Little Calumet River (North). In total, the CWS is a 76.3 mi branching network of navigable waterways controlled by hydraulic structures in which the majority of flow is treated sewage effluent. The dominant uses of the CWS are for commercial and recreational navigation and for urban drainage, i.e. draining combined sewer overflows, stormwater runoff, and treated wastewater from the Chicago area away from Lake Michigan. The Calumet and Chicago River Systems are shown in Figure 1.1.

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

The MWRDGC will soon be faced with a number of difficult management issues including the impact of reduced discretionary diversions from Lake Michigan for water-

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

Before the water-quality model was calibrated, the previously calibrated hydraulic model (Shrestha and Melching, 2003) was tested for the water-quality calibration study period. Hydraulic verification of the previously calibrated model for the time period of April 1 to May 4, 2002, is presented in Chapter 2. Model hydraulics were calibrated using hourly stage data at three gages operated by the MWRDGC along the CSSC and at the downstream boundary at Romeoville, and daily flow data collected near the Chicago River Controlling Works (CRCW) and O'Brien Dam and Lock (O'Brien) upstream boundaries. Calibration of the water quality-model is described in Chapter 3. Data used in calibration, assumptions, and calibration results are explained in this chapter.

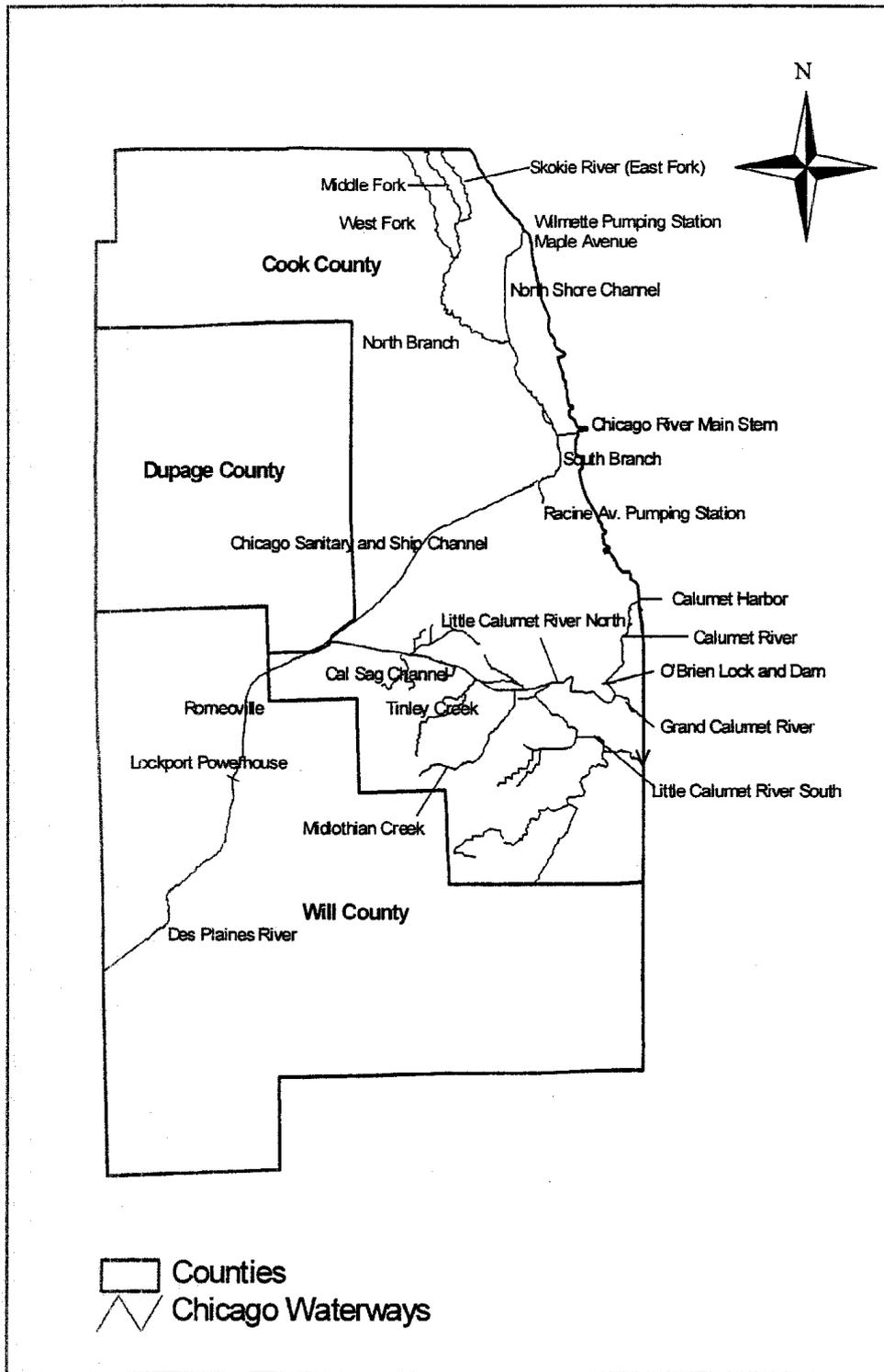


Figure 1.1. Schematic diagram of the Calumet and the Chicago River Systems

The U.S. Army Corps of Engineers is evaluating the possibility of changing the Code of Federal Regulations (CFR) with respect to minimum navigational water levels in the CWS during storm periods. Currently, the CFR (Title 33 Part 207 Sections 425 and 450) requires that water levels at CRCW and O'Brien must be maintained at -2 ft (-0.610 m) relative to the City of Chicago Datum (CCD, 579.48 ft = 176.626 m above mean sea level). In anticipation of storms the MWRDGC often draws down the CWS to provide storage space for runoff and increase the hydraulic gradient for moving flood water faster out of the CWS while maintaining water levels at or above -2 ft CCD at CRCW and O'Brien by taking water (called "navigation make up water") from Lake Michigan. If the storm does not materialize or it is smaller than expected the MWRDGC must also take navigation make up water to refill the CWS. It has been proposed that a water level as low as -3 ft CCD (-0.914 m) be allowed during storm periods to reduce diversions from Lake Michigan. During the April 1 to May 4, 2002, study period water levels were allowed to go below -2 ft CCD in order to evaluate the effects of lower water levels on the diversion, navigation, water quality, and other features of the CWS. The model was used to determine the diversion necessary to maintain water levels at or above -2 ft CCD and the effect of increased drawdown on water quality. For those periods when water levels went below -2 ft CCD water levels were set to -2 ft CCD and the calibrated model was run under that condition to observe the effect of lake water diversion on dissolved oxygen. Results of the scenario in which water level boundaries were set to -2 ft CCD are given in Chapter 4.

## Chapter 2 - HYDRAULIC MODEL VERIFICATION

### *2.1 Introduction*

The unsteady-flow model for the CWS 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 DUFLOW model developed in The Netherlands was selected for the calibration and simulations. The model was calibrated using hourly stage data at three gages operated by the MWRDGC along the CSSC and at the downstream boundary at Romeoville operated by the U.S. Geological Survey (USGS), and using daily flow data collected by the USGS near the CRCW and O'Brien upstream boundaries.

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

## **2.2 Hydraulic Data used for the Model Input**

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

### **2.2.1 Measured Inflows, Outflows, and Water-Surface Elevations**

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

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

The data from these gages are used as the primary upstream elevation versus time (hourly) boundary conditions for the unsteady-flow water-quality model. Flow versus time data (on a 15-minutes basis) from the USGS gage on the CSSC at Romeoville are used as the downstream boundary condition for the model. The data from the USGS gage on the Little Calumet River (South) at South Holland provide a flow versus time upstream boundary condition for the water-quality model. Two tributaries to the Calumet-Sag Channel are gaged by the USGS, Tinley Creek near Palos Park and Midlothian Creek at Oak Forest. The USGS gage on the Grand Calumet River at Hohman Avenue at Hammond, Ind. is considered as tributary flow to the Little Calumet River

(North). Flow on the North Branch Chicago River is measured just upstream of its confluence with the North Shore Channel at the USGS gage at Albany Avenue.

There also are inflows coming from MWRDGC facilities. Hourly flow data are available from the MWRDGC for the treated effluent discharged to the CWS by each of the four Water Reclamation Plants (WRPs)—North Side, Stickney, Calumet, and Lemont. In addition, flows discharged to the CWS at three combined sewer overflow (CSO) pumping stations—North Branch, Racine Avenue, and 125<sup>th</sup> Street—were estimated from operating logs of these stations. The boundary conditions and tributary inflows for the DUFLOW model of the CWS are summarized in Section 2.2.3.

## **2.2.2 Estimation of Flow for Ungaged Tributaries and Combined Sewer Overflows**

It is necessary to estimate the inflows from ungaged-tributary watersheds. The same procedure was followed as applied in the original hydraulic calibration of the model (Shrestha and Melching, 2003). In the original hydraulic calibration, flows on Midlothian Creek were used to estimate flows on ungaged 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 2.1. 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 2.1.** Calculation of ungaged tributaries and watersheds

| <b>Stream Ungaged</b>         | <b>Ratio with Midlothian*</b> |
|-------------------------------|-------------------------------|
| 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                         |
| Ungaged Des Plaines Watershed | 0.703                         |
| Calumet Union Ditch           | 1.168                         |
| Cal-Sag Watershed West        | 0.991                         |

\*The gaged Midlothian Creek drainage area is 12.6 mi<sup>2</sup>, but these ratios are computed to the total Midlothian Creek drainage area of 20 mi<sup>2</sup>. 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<sup>2</sup> and 11.2 mi<sup>2</sup> for Midlothian and Tinley Creeks, respectively.

All 3 CSO pumping stations discharged to the CWS during the storm of April 8<sup>th</sup> and 9<sup>th</sup>. The Racine Avenue and North Branch Pumping Stations worked for a total of 10 hours on April 8<sup>th</sup> and 9<sup>th</sup> and the 125<sup>th</sup> Street Pumping Station worked for 12 hours on April 9<sup>th</sup>. Hourly flows from these stations were estimated from pump operation records of on and off times and rated capacity of the various pumps and then input to the model. In the hydraulic calibration (Shrestha and Melching, 2003), the flows from the North Branch of the Chicago River at Albany Avenue and the North Branch Pumping Station were considered a combined input, but for the water-quality modeling these two inputs have now been separated.

The flow from other CSO drainage areas during storms has a substantial effect on the CWS. There are more than 150 dropshafts from the combined sewers to the Tunnel and

Reservoir Plan tunnels and nearly 200 CSOs in the CWS drainage area and 6 CSO locations were used to represent whole system in the original hydraulic calibration report (Shrestha and Melching, 2003). Since it is practically difficult to introduce all CSO locations in the modeling, 28 representative CSO locations were identified and flow distribution was done on the basis of drainage area for each of these locations. By increasing the number of CSOs from 6 to 28, more appropriate CSO loads are provided. Figure 2.1 and Table 2.2 give the locations and drainage areas of the 28 representative CSO locations. The volume of CSO was determined from the system wide flow balance and water level measurements at Romeoville. The flow balance calculation is explained in Section 2.5.

### **2.2.3 Summary of Boundary Conditions and Tributary Inflows**

Boundary and initial conditions for the water-quality calibration period were set by data collected by the USGS and the MWRDGC at the three lake front control structures and USGS data at Romeoville and for the tributary flows. Data collected by the MWRDGC for the discharges from different water reclamation plants also were used.

Boundary Locations:

- a. Chicago River at Columbus Drive
- b. North Shore Channel at Wilmette
- c. Calumet River at O'Brien Lock and Dam
- d. Little Calumet River (South) at Cottage Grove Avenue (South Holland)
- e. CSSC at Romeoville (downstream boundary)

The major flows into CWS have been identified as follows:

- a. North Side Water Reclamation Plant
- b. Stickney Water Reclamation Plant
- c. Calumet Water Reclamation Plant

and the minor flows into the CWS are from:

- a. North Branch Chicago River at Albany Avenue
- b. Racine Avenue Pumping Station
- c. North Branch Pumping Station
- d. 125<sup>th</sup> Street Pumping Station
- e. Lemont Water Reclamation Plant
- f. Citgo Petroleum
- g. Tinley Creek+Navajo Creek (i.e. Navajo Creek estimated based on area ratio with Midlothian Creek and added with nearby Tinley Creek)
- h. Midlothian Creek
- i. Grand Calumet River
- j. Mill+Stony Creek (West)\*
- k. Stony Creek (East)\*
- l. Des Plaines River Basin\*
- m. Calumet Union Ditch\*
- n. Cal-Sag Watershed West\*
- o. 28 CSO locations

\* These flows were estimated based on Midlothian Creek flows



**Table 2.2.** Drainage areas of each of the 28 representative combined sewer overflow (CSO) locations

| CSO Number | River Mile relative to Lockport* | Drainage Area (mi <sup>2</sup> ) | Waterway                        |
|------------|----------------------------------|----------------------------------|---------------------------------|
| 1          | 49                               | 8.91                             | North Shore Channel             |
| 2          | 47                               | 8.48                             | North Shore Channel             |
| 3          | 45                               | 8.65                             | North Shore Channel             |
| 4          | 43                               | 2.71                             | North Shore Channel             |
| 5          | 40                               | 4.84                             | North Branch Chicago River      |
| 6          | 39                               | 11.57                            | North Branch Chicago River      |
| 7          | 38                               | 7.16                             | North Branch Chicago River      |
| 8          | 36                               | 4.83                             | North Branch Chicago River      |
| 9          | 35                               | 3.52                             | North Branch Chicago River      |
| 10         | 35                               | 1.63                             | Chicago River Main Stem         |
| 11         | 34                               | 2.45                             | South Branch Chicago River      |
| 12         | 32                               | 9.55                             | South Branch Chicago River      |
| 13         | 30                               | 3.90                             | Chicago Sanitary and Ship Canal |
| 14         | 29                               | 12.44                            | Chicago Sanitary and Ship Canal |
| 15         | 27                               | 10.75                            | Chicago Sanitary and Ship Canal |
| 16         | 26                               | 20.56                            | Chicago Sanitary and Ship Canal |
| 17         | 25                               | 20.57                            | Chicago Sanitary and Ship Canal |
| 18         | 21                               | 4.78                             | Chicago Sanitary and Ship Canal |
| 19         | 25                               | 8.45                             | Calumet-Sag Channel             |
| 20         | 27                               | 4.02                             | Calumet-Sag Channel             |
| 21         | 28                               | 10.70                            | Little Calumet River (North)    |
| 22         | 30                               | 4.10                             | Little Calumet River (North)    |
| 23         | 31                               | 3.58                             | Little Calumet River (North)    |
| 24         | 34                               | 5.12                             | Little Calumet River (North)    |
| 25         | 35                               | 5.64                             | Little Calumet River (North)    |
| 26         | 31                               | 1.40                             | Little Calumet River (South)    |
| 27         | 32                               | 6.17                             | Little Calumet River (South)    |
| 28         | 35                               | 0.62                             | Little Calumet River (South)    |

\*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.

In 1995, the USGS did an evaluation of direct groundwater inflows to the CWS 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 cfs. Therefore, the effects of direct groundwater inflow to the CWS was not directly considered in the water balance for the DUFLOW model. However, for tributary areas draining directly to the CWS groundwater inflows are considered as part of the area ratio estimate of flows from these areas.

In this model, the upstream boundary conditions are water-surface elevations at the first 3 locations and flow at the fourth location and the downstream boundary condition is flow. By doing this, it is possible to compare computed discharge at the upstream boundaries and water-surface elevation computed at the downstream boundary to the measured values at these locations.

### ***2.3 Channel Geometry and Roughness Coefficient***

The channel geometry is represented as a series of 193 measured cross sections in the calibrated hydraulic model. The same channel geometry values were used for the verification simulations. The DUFLOW model uses Chezy's roughness coefficient,  $C$ , to calculate hydraulic resistance. For verification purposes, 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 given in Table 4.2 of Shrestha and Melching (2003).

## **2.4 Model Verification Locations**

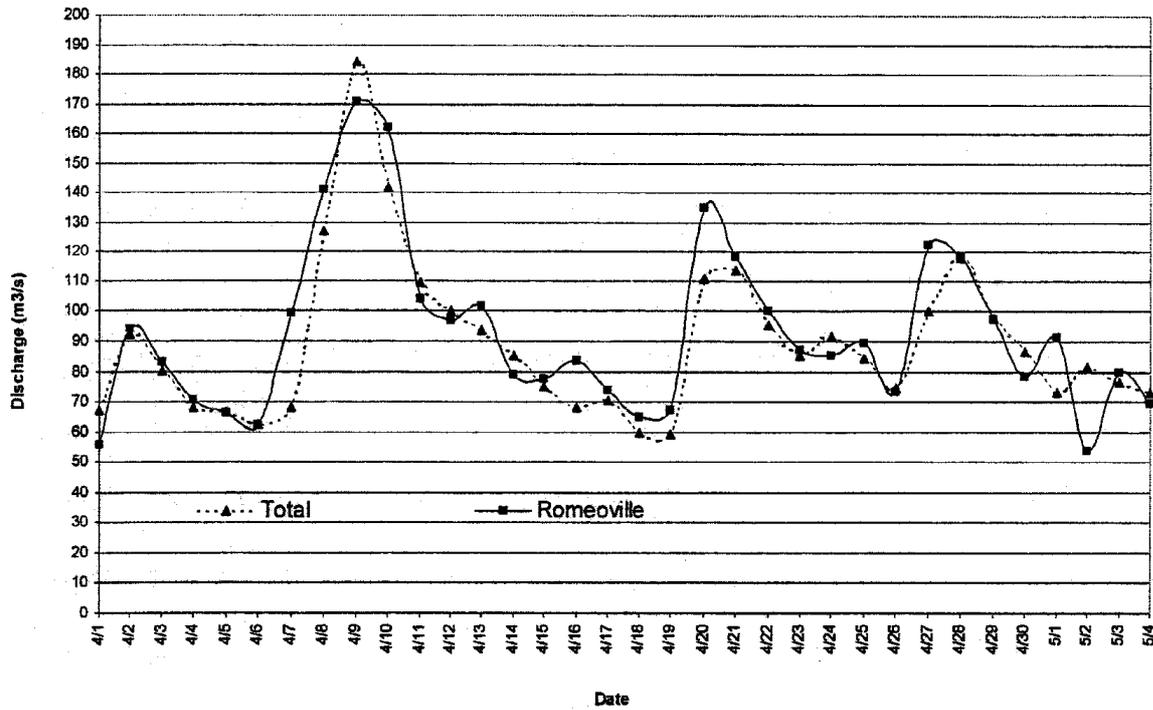
Although flow in the various branches of the CWS are not measured, water-surface elevation recorded at different locations was used for calibration and verification of the model. The water-surface elevation recorded at Western Avenue, Willow Springs, and Cal-Sag Junction by the MWRDGC and at Romeoville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

## **2.5 Flow Balance**

The inflow to the CWS is comprised of flows from tributaries, water reclamation plants, pumping stations, CSOs, and from Lake Michigan at the controlling structures. All the inflows to the system are measured as outflow at Romeoville. Missing data from gaged sites, ungaged tributaries, and CSO flows have been estimated by various mathematical and statistical methods described in detail in Shrestha and Melching (2003). During the calculation of the flow balance, it is assumed that the difference in the water balance due to the travel time and change in storage are negligible (over the entire simulated period—more than one month). Comparison of the summation of all inflows (except CSOs) to the system and outflow at Romeoville is shown in Figure 2.2. All inflows to the system and flow at Romeoville for the 4/1/2002-5/4/2002 period is given in Table 2.3. Over the full

study period the inflows (except CSOs) were 3.27 % lower than the outflow at Romeoville.

During the April 8<sup>th</sup> event the measured and estimated inflows were insufficient to maintain simulated water-surface elevations at Romeoville near measured water-surface elevations. If the simulated water-surface elevation is substantially below the observed value, the hydraulic model is artificially dewatering the CWS in order to match the observed flow at Romeoville indicating that the CWS is receiving insufficient inflow. Thus, CSO volume was added until reasonable water-surface elevations were simulated at Romeoville. This CSO volume is proportioned on the basis of CSO drainage areas listed in Table 2.2 divided by the total CSO drainage area (i.e. volume CSO 1 = [Area CSO 1/Total CSO area] x Total CSO volume) and applied uniformly in time over the period of operation of Racine Avenue Pumping Station. For the April 8<sup>th</sup> event a total CSO volume of 140 m<sup>3</sup>/s for 10 hours was input to the CWS simulation. This translates to 1.72 m<sup>3</sup>/s over the entire period, which is more than half the discrepancy in Table 2.3. The remaining discrepancy results because of localized CSO flows between April 19 and 27<sup>th</sup> (as discussed in Section 3.5.2.2), errors in the area-ratio based estimates of flows from ungaged tributaries primarily due to rainfall areal variability, travel time issues between inflows and outflows, and errors in the various measurements of inflows and outflows. In the hydraulic model this imbalance is accounted for in the hydraulic model by increasing the flow from Lake Michigan primarily at Wilmette (see Section 2.6).



**Figure 2.2.** Comparison of the summation of all measured or estimated (except combined sewer overflows) inflows (Total) and the measured outflow at Romeoville

**Table 2.3.** Balance of average daily flows for the Chicago Waterway System for the period of April 1 to May 4, 2002

| Inflows                                     | Flow (m <sup>3</sup> /s) |
|---|--------------------------|
| Mill Creek + Stoney Creek (W)               | 1.29                     |
| Narajo Creek + Calumet-Sag basin            | 0.30                     |
| Calumet Union Ditch                         | 0.92                     |
| Stoney Creek (E)                            | 0.38                     |
| Calumet-Sag End Watershed                   | 0.78                     |
| Lower Des Plaines basin                     | 0.55                     |
| Citgo Petroleum                             | 0.20                     |
| Lemont Water Reclamation Plant              | 0.13                     |
| Calumet Water Reclamation Plant             | 15.06                    |
| Grand Calumet River                         | 0.24                     |
| Racine Avenue Pump Station                  | 0.38                     |
| 125 <sup>th</sup> Street Pump Station       | 0.08                     |
| North Branch Pump Station                   | 0.10                     |
| Midlothian Creek                            | 0.78                     |
| Chicago River at Columbus Drive             | 0.47                     |
| O'Brien Lock and Dam                        | 1.51                     |
| North Shore Channel at Wilmette             | 0.13                     |
| Tinley Creek                                | 1.10                     |
| Little Calumet River at South Holland       | 9.84                     |
| North Branch Chicago River at Albany Avenue | 5.17                     |
| Stickney Water Reclamation Plant            | 37.54                    |
| Northside Water Reclamation Plant           | 12.78                    |
| Romeoville (Outflow)                        | -92.76                   |
| Total Inflow                                | 89.73                    |
| Difference (m <sup>3</sup> /s)              | -3.03                    |
| % Difference                                | -3.27                    |

## **2.6 Results of the Hydraulic Verification**

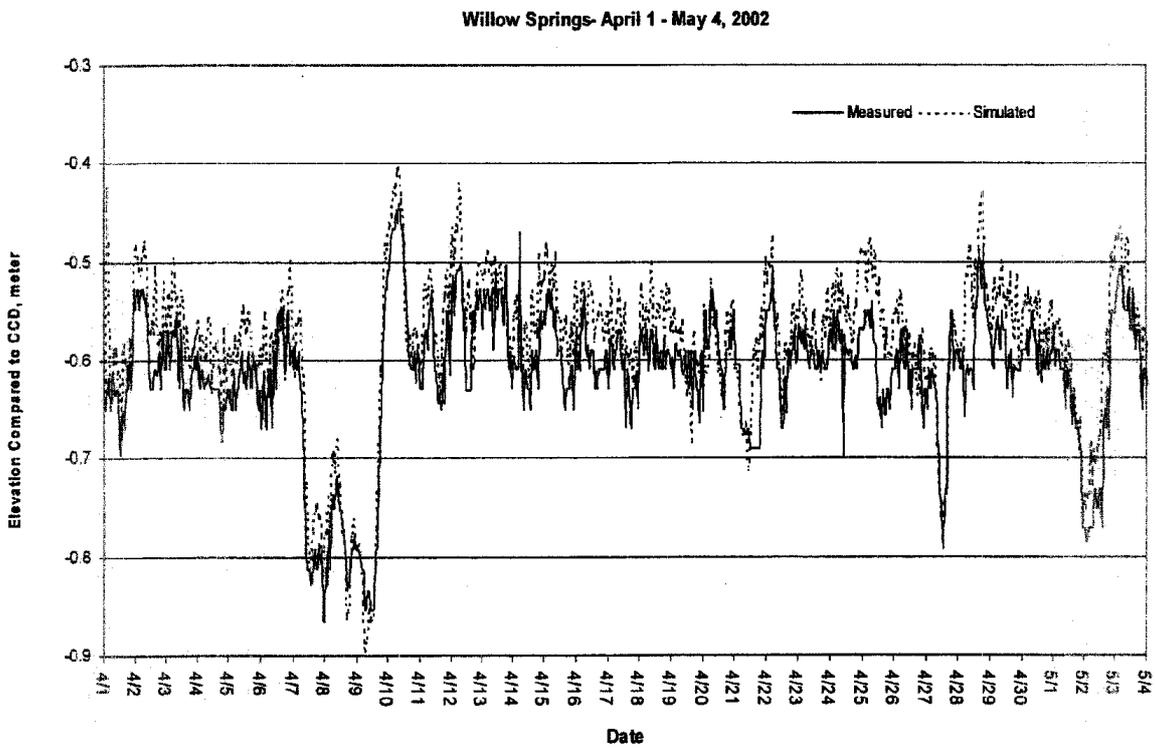
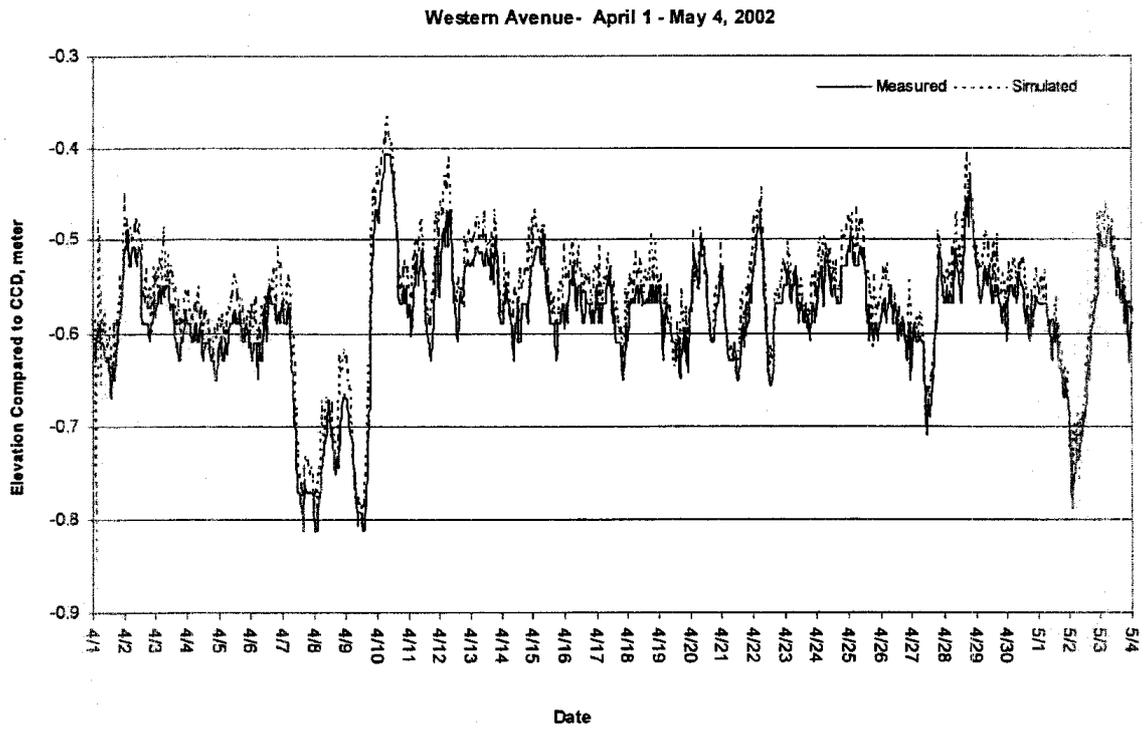
The comparison of measured and simulated water-surface elevations at the locations used in the original model calibration and verification is shown in Figure 2.3. Two new locations were used in this study, and the results at these locations are shown in Figure 2.4. Although data from Lawrence Avenue on the North Branch Chicago River and Southwest Highway on the Calumet-Sag Channel were not used for calibration, verification results showed that the model could estimate measured water-surface elevations at these locations with a high accuracy. Statistical analysis given in Table 2.4 and 2.5 (note: the difference in the number of data in the table for the various locations results because of different amounts of missing or erroneous data at these locations) showed that difference between the measured and simulated stages are all below 7 % relative to the depth of the water (where depth is measured relative to the thalweg of the channel). Mean and median values of the absolute value of the difference between the measured and simulated stages are below 1% relative to the depth of the water at all locations. The simulated water-surface elevations were within 1 % of the measured values with respect to the depth for 70-95.7% of the values and within 2% for 89-99.8% of the values. These high percentages of small errors and the high correlation coefficients (0.8-0.94) indicate an excellent hydraulic verification of the model. Since the calibrated model can predict stages throughout the CWS with high accuracy, this model can be safely used for the water-quality calibration.

**Table 2.4.** Percentage of the hourly water-surface elevations for which the error in simulated versus measured values relative to the depth of flow (measured from the thalweg of the channel) is less than the specified percentage

| Location                            | Percentage |           |
|-------------------------------------|------------|-----------|
|                                     | <±1% of D  | <±2% of D |
| Lawrence Avenue (North Branch)      | 70         | 89        |
| Southwest Highway (Cal-Sag Channel) | 70         | 95        |
| Western Avenue (CSSC)               | 95         | 99.8      |
| Willow Springs (CSSC)               | 95.7       | 99.8      |
| Cal-Sag Junction                    | 70         | 94.5      |
| Romeoville (CSSC)                   | 87         | 98.4      |

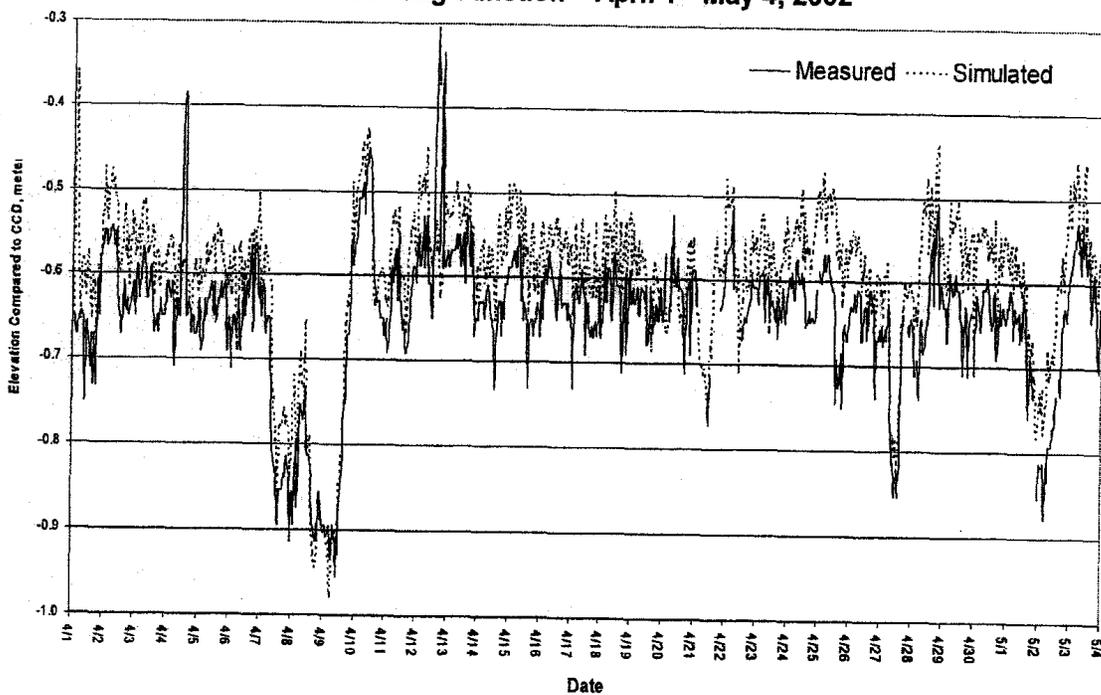
**Table 2.5.** Comparison of simulated and measured water-surface elevations relative to CCD, April 1-May 4, 2002 [note: Elevation Error =simulated-measured; Abs Error =absolute value of simulated-measured; Percent Error =(simulated-measured)/measured x 100; Abs Percent Error =absolute value of (simulated-measured)/measured x 100; Percent Error wrt Depth = (simulated elevation-measured elevation)/measured depth x 100; Abs Percent Error wrt Depth =absolute value of (simulated elevation-measured elevation)/measured depth x 100]

|                             |                | Measured Elevation (m) | Simulated Elevation (m)           | Measured Water Depth (m) | Elevation Error (m) | Abs Error | Percent Error | Abs Percent Error | Percent Error wrt Depth | Abs Percent Error wrt Depth |
|-----------------------------|----------------|------------------------|-----------------------------------|--------------------------|---------------------|-----------|---------------|-------------------|-------------------------|-----------------------------|
| Lawrence Avenue             | Min.           | -0.75                  | -0.70                             | 2.74                     | -0.21               | 0.00      | -67.14        | 0.01              | -6.95                   | 0.00                        |
|                             | Max.           | -0.14                  | -0.18                             | 3.39                     | 0.19                | 0.21      | 36.54         | 67.14             | 6.21                    | 6.95                        |
|                             | Mean           | -0.46                  | -0.47                             | 3.05                     | 0.00                | 0.03      | -2.17         | 6.57              | 0.12                    | 0.89                        |
|                             | Med.           | -0.48                  | -0.48                             | 3.04                     | 0.00                | 0.02      | -0.45         | 3.73              | 0.07                    | 0.58                        |
|                             | STD            | 0.10                   | 0.08                              | 0.10                     | 0.04                | 0.03      | 10.20         | 8.09              | 1.30                    | 0.96                        |
|                             | # of Data =811 |                        | Correlation Coefficient, R = 0.91 |                          |                     |           |               |                   |                         |                             |
| Western Avenue              | Min.           | -0.81                  | -0.84                             | 6.62                     | -0.12               | 0.00      | -33.95        | 0.01              | -1.81                   | 0.00                        |
|                             | Max.           | -0.41                  | -0.36                             | 7.02                     | 0.21                | 0.21      | 19.57         | 33.95             | 3.14                    | 3.14                        |
|                             | Mean           | -0.58                  | -0.56                             | 6.85                     | -0.02               | 0.03      | 4.10          | 4.90              | -0.35                   | 0.42                        |
|                             | Med.           | -0.57                  | -0.55                             | 6.86                     | -0.02               | 0.03      | 4.04          | 4.34              | -0.35                   | 0.37                        |
|                             | STD            | 0.07                   | 0.07                              | 0.07                     | 0.03                | 0.02      | 4.46          | 3.56              | 0.38                    | 0.31                        |
|                             | # of Data =815 |                        | Correlation Coefficient, R = 0.93 |                          |                     |           |               |                   |                         |                             |
| Willow Springs              | Min.           | -0.87                  | -0.90                             | 7.20                     | -0.22               | 0.00      | -23.47        | 0.01              | -2.95                   | 0.00                        |
|                             | Max.           | -0.44                  | -0.40                             | 7.63                     | 0.11                | 0.22      | 34.01         | 34.01             | 1.45                    | 2.95                        |
|                             | Mean           | -0.61                  | -0.58                             | 7.46                     | -0.03               | 0.04      | 5.55          | 6.67              | -0.46                   | 0.55                        |
|                             | Med.           | -0.61                  | -0.57                             | 7.46                     | -0.03               | 0.04      | 5.69          | 6.10              | -0.46                   | 0.49                        |
|                             | STD            | 0.07                   | 0.08                              | 0.07                     | 0.04                | 0.03      | 5.80          | 4.48              | 0.48                    | 0.38                        |
|                             | # of Data =814 |                        | Correlation Coefficient, R = 0.89 |                          |                     |           |               |                   |                         |                             |
| Cal-Sag Junction            | Min.           | -0.95                  | -0.98                             | 7.60                     | -0.29               | 0.00      | -268.6        | 0.00              | -3.65                   | 0.00                        |
|                             | Max.           | -0.19                  | -0.36                             | 8.37                     | 0.52                | 0.52      | 44.40         | 268.67            | 6.17                    | 6.17                        |
|                             | Mean           | -0.64                  | -0.59                             | 7.92                     | -0.05               | 0.06      | 7.50          | 9.93              | -0.65                   | 0.77                        |
|                             | Med.           | -0.63                  | -0.58                             | 7.93                     | -0.05               | 0.06      | 8.58          | 8.93              | -0.68                   | 0.71                        |
|                             | STD            | 0.08                   | 0.09                              | 0.08                     | 0.05                | 0.04      | 13.45         | 11.77             | 0.68                    | 0.53                        |
|                             | # of Data =787 |                        | Correlation Coefficient, R = 0.80 |                          |                     |           |               |                   |                         |                             |
| Romeoville                  | Min.           | -1.38                  | -1.53                             | 7.55                     | -0.21               | 0.00      | -29.45        | 0.00              | -2.60                   | 0.00                        |
|                             | Max.           | -0.49                  | -0.42                             | 8.43                     | 0.22                | 0.22      | 32.89         | 32.89             | 2.73                    | 2.73                        |
|                             | Mean           | -0.66                  | -0.67                             | 8.26                     | 0.01                | 0.04      | -0.67         | 6.10              | 0.08                    | 0.50                        |
|                             | Med.           | -0.62                  | -0.62                             | 8.30                     | 0.00                | 0.03      | -0.45         | 5.02              | 0.03                    | 0.37                        |
|                             | STD            | 0.13                   | 0.16                              | 0.13                     | 0.06                | 0.04      | 7.97          | 5.17              | 0.68                    | 0.47                        |
|                             | # of Data =815 |                        | Correlation Coefficient, R = 0.94 |                          |                     |           |               |                   |                         |                             |
| Southwest Highway (Cal-Sag) | Min.           | -0.83                  | -0.80                             | 3.13                     | -0.40               | 0.0       | -21.46        | 0.0               | -11.84                  | 0.0                         |
|                             | Max.           | -0.33                  | -0.19                             | 3.64                     | 0.10                | 0.4       | 67.69         | 67.69             | 2.91                    | 11.84                       |
|                             | Mean           | -0.57                  | -0.56                             | 3.40                     | -0.01               | 0.03      | 1.47          | 4.78              | -0.28                   | 0.80                        |
|                             | Med.           | -0.57                  | -0.55                             | 3.39                     | -0.01               | 0.02      | 1.45          | 4.02              | -0.24                   | 0.66                        |
|                             | STD            | 0.07                   | -0.07                             | 0.07                     | 0.04                | 0.02      | 6.28          | 4.32              | 1.06                    | 0.74                        |
|                             | # of Data =813 |                        | Correlation Coefficient, R = 0.87 |                          |                     |           |               |                   |                         |                             |



**Figure 2.3.** Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for April 1- May 4, 2002

### Cal Sag Junction - April 1 - May 4, 2002



### Romeoville - April 1 - May 4, 2002

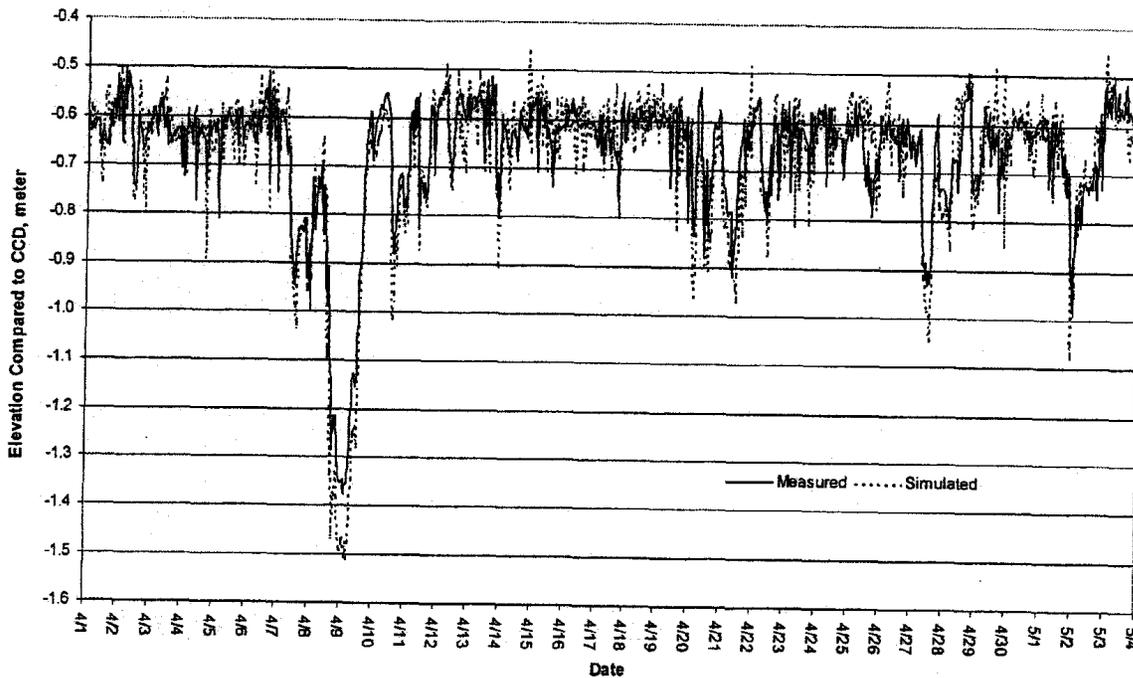
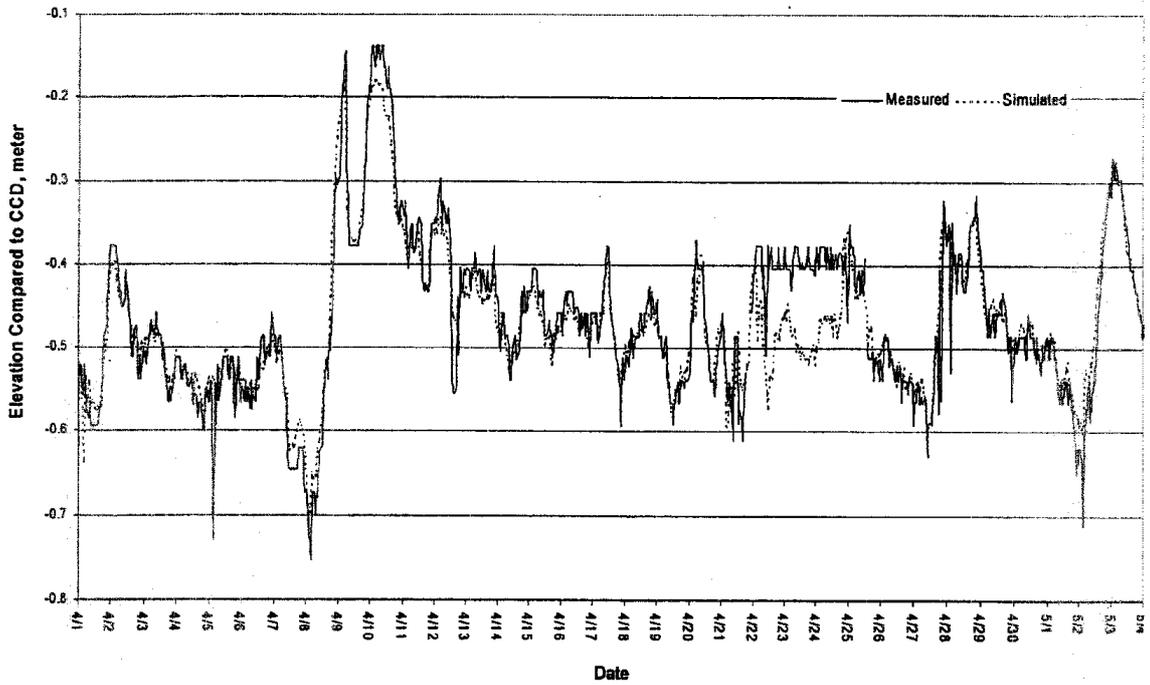


Figure 2.3. (cont.) Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for April 1- May 4, 2002

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



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

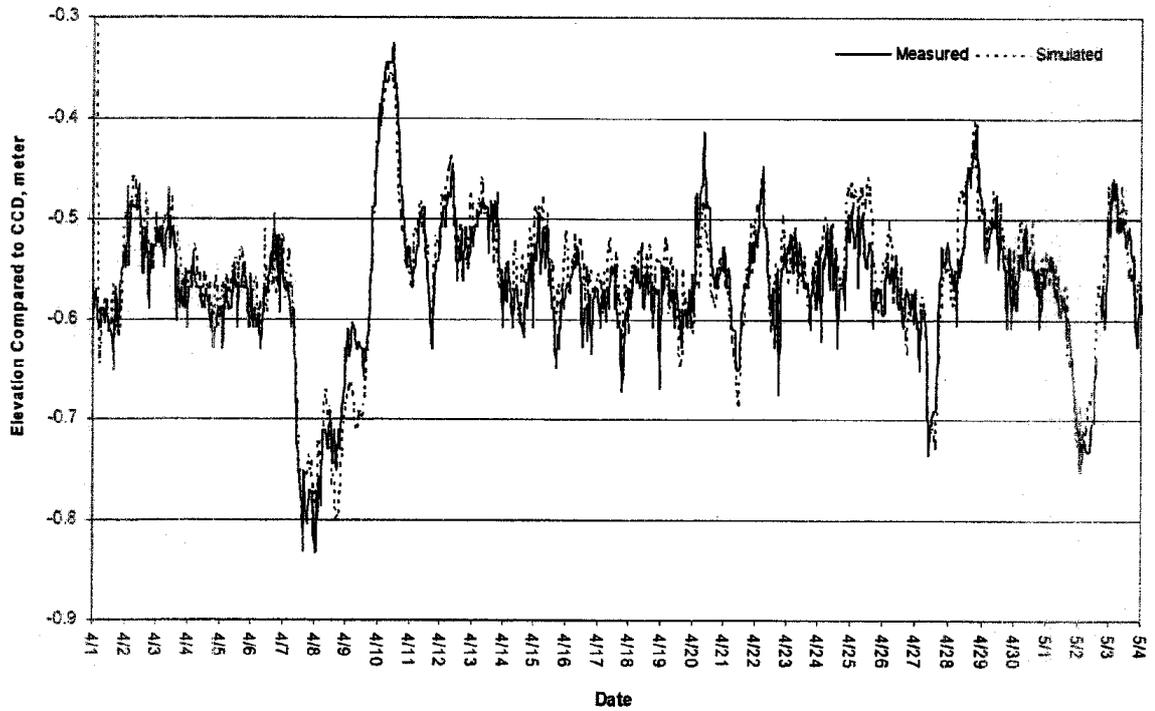


Figure 2.4. Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at new locations on the Chicago Waterway System for April 1- May 4, 2002

The comparison of measured and simulated average daily flows at the boundaries is shown in Figure 2.5. Both the measured and simulated flows at these locations are very small compared to the total flow at Romeoville. For most of the simulation period the general trends of the simulated/measured values are similar, however, during storm periods some deviations are observed. Similar deviations were found in the original hydraulic calibration (Shrestha and Melching, 2003), and readers should review Shrestha and Melching (2003) to understand the causes of these deviations. Comparison of measured and simulated average monthly discharges at the boundaries is given in Table 2.6. The simulated inflows at the boundaries is 3.32 m<sup>3</sup>/s greater than the measured inflows at the boundaries this is within 10 percent of difference (3.03 m<sup>3</sup>/s) between inflows and outflows to the CWS summarized in Table 2.3.

**Table 2.6** Comparison of average simulated and measured flow at the boundaries

|                 | <b>Measured<br/>(m<sup>3</sup>/s)</b> | <b>Simulated<br/>(m<sup>3</sup>/s)</b> |
|-----------------|---------------------------------------|--|
| <b>Columbus</b> | 0.47                                  | -0.67                                  |
| <b>Wilmette</b> | 0.13                                  | 1.38                                   |
| <b>O'Brien</b>  | 1.51                                  | 4.72                                   |

Since the system is dominated mainly by treatment plant and tributary flows, the effects of the overestimate of inflows at Wilmette and O'Brien and the underestimate of inflows at Columbus Drive on water-quality simulation accuracy decrease as the water gets farther from these boundaries. Detailed discussion of water-quality simulations at the boundaries is given in Section 3.5.2.4.

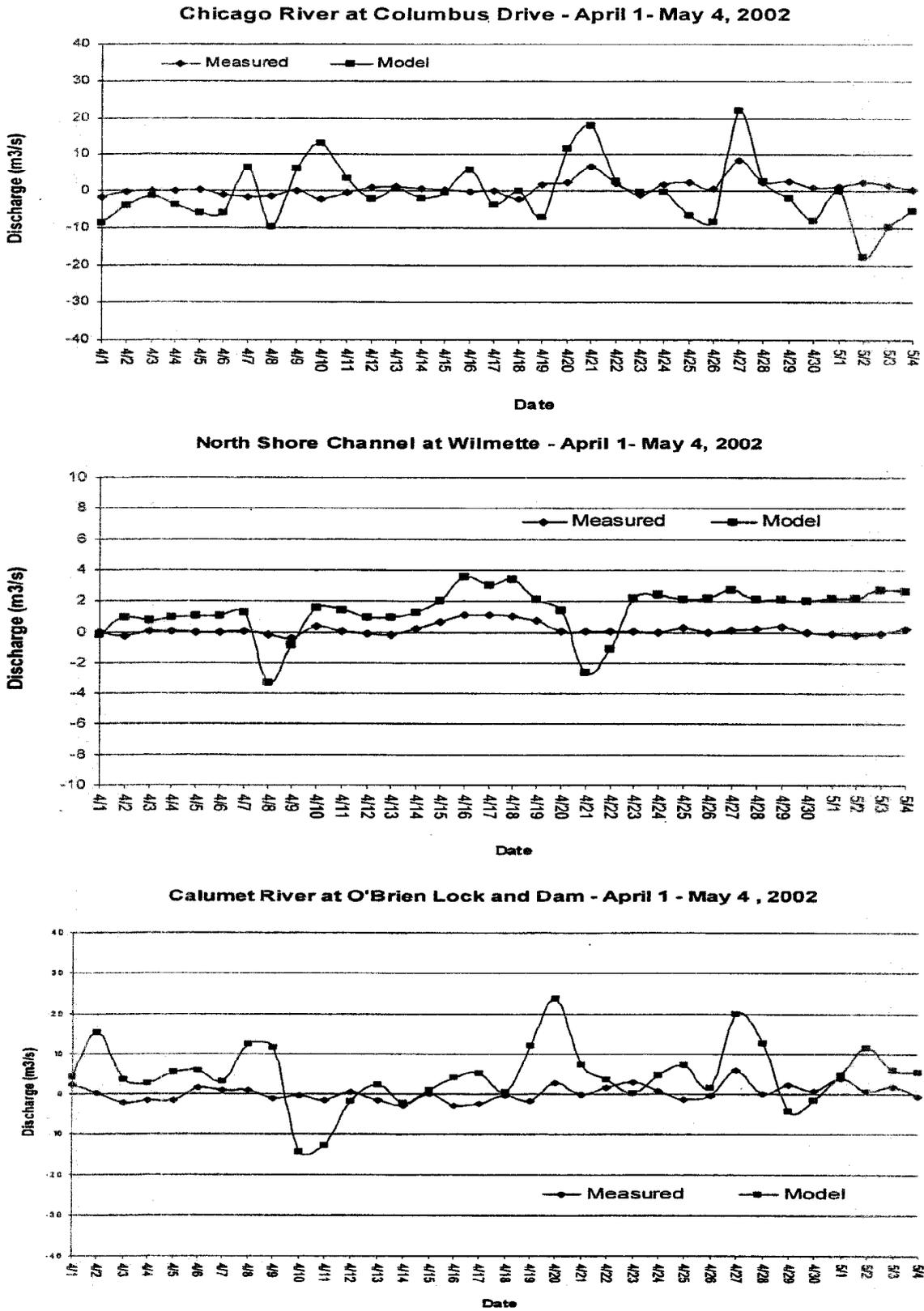


Figure 2.5 The comparison of measured and simulated average daily flows at the boundaries

## **Chapter 3 – CALIBRATION OF THE WATER QUALITY MODEL**

### ***3.1 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 expensive, integral studies. It enables water managers to calculate unsteady flows in networks of canals, rivers, and channels. It also is useful for simulating the transport of substances in free-surface flow. More complex water-quality processes can be simulated as well.

The DUFLOW modeling system is designed for various categories of users. The model can be used by water authorities, designers, and educational institutions. DUFLOW runs on a personal computer with a graphical user interface. It can, therefore, be operated in most scientific or engineering environments.

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 oxygen using the same formulations as applied in the U.S. Environmental Protection Agency WASP version 4 (Ambrose et al., 1988). EUTROF1 is particularly suitable to study the short-

term behavior of systems. If the long-term functioning of a system is of interest the other eutrophication model, EUTROF2, is more appropriate (DUFLOW, 2000). In addition to these two built-in water-quality models, there are an abundance of formulations proposed in the literature. DUFLOW gives great freedom to the user in formulating the production or destruction of biological or chemical constituents because users may write their own water-quality simulation routines and easily incorporate them DUFLOW (DUFLOW, 2000).

In this study, EUTROF2 was selected as the appropriate unsteady-flow water-quality model for the CWS. In EUTROF2, three algal species can be defined, and the model also describes the interaction between the sediment and the overlying water column, which was considered a very important issue for the CWS. An important topic in water-quality problems is the interaction between the bottom layer and the mass above. EUTROF2 distinguishes among transported material that flows with water, bottom materials that are not transported material that flow with water, and bottom materials that are not transported but that can be subject to similar interactions to those for the water column. The following state variables which are represented as both water and sediment components are included in the EUTROF2 model: algal biomass species, suspended solids concentration, total inorganic phosphorus, total organic phosphorus, total organic nitrogen, ammonia nitrogen, nitrate nitrogen, DO, and biochemical oxygen demand (BOD). The complete EUTROF2 model is given in Appendix A. The model given in Appendix A includes a correction to the estimation of the reaeration-rate coefficient via the O'Connor-Dobbins (1958) formula. In the original EUTROF2 model, the reaeration-

rate coefficient was inversely proportional to the square root of the depth when in fact it is inversely proportional to depth to the 3/2 power.

### **3.2 Water-Quality Input Data**

The water quality in the modeled portion of the CWS is affected by the operation of four Sidestream Elevated Pool Aeration (SEPA) stations and two instream aeration stations. The CWS also receives pollutant loads from four water reclamation plants, nearly 200 CSOs (condensed to 28 representative locations to facilitate the modeling), direct diversions from Lake Michigan, and eleven tributary streams or drainage areas. Assumptions used to consider the effects of the aeration stations on water quality and to determine the various pollutant loadings are discussed in this section as are the constituent concentrations for the various inflows to the CWS.

#### **3.2.1 SEPA stations**

As a result of substantial pollutant loading and low in-stream velocities, dissolved oxygen (DO) concentrations in the CWS historically have been low. In 1984 the MWRDGC issued a feasibility report on a new concept of artificial aeration referred to as Sidestream Elevated Pool Aeration (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.

Finally, even though SEPA station #2 is downstream from the Calumet WRP, the distance is too small (0.1 mi) for the Calumet WRP to have much effect in reducing DO concentrations. Thus, at SEPA station #2 upstream DO concentrations were very close to saturation during the study period, and the DO load input by SEPA station #2 was felt to be minimal and this load was not included in the modeling. The locations of the SEPA stations are listed in Table 3.1.

**Table 3.1** Locations of Sidestream Elevated Pool Aeration (SEPA) stations

| SEPA STATION # | Location              | River Mile from Lockport |
|----------------|-----------------------|--------------------------|
| 3              | Blue Island           | 27                       |
| 4              | Worth (Harlem Avenue) | 20.7                     |
| 5              | Cal-Sag Junction      | 12.3                     |

Two previously conducted studies (Butts et al., 1999 and 2000) were used to examine the efficiency of and calculate oxygen load from the SEPA stations. Efficiencies of the stations at different working conditions are summarized in Table 3.2-3.4.

**Table 3.2** Mean of Manually Measured Dissolved Oxygen (DO) and Temperature Values for Vertically Averaged Intake and Outfall Values for Different Pump Operations at the Sidestream Elevated Pool Aeration Stations (after Butts et al., 1999)

| SEPA Station | # of pumps | Temperature (°C) |      | DO (mg/L) |         | Saturation Percentage |                    |
|--------------|------------|------------------|------|-----------|---------|-----------------------|--------------------|
|              |            | In               | Out  | Intake    | Outfall | Intake                | Outfall - Observed |
| 3            | 1          | 24.4             | 24.3 | 5.4       | 7.9     | 64.9                  | 93.8               |
|              | 2          | 20.2             | 20.1 | 5.9       | 8.9     | 64.8                  | 98.0               |
|              | 3          | 19.4             | 19.3 | 5.8       | 8.9     | 63.0                  | 95.9               |
| 4            | 1          | 22.2             | 21.9 | 5.3       | 8.6     | 59.8                  | 98.1               |
|              | 2          | 22.0             | 22.0 | 4.3       | 8.4     | 48.5                  | 96.3               |
|              | 3          | 22.3             | 22.2 | 6.3       | 8.8     | 71.2                  | 99.7               |
| 5            | 1          | 21.7             | 22.0 | 5.1       | 8.5     | 58.4                  | 96.7               |
|              | 2          | 14.3             | 14.4 | 6.6       | 9.3     | 64.7                  | 90.8               |
|              | 3          | 18.6             | 18.5 | 6.9       | 9.5     | 74.1                  | 100.3              |
|              | 4          | 25.0             | 25.0 | 5.0       | 8.4     | 60.4                  | 101.0              |

**Table 3.3** Mean of Manually Measured Dissolved Oxygen (DO) and Temperature Values for Vertically Averaged Intake and Outfall Values for Different Seasons at the Sidestream Elevated Pool Aeration (SEPA) stations (after Butts et al., 1999)

| SEPA Station | Date         | Temperature (°C) |      | DO (mg/L) |         | Saturation Percentage |                    |
|--------------|--------------|------------------|------|-----------|---------|-----------------------|--------------------|
|              |              | In               | Out  | Intake    | Outfall | Intake                | Outfall - Observed |
| 3            | 8/95-6/97    | 22.2             | 22.2 | 5.6       | 8.5     | 63.5                  | 97.4               |
| 4            | 8/95-6/97    | 22.5             | 22.4 | 5.4       | 8.6     | 61.5                  | 99.1               |
| 5            | 8/95-6/97    | 22.2             | 22.3 | 5.2       | 8.6     | 59.6                  | 97.9               |
|              |              |                  |      |           |         |                       |                    |
| 3            | Summer       | 24.4             | 24.3 | 5.2       | 8.1     | 62.4                  | 96.9               |
|              | Fall         | 20.0             | 20.0 | 6.1       | 9.1     | 67.0                  | 99.4               |
|              | Spring       | 15.1             | 15.1 | 6.9       | 10.0    | 68.3                  | 99.2               |
|              | Early Summer | 21.8             | 21.7 | 5.1       | 8.3     | 57.8                  | 94.5               |
|              |              |                  |      |           |         |                       |                    |
| 4            | Summer       | 24.8             | 24.7 | 4.9       | 8.2     | 58.7                  | 99.0               |
|              | Fall         | 19.8             | 19.8 | 5.9       | 9.3     | 64.1                  | 101.3              |
|              | Spring       | 14.5             | 14.8 | 7.4       | 9.8     | 73.0                  | 96.5               |
|              | Early Summer | 22.8             | 22.9 | 5.2       | 8.5     | 60.5                  | 98.3               |
|              |              |                  |      |           |         |                       |                    |
| 5            | Summer       | 24.9             | 25.0 | 4.5       | 8.1     | 54.7                  | 97.5               |
|              | Fall         | 19.4             | 19.6 | 6.2       | 9.3     | 67.1                  | 100.7              |
|              | Spring       | 14.5             | 14.4 | 7.2       | 9.6     | 70.5                  | 93.6               |
|              | Early Summer | 22.5             | 22.6 | 4.6       | 8.6     | 52.6                  | 98.5               |

**Table 3.4** Mean Dissolved Oxygen (DO) Values and Percent Saturation at the Sidestream Elevated Pool Aeration (SEPA) stations 3, 4, and 5 for Different Seasons and Pump Operations (after Butts et al., 1999)

|                             |           | Dissolved Oxygen |        |        |              |                 |        |        |        |        |                  |
|-----------------------------|-----------|------------------|--------|--------|--------------|-----------------|--------|--------|--------|--------|------------------|
|                             |           | Event            |        |        |              | Number of Pumps |        |        |        |        |                  |
| SEPA                        | Location  | Summer           | Fall   | Spring | Early Summer | 1               | 2      | 3      | 4      | Mean   | Total # readings |
| <i>Percent Saturation</i>   |           |                  |        |        |              |                 |        |        |        |        |                  |
| 3                           | Intake    | 72.26            | 69.6   | 70.29  | 64.63        | 66.38           | 68.57  | 71.72  |        | 68.59  | 4691             |
|                             | Outfall   | 100.2            | 101    | 101.84 | 99.31        | 101.02          | 100.81 | 99.46  |        | 100.32 | 6035             |
| 4                           | Intake    | 65.18            | 62.59  | 70.36  | 64.15        | 62.37           | 67.18  | 69.05  |        | 66.25  | 4940             |
|                             | Outfall   | 101.02           | 108.5  | 97.94  | 103          | 101.26          | 104.56 | 101.67 |        | 101.85 | 5122             |
| 5                           | Intake    | 57.04            | 64.25  | 67.33  | 55.92        | 54.4            | 57.86  | 64.33  | 66.09  | 59.75  | 5071             |
|                             | Outfall C | 100.55           | 104.31 | 95.34  | 99.1         | 92.56           | 100.13 | 102.06 | 101.68 | 98.49  | 5737             |
|                             | Outfall S | 98.92            | 104.32 | 94.68  | 100.91       | 93.98           | 98.73  | 101.19 | 102.23 | 98.39  | 6758             |
| <i>Concentration (mg/L)</i> |           |                  |        |        |              |                 |        |        |        |        |                  |
| 3                           | Intake    | 5.81             | 6.4    | 7.02   | 5.49         | 6.39            | 6.52   | 6.52   |        | 6.41   | 4691             |
|                             | Outfall   | 8.06             | 9.29   | 10.19  | 8.48         | 9.43            | 9.28   | 8.64   |        | 9.21   | 6035             |
| 4                           | Intake    | 5.23             | 5.8    | 6.86   | 5.46         | 5.79            | 6.28   | 6.59   |        | 6.2    | 4940             |
|                             | Outfall   | 8.07             | 10.08  | 9.82   | 8.69         | 9.19            | 9.14   | 8.87   |        | 9.11   | 5122             |
| 5                           | Intake    | 4.55             | 5.98   | 6.59   | 4.79         | 4.84            | 5.12   | 5.53   | 5.62   | 5.32   | 5071             |
|                             | Outfall C | 7.99             | 9.73   | 9.49   | 8.36         | 8.28            | 8.95   | 8.87   | 8.78   | 8.78   | 5737             |
|                             | Outfall S | 7.86             | 9.72   | 9.46   | 8.47         | 8.51            | 8.98   | 8.99   | 9.02   | 8.93   | 6758             |

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

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

where:

$Q_P$  = Flow through SEPA station,  $\text{m}^3/\text{s}$

= Number of Pumps Operating x Pump Capacity

$C_{\text{SAT}}$  = Saturation concentration of dissolved oxygen,  $\text{mg/L}$ ,

(determined from continuous in-stream temperature data)

$C_{UPSTREAM}$  = Dissolved oxygen concentration (mg/L) upstream of SEPA station from continuous in-stream monitoring data

$\alpha$  = Fraction of saturation achieved = f(number of pumps in operation), from Butts et al. (1999)

These oxygen loads were directly input to the CWS as a point source in the DUFLOW water-quality simulation. Daily DO loads from SEPA stations are given in Appendix B. The fraction of saturation achieved is listed in Table 3.5, which was determined from Table 3.2-3.4.

**Table 3.5** Fraction of dissolved oxygen saturation achieved by the Sidestream Elevated Pool Aeration (SEPA) stations with different pump operations (after Butts et al., 2000)

| SEPA Station | Number of Pumps |      |      |      |
|--------------|-----------------|------|------|------|
|              | 1               | 2    | 3    | 4    |
| 3            | 1.01            | 1.01 | 0.99 |      |
| 4            | 1.01            | 1.05 | 1.02 |      |
| 5            | 0.93            | 0.98 | 1.02 | 1.02 |

Flow through the SEPA station was calculated using the pump operation schedule and pump capacities. The pump operation schedule was provided by the MWRDGC. During the study period (April 1- May 4, 2002), most of the time SEPA stations were in use and just one pump was operating. Design features of SEPA stations are given in Table 3.6.

**Table 3.6** Engineering Design Features of the Sidestream Elevated Pool Aeration (SEPA) stations (after Butts et al., 2000)

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

The DO saturation concentration is a function of elevation and temperature. The DO saturation concentration for various water temperatures was computed using the Committee on Sanitary Engineering Research (1960) DO saturation formula:

$$S_T = 14.652 - 0.41022 \times T + 0.007991 \times T^2 - 0.000077774 \times T^3$$

where:

$S_T$  = DO saturation concentration, at sea level, mg/L

$T$  = Water temperature, °C. The temperature at the upstream continuous monitoring station was used.

This formula represents saturation levels at sea level. The sea level concentrations calculated by the formula must be corrected for differences in air pressure caused by air temperature changes and for elevations above sea level. Butts et al. (1999) developed the following formula:

$$f = (2116.8 - ((0.08 - 0.000115 \times s) \times E)) / 2116.8$$

where:

$f$  = correction factor above sea level

$s$  = air temperature, °C

$E$  = Site Elevation, feet above mean sea level (ft-msl)

A mean elevation of 578.6 ft-msl was used for all SEPA stations. Ambient water temperatures were used to approximate “s” in this equation.

### 3.2.2 In-Stream Aeration Stations

Because of problems with low DO in the past, two diffused aeration stations were built. In 1979, the Devon Avenue station was completed on The North Shore Channel. A second aeration station was constructed at Webster Street on the North Branch of the Chicago River 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 oxygen loads from the in-stream aeration stations. Figure 3.1-3.3 graphically show the relation observed between oxygen absorption and upstream DO saturation levels for one, two, and three-blower operation at the Devon Avenue facility.

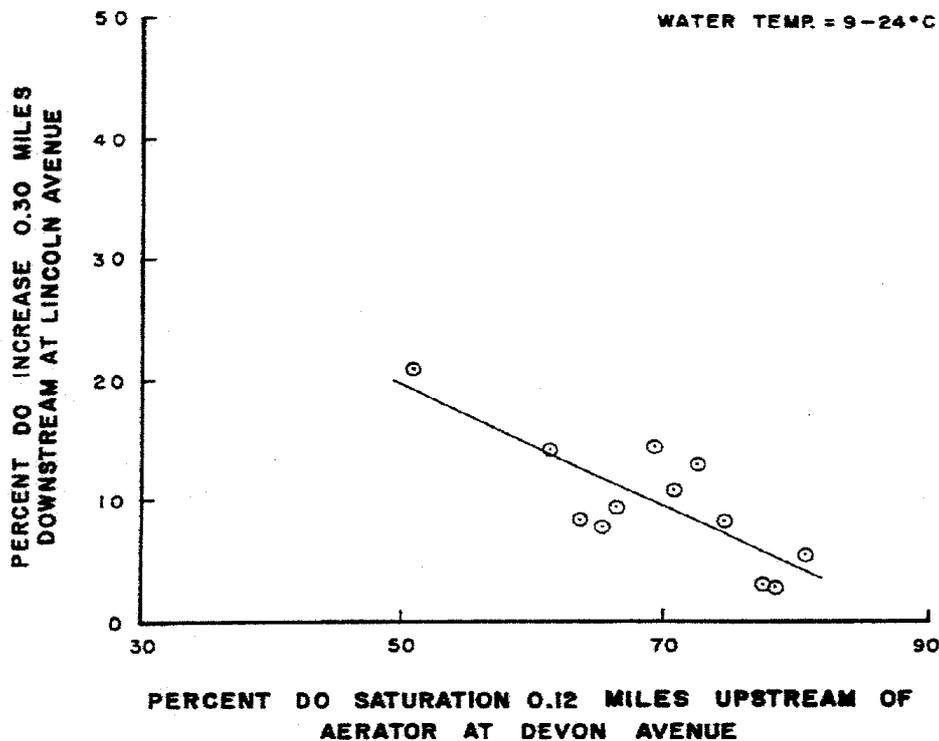


Figure 3.1 Effect of upstream Dissolved Oxygen (DO) saturation on downstream DO absorption with one blower in operation at Devon Avenue (after Polls et al., 1982)

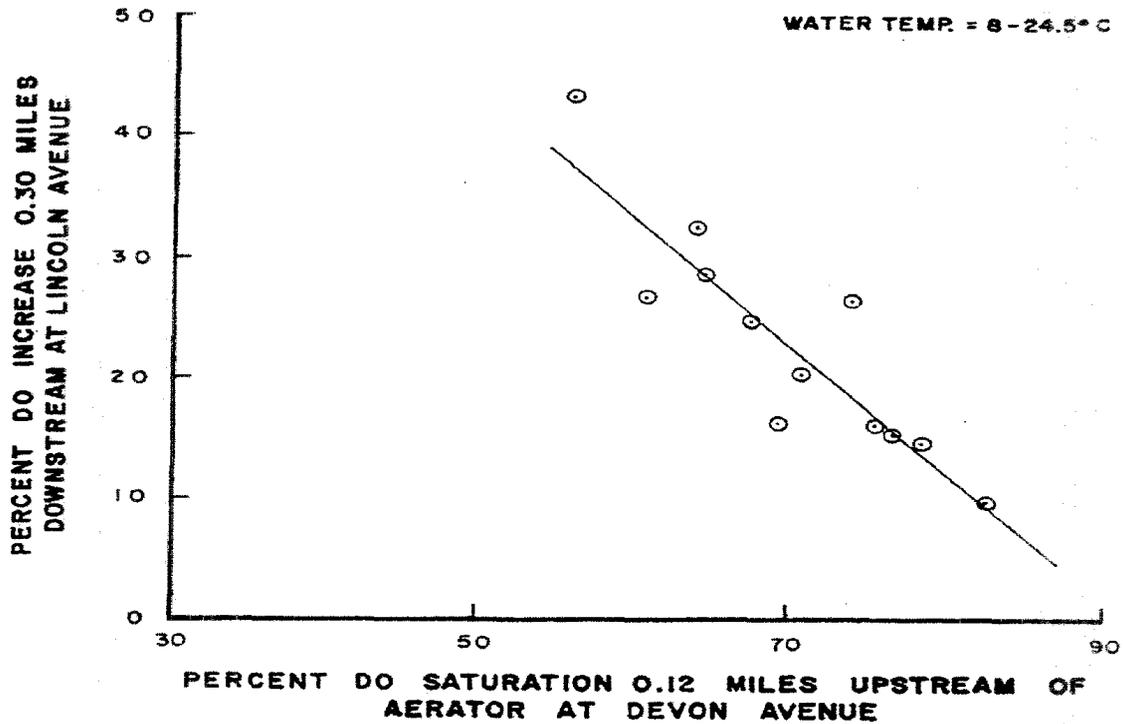


Figure 3.2 Effect of upstream Dissolved Oxygen (DO) saturation on downstream DO absorption with two blowers in operation at Devon Avenue (after Polls et al., 1982)

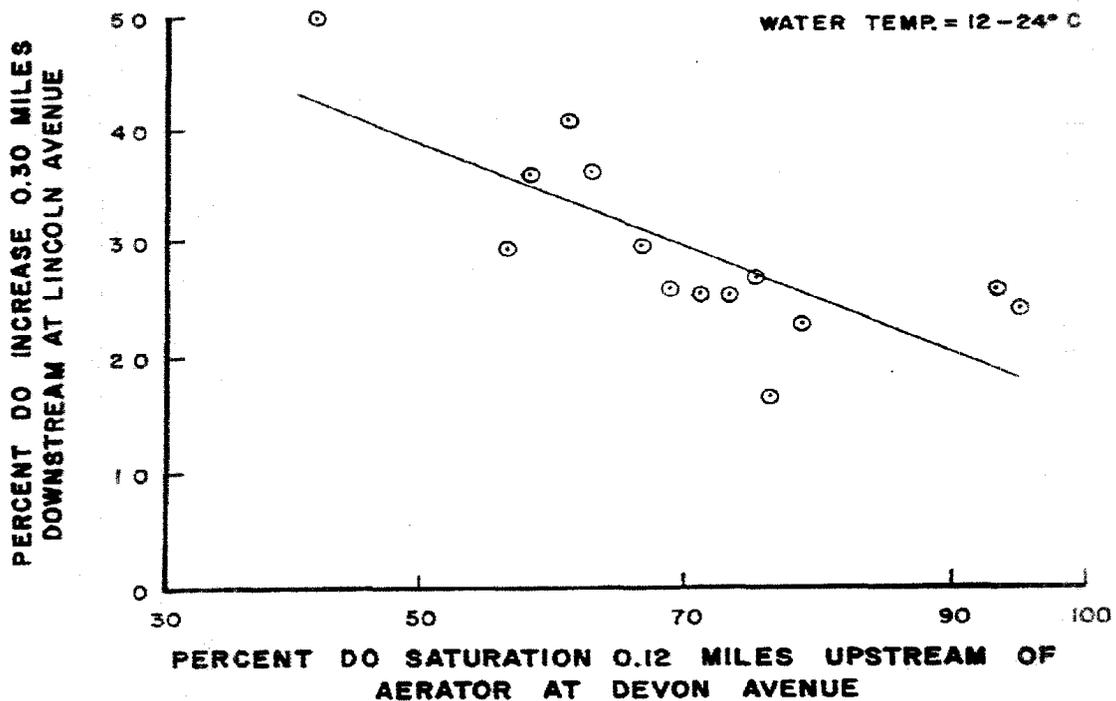


Figure 3.3 Effect of upstream Dissolved Oxygen (DO) saturation on downstream DO absorption with three blowers in operation at Devon Avenue (after Polls et al., 1982)

The data plotted in Figure 3.1-3.3 reflect percent increases in DO concentrations recorded 0.30 miles downstream of the diffusers. Each of the data points was averaged for two percent increments in DO saturation levels measured at Devon Avenue, 0.12 miles upstream of the aeration station. The correlation coefficients of the linear relations shown on the figures were -0.77, -0.89, and -0.76, respectively, thus, indicating that a relation existed between the percentage of DO saturation upstream of the aerator and the percentage increase in DO concentration downstream of the aerator.

Equations describing the effects of upstream DO saturation on downstream DO absorption with different numbers of blowers in operation are given below (Polls et al., 1982):

$$DO_{\text{increase}} = 0.455 * DO_{\text{saturation}} + 61.75 \quad (3 \text{ blowers in operation})$$

$$DO_{\text{increase}} = 1.048 * DO_{\text{saturation}} + 96.42 \quad (2 \text{ blowers in operation})$$

$$DO_{\text{increase}} = -0.516 * DO_{\text{saturation}} + 45.57 \quad (1 \text{ blower in operation})$$

where:

$$DO_{\text{increase}} = \text{Percent DO increase - 0.30 miles downstream of aeration station at Lincoln Avenue}$$

$$DO_{\text{saturation}} = \text{Percent DO saturation - 0.12 miles upstream of aeration station at Devon Avenue}$$

Although these regression equations were developed for the Devon Avenue aeration station, it was assumed that they also are valid for the Webster Street aeration station. Therefore, the same equations were used for both of the stations in the water-quality

modeling. Blower operation hours were provided by the MWRDGC. Unfortunately only the total number of operating hours per day was provided. Since blower start and stop times are unknown, blower operation hours were carefully determined using time intervals where increases and decreases in DO concentrations were observed downstream of the aeration stations. Addison and Division Street continuous DO station observations were used for downstream of Devon Avenue and Webster Street aeration stations, respectively. The following equation is used to calculate DO load for input to the model:

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

where:

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

$\%DO_{\text{increase}}$  = Percent DO increase downstream of the aeration station

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

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

Discharge and DO concentration upstream of Devon Avenue were calculated using a mass balance approach. The North Side WRP and North Shore Channel at Main Street continuous DO concentration and discharges were used to calculate DO and discharge upstream of Devon Avenue aeration station. The Fullerton Avenue continuous DO monitoring site measurements were used for the Webster Street aeration station calculations. Daily DO load from in-stream aeration stations are given in Appendix B.

### 3.2.3 Water Reclamation Plants

Five point sources of flow potentially affect the water quality in the CWS: the North Side WRP, Stickney WRP, Calumet WRP, Lemont WRP, and the Citgo Petroleum Corporation outfall. Measured daily concentrations were used in the model for the four WRPs. The summation of the discharges from the North Side, Stickney, and Calumet WRPs has the greatest contribution of loads to the CWS. Daily measured concentration from these 3 WRPs are given in Figure 3.4-3.6, respectively. In these figures and throughout the report the constituent abbreviations are as follows: DO = dissolved oxygen, BOD5 = 5-day biochemical oxygen demand, TSS = total suspended solids, TKN = total Kjeldahl nitrogen as nitrogen, NH4-N = ammonia as nitrogen, Org-N = organic nitrogen as nitrogen, NO3 = nitrate as nitrogen, and P-tot = total phosphorus. The load from the Citgo Petroleum outfall was not considered in this study because of lack of water-quality data on this discharge and the insignificant amount of flow contributed by this discharger.

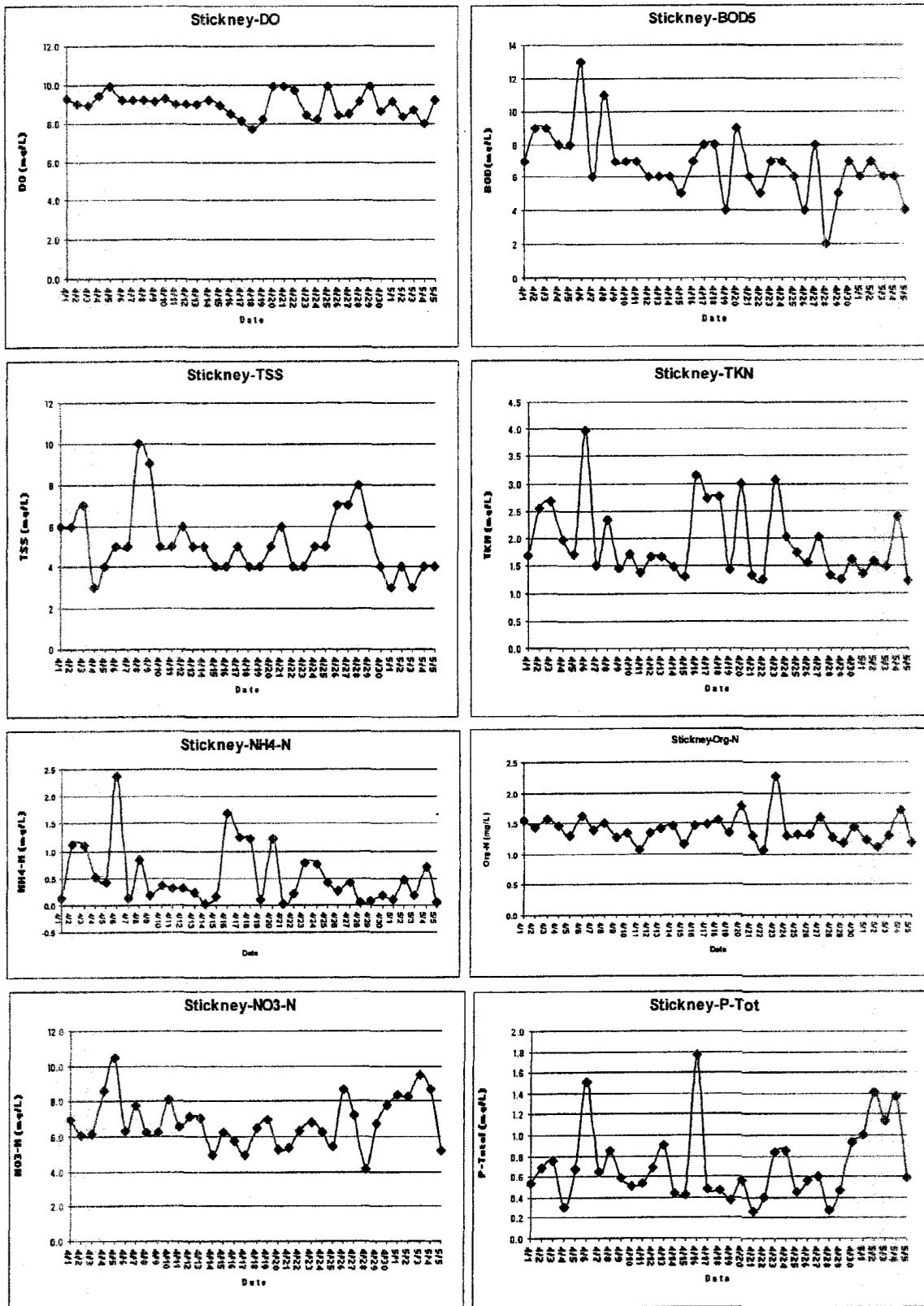


Figure 3.4. Stickney Water Reclamation Plant daily effluent concentrations for April 1-May 5, 2002

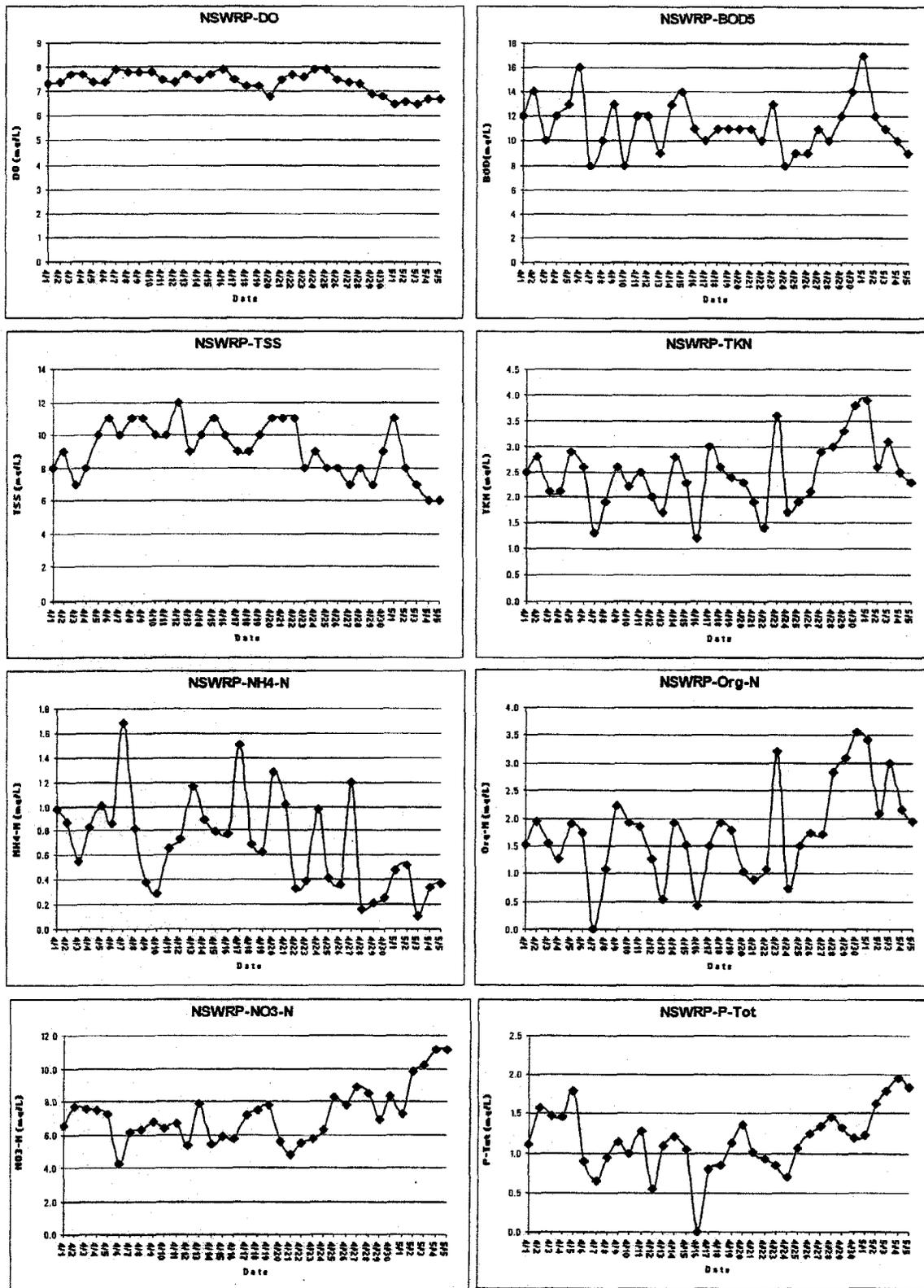


Figure 3.5. North Side Water Reclamation Plant daily effluent concentrations for April 1-May 5, 2002

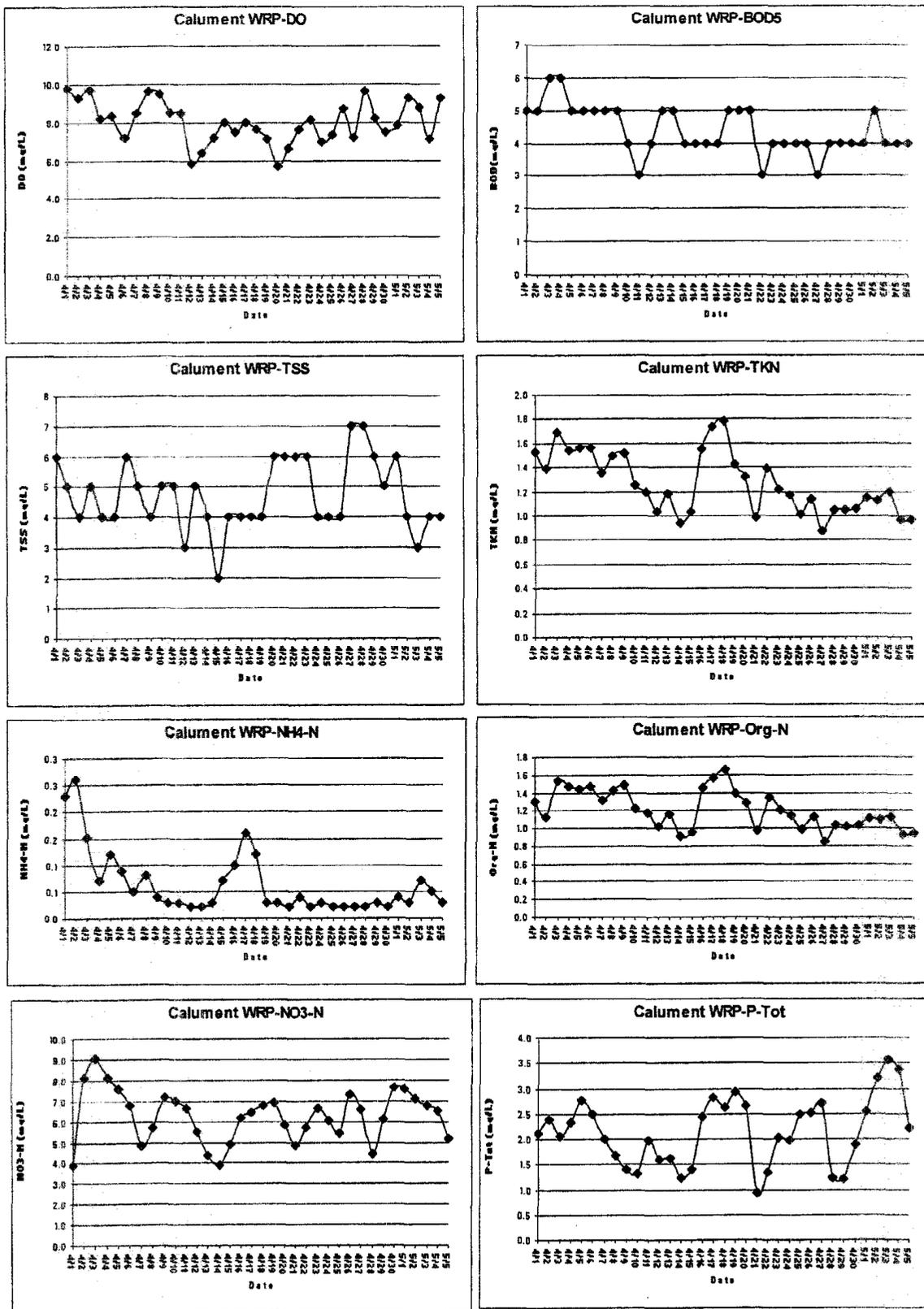


Figure 3.6. Calumet Water Reclamation Plant daily effluent concentrations for April 1-May 5, 2002

### 3.2.4 Tributaries

There are two data categories related to the tributaries:

- i) Dry weather long-term average concentrations
- ii) Wet weather event mean concentrations

Values for each of these categories are discussed in the following subsections.

#### 3.2.4.1 Dry Weather Concentrations

Long-term average values are used for the dry-weather concentrations. All water-quality data used for dry-weather concentrations were collected as a part of the MWRDGC monthly waterway sampling program.

Average concentrations for 2001-2002 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 of the South Holland gage) and at Ashland Avenue (downstream of the South Holland gage) and Thorn Creek at 170<sup>th</sup> Street (upstream of the South Holland gage). Results are listed in Table 3.7, where NO<sub>2</sub>+NO<sub>3</sub>-N represents nitrite plus nitrate as nitrogen and P-Sol represents soluble phosphorus.

**Table 3.7.** Little Calumet River at South Holland dry-weather concentrations

| <b>BOD5</b>   | <b>TSS</b>    | <b>DO</b>     | <b>TKN</b>    | <b>NH<sub>4</sub>-N</b> | <b>Org-N</b>  | <b>P-Tot</b>  | <b>NO<sub>2</sub>+NO<sub>3</sub>-N</b> | <b>P-Sol</b>  |
|---------------|---------------|---------------|---------------|-------------------------|---------------|---------------|--|---------------|
| <b>(mg/L)</b> | <b>(mg/L)</b> | <b>(mg/L)</b> | <b>(mg/L)</b> | <b>(mg/L)</b>           | <b>(mg/L)</b> | <b>(mg/L)</b> | <b>(mg/L)</b>                          | <b>(mg/L)</b> |
| 3.15          | 53.05         | 5.61          | 1.71          | 0.30                    | 1.42          | 1.19          | 3.39                                   | 0.97          |

Concentrations measured between 1990-2002 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 3.8.

**Table 3.8.** Grand Calumet River at Hohman Avenue dry-weather concentrations

| <b>BOD5<br/>(mg/L)</b> | <b>TSS<br/>(mg/L)</b> | <b>DO<br/>(mg/L)</b> | <b>TKN<br/>(mg/L)</b> | <b>NH4-N<br/>(mg/L)</b> | <b>Org-N<br/>(mg/L)</b> | <b>P-Tot<br/>(mg/L)</b> | <b>NO2+NO3-<br/>N (mg/L)</b> | <b>P-Sol<br/>(mg/L)</b> |
|------------------------|-----------------------|----------------------|-----------------------|-------------------------|-------------------------|-------------------------|------------------------------|-------------------------|
| 6.69                   | 37.63                 | ***                  | 4.48                  | 2.09                    | 2.41                    | 0.76                    | 8.04                         | 0.22                    |

\*\*\* For DO measured hourly concentrations on the Grand Calumet River at Torrence Avenue were assigned to the inflows on the Grand Calumet River at Hohman Avenue

Average concentrations (2000-2002) for the North Branch Chicago River at Albany Avenue are given in Table 3.9.

**Table 3.9.** North Branch Chicago River at Albany Avenue dry-weather concentrations

| <b>BOD5<br/>(mg/L)</b> | <b>TSS<br/>(mg/L)</b> | <b>DO<br/>(mg/L)</b> | <b>TKN<br/>(mg/L)</b> | <b>NH4-N<br/>(mg/L)</b> | <b>Org-N<br/>(mg/L)</b> | <b>P-Tot<br/>(mg/L)</b> | <b>NO2+NO3-<br/>N (mg/L)</b> | <b>P-Sol<br/>(mg/L)</b> |
|------------------------|-----------------------|----------------------|-----------------------|-------------------------|-------------------------|-------------------------|------------------------------|-------------------------|
| 4.0                    | 23.12                 | 7.5                  | 1.71                  | 0.36                    | 1.34                    | 0.85                    | 3.41                         | 0.81                    |

Since the data collected by the MWRDGC during 2001-2004 show that the chlorophyll-a concentration varies drastically from month to month, average April and May chlorophyll-a concentrations calculated for the Little Calumet at South Holland and North Branch Chicago River at Albany Avenue. The chlorophyll-a concentration for the Little Calumet River at South Holland was computed using the same mass balance approach applied for the other constituents. Results are listed in Table 3.10.

**Table 3.10** North Branch Chicago River at Albany Avenue and Little Calumet at South Holland chlorophyll-a concentrations

| <b>Location</b> | <b>Chlorophyll-a (ug/L)</b> |            |
|-----------------|-----------------------------|------------|
|                 | <b>April</b>                | <b>May</b> |
| Albany Avenue   | 58.8                        | 22.1       |
| South Holland   | 16.5                        | 4.5        |

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

### 3.2.4.2 Wet Weather Concentrations

Event mean concentrations were calculated using water-quality data collected during storm events by the MWRDGC. In most cases, the total load resulting from the runoff event is more important than the individual concentrations within the event due to the fact that runoff events are relatively short, the receiving water body provides some mixing, and the concentration in the receiving water body is a response to the total load rather than the concentration variability within the event (Novotny and Olem, 1994, p. 484). Hence, event mean concentrations were used to characterize all storms in this study. Concentrations for the Little Calumet River at South Holland were calculated using storm data on the Little Calumet River at Ashland Avenue. Results are given in Table 3.11.

**Table 3.11.** Event mean concentrations measured at the Little Calumet River at Ashland Avenue

| Date              | BOD5<br>(mg/L) | P-Tot<br>(mg/L) | TKN<br>(mg/L) | NH4-N<br>(mg/L) | NO2-N<br>(mg/L) | NO3-N<br>(mg/L) | TSS<br>(mg/L) |
|-------------------|----------------|-----------------|---------------|-----------------|-----------------|-----------------|---------------|
| April 7-9, 2002   | 4.92           | 0.79            | 2.17          | 0.34            | 0.07            | 1.74            | 131.95        |
| April 18-21, 2002 | 3.44           | 1.22            | 1.72          | 0.28            | 0.09            | 1.99            | 55.76         |
| May 1-2, 2002     | 3.00           | 1.15            | 1.42          | 0.13            | 0.06            | 2.07            | 41.17         |

Event mean concentrations for the North Branch Chicago River at Albany Avenue are given in Table 3.12.

**Table 3.12.** Event mean concentrations measured at the North Branch Chicago River at Albany Avenue

| Date              | BOD5<br>(mg/L) | P-Tot<br>(mg/L) | TKN<br>(mg/L) | NH4-N<br>(mg/L) | NO2-N<br>(mg/L) | NO3-N<br>(mg/L) | TSS<br>(mg/L) |
|-------------------|----------------|-----------------|---------------|-----------------|-----------------|-----------------|---------------|
| April 7-9, 2002   | 6.34           | 0.72            | 2.04          | 0.20            | 0.05            | 2.51            | 65.50         |
| April 18-21, 2002 | 2.18           | 0.63            | 1.28          | 0.06            | 0.06            | 2.97            | 14.94         |
| May 1-2, 2002     | 4.00           | 0.61            | 2.01          | 0.03            | 0.05            | 3.08            | 31.44         |

Other tributaries are based on Little Calumet River event mean concentrations.

### 3.2.5 Combined Sewer Overflows

There are nearly 200 CSO locations discharging to the modeled portion of the CWS and they are represented by 28 CSO locations in the model (Figure 2.1 and Table 2.2). In addition to CSO locations there are 3 CSO pumping stations. Water-quality parameters were measured by the MWRDGC at the pumping stations during the April 7-9 storm period. On April 9, 2002 a single DO concentration of 2.5 mg/L was measured at the Racine Avenue Pump Station and a single DO concentration of 4.3 mg/L was measured at the 125<sup>th</sup> Street Pumping Station. Because of the substantial variability in DO concentrations during an overflow event, it was decided to determine the event mean DO concentration for all CSOs as part of the DO calibration for entire CWS. A DO concentration of 6.5 mg/L was selected by iteration such that reasonable agreement between measured and simulated DO concentrations was obtained during the period affected by the CSO event. This value is reasonable compared to monthly samples of DO concentration for the Racine Avenue Pump Station for March 2002-November 2003, which range from 0-9.3 mg/L with a mean of 4.5 mg/L and standard deviation of 2.9 mg/L. Also DO concentrations of inflows entering the TARP drop shafts collected in 1997 and 1999 had a mean of 6.3 mg/L and a standard deviation of 2.1 mg/L. During the storm period all three Street Pumping Stations were in use.

North Branch Pumping Station measurements were used for North Shore Channel and North Branch CSOs. Results are given in Table 13.

**Table 3.13.** Concentrations measured at the North Branch Pumping Station in April 2002

| <b>BOD5</b>   | <b>P-Tot</b>  | <b>TKN</b>    | <b>NH4-N</b>  | <b>NO2-N</b>  | <b>NO3-N</b>  | <b>TSS</b>    |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| <b>(mg/L)</b> |
| 48.5          | 1.59          | 8.265         | 3.835         | 0.066         | 0.697         | 62.5          |

The Chicago River Main Stem, South Branch, and CSSC CSO water-quality parameters were determined using concentrations measured at the Racine Avenue Pumping Station.

Results are given in Table 3.14.

**Table 3.14.** Concentrations measured at the Racine Avenue Pumping Station in April 2002

| <b>BOD5</b>   | <b>P-Tot</b>  | <b>TKN</b>    | <b>NH4-N</b>  | <b>NO2-N</b>  | <b>NO3-N</b>  | <b>TSS</b>    |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| <b>(mg/L)</b> |
| 38            | 1.66          | 9.32          | 2.52          | 0.099         | 0.346         | 182           |

The Calumet-Sag Channel and Little Calumet River CSO water-quality parameters were determined using concentrations measured at the 125<sup>th</sup> Street Pumping Station. Results are given in Table 3.15.

**Table 3.15.** Concentrations measured at the 125<sup>th</sup> Street Pumping Station in April 2002

| <b>BOD5</b>   | <b>P-Tot</b>  | <b>TKN</b>    | <b>NH4-N</b>  | <b>NO2-N</b>  | <b>NO3-N</b>  | <b>TSS</b>    |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| <b>(mg/L)</b> |
| 24            | 4.05          | 6.11          | 1.55          | 0.107         | 2.215         | 30            |

### **3.2.6 Boundaries**

There are 3 upstream boundaries in the water-quality model: near the Chicago River Controlling Works at the Chicago River at Columbus Drive, near the Wilmette Pumping Station at the North Shore Channel at Maple Avenue, and O'Brien Lock and Dam. Historic plots of data (1990-2002) show that there are seasonal and monthly variations at these locations and nitrogen compound concentrations for the Chicago River at

Columbus Drive changed after 1997. Chlorophyll-a concentration also shows monthly variations according to the measurements done between 2001 and 2004.

The BOD and ammonia concentrations measured near the lake front in April and May are higher than those measured in summer months because of the mixing of North Shore Channel and Lake Michigan flows at Wilmette and North Branch Chicago River and Lake Michigan flows at Columbus Drive in April and May. In the summer, the flow near the lake front primarily is Lake Michigan water because of the discretionary diversion from the lake. The inflow at the lake front boundaries should reflect the quality of Lake Michigan water rather than the mixed flows measured in April and May. Thus, the concentrations of BOD, ammonia, nitrate, etc. at Wilmette and Columbus Drive were set equal to the mean measured concentration during periods with discretionary diversion. Daily water temperature data near the lake shore was obtained from the Chicago Department of Water Management. These data were used to compute the saturation concentration of DO for Lake Michigan water for the April 1 to May 4 period. Comparison of DO saturation concentrations for summer months with daily average monitoring data near the lake front during discretionary flow periods indicate that the Lake Michigan water is a little less than saturated. Nevertheless saturation was assumed for convenience.

April and May average concentrations were used in the water-quality model for the Calumet River at O'Brien Lock and Dam since its concentrations were based on measurements at 130<sup>th</sup> Street upstream from the dam. Results are given in Figures 3.7-3.9 and Table 3.16.

**Table 3.16. Mean concentrations at the water-quality model boundaries for 1990-2002**

| Location       | Date   | BOD5<br>(mg/L) | TSS<br>(mg/L) | DO<br>(mg/L) | TKN*<br>(mg/L) | NH4-N*<br>(mg/L) | Org N*<br>(mg/L) | P-Tot.<br>(mg/L) | NO2+NO3<br>(mg/L) | Sol. P.<br>(mg/L) | Chll-a<br>(ug/L) |
|----------------|--------|----------------|---------------|--------------|----------------|------------------|------------------|------------------|-------------------|-------------------|------------------|
| Columbus Drive | Summer | 1.63           | 9.80          | **           | 0.42           | 0.04             | 0.38             | 0.09             | 0.26              | 0.04              | 1.4              |
| Wilmette       | Summer | 2.96           | 11.33         | **           | 0.49           | 0.09             | 0.41             | 0.09             | 0.22              | 0.04              | 1.5              |
| O'Brien        | April  | 3.50           | 14.65         | ***          | 1.26           | 0.37             | 0.97             | 0.26             | 1.09              | 0.22              | 8.8              |
|                | May    | 5.33           | 12.94         | ***          | 0.81           | 0.25             | 0.60             | 0.33             | 1.01              | 0.31              | 6.5              |

\* Mean concentrations for nitrogen compounds were calculated for the period of 1997-2002

\*\* Saturation DO concentrations calculated using daily water temperature data near the lake shore

\*\*\* Continuous hourly DO measurements

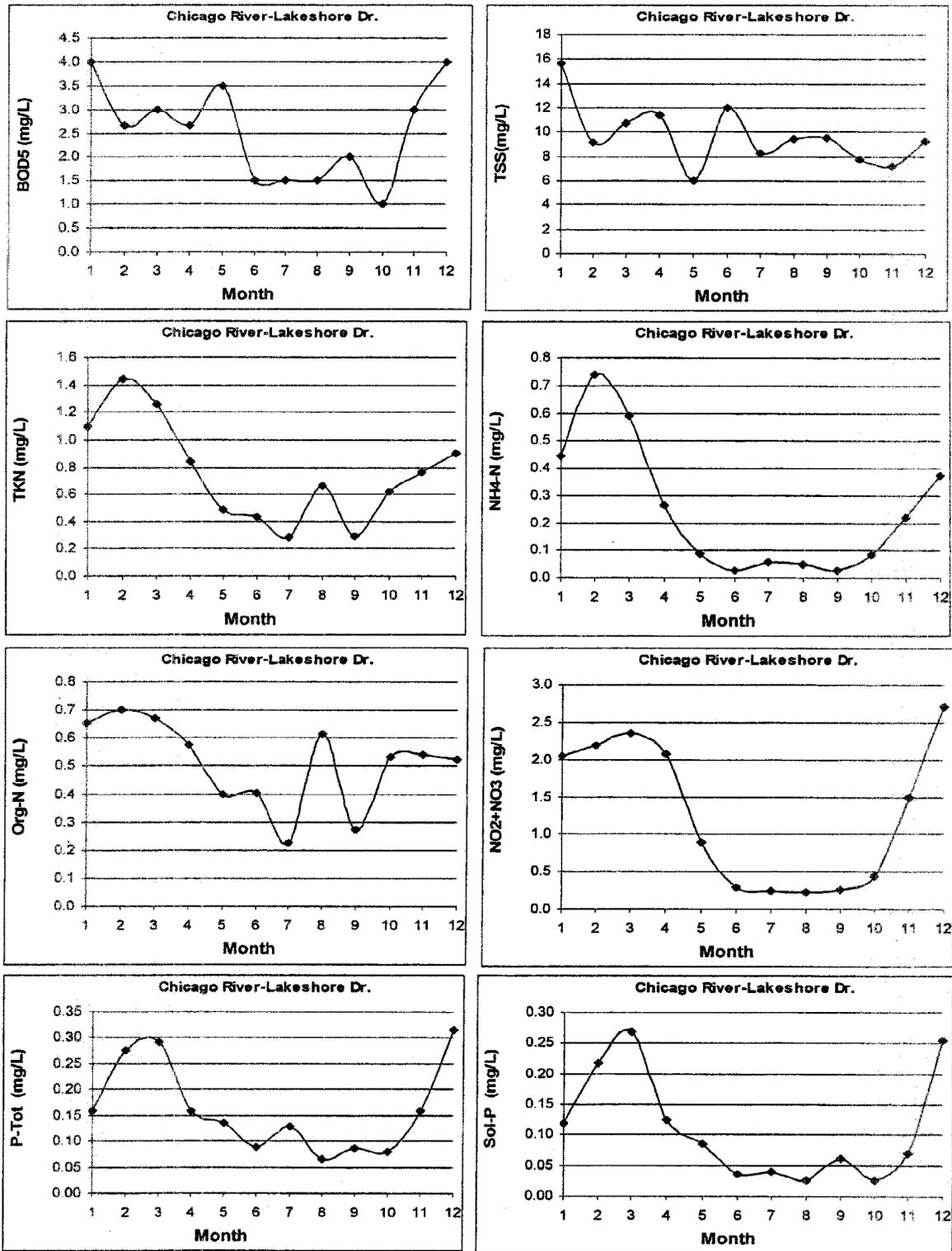
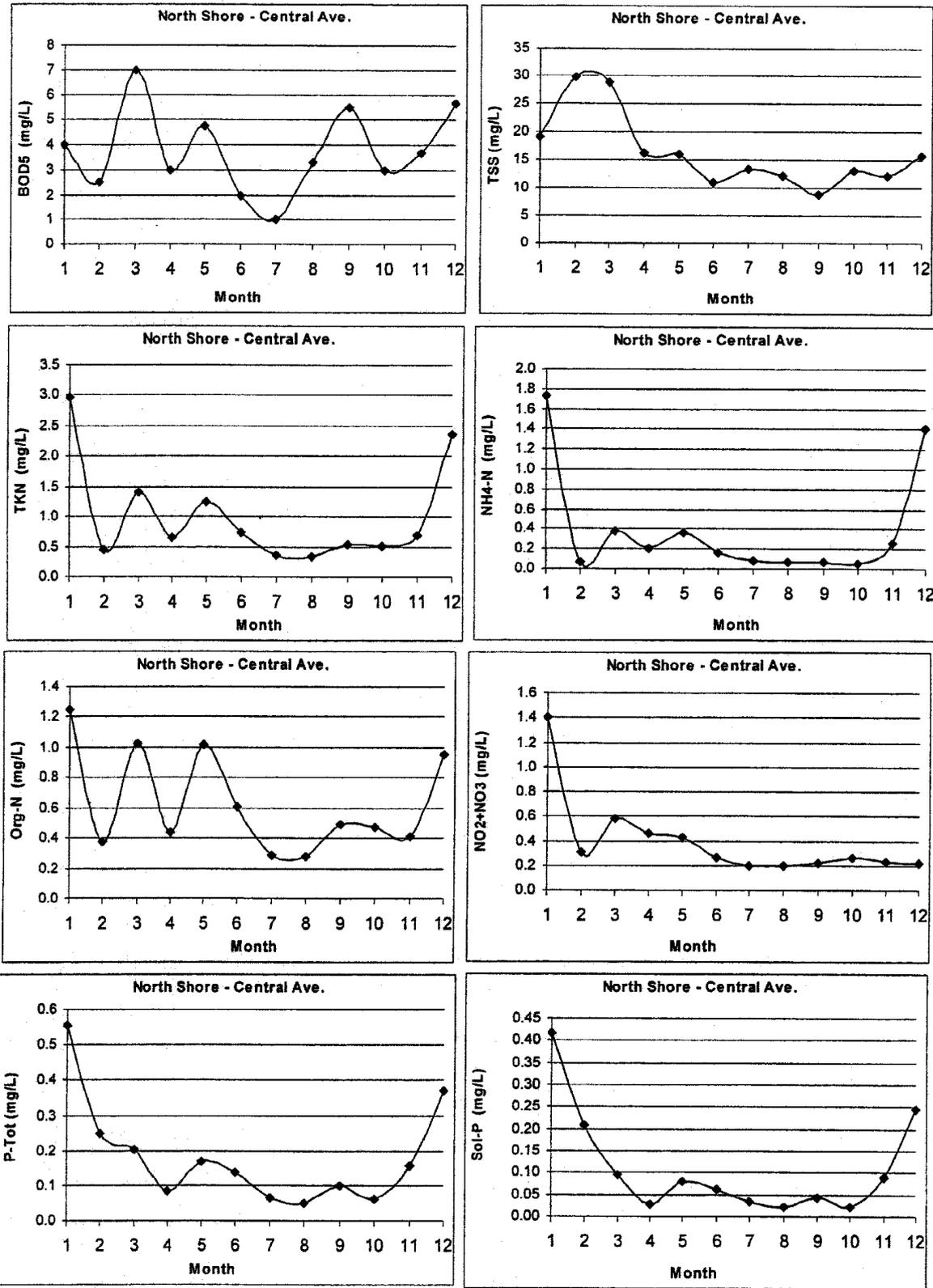


Figure 3.7. Monthly mean concentrations for the Chicago River Main Stem at Lake Shore Drive for 1997-2002 taken as representative of the boundary condition at Columbus Drive 0.3 mi downstream



**Figure 3.8.** Monthly mean concentrations for the North Shore Channel at Central Avenue for 1990-2002

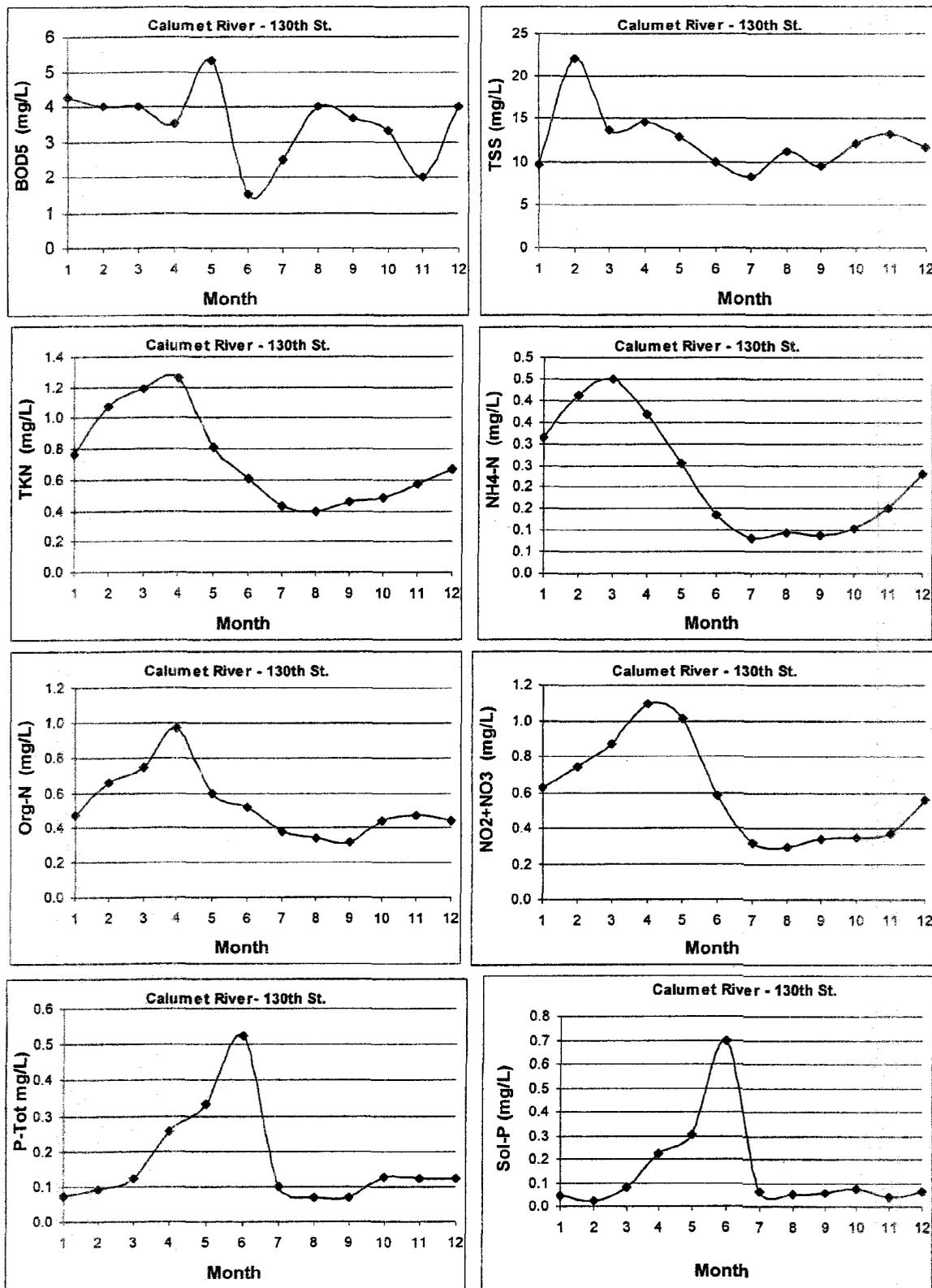


Figure 3.9. Monthly mean concentrations for the Calumet River at 130<sup>th</sup> Street for 1990-2002

### **3.3 Initial Conditions**

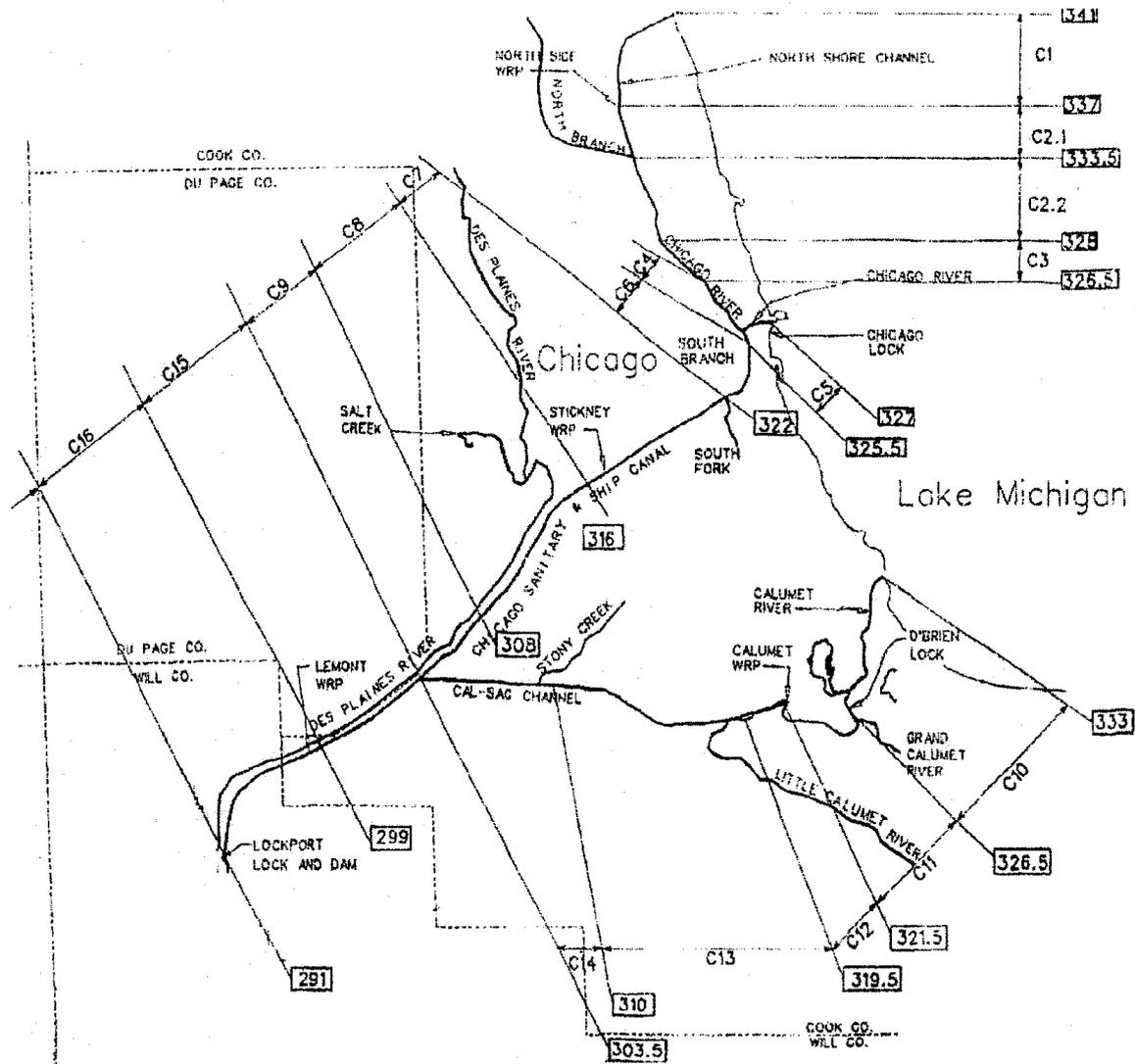
To start the computations, initial values for water-surface elevation and discharge, and all state variables (concentrations) are required by the DUFLOW model. Initial conditions are introduced for each DUFLOW point, i.e. each node (water quality and DO monitoring sites), or schematization points (discharge points). As stated in 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 (1<sup>st</sup> measurement of the simulation period) were introduced at each node by adding the cumulative flow as tributaries or treatment facilities discharge to the CWS. Water-surface elevation data provided by the MWRDGC (Lawrence Avenue, Southwest Highway, Western Avenue, Willow Springs, and Cal-Sag Junction) and the USGS (boundary conditions) were used to set initial conditions for water-surface elevation at each node by linear interpolation. The effect of the initial conditions can be seen in the various figures of results. For water-surface elevation (Figures 2.3 and 2.4) it can be seen that the errors resulting from the assumed initial flows and water-surface elevations are eliminated within a few hours on April 1. Initial conditions for the water-quality constituents were introduced based on the water-quality measurements provided by MWRDGC at several sampling locations. For DO concentrations, the first measurement of the simulation period was selected as the initial condition. For DO concentrations (Figures 3.22-3.34) it also can be seen that the errors resulting from the assumed initial conditions are eliminated with a few hours on

April 1. Default DUFLOW EUTROF2 sediment concentrations were used as initial conditions. Initial conditions, calculation nodes, and sections are given in Appendix C.

### ***3.4 Calibration of the Water-Quality Model***

As a part of the calibration process, the QUAL2EU model developed by the Camp Dresser & McKee (CDM, 1992) was used as a starting point. The study area was divided into 17 reaches for water-quality simulation (CDM, 1992). The CDM reaches are shown in Figure 3.10. In this study, the CWS also was divided into 17 reaches. Fifteen of the reaches used in this study are identical to those used by CDM. CDM Reach C10 is outside the boundaries of this study, and only about half of reach C16 is included in this study from river mile 8 to river mile 5.1 (the USGS Romeoville gage) where the river miles are from Lockport. Reach C17 (not shown in Figure 3.10) is the reach on the Little Calumet River (South) from the USGS South Holland gage to the confluence with the Calumet-Sag Channel. The river miles bounding the reaches used in this study are listed in Table 3.17. Within these reaches computational nodes have been placed at approximately 1,640 ft (500 m) intervals.



**Figure 3.10.** Chicago Waterway System reaches (after CDM, 1992). The numbers in boxes are the river miles from the mouth of the Illinois River at Grafton, Ill., by subtracting 291 from these numbers the river miles from Lockport, Ill., used in this study are obtained.

The following parameters were set as space and time dependent: Temperature, diffusive exchange rate constant for sediment, nitrification rate constant, BOD decay rate, and dispersion. Since the reaeration-rate coefficient is automatically calculated by the model using the O'Connor-Dobbins (1958) formula, it was not used as a calibration variable. Constant algal maximum growth, die-off, settling, and respiration rates were used throughout the simulation period at all locations.

### In-Stream Water-Quality Data

The water-quality model was calibrated using monthly grab sample data at 18 locations and hourly DO data at 24 locations all collected by the MWRDGC. The locations of water quality and DO sampling stations are given in Table 3.17. The model was run with a 15-min. time step for the period of April 1 to May 4, 2002.

### Temperature (°C)

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 with a coefficient, determining the change per °C difference from the reference temperature. The plots of the average temperature values (for the period of April 1 to May 4, 2002) show that the average temperature varies from 9 to 18 °C along the North Shore Channel, North Branch Chicago River, South Branch Chicago River, and the CSSC (Figure 3.11); and 10 to 14°C along the Calumet River System (Calumet River, Little Calumet River (north), and Calumet-Sag Channel) (Figure 3.12).

In order to eliminate the bias that might result from constant temperature usage, 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.

**Table 3.17.** 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 Waterway System used for calibration

| Station Location               | Data Available | Waterway                        | River Mile |
|--------------------------------|----------------|---------------------------------|------------|
| Central Street                 | WQ             | North Shore Channel             | 49.4       |
| Simpson Street                 | DO             | North Shore Channel             | 48.5       |
| Main Street                    | DO             | North Shore Channel             | 46.7       |
| Oakton Street                  | WQ             | North Shore Channel             | 46         |
| Touhy Avenue                   | WQ             | North Shore Channel             | 45.2       |
| Foster Avenue                  | WQ             | North Shore Channel             | 44         |
| 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       |
| Michigan Avenue                | DO             | Chicago River Main Stem         | 35.4       |
| Clark Street                   | DO             | Chicago River Main Stem         | 34.9       |
| Madison Street                 | WQ             | South Branch Chicago River      | 34.3       |
| Jackson Boulevard              | DO             | South Branch Chicago River      | 34         |
| 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                 | WQ             | Calumet-Sag Channel             | 28.1       |
| Division Street                | DO             | Calumet-Sag Channel             | 27.6       |
| Kedzie Avenue                  | DO             | Calumet-Sag Channel             | 26.1       |
| Cicero Avenue                  | DO, WQ         | Calumet-Sag Channel             | 24         |
| Harlem Avenue                  | DO             | Calumet-Sag Channel             | 20.5       |
| Southwest Highway              | DO             | Calumet-Sag Channel             | 19.7       |
| 104th Street                   | DO             | Calumet-Sag Channel             | 16.3       |
| Route 83                       | DO, WQ         | Calumet-Sag Channel             | 13.3       |

\*DO =Continuous (hourly) dissolved oxygen and temperature data;

\*\*WQ = Monthly grab sample water quality measurements

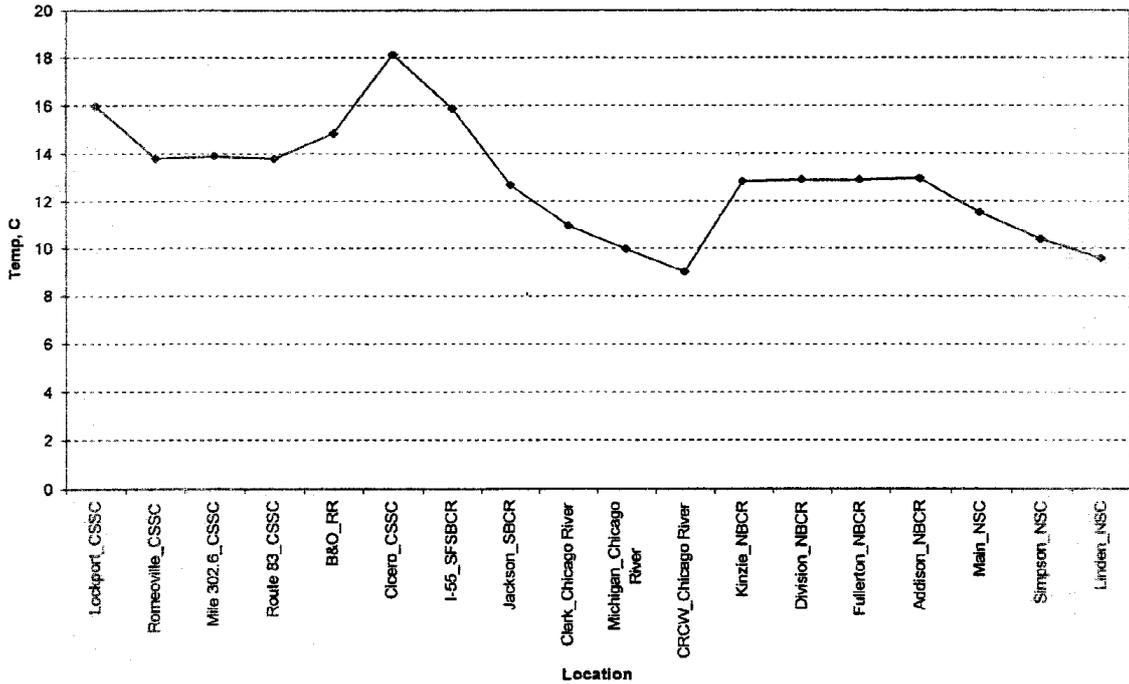


Figure 3.11. Temperature variation on the North Shore Channel, North Branch Chicago River, South Branch Chicago River, and Chicago Sanitary and Ship Canal

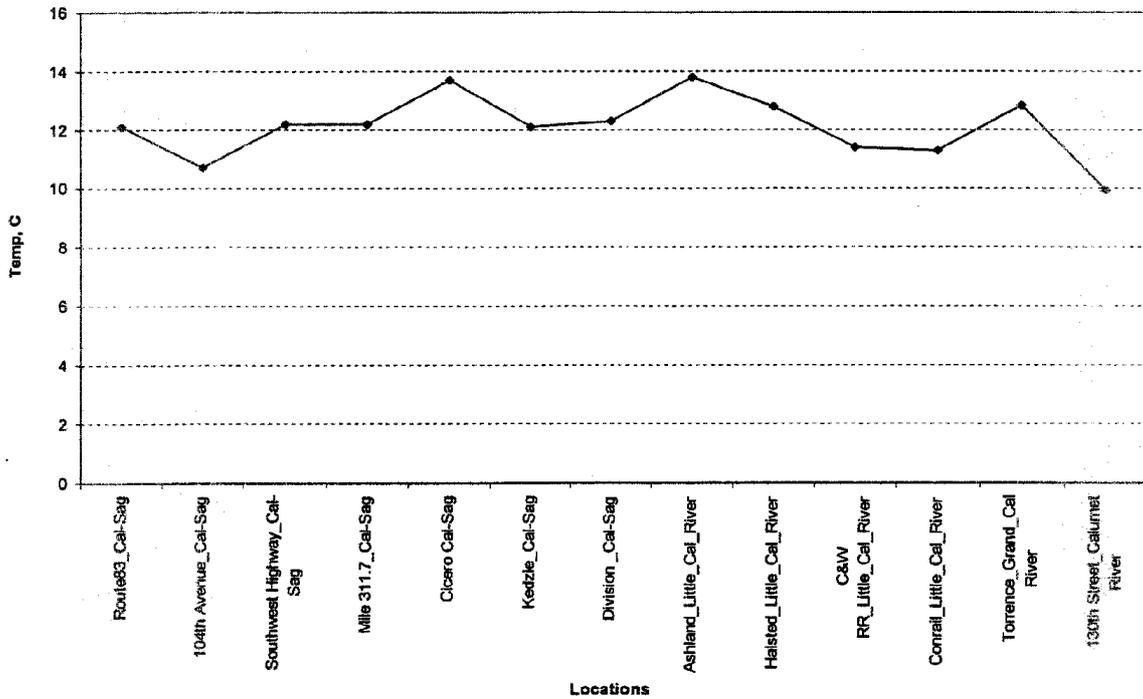


Figure 3.12. Temperature variation on the Calumet River, Little Calumet River (North), and Calumet-Sag Channel

Diffusive exchange rate constant (m<sup>2</sup>/day)

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

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

where:

SOD = Sediment Oxygen Demand (g/(day\*m<sup>2</sup>))

E<sub>dif</sub> = Diffusive exchange rate constant (m<sup>2</sup>/day)

HB = Depth of sediment top layer (m)

O<sub>2w</sub> = Water column dissolved oxygen concentration (mg/L)

O<sub>2B</sub> = Dissolved oxygen concentration in the pore water in the sediment bed (mg/L)

In November 2001, the MWRDGC did a survey of sediment depth and composition at 20 locations in the CWS. The sediment survey results were used during the calibration processes to set E<sub>dif</sub> values to nearly zero or zero where little bed sediment was found, essentially, setting SOD to zero at these locations. Values of E<sub>dif</sub> for other reaches were determined by calibration. The sediment survey indicated ranges of sediment depth, such as “sediment approximately one to two feet thick was collected near the southeast bank of the channel, 250 feet upstream from Simpson Street”, however, in the modeling the default value of 20 cm was used for the depth of the top (active) sediment layer.

BOD water column oxidation rate and nitrification rate constant ( $\text{day}^{-1}$ )

BOD decay and nitrification constants ( $k_{\text{BOD}}$  and  $k_{\text{nit}}$ ) play important roles in water-quality models. Different values were determined for different reaches by calibration. For reaches C1-C4 it was necessary to use different values of  $k_{\text{nit}}$  for different time periods. It was observed that  $\text{NH}_4\text{-N}$  concentration along the North Shore Channel downstream from the North Side WRP and North Branch Chicago River are higher than all other locations in the system (Figure 3.17). As can be seen from temperature plot of North Branch Chicago River at Division Street (Figure 3.13), temperature increases drastically after the second week of April. Average temperatures are 11 and 14.3 °C between April 1-15 and April 16-May 4, respectively. Although it is possible to see that kind of temperature trend at other locations, the combined effect of higher  $\text{NH}_4\text{-N}$  concentrations, relatively lower flowrates, and temperature variation makes it necessary to use different  $k_{\text{nit}}$  values for different time periods for reaches C1-C4.

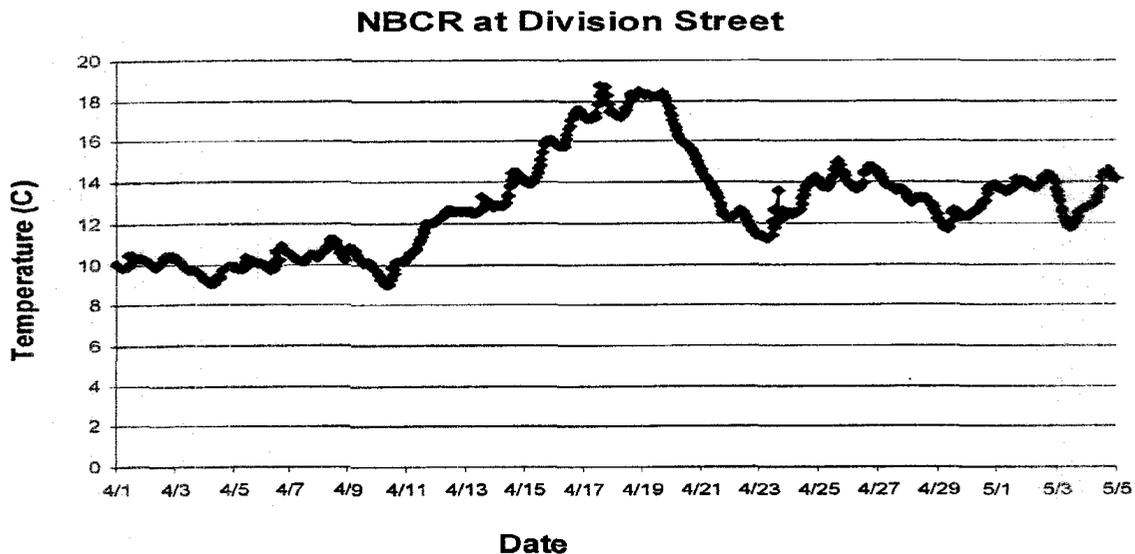


Figure 3.13 Temperature profile at Division Street on North Branch Chicago River

Since the values of  $k_{\text{BOD}}$  and  $k_{\text{nit}}$  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.

### Dispersion ( $\text{m}^2/\text{s}$ )

The model requires entering dispersion coefficients at each node. The value of the dispersion coefficient,  $D$ , either can be defined by the user or can be calculated using the properties of the flow. During the calibration procedure, it was found that the dispersion coefficient plays an important role at some locations. For these sites different dispersion coefficients were used for high flow and low flow periods.

For most flow conditions in the majority of the CWS the amount of nonuniformity in the velocity distribution is fairly low. Thus, dispersion plays a minor role in the majority of the CWS and relatively low values of  $D$  result in reasonable simulations of DO concentrations. However, during storms reaches C2.2 and C7 (see Figure 3.10) receive large lateral inflows from the North Branch of the Chicago River and the North Branch Pumping Station for C2.2 and from the Racine Avenue Pumping Station (through the South Branch of the Chicago River) and the Stickney WRP for C7. These large lateral inflows greatly increase the turbulence and, thus, the dispersion in these reaches. The increased dispersion in reach C7 carries over to reach C8. Thus, higher values of  $D$  were

used in these reaches during storms (April 9-13 for Reach C2.2, April 9-23 and April 26-27 for Reach C7, and April 9-14 and April 26-May 2 for Reach C8) as indicated in Table 3.18. Because only two periods required the use of a higher dispersion coefficient it was not possible to determine a cutoff value that separates high flow from low flow periods. As more periods are studied in the final calibration and verification of the model, rules for applying higher dispersion values will be developed.

#### Algal Simulation Parameters

Algal maximum growth rate, die-off rate, settling rate, and respiration rate are the algal rate parameters used in EUTROF2 model. Algal growth is limited by the availability of nutrients and light, and also is affected by temperature. 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.

#### Calibrated Model Parameters

The values of the diffuse exchange rate coefficient,  $E_{dif}$ , BOD water column oxidation rate ( $k_{bod}$ ), nitrification rate constant ( $k_{nit}$ ), and high flow and low flow dispersion coefficients,  $D$ , determined by calibration are listed in Table 3.18 for each reach. The calibrated values of  $2.0 \text{ day}^{-1}$ ,  $0.4 \text{ day}^{-1}$ ,  $0.001 \text{ m/day}$ ,  $0.2 \text{ day}^{-1}$  were used for algal maximum growth rate, die-off rate, settling rate, and respiration rate, respectively at all locations. For all other model coefficients and parameters, default values given in EUTROF2 were used (Appendix A). The calibrated BOD decay rate, rate coefficient for

NH4-N to NO2-N, and rate coefficient for NO2-N to NO3-N used by CDM (1992) in the QUAL2EU water-quality model for the October 1990 event are given Table 3.19 for comparison purposes. These values were the starting point for this study. Since calibration periods (April-May 2002 in this study and October 1990 in CDM (1992)) and water-quality models (DUFLOW and QUAL2EU) are not same, the calibration process ended up with different parameter values.

**Table 3.18** Reach calibration parameters used in the DUFLOW water-quality model for April 1 to May 4, 2002

| Reach Name | Waterway            | River Mile from Lockport | Kbod (day <sup>-1</sup> ) | Knit (day <sup>-1</sup> ) | Edif (m <sup>2</sup> /day) | D (m <sup>2</sup> /s) |
|------------|---------------------|--------------------------|---------------------------|---------------------------|----------------------------|-----------------------|
| C1         | North Shore Channel | 50-46                    | 0.2                       | (0.4 ; 1.3)*              | 0.0200                     | 15                    |
| C2.1       | North Shore Channel | 46-42.6                  | 0.2                       | (0.4 ; 1.3)               | 0.0000                     | 15                    |
| C2.2       | North Branch        | 42.6-37                  | 0.2                       | (0.4 ; 1.3)               | 0.0020                     | (15 ; 1000)**         |
| C3         | North Branch        | 37-35.5                  | 0.2                       | (0.4 ; 1.3)               | 0.0020                     | 15                    |
| C4         | North Branch        | 35.5-34.5                | 0.20                      | 0.15                      | 0.0020                     | 15                    |
| C5         | Main Stem           | 34.5-36                  | 0.1                       | 0.05                      | 0.0200                     | 1                     |
| C6         | South Branch        | 34.5-31                  | 0.0001                    | 0.0001                    | 0.0000                     | 15                    |
| C7         | CSSC                | 31-25                    | 0.1                       | 0.09                      | 0.0020                     | (15 ; 1000)           |
| C8         | CSSC                | 25-17                    | 0.1                       | 0.09                      | 0.0000                     | (60 ; 1000)           |
| C9         | CSSC                | 17-12.5                  | 0.01                      | 0.1                       | 0.0000                     | 60                    |
| C15        | CSSC                | 12.5-8                   | 0.01                      | 0.1                       | 0.0000                     | 50                    |
| C16        | CSSC                | 8-5.1                    | 0.01                      | 0.1                       | 0.0000                     | 50                    |
| C11        | Little Calumet (N)  | 35.5-30.5                | 0.05                      | 0.1                       | 0.0002                     | 15                    |
| C12        | Little Calumet (N)  | 30.5-28.5                | 0.05                      | 0.1                       | 0.0200                     | 15                    |
| C12.1      | Little Calumet (S)  |                          | 0.035                     | 0.30                      | 0.0020                     | 15                    |
| C13        | Calumet-Sag         | 28.5-19                  | 0.005                     | 0.005                     | 0.0000                     | 15                    |
| C14        | Calumet-Sag         | 19-12.5                  | 0.005                     | 0.005                     | 0.0000                     | 10                    |

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

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

**Table 3.19** Reach calibration parameters used in the QUAL2EU water-quality model developed by Camp, Dresser & McKee (CDM, 1992) for October 1990

| Reach Name | Waterway            | River Mile from Lockport | kbod (day <sup>-1</sup> ) | k(NH <sub>4</sub> -N to NO <sub>2</sub> -N)* (day <sup>-1</sup> ) | k(NO <sub>2</sub> -N to NO <sub>3</sub> -N)** (day <sup>-1</sup> ) |
|------------|---------------------|--------------------------|---------------------------|---|--|
| C1         | North Shore Channel | 50-46                    | 0.01                      | 0.1   | 0.2  |
| C2.1       | North Shore Channel | 46-42.6                  | 0.01                      | 0.2   | 0.2  |
| C2.2       | North Branch        | 42.6-37                  | 0.01                      | 0.3   | 1.0  |
| C3         | North Branch        | 37-35.5                  | 0.01                      | 0.3   | 0.8  |
| C4         | North Branch        | 35.5-34.5                | 0.01                      | 0.3   | 0.6  |
| C5         | Main Stem           | 34.5-36                  | 0.01                      | 0.1   | 0.2  |
| C6         | South Branch        | 34.5-31                  | 0.01                      | 0.1   | 0.3  |
| C7         | CSSC                | 31-25                    | 0.01                      | 0.1   | 0.3  |
| C8         | CSSC                | 25-17                    | 0.06                      | 0.2   | 0.3  |
| C9         | CSSC                | 17-12.5                  | 0.06                      | 0.2   | 0.3  |
| C15        | CSSC                | 12.5-8                   | 0.04                      | 0.2   | 0.8  |
| C16        | CSSC                | 8-5.1                    | 0.06                      | 0.2   | 1.0  |
| C11        | Little Calumet (N)  | 35.5-30.5                | 0.01                      | 0.1   | 0.3  |
| C12        | Little Calumet (N)  | 30.5-28.5                | 0.09                      | 0.3   | 1.5  |
| C13        | Calumet-Sag         | 28.5-19                  | 0.09                      | 0.3   | 0.8  |
| C14        | Calumet-Sag         | 19-12.5                  | 0.09                      | 0.1   | 0.4  |

\*k(NH<sub>4</sub>-N to NO<sub>2</sub>-N): Rate coefficient for NH<sub>4</sub>-N to NO<sub>2</sub>-N;

\*\* k(NO<sub>2</sub>-N to NO<sub>3</sub>-N): Rate coefficient for NO<sub>2</sub>-N to NO<sub>3</sub>-N

### **3.5 Calibration Results**

In the following subsections calibration results are presented. First, the simulated BOD, ammonia, nitrate, and chlorophyll-a concentrations are compared with historic measurements. Then, simulated and measured hourly DO concentrations are compared at the 26 DO measurement locations.

#### **3.5.1 Biochemical Oxygen Demand, Ammonia, Nitrate and Chlorophyll-a**

When calculating the processes that affect DO in a stream system, DUFLOW also computes the concentration changes in space and time of BOD, organic nitrogen, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, total inorganic phosphorus, total organic phosphorus, suspended solids, and algal biomass species. The MWRDGC collects monthly samples of BOD (at the request of this project), total Kjeldahl nitrogen, organic nitrogen, ammonia nitrogen, nitrite plus nitrate nitrogen, chlorophyll-a, total phosphorus, soluble phosphorus, and total suspended solids among many other constituents (see for example, Abedin et al., 1999) at 18 locations in the simulated portion of the CWS (Table 3.17). This means that only one measured value of the other constituents simulated with DUFLOW was available for the study period, which is insufficient to evaluate the simulation accuracy of the model. Thus, historical data were evaluated at each of the 18 locations to try to identify periods for which water-quality loading conditions at each location were similar to that of the study period. For most constituents at most locations the monthly sample data from 1990 through 2002 indicated no trends (substantial changes in the mean concentration) over time although seasonal

variations were observed at the lake boundaries because of changes in discretionary diversion throughout the year. However, ammonia nitrogen concentrations downstream from the Calumet and Stickney WRPs showed a marked decrease beginning in 1996 and corresponding nitrite plus nitrate nitrogen concentrations increased at this time. These changes in water quality resulted from a change in blower operations at these WRPs. This effect also extended upstream of the Calumet WRP to Indiana Avenue and upstream of the Stickney WRP to Cicero Avenue indicating the presence of bi-directional flows in the Little Calumet River (North) and the CSSC. The MWRDGC has been collecting monthly samples of chlorophyll-a since September 2001 and time series plots of chlorophyll-a (2001-2004) indicated monthly variations over time throughout the CWS.

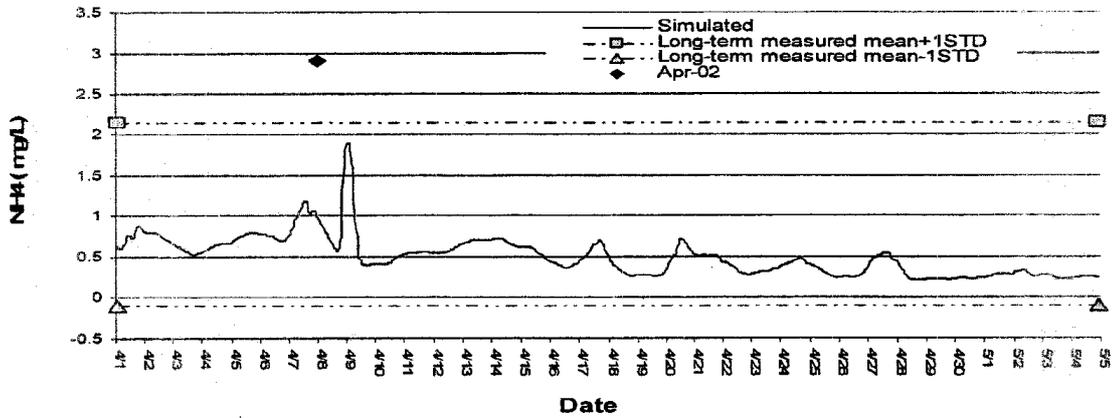
Once the periods of consistent data were determined, the mean, median, standard deviation, maximum, and minimum were determined for each constituent at each location. Calibration of the simulation for BOD, ammonia nitrogen, and nitrate nitrogen concentrations proceeded by examining the agreement between the mean of simulated concentrations with mean of long-term in-stream measurements of BOD, ammonia nitrogen, and nitrate nitrogen. Because of limited data, simulated chlorophyll-a concentrations were compared only with April 2002 concentrations.

Adjustments were made to the BOD decay rate ( $k_{\text{bod}}$ ), and nitrification rate ( $k_{\text{nit}}$ ), such that the simulated BOD, ammonia nitrogen, and nitrate nitrogen concentrations had similar spatial distributions throughout the CWS as for the long-term historic data. In this process, the simulated values of each constituent at each location were compared to the

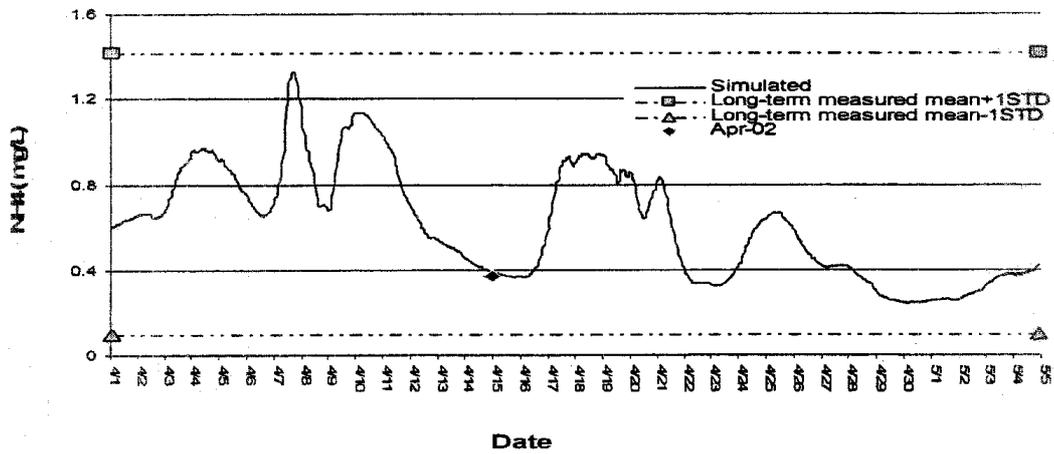
mean and one standard deviation confidence bounds determined from the measured values. The comparison was done graphically as shown, for example, in Figure 3.14 and 3.15 for ammonia nitrogen and BOD, respectively, to try to determine if the model was yielding unusually high or low concentrations, and if so, to determine a cause for these concentrations. April 2002 measurements also are presented in these figures. It should be noted that for ammonia at some locations shown in Figure 3.14 the mean minus one standard deviation confidence bound results in a negative concentration. Figure 3.14 and 3.15 show that simulated hourly BOD and ammonia nitrogen concentrations are inside the one standard deviation confidence bounds for most of the simulation period except for storm periods. During storm periods BOD and ammonia nitrogen concentrations increase and can reach values higher than the upper confidence bound. The monthly samples are predominantly composed of samples taken during low flow, and, thus, concentrations above the upper confidence bound were expected because of high pollution loads coming from CSOs during storms. Thus, the calibrated simulation results do not yield any unusually high or low constituent concentrations. The values of  $k_{\text{bod}}$  and  $k_{\text{nit}}$  then were slightly modified in the calibration for the hourly DO concentrations.

Figure 3.16-3.18 compare the mean of the simulated concentrations with the mean and one standard deviation confidence bounds of the measured historic data and with the concentrations measured in April 2002 for BOD, ammonia nitrogen, and nitrate nitrogen, respectively. The comparison is done as trajectories along the (a) North Shore Channel, North Branch Chicago River, South Branch Chicago River, and CSSC, and (b) the Calumet River, Little Calumet River (North), and Calumet-Sag Channel.

North Branch Chicago River at Diversey Street - April 1- May 4, 2002



CSSC at Route 83 - April 1- May 4, 2002



Calumet-Sag Channel at Cicero Avenue - April 1- May 4, 2002

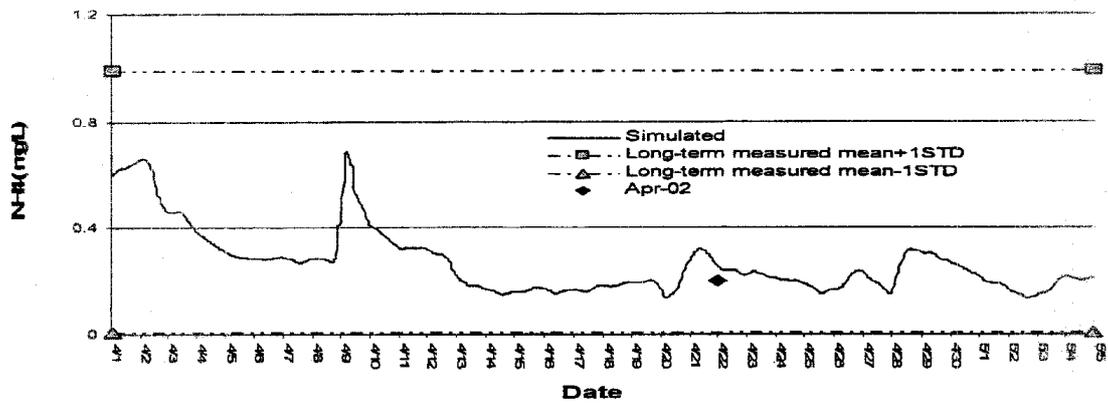
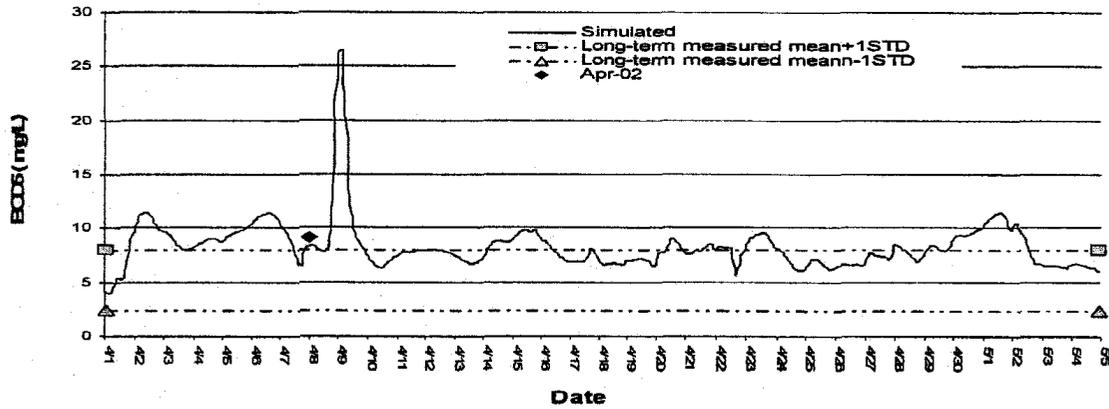
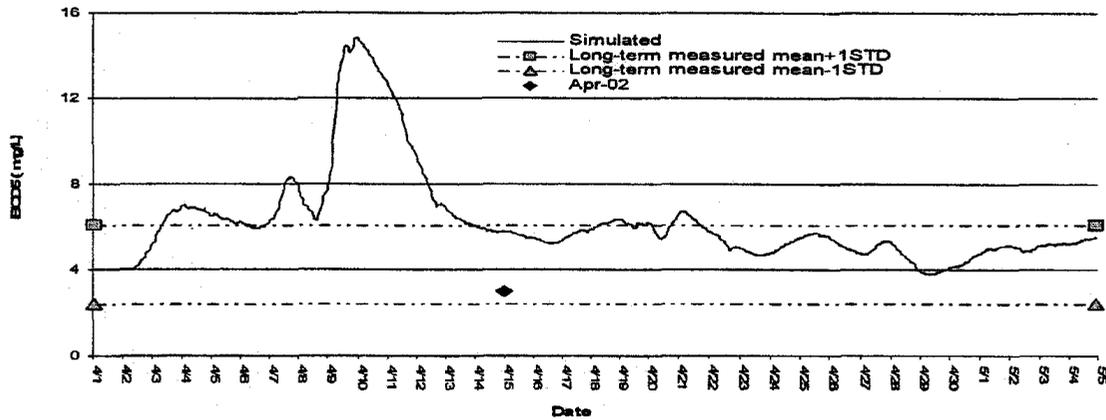


Figure 3.14. Comparison of long term measured mean plus or minus one standard deviation, and simulated hourly ammonia nitrogen (NH<sub>4</sub>-N) concentrations at different locations in the Chicago Waterway System

North Branch Chicago River at Diversey Street - April 1- May 4, 2002



CSSC at Route 83 - April 1- May 4, 2002



Calumet-Sag Channel at Cicero Avenue - April 1- May 4, 2002

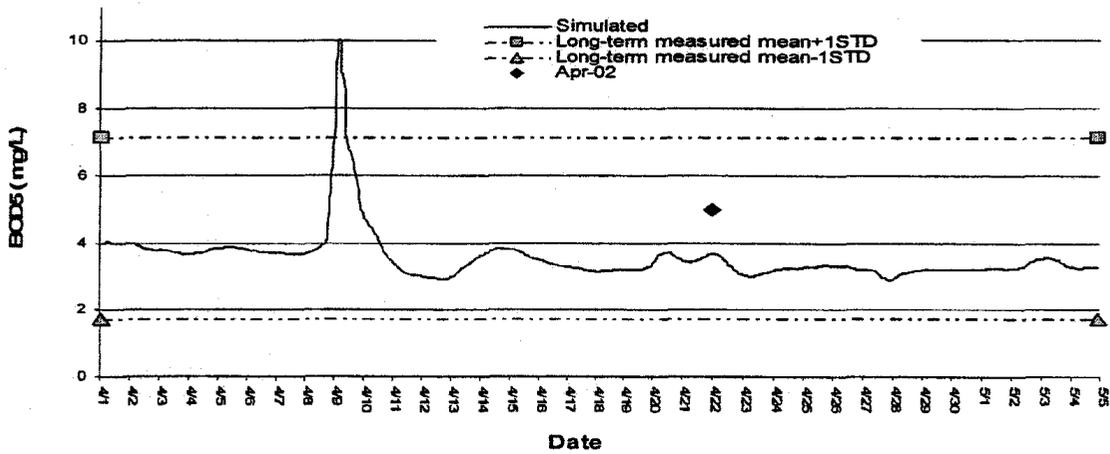
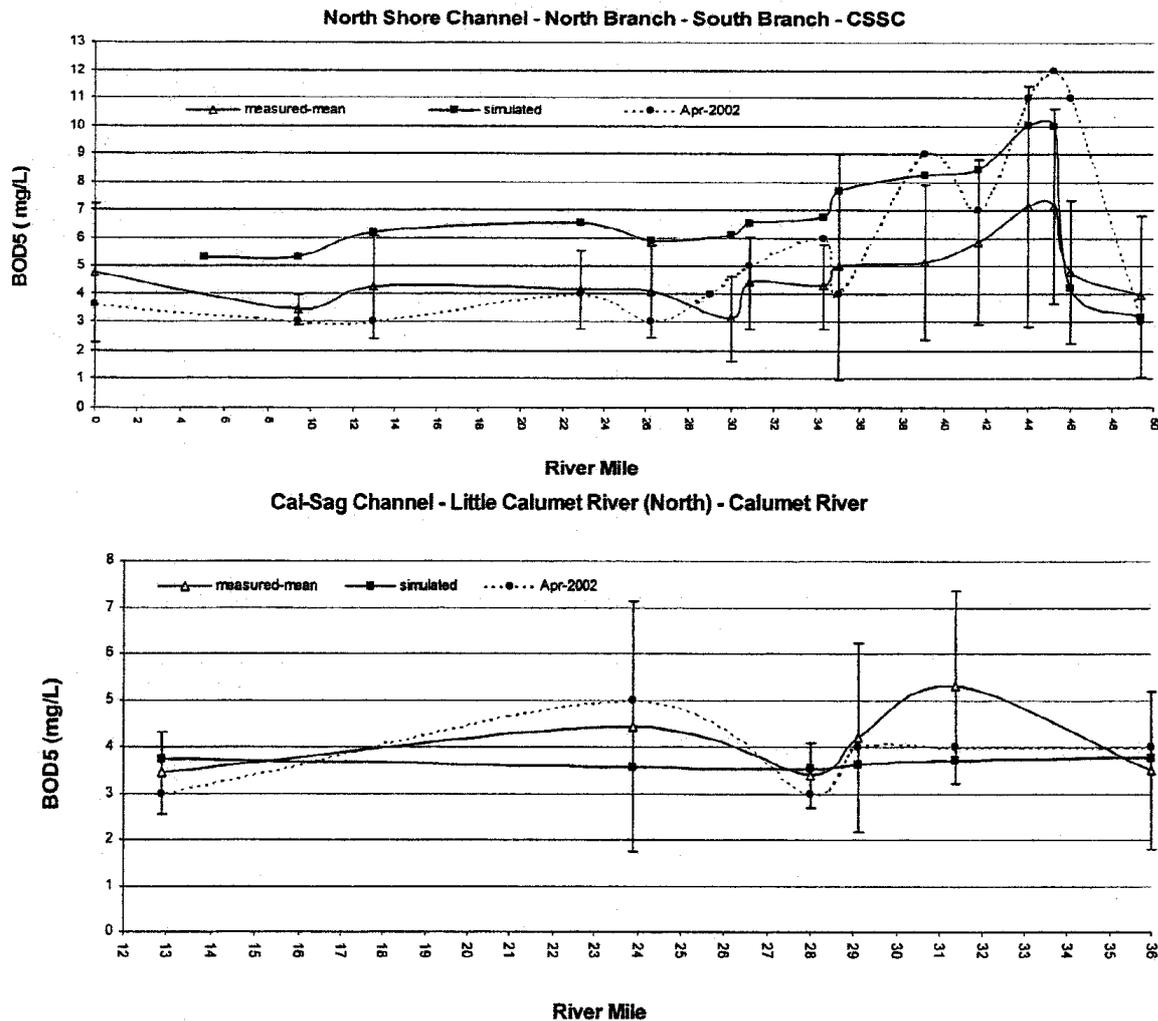


Figure 3.15. Comparison of long term measured mean plus or minus one standard deviation, and simulated hourly biochemical oxygen demand (BOD5) concentrations at different locations in the Chicago Waterway System

At 7 locations the mean of the simulated BOD concentration is outside the one standard deviation confidence bounds (Figure 3.16). Three measured values (April 2002) were outside the one standard deviation bounds (Figure 3.16). This may have resulted because the number of measured BOD concentrations is relatively small because the MWRDGC only recently (2001-2002) started collecting in-stream BOD data. BOD concentrations measured in April 2002 are greater than both simulated and long-term average concentrations in the upper portion of the North Branch Chicago River and the North Shore Channel. All simulated mean BOD concentrations (Figure 3.16) are within  $\pm 1$  standard deviation of the measured concentrations in the Calumet-Sag Waterway System. Carbonaceous BOD decay occurs very slowly in most of the CWS. BOD decay rate tends to increase downstream from the WRPs.



**Figure 3.16.** Comparison of long-term measured mean (plus or minus one standard deviation), simulated mean, and measured biochemical oxygen demand (BOD) concentrations in the Chicago Waterway System for April 1-May 4, 2002

Three forms of nitrogen: organic, ammonia, and nitrate all as nitrogen were calibrated using DUFLOW. Calibrated ammonia nitrogen and nitrate nitrogen results are shown in Figure 3.17 and 3.18, respectively. Although the mean of the simulated ammonia nitrogen concentrations are lower than the mean of the measured ammonia nitrogen concentrations, they are still within the 1 standard deviation confidence bounds at all locations. Nitrate nitrogen concentrations increase just after the WRPs. The simulated and measured nitrate nitrogen concentrations have very good agreement in the Calumet-

Sag Waterway System. Although the simulated nitrate nitrogen concentrations are higher than long-term measured mean concentrations along the North Shore Channel, North Branch, South Branch, and CSSC, the rest of the simulated mean concentrations are very close to the measured mean concentrations.

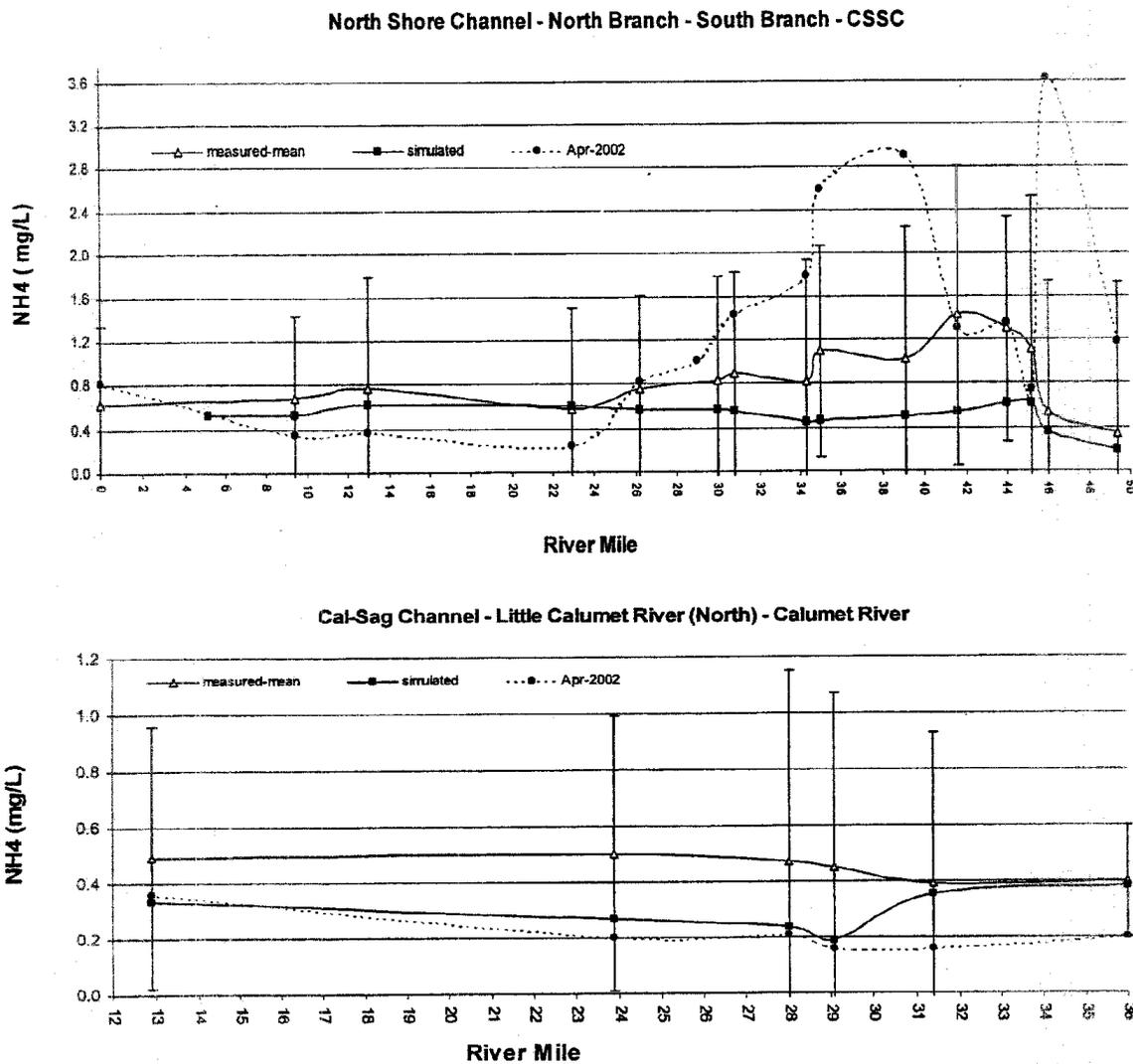
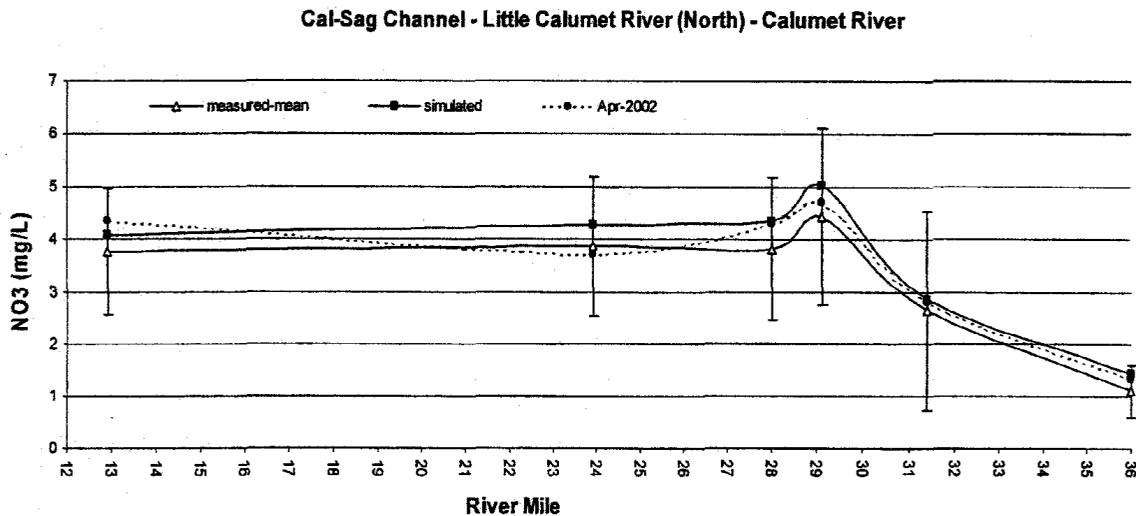
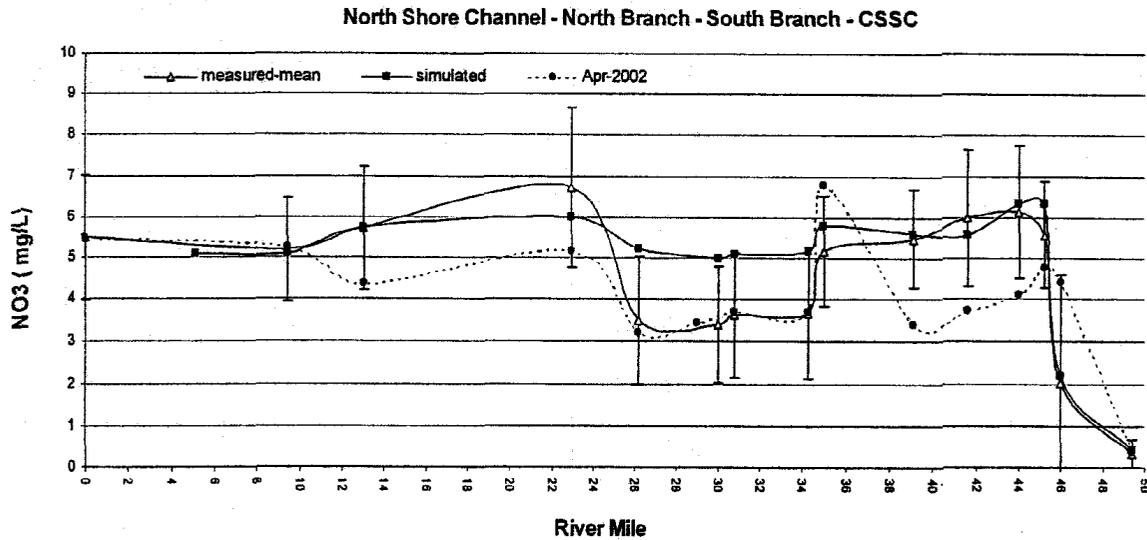


Figure 3.17 Comparison of long-term measured mean (plus or minus one standard deviation), simulated mean, and measured ammonia nitrogen (NH<sub>4</sub>-N) concentrations in the Chicago Waterway System for April 1-May 4, 2002

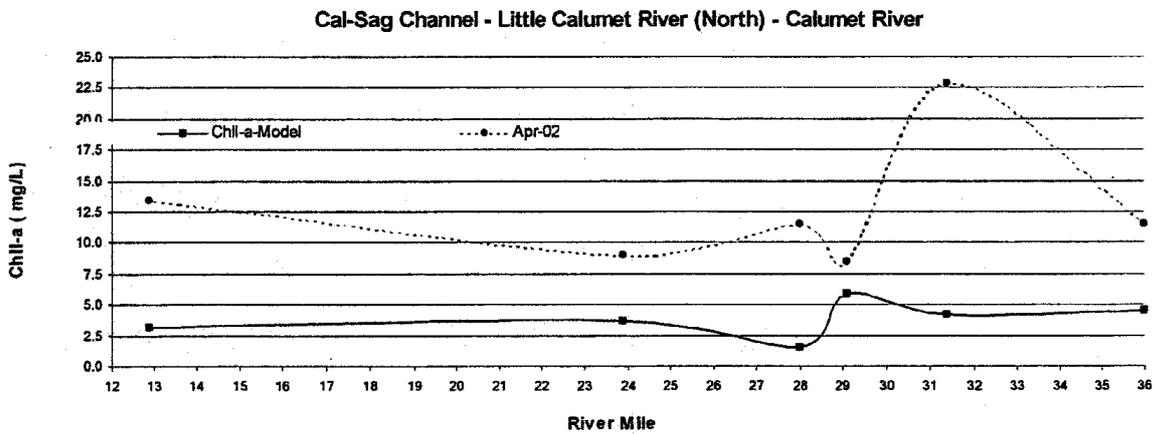
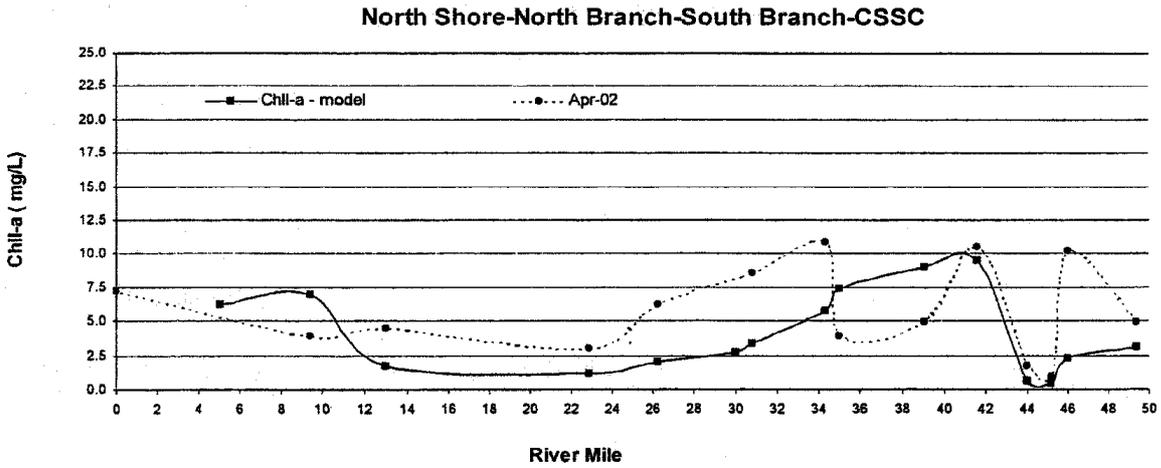


**Figure 3.18.** Comparison of long-term measured mean (plus or minus one standard deviation), simulated mean, and measured nitrate nitrogen (NO<sub>3</sub>-N) concentrations in the Chicago Waterway System for April 1-May 4, 2002

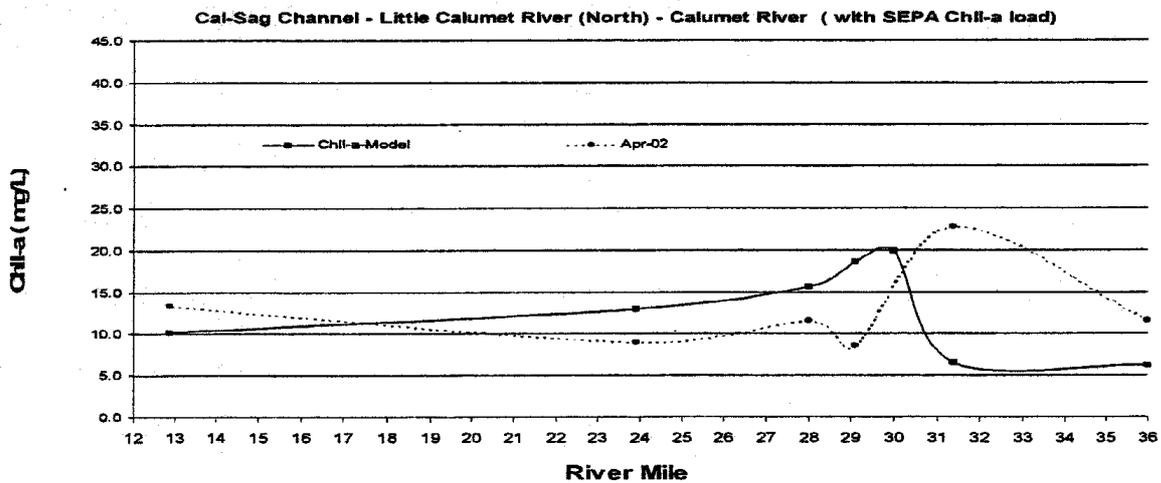
Calibrated chlorophyll-a results are shown in Figure 3.19. Simulated values were compared with a single measurement (made on April 8 for the North Shore Channel and North Branch Chicago River, April 15 for the South Branch Chicago River and CSSC, and April 22 for the Calumet River System) at each location. The limited number of data makes it difficult to calibrate and test the power of model for this constituent. But it is

still possible to make some comments based on Figure 3.19. The simulated and measured chlorophyll-a concentrations have good agreement in the Chicago River System except for the North Shore Channel. The model gives lower concentrations along the North Shore Channel until North Shore Water Reclamation Plant. Similar trends were observed in NH<sub>4</sub>-N and BOD<sub>5</sub> simulations (Figures 3.16-3.17). As can be seen from Figure 3.19, the simulated chlorophyll-a concentration along Calumet River System is always lower than measured concentrations. Many variations of the previously discussed algal rate parameters were tried in order to match the observed data but these trials did not give successful results. The temperature and incoming radiation during the study period were insufficient to cause an algal community to grow in the main waterways. Thus, it was speculated that the algae was growing in the SEPA pools and then entering the waterways. Large growth of aquatic vegetation has been observed in the SEPA pools, thus, the conditions for algal growth appear good in the SEPA pools. The SEPA stations were made a source of chlorophyll and reasonable agreement was obtained in the simulation of measured chlorophyll-a concentrations (Figure 3.20). Future studies on SEPA stations and simulations of different periods will help to better understand the effect of SEPA stations on chlorophyll-a concentration in the Calumet River System.

In summary, the comparisons of the simulated constituent concentrations with long-term mean measured concentrations, one standard deviation confidence bounds, and concentrations measured in April 2002 did not indicate anything unusual. Thus, the DUFLOW simulation of these constituents was considered acceptable.



**Figure 3.19** Comparison of simulated mean and measured chlorophyll-a concentrations in the Chicago Waterway System for April 1-May 4, 2002



**Figure 3.20** Comparison of simulated mean and measured chlorophyll-a concentrations in the Calumet River System with the SEPA stations providing chlorophyll-a loads for April 1-May 4, 2002

### **3.5.2 Dissolved Oxygen Concentration**

Simulated DO concentrations were compared with hourly measured DO concentrations at 26 locations for the period of April 1 to May 4, 2002 (the 24 locations listed in Table 3.17 plus the North Shore Channel at Linden Street and the Calumet River at 130<sup>th</sup> Street. Results are presented in 4 categories: North Branch Chicago River, South Branch Chicago River and Chicago Sanitary and Ship Canal, Calumet-Sag Channel, and boundary conditions (this includes DO monitoring sites on the North Shore Channel, Chicago River main stem, Little Calumet (South) and Little Calumet River (North) upstream of the Calumet WRP).

#### **3.5.2.1 North Branch Chicago River**

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

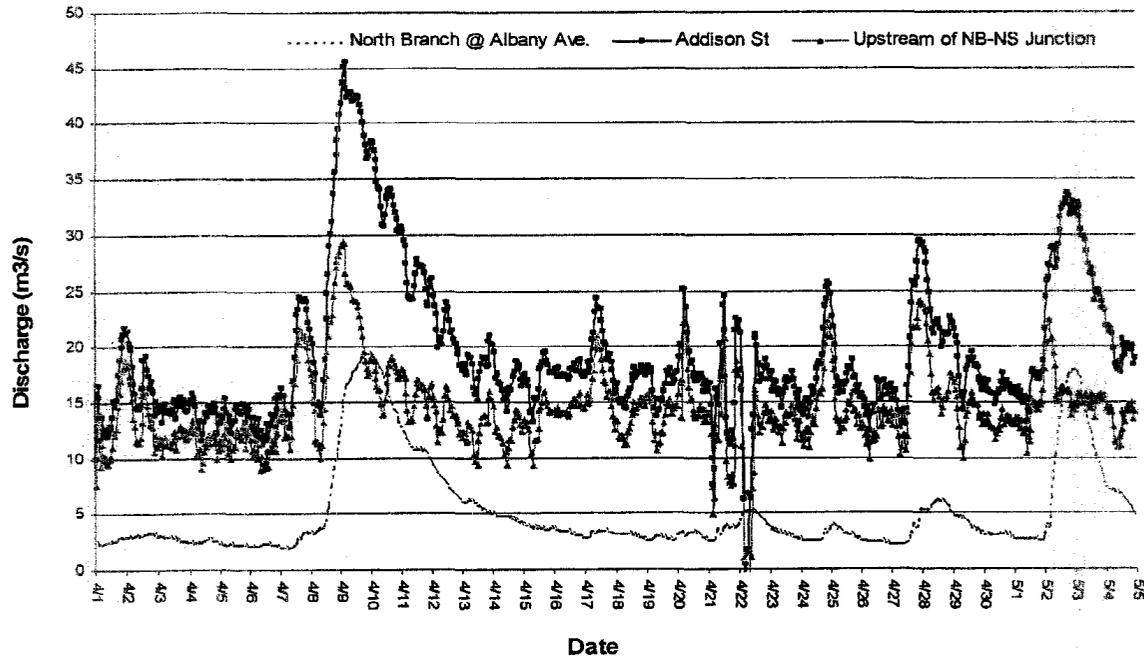
Statistical comparison between daily average simulated and measured dissolved oxygen concentrations are listed in Table 3.20.

**Table 3.20** Comparison of daily average simulated and measured dissolved oxygen concentrations on North Branch Chicago River, April 1-May 4, 2002 [note: Error = average of simulated-measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100, Abs. Error = Average absolute value of simulated-measured; Abs. % Error = Average absolute value of (simulated-measured)/average measured x 100]

| Location         | Average Measured in mg/L | Average Simulated in mg/L | Error | % Error | Abs. Error | Abs. % Error |
|------------------|--------------------------|---------------------------|-------|---------|------------|--------------|
| Addison Street   | 7.08                     | 7.33                      | 0.25  | 3.53    | 0.44       | 6.41         |
| Fullerton Avenue | 5.78                     | 6.85                      | 1.08  | 18.69   | 1.10       | 20.50        |
| Division Street  | 6.11                     | 6.74                      | 0.63  | 10.31   | 0.70       | 11.89        |
| Kinzie Street    | 6.13                     | 6.12                      | -0.02 | -0.33   | 0.61       | 9.93         |

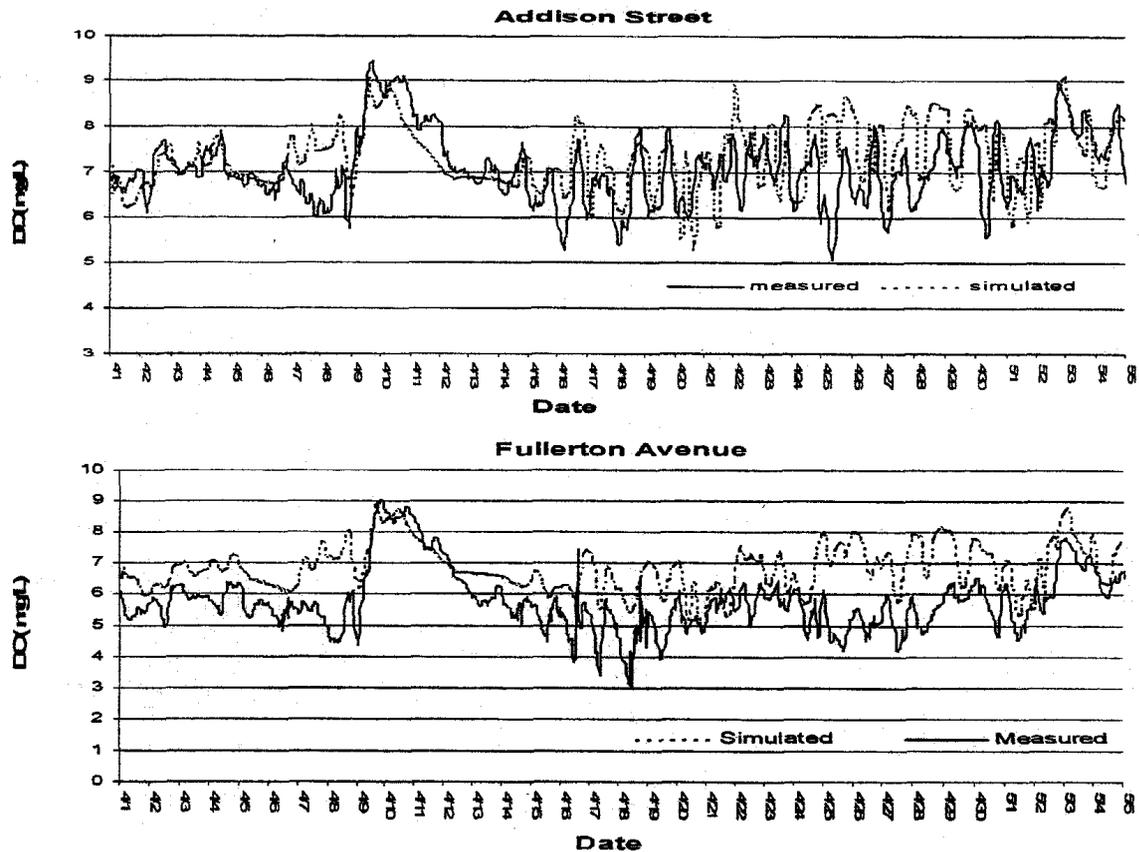
The Addison Street DO monitoring site is the first station at which the combined effects of the North Branch Chicago River flow, North Side WRP flow, and Devon Avenue aeration station are observed. Significant DO fluctuations within very short time intervals are the main characteristics of this location (Figure 3.22). After introducing the Devon Avenue aeration station to the water-quality model, it was clearly observed that almost all fluctuations were as a result of operation of the Devon Avenue aeration station. Average DO concentrations at Addison Street, North Branch Chicago River at Albany Avenue, and the North Shore WRP are around 7, 7.5, and 7.4 mg/L, respectively. As can be seen from Figure 3.21, flow at Addison Street is dominated by North Shore Channel flow (i.e. North Side WRP flow) during dry weather periods. Whereas, during storm periods (April 8-13 and May 2-4), flow on the North Branch Chicago River at Albany Avenue has a significant effect on Addison Street flow. For this reason, instead of using long-term average DO concentrations, wet weather DO concentrations were calculated using a mass balance for the North Branch Chicago River at Albany Avenue just for April 10-11 and May 3, 2002. Since the Devon Avenue aeration station was in operation less than 2 hrs on April 10-11 and on May 3, the effect of the aeration station on DO concentrations is

insignificant and mass balance results are reliable enough to use as input to the water-quality model. For the other days (dry weather period), long-term average DO values were used for the North Branch at Albany Avenue.



**Figure 3.21.** Flow comparison: North Branch Chicago River at Albany Avenue and at Addison Street and Upstream of the North Branch-North Shore Channel Junction for the period of April 1- May 4, 2002

The comparison of simulated and measured DO concentrations at Addison Street and Fullerton Avenue is shown in Figure 3.22

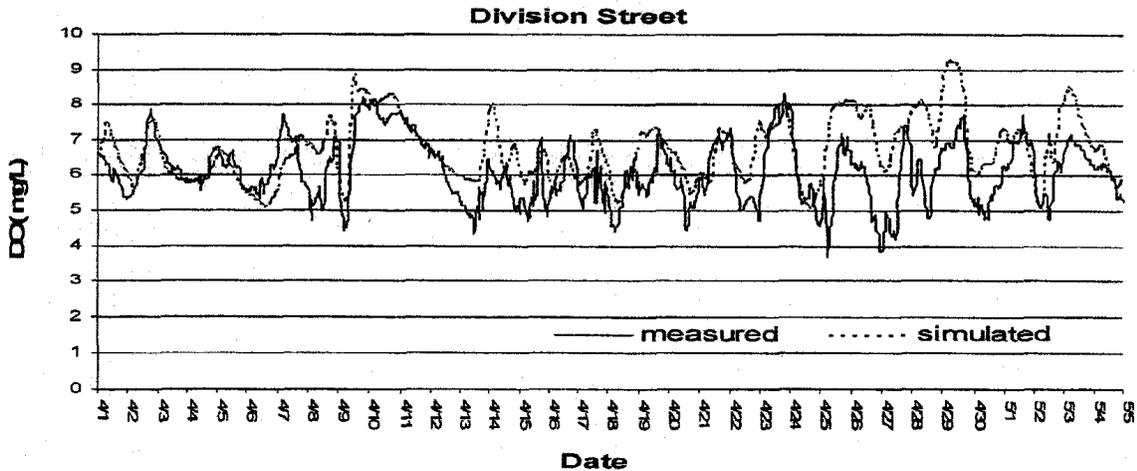


**Figure 3.22.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Addison Street and Fullerton Avenue on the North Branch Chicago River

Figure 3.22 shows good agreement between the simulated and measured DO concentrations especially at Addison Street. The average absolute percent error in the simulated daily average DO concentrations is just 6.41% at Addison Street. Although average absolute percent error in the simulated daily average DO concentrations is 20.5% at Fullerton Avenue, general trend of dissolved oxygen fluctuations throughout the simulations period (especially for April 8-14 storm period) is well captured. Further as indicated in Table 3.20 the overestimation in DO concentrations at Fullerton Avenue and

Division Street is completely eliminated by the time flow reaches Division Street, indicating reasonable system wide model performance. Since no point source or tributary enters the CWS between these two locations, a similar DO trend is observed at both stations. The successfully simulated storm period (April 8-14) DO concentrations show that accurate wet weather DO concentrations were used. A dispersion coefficient of 15 m<sup>2</sup>/s was used for most of the calibration period and just for April 9-13 storm event a higher dispersion coefficient (1,000 m<sup>2</sup>/s) was used to improve the storm period simulation results. Adjustments were made to the carbonaceous BOD decay rate ( $k_{\text{bod}}$ ) and the nitrification rate ( $k_{\text{nit}}$ ) to calibrate the model. A constant  $k_{\text{bod}}$  value of 0.2 day<sup>-1</sup> was used throughout the simulation period. After several trial runs it was observed that the nitrification rate ( $k_{\text{nit}}$ ) tended to be higher after April 15 for the related reaches. So two different reaction rate constants were used for the periods of April 1-15 ( $k_{\text{nit}} = 0.40$  day<sup>-1</sup>) and April 16 - May 4, 2002: ( $k_{\text{nit}} = 1.3$  day<sup>-1</sup>) as discussed in Section 3.4.

Division Street is the first DO monitoring station downstream from the Webster Street aeration station. The Webster Street aeration facility causes significant DO fluctuations within the day depending on the operation schedule. The Division Street DO concentration pattern was carefully examined to determine blower operation hours and the number of blowers in operation and then the Devon Avenue aeration station DO efficiency regression results were used to calculate the DO load from the Webster Street aeration station. Comparison of simulated and measured DO values at Division Street are given in Figure 3.23.

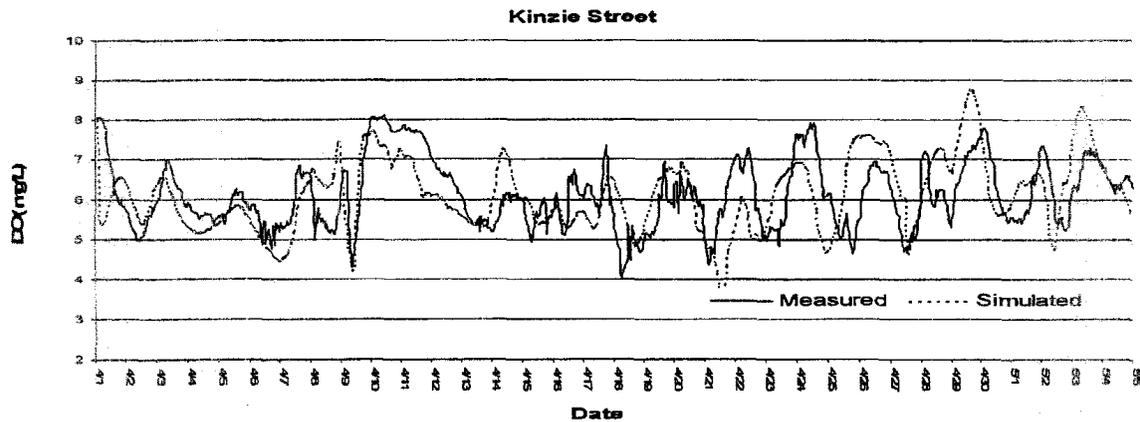


**Figure 3.23.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Division Street on the North Branch Chicago River

Measured and simulated DO concentrations at Division Street (Figure 3.23) are in very close agreement for most of the simulation period. The average simulated and measured dissolved oxygen concentrations are 6.11 mg/L and 6.74 mg/L, respectively, an overall error less than 10 %. The average absolute error in the average daily DO concentrations is 11.9 %. Storm period DO concentrations were successfully simulated. A constant dispersion coefficient ( $15 \text{ m}^2/\text{s}$ ) was used for the entire simulation period. Like the previous case, two different values were used for  $k_{\text{nit}}$  for the periods April 1-15 and April 16 - May 4: 0.4 and  $1.3 \text{ day}^{-1}$ . A constant  $k_{\text{bod}}$  value of  $0.2 \text{ day}^{-1}$  was used throughout the simulation period.

Kinzie Street is the last DO station on the North Branch Chicago River. It is located 0.2 mi upstream from North Branch Chicago River junction with the Chicago River main stem and South Branch. Like the other North Branch DO stations, significant DO fluctuations are observed at this station (Figure 3.24). The DO concentration never goes

under 4 mg/L and the average DO concentration is around 6 mg/L for the simulation period. The measured and simulated DO concentrations have good agreement (Figure 3.24). Although there are some differences, since the average absolute percent error is less than 10%, it can be said that the general trends of measured DO concentrations were successfully simulated. Dispersion,  $k_{nit}$ , and  $k_{bod}$  constants are 15 m<sup>2</sup>/s, 0.15 day<sup>-1</sup>, and 0.20 day<sup>-1</sup> respectively, for this reach.



**Figure 3.24.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Kinzie Street on the North Branch Chicago River

### 3.5.2.2 South Branch Chicago River and Chicago Sanitary and Ship Channel (CSSC)

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

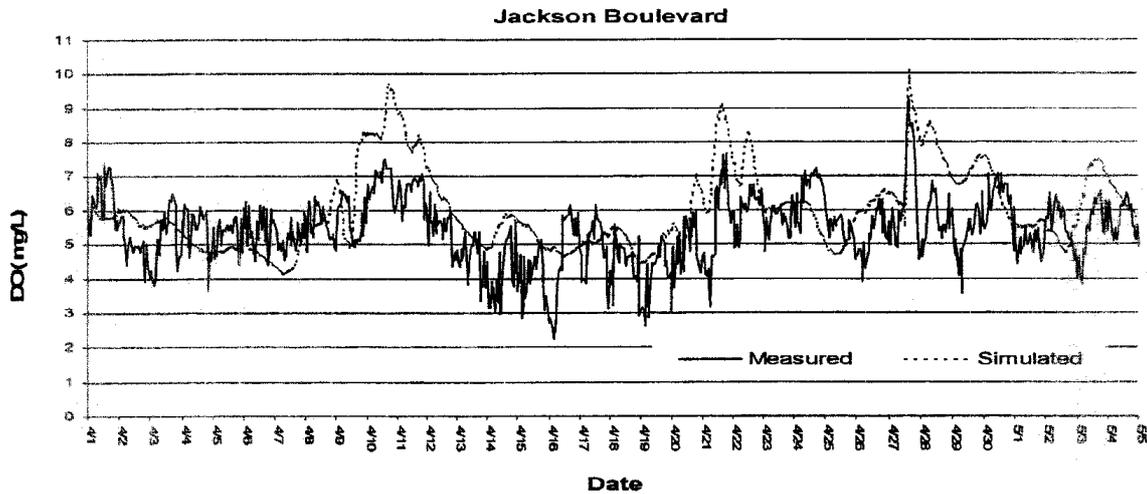
Statistical comparison between daily average simulated and measured dissolved oxygen concentrations are listed in Table 3.21

**Table 3.21** Comparison of daily average simulated and measured dissolved oxygen concentrations on South Branch Chicago River and Chicago Sanitary and Ship Channel, April 1-May 4, 2002 [note: Error = average of simulated-measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100, Abs. Error = Average absolute value of simulated-measured; Abs. % Error = Average absolute value of (simulated-measured)/average measured x 100]

| Location                    | Waterway     | Average Measured in mg/L | Average Simulated in mg/L | Error | % Error | Abs. Error | Abs. % Error |
|-----------------------------|--------------|--------------------------|---------------------------|-------|---------|------------|--------------|
| Jackson Boulevard           | South Branch | 5.42                     | 6.02                      | 0.59  | 10.89   | 0.86       | 15.98        |
| Cicero Avenue               | CSSC         | 5.23                     | 5.46                      | 0.24  | 4.59    | 0.79       | 15.76        |
| Baltimore and Ohio Railroad | CSSC         | 6.04                     | 6.40                      | 0.36  | 5.96    | 0.79       | 14.06        |
| Route 83                    | CSSC         | 5.41                     | 5.89                      | 0.58  | 10.72   | 0.67       | 12.86        |
| River Mile 11.6             | CSSC         | 6.24                     | 6.46                      | 0.22  | 3.53    | 0.58       | 9.42         |
| Romeoville                  | CSSC         | 5.90                     | 6.17                      | 0.28  | 4.75    | 0.50       | 8.77         |

Jackson Boulevard is located just downstream of the junction of the Chicago River North Branch, South Branch, and main stem. Although DO concentrations of the North Branch Chicago River at Kinzie Street and the Chicago River at Clark Street are always higher than 4 mg/L, low DO concentrations (<4 mg/L) are observed for some periods at Jackson Boulevard (Figure 3.25). This finding suggests that DO concentrations at Jackson Boulevard are affected by both upstream and downstream locations. Simulated and measured DO concentrations are shown in Figure 3.25. The simulated DO concentrations follow the general trend of the measured DO concentrations very well, but the measured concentrations include many short term fluctuations that could not be reproduced with the model. The water-quality model is primarily driven by daily mean concentrations at the WRPs, and, thus, cannot match short-term fluctuations. Simulated DO concentrations are 2 mg/L higher than measured values between April 10 and 12. Monthly average values of measured and simulated dissolved oxygen concentrations are 5.42 mg/L and 6.02 mg/L,

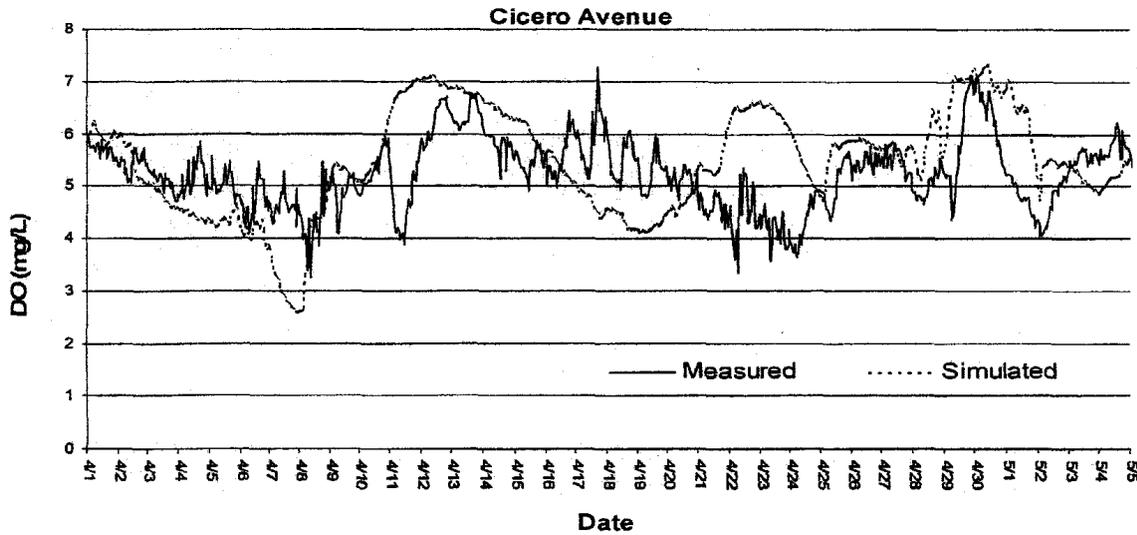
respectively, a little more than 10 % overall error, and the average absolute error in daily average DO concentrations is 16.0 %. Very small  $k_{\text{bod}}$  and  $k_{\text{nit}}$  values ( $0.0001 \text{ day}^{-1}$ ) were used for this reach.



**Figure 3.25.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Jackson Boulevard on the South Branch Chicago River

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. 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 CWS, the flow leaving the Stickney WRP often flows both ways (upstream and downstream) when leaving the plant. Until the first storm, simulated DO concentrations are very close to the measured concentrations (Figure 3.26). The complexity of the hydraulic behavior of the CWS makes this station one of the most difficult locations to calibrate. The average absolute error in daily average DO concentrations is 15.8 %. Although the difference between simulated and measured values goes up to 2.5 mg/L on April 17, the overall trend of the measured DO concentrations at this station was well simulated by the model. Two

different dispersion coefficient values were used in this reach for high and low flow periods: 1,000 m<sup>2</sup>/s and 15 m<sup>2</sup>/s (for the majority of days in the calibration period), respectively. Values of 0.1 day<sup>-1</sup> and 0.09 day<sup>-1</sup> were used for both  $k_{\text{bod}}$  and  $k_{\text{nit}}$ , respectively.

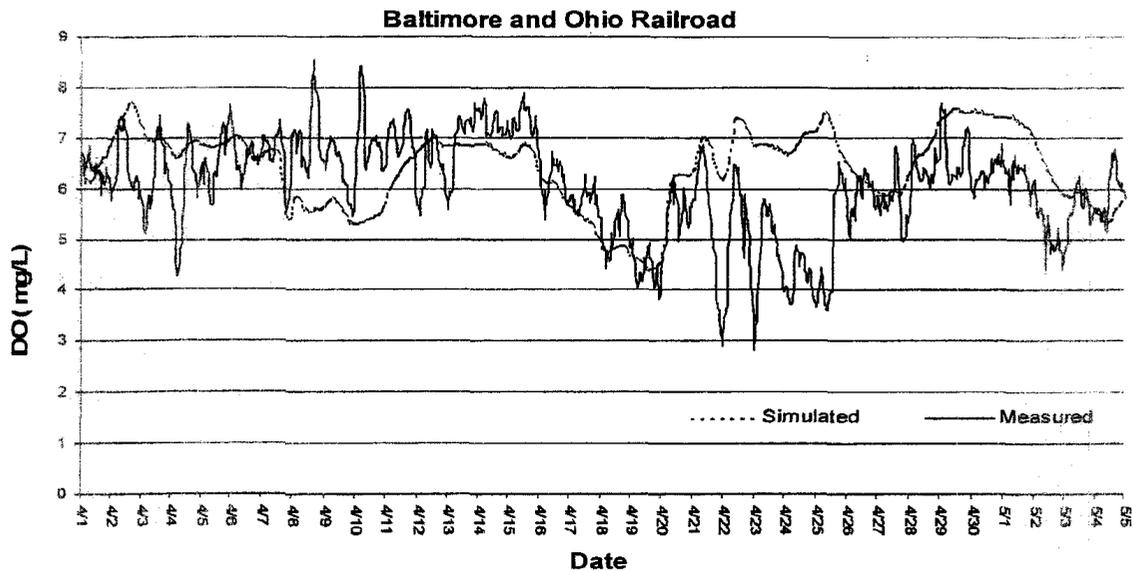


**Figure 3.26.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Cicero Avenue on the Chicago Sanitary and Ship Canal

The Baltimore and Ohio Railroad (B&O RR) is located downstream of the Stickney WRP. Therefore, the effect of the Stickney WRP is very obvious at this location. The DO concentration is relatively higher than that at Cicero Avenue until April 15 (Figure 3.27). The DO concentrations go down to 4 mg/L from 7 mg/L from April 21-25. The simulated DO concentrations agree well with measured DO concentrations for all periods except this April 21-25 period. The average absolute error in daily average DO concentrations is 14 %. There are four significant DO drops between April 21 and 25 that the model could not simulate. The flow balance (Figure 2.2) indicates storm runoff beginning on April 19 and continuing through April 23, thus, the low DO concentrations occurring between

April 21 and 25 could be the result of localized CSOs. Similar results were not seen on the North Shore Channel during this period because rainfall data collected by the Illinois State Water Survey (Westcott, 2003) indicated heavier rainfall in southern Cook County than in northern Cook County. The model could not match the low DO concentrations during this period because CSO inputs were not applied during this period. The simulated and measured water-surface elevation at Romeoville showed good agreement during this storm period, thus, no independent means of estimating CSO volume was possible.

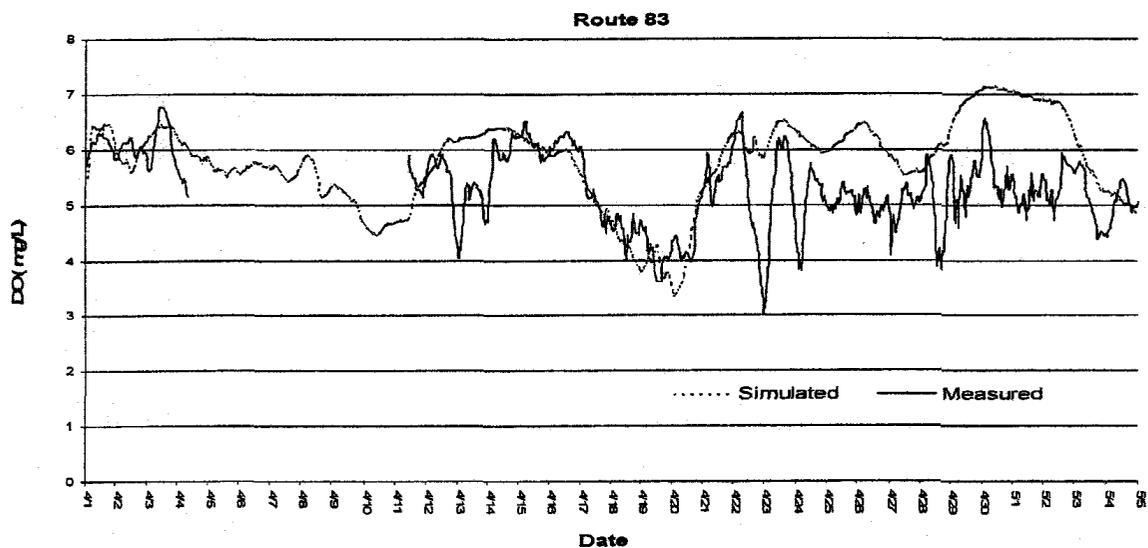
For locations downstream from the Stickney WRP, values of 0.1 and 0.09 day<sup>-1</sup> were used for  $k_{\text{bod}}$  and  $k_{\text{nit}}$ , respectively. Dispersion coefficients of 1,000 m<sup>2</sup>/s and 60 m<sup>2</sup>/s were used for higher (storm periods) and lower flows, respectively.



**Figure 3.27.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at the Baltimore and Ohio Railroad on the Chicago Sanitary Ship Canal

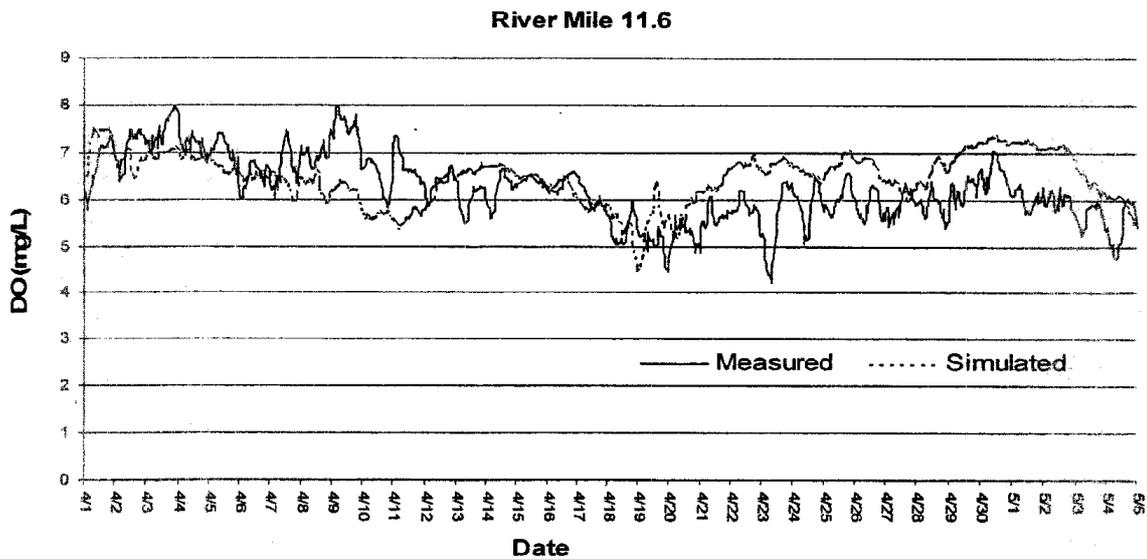
The last DO location on the CSSC upstream from the junction with the Cal-Sag Channel is Route 83. The comparison of simulated and measured DO concentrations is shown in

Figure 3.28. The measured DO concentrations are missing from April 3 to 11. Since DO concentrations pattern is very similar to B&O RR, it is still possible to make comments on the time interval where data are missing. Like B&O RR, simulated and measured values are very close until April 21. The model could not simulate sudden DO drop from 6.8 to 3 mg/L and the jump from 3 to 6.2 mg/L between April 21 and 23. After April 23, simulated values tend to be a little higher than measured values. Again as for B&O RR localized unmodeled CSOs may be the cause of the discrepancy between simulated and observed DO concentrations. Despite the large overestimation beginning April 21, the overall average DO concentration is only oversimulated by 10.7 %, and the average absolute error in daily average DO concentrations is 12.9 %. Values of 0.01 and 0.1 day<sup>-1</sup> were used for  $k_{bod}$  and  $k_{nit}$ , respectively. A constant value of 60 m<sup>2</sup>/s was used for the dispersion coefficient.



**Figure 3.28.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Route 83 on the Chicago Sanitary and Ship Canal

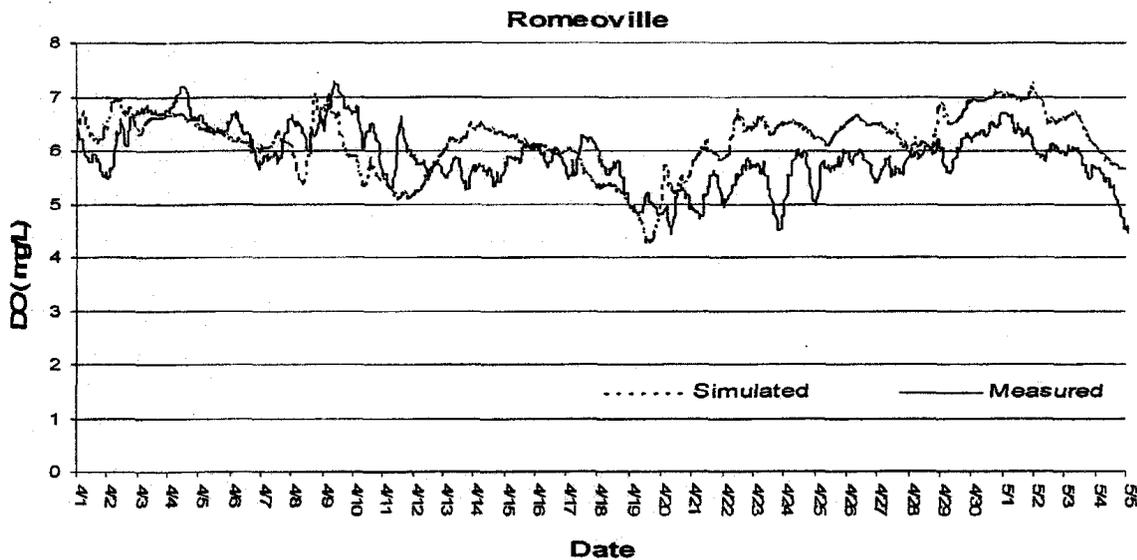
River Mile 11.6 is located 0.8 mi downstream from Calumet-Sag Channel Junction with the CSSC. The comparison between the measured and simulated DO concentrations shows good agreement (Figure 3.29) with a 9.4 % average absolute error in the daily average DO concentrations. Simulated concentrations are lower than measured concentrations from April 8 to 11 (storm period). Although DO concentration decreases to nearly 4 mg/L on April 23, the model could not capture this drop. This result may again result from unmodeled CSOs in the southern portion of the CSSC during this time period.



**Figure 3.29.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at River Mile 11.6 on the Chicago Sanitary and Ship Canal

Romeoville is the downstream boundary condition for the water-quality model. As can be seen from Figure 3.30, the simulated and measured DO concentrations are generally in good agreement. The average absolute error in the daily average DO concentrations is 8.8 % and the difference between the overall average simulated and measured dissolved oxygen concentrations is just 0.28 mg/L. From the B&O RR to Romeoville the sharp

decrease in DO concentrations on April 23 was observed with the simulated DO concentrations higher than the measured concentrations. As discussed earlier, this probably resulted from CSO loads resulting from a storm event, which was not considered as input to the modeled system. If more detailed CSO loading data were available, the model could have predicted DO concentrations for each CSO event more correctly. From the Calumet-Sag Channel Junction with the CSSC to Romeoville, the same values of calibration parameters were used:  $50 \text{ m}^2/\text{s}$ ,  $0.01 \text{ day}^{-1}$ , and  $0.1 \text{ day}^{-1}$  for the dispersion coefficient,  $k_{\text{bod}}$  and  $k_{\text{nit}}$ , respectively.



**Figure 3.30.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Romeoville on the Chicago Sanitary and Ship Canal

### 3.5.2.3 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 DO stations represent each reach: i) Halsted Street, ii)

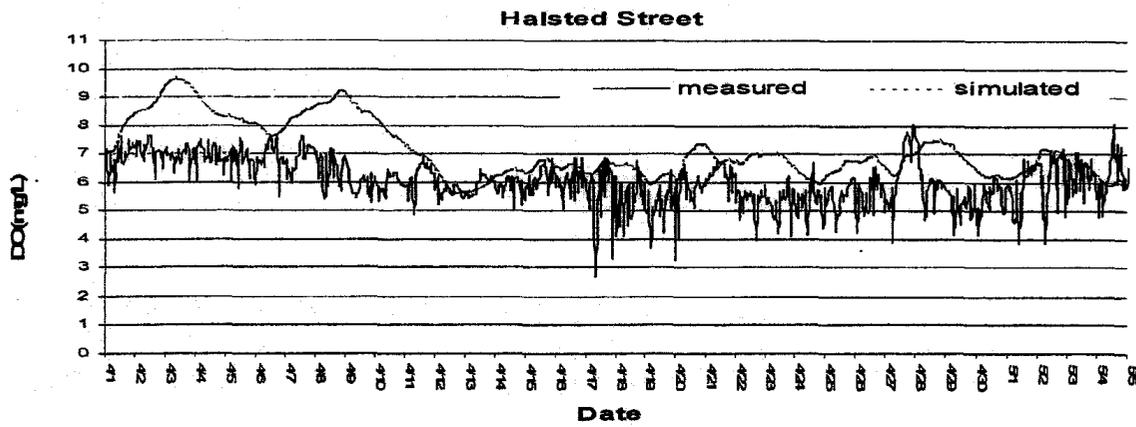
Division Street, Kedzie Avenue, Cicero Avenue, Harlem Avenue, and Southwest Highway, and iii) Route 83. Very similar calibrated parameter values were used throughout the Calumet-Sag Channel. The dispersion coefficient varies between 10 and 15 m<sup>2</sup>/s. Values of  $k_{\text{bod}}$  and  $k_{\text{nit}}$  are both 0.005 day<sup>-1</sup>. Higher values of reaction constants were used between the Calumet WRP and the junction of the Little Calumet River and the Calumet-Sag Channel (Halsted Street reach). Values of 0.05 and 0.1 day<sup>-1</sup> were used for  $k_{\text{bod}}$  and  $k_{\text{nit}}$ , respectively, for the Halsted Street reach. Statistical comparison between daily average simulated and measured dissolved oxygen concentrations are listed in Table 3.22.

**Table 3.22** Comparison of daily average simulated and measured dissolved oxygen concentrations on Calumet-Sag and Little Calumet (North, downstream from Calumet WRP), April 1-May 4, 2002 [note: Error = average of simulated-measured in mg/L; % Error = Average of (simulated-measured)/average measured x 100, Abs. Error = Average absolute value of simulated-measured; Abs. % Error = Average absolute value of (simulated-measured)/average measured x 100]

| Location          | Waterway           | Average Measured in mg/L | Average Simulated in mg/L | Error | % Error | Abs. Error | Abs. % Error |
|-------------------|--------------------|--------------------------|---------------------------|-------|---------|------------|--------------|
| Halsted Street    | Little Calumet (N) | 6.05                     | 7.11                      | 1.07  | 17.69   | 1.09       | 18.00        |
| Division Street   | Calumet-Sag        | 6.58                     | 6.99                      | 0.41  | 8.06    | 0.53       | 9.07         |
| Kedzie Avenue     | Calumet-Sag        | 7.56                     | 7.50                      | -0.06 | -0.79   | 0.59       | 7.96         |
| Cicero Avenue     | Calumet-Sag        | 6.59                     | 7.22                      | 0.63  | 9.56    | 0.70       | 11.04        |
| Harlem Avenue     | Calumet-Sag        | 7.43                     | 7.60                      | 0.17  | 2.29    | 0.58       | 8.08         |
| Southwest Highway | Calumet-Sag        | 7.39                     | 7.85                      | 0.47  | 6.36    | 0.63       | 9.20         |
| Route 83          | Calumet-Sag        | 7.65                     | 7.76                      | 0.11  | 1.44    | 0.55       | 7.33         |

Halsted Street is located downstream of the Calumet WRP. Although fluctuations in DO are observed, measured DO concentration is fairly constant throughout the simulation period (Figure 3.31). The simulated DO concentrations follow the general trend of the measured DO concentrations very well, but the measured concentrations include many short term fluctuations that could not be reproduced with the model. The water-quality

model is primarily driven by daily mean concentrations at the WRPs, and, thus, cannot match short-term fluctuations. Simulated DO concentrations are higher than measured concentrations until April 11. After April 11, simulated and measured DO concentrations show a similar trend and good agreement. Since the model could not successfully simulate the first 10 days of the simulation period, overall absolute error in the daily average DO concentrations (18%) is larger than that of other Calumet-Sag locations.



**Figure 3.31.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Halsted Street on the Little Calumet River (North)

The comparisons of simulated and measured DO concentrations have very good agreement between Division Street and Southwest Highway. The results are shown in Figure 3.32 and 3.33. The average absolute errors in the daily average DO concentrations vary between 8 % and 11 %. Measured DO concentrations are always higher than 4 mg/L at all stations. After April 11, average daily DO concentration decreases 2 mg/L. The simulated DO concentrations at Kedzie Avenue are slightly lower than measured values.

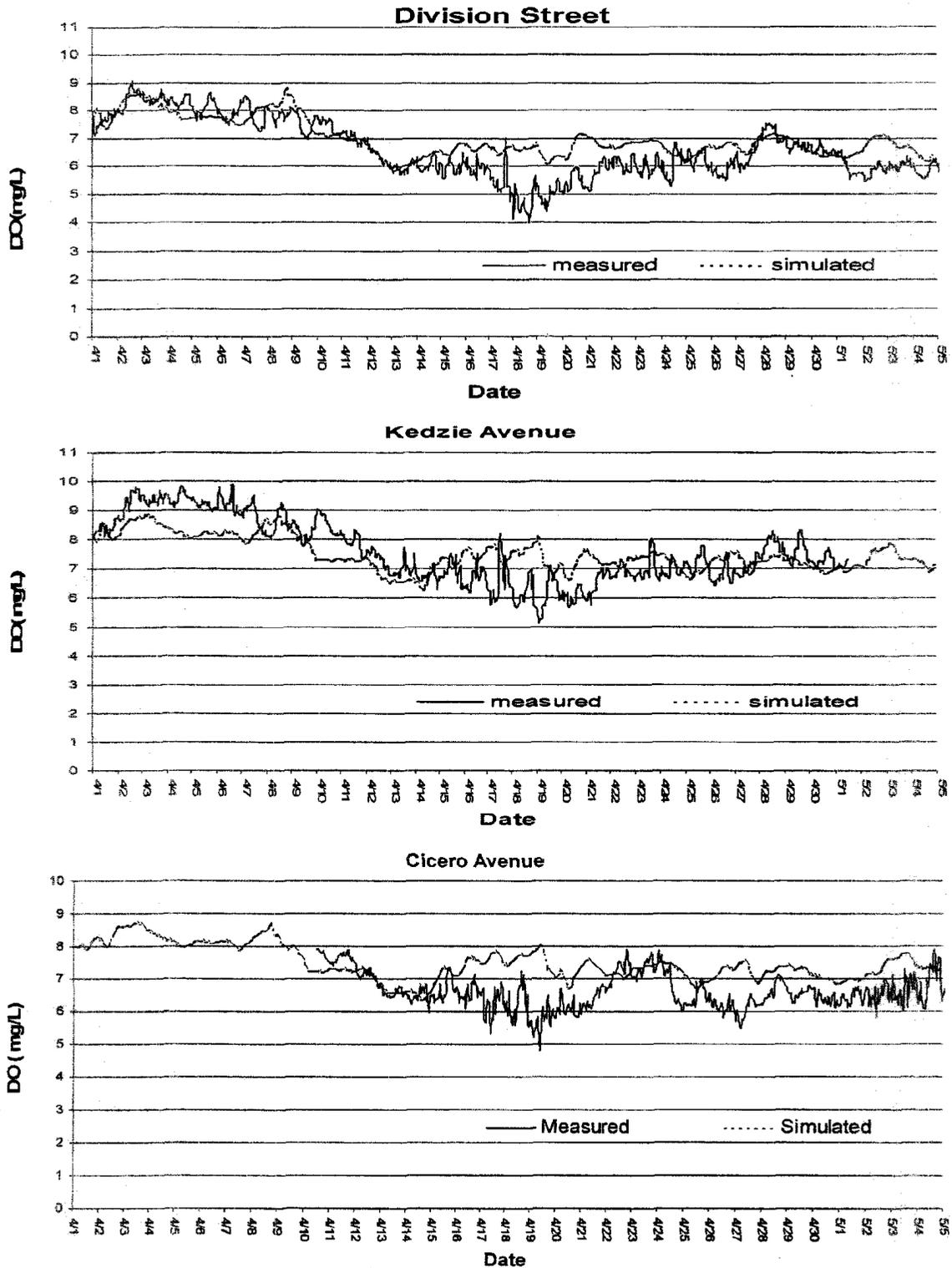
The last DO station on the Calumet-Sag Channel is at Route 83. Just like other Calumet-Sag Channel locations, measured values were successfully simulated with the model (Figure 3.34). The average absolute error in the daily average DO concentrations is just 7.3 % at this location. Although reaction constants were kept as low as possible to increase simulated DO concentrations, simulated DO concentrations are still slightly lower than measured concentrations. During the April 7-9 storm period the difference between measured and the simulated DO concentrations is about 1 mg/L.

#### **3.5.2.4 Boundaries (North Shore Channel, Chicago River Main Stem, Little Calumet River (North and South))**

Although the model simulated and measured DO concentrations agreed well most locations throughout the CWS downstream from the WRPs, the same success was not archived at locations close to the boundary conditions and/or upstream from the WRPs.

The comparison of simulated and measured DO concentrations on the North Shore Channel at Linden, Simpson, and Main Streets is shown in Figure 3.35. The flows at these sites are really low and because of the imbalance between inflows and outflows to the CWS in the modeling and the hydraulic complexities of the CWS the simulated inflow to the North Shore Channel from Lake Michigan is greater than the measured inflow from Lake Michigan (Table 2.6 and Figure 2.5). With the higher amount of Lake Michigan inflow in the simulation, the simulated DO concentrations tended to be higher than the measured DO concentrations on the North Shore Channel. The quality of the DO

simulation on the North Shore Channel upstream of the North Side WRP can only be improved by having much more accurate information on inflows to and water-surface elevations on the North Shore Channel.



**Figure 3.32.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Division Street, Kedzie Avenue, and Cicero Avenue on the Calumet-Sag Channel

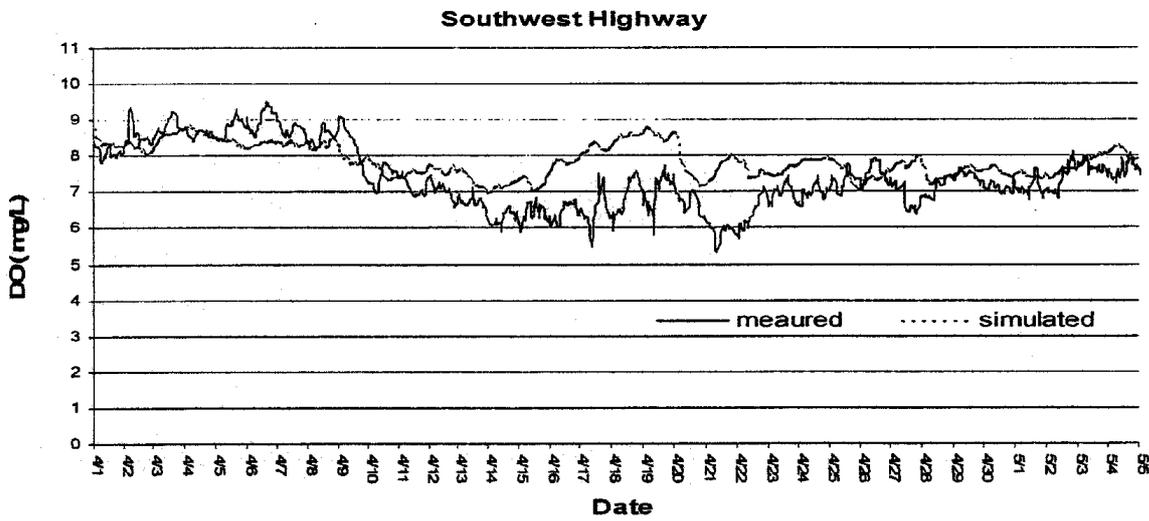
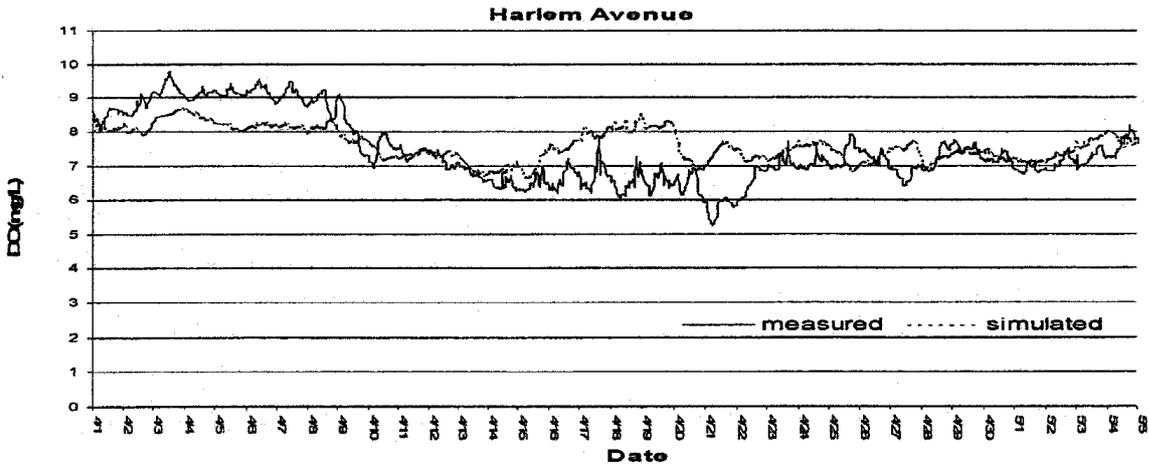


Figure 3.33. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Harlem Avenue and Southwest Highway on the Calumet-Sag Channel

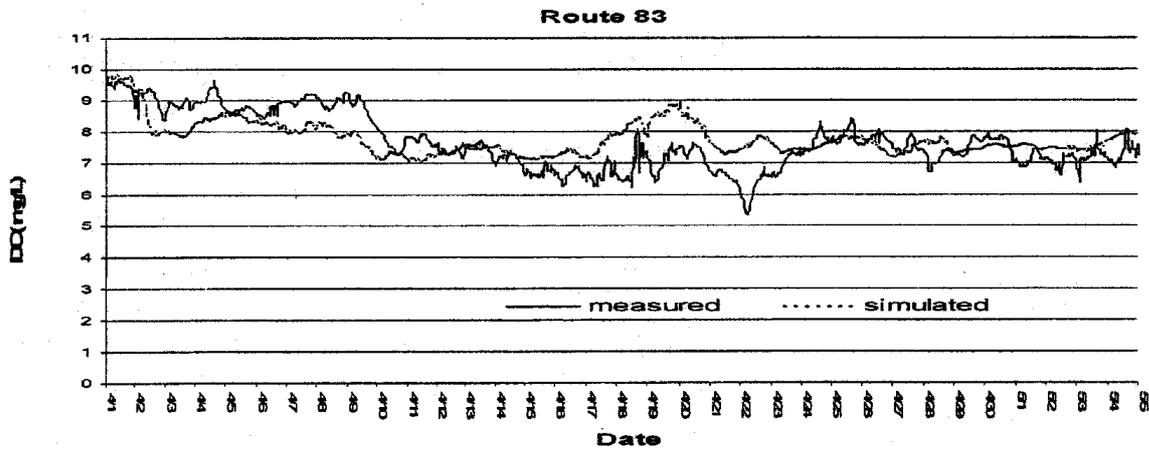


Figure 3.34. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Route 83 on the Calumet-Sag Channel

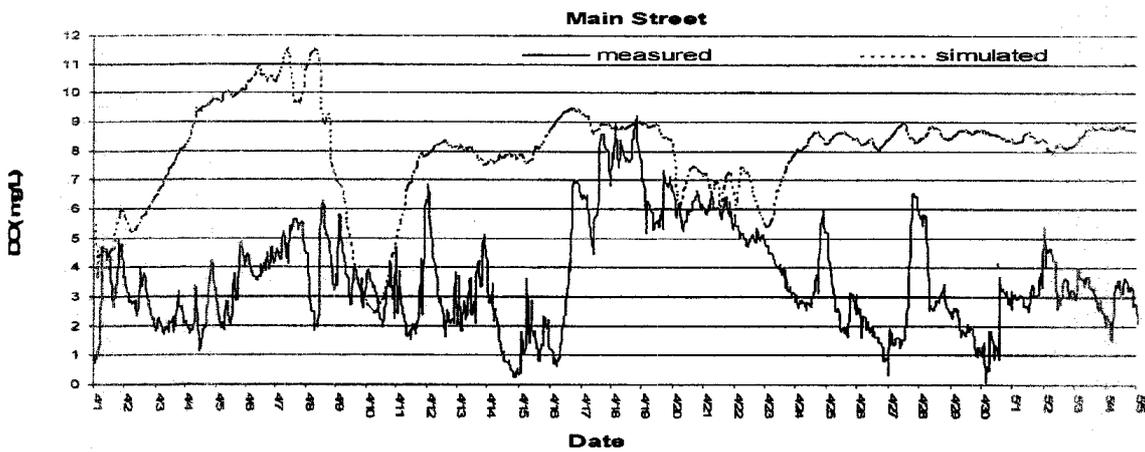
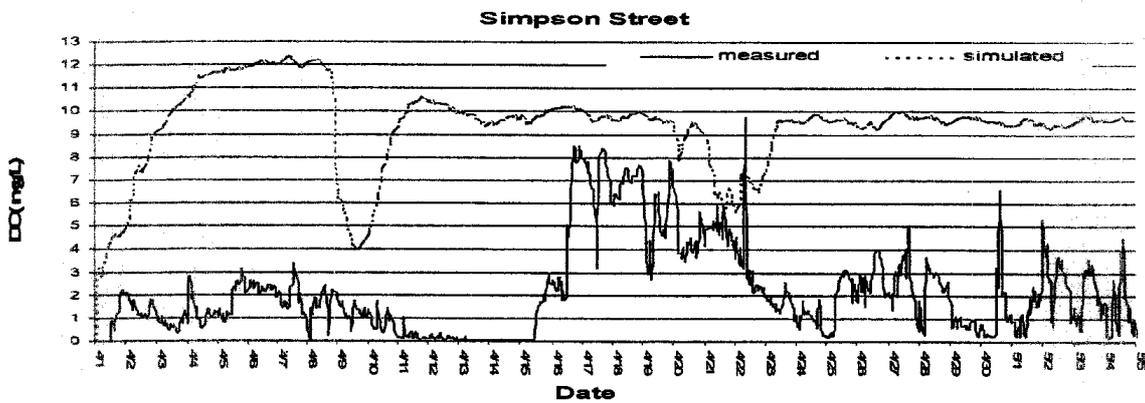
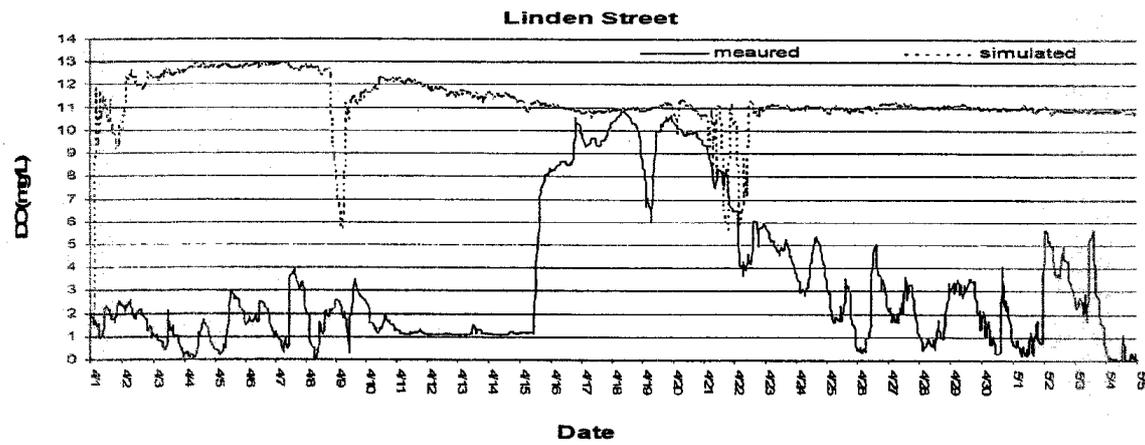


Figure 3.35. Comparison of simulated and measured dissolved oxygen (DO) concentrations at Linden, Simpson, and Main Streets on the North Shore Channel

The Chicago River main stem results are shown in Figure 3.36. Figure 3.37 shows the measured DO concentrations on the Chicago River at the CRCW and Clark Street and on the North Branch Chicago River at Kinzie Street. From this figure it is clear that at times the flow at Clark Street primarily is water from Lake Michigan (DO concentrations similar to CRCW), at other times the flow at Clark Street primarily is from the North Branch Chicago River (DO concentrations similar to Kinzie Street), and for the majority of the time the flow is a mixture of Lake Michigan and North Branch water (DO concentrations between those of CRCW and Kinzie Street). Thus, in order to simulate the DO concentrations in the Chicago River main stem the hydraulics of the main stem must be very accurately simulated. Because a water-surface elevation boundary condition is applied at Columbus Drive, flow is calculated by the model at Columbus Drive. Because of the imbalance between inflows and outflows to the CWS in the modeling and the hydraulic complexities of the CWS the simulated inflows to the Chicago River main stem tend to be underestimated (Table 2.6 and Figure 2.5). Therefore, the simulated flows at Clark Street and Michigan Avenue have less Lake Michigan water than in the actual river, and DO concentrations often are substantially underestimated. Without a substantial improvement in the flow balance for the CWS, DO concentrations will be poorly simulated on the Chicago River main stem.

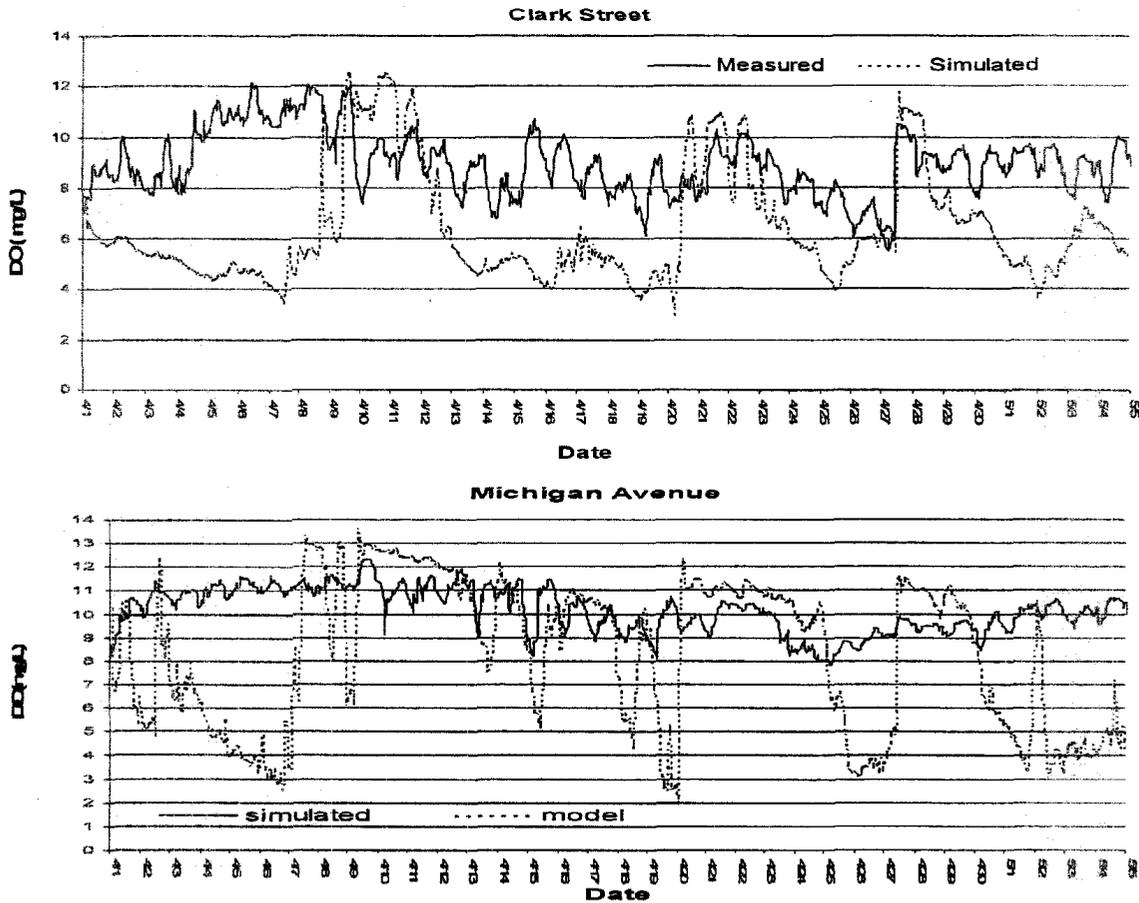


Figure 3.36. Comparison of measured and simulated dissolved oxygen (DO) concentrations at Clark Street and Michigan Avenue on the Chicago River Main Stem

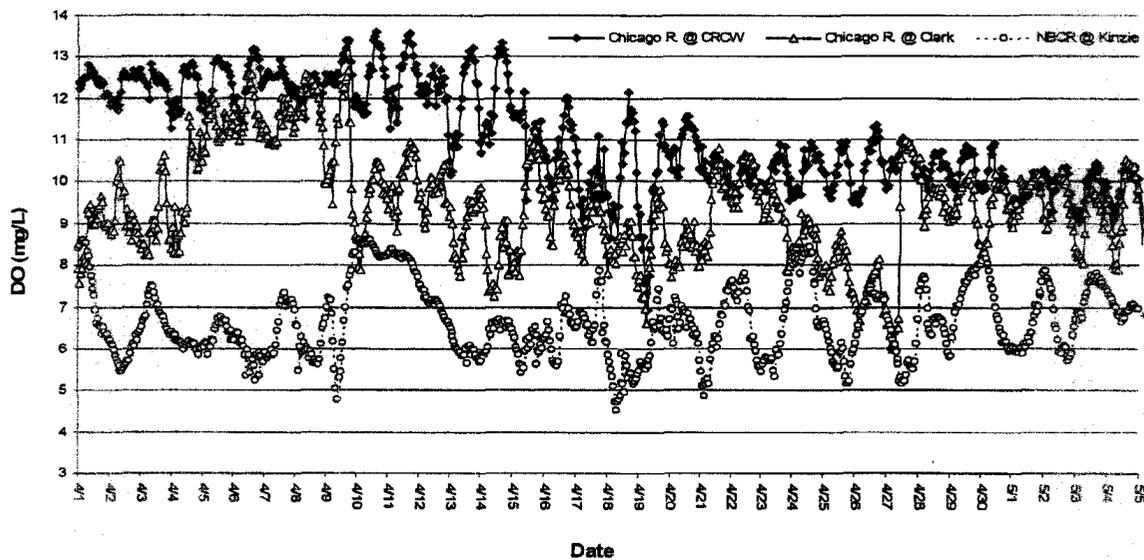
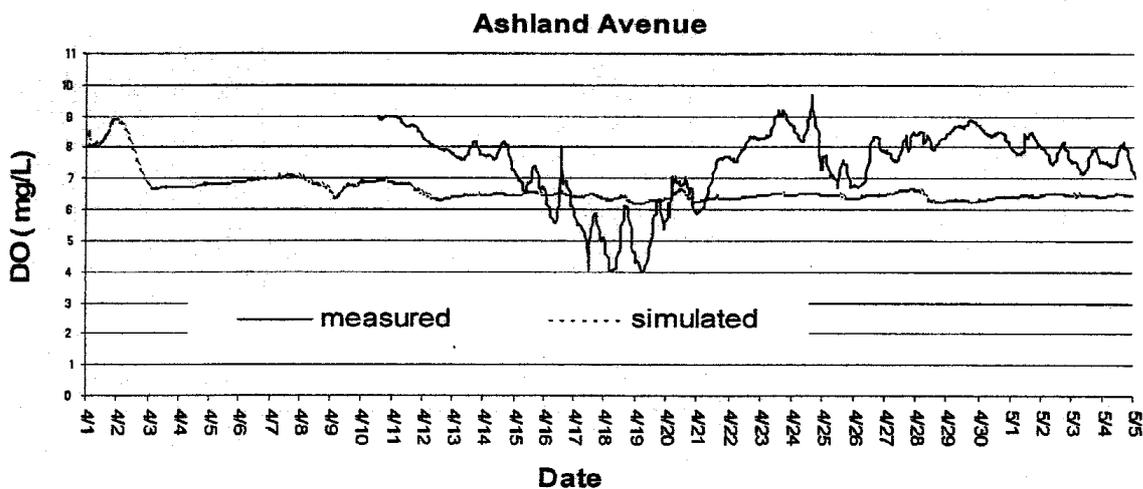


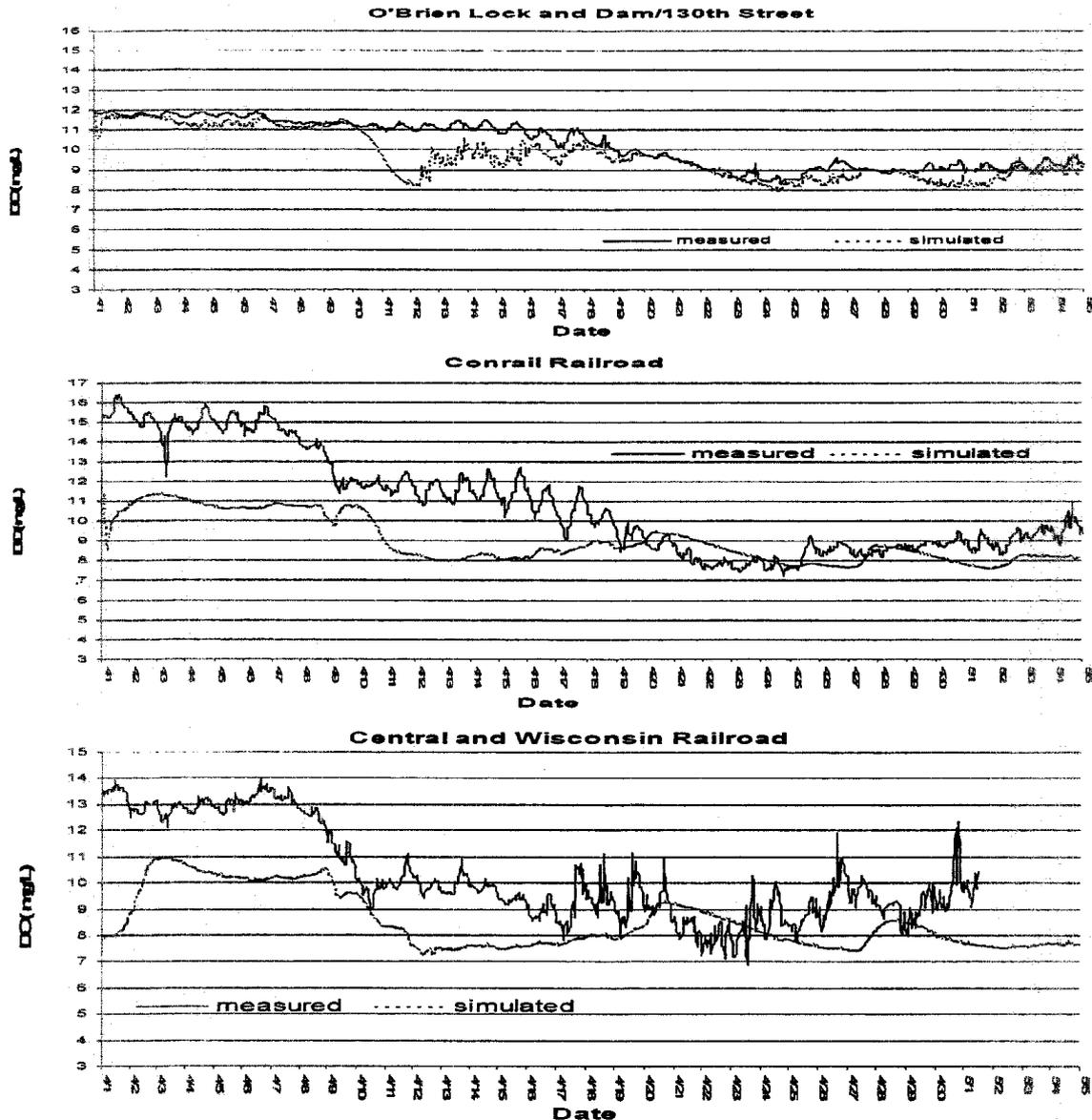
Figure 3.37. Comparison of measured dissolved oxygen (DO) concentrations on the Chicago River at the Chicago River Controlling Works (CRCW) and Clark Street and on the North Branch Chicago River at Kinzie Street

Comparison of measured and simulated dissolved oxygen concentrations on the Little Calumet River (South) at Ashland Avenue is given in Figure 3.38. Since there is no continuous dissolved oxygen station on South Holland at Little Calumet River (South), long-term average dissolved oxygen concentration was used at the South Holland boundary. Because a constant DO concentration was used at the South Holland, it was impossible to capture hourly variations at Ashland Avenue. Measured and simulated average DO concentrations at Ashland Avenue are 7.5 and 6.7 mg/L, respectively. Since the data between April 1 and April 11 are missing at the Ashland Avenue station, the average value of measured DO concentrations (7.5 mg/L) does not reflect the possible low dissolved oxygen concentrations that could occur during April 8-9 storm period. Thus, it is possible that the value of 7.5 mg/L is higher than actual average dissolved oxygen concentration. Since Calumet-Sag Channel flows are mainly dominated by Little Calumet River (North) flows, the effect of underestimated DO concentrations along Little Calumet River (South) on Calumet-Sag Channel and downstream from Calumet-Sag Channel and CSSC junction is not significant.



**Figure 3.38** Comparison of measured and simulated dissolved oxygen (DO) concentrations at Ashland Avenue on the Little Calumet River (South)

Little Calumet River (North) and Calumet River boundary condition results are shown in Figure 3.39. In the case of the O'Brien Lock and Dam boundary condition measured DO concentrations at 130<sup>th</sup> Street upstream of O'Brien were taken as representative of Lake Michigan water for the simulation comparison. All simulated DO concentrations are lower than measured DO concentrations. The differences between simulated and measured DO concentrations reach their maximum values in the first week April.



**Figure 3.39.** Comparison of measured and simulated dissolved oxygen (DO) concentrations at O'Brien Lock and Dam on the Calumet River (with the measured concentrations at 130<sup>th</sup> Street used for comparison with the simulation results), and Conrail Railroad and the Central and Wisconsin Railroad both on the Little Calumet River (North)

Saturation DO concentrations calculated using hourly water temperature are shown in Figure 3.40 with the measured DO concentrations for the Little Calumet River (North) and Calumet River boundary condition. The results are surprising because all measured DO concentrations are higher than saturation DO concentrations during the first week of April. The mechanism or process resulting in supersaturated DO concentrations in the Calumet River and Little Calumet River (North) during this time period is unknown, and, thus, cannot be simulated resulting in the discrepancy between simulated and measured DO concentrations in early April shown in Figure 3.39. The undersimulated DO concentrations throughout the rest of the study period shown in Figure 3.39 result from the flow imbalance previously described for the Chicago River main stem.

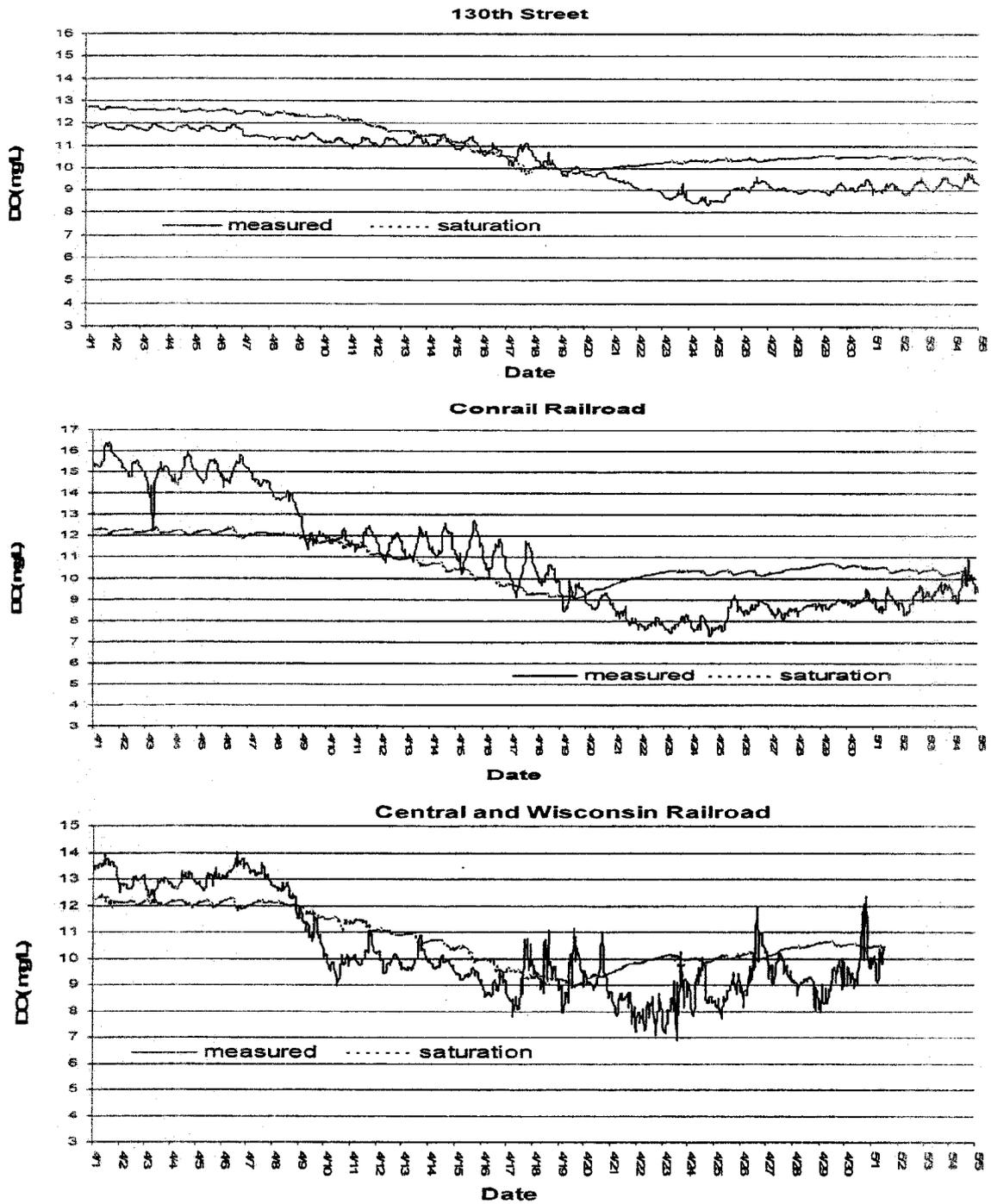
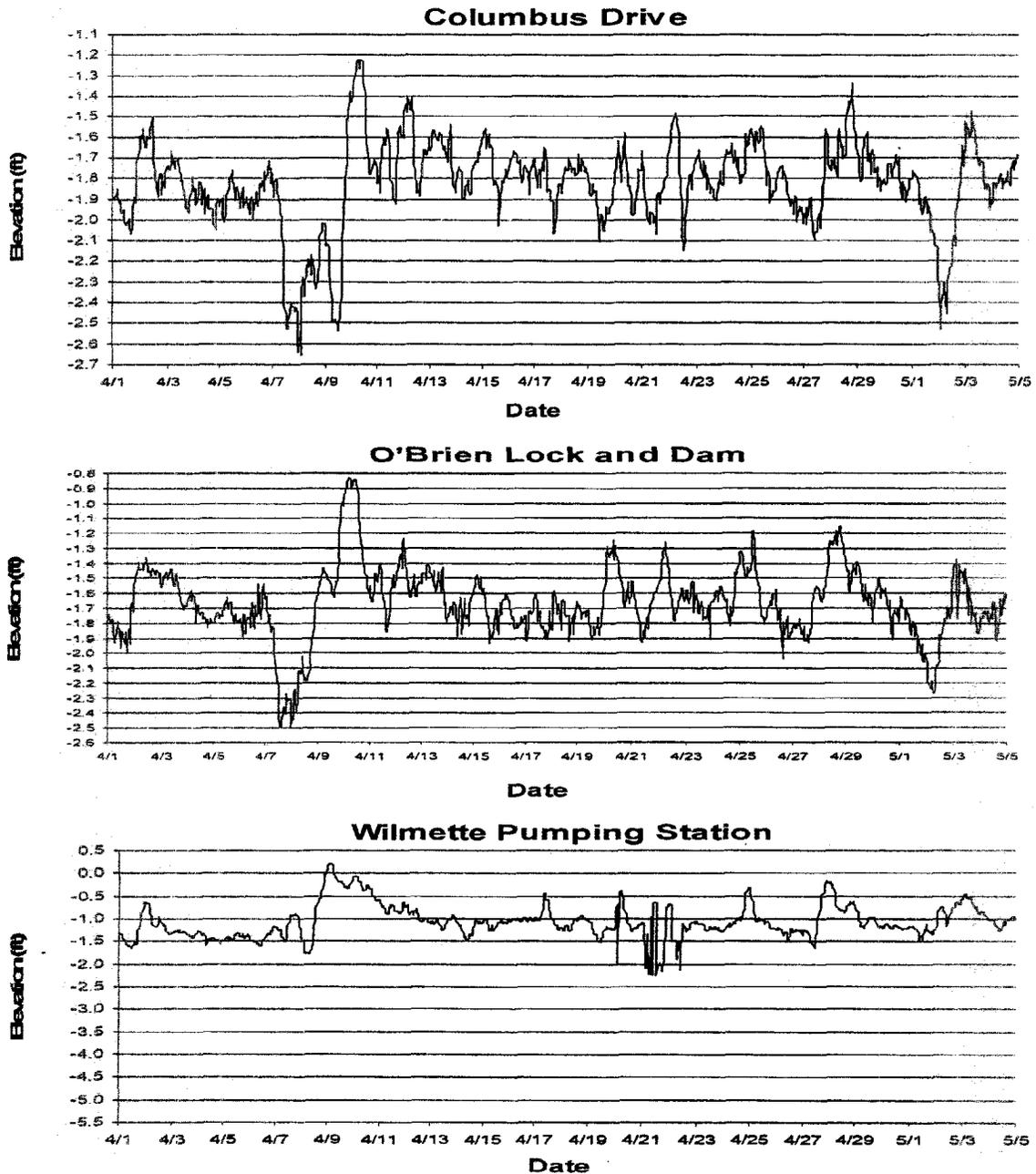


Figure 3.40. Comparison of measured and saturation dissolved oxygen (DO) concentrations on the Calumet River at 130<sup>th</sup> Street, on the Little Calumet River (North) at Conrail Railroad and at the Central and Wisconsin Railroad

## Chapter 4 - SCENARIO RESULTS

The current Code of Federal Regulations (CFR) requires that the water-surface elevation at the two lake front control structures (O'Brien Lock and Dam and CRCW) must be kept greater than or equal to  $-2$  ft ( $-0.610$  m) relative to the City of Chicago Datum (CCD,  $579.48$  ft =  $176.626$  m above mean sea level). In anticipation of storms the MWRDGC often draws down the CWS to provide storage space for runoff and increase the hydraulic gradient for moving flood water faster out of the CWS while maintaining water levels at or above  $-2$  ft CCD at CRCW and O'Brien by taking water (called "navigation make up water") from Lake Michigan. If the storm does not materialize or it is smaller than expected the MWRDGC must also take navigation make up water to refill the CWS. Because diversion of water from Lake Michigan is carefully regulated, the State of Illinois requested that the U.S. Army Corps of Engineers evaluate the effects of allowing water-surface elevations to go as low as  $-3$  ft CCD during or after expected storm periods. The goal of the study would be to see if the benefits of the reduction of navigation make up water would outweigh any adverse impacts to water quality, navigation, and other uses/interests. If the adverse effects of reducing the minimum water-surface elevation to  $-3$  ft CCD only during and immediately after storms or anticipated storms were found to be minimal, then a change in the CFR might be recommended. This water-quality evaluation is just a part of larger study being done by the U.S. Army Corps of Engineers to evaluate the possible changes in the CFR and in navigation make-up water. Other issues being evaluated by the Corps include effects on navigation through a survey of barge operators, an economic analysis, and other potential effects of the change.

In order to study the effects of the allowing water-surface elevations to be less than -2 ft CCD, the MWRDGC was allowed to drain the canal below -2 ft CCD for two storms during the April 1 to May 4, 2002, study period. The measured water-surface elevations at the lake front boundaries during the study period are shown in Figure 4.1.



**Figure 4.1.** Water-surface elevations relative to the City of Chicago Datum at the upstream boundaries to the DUFLOW model of the Chicago Waterway System

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

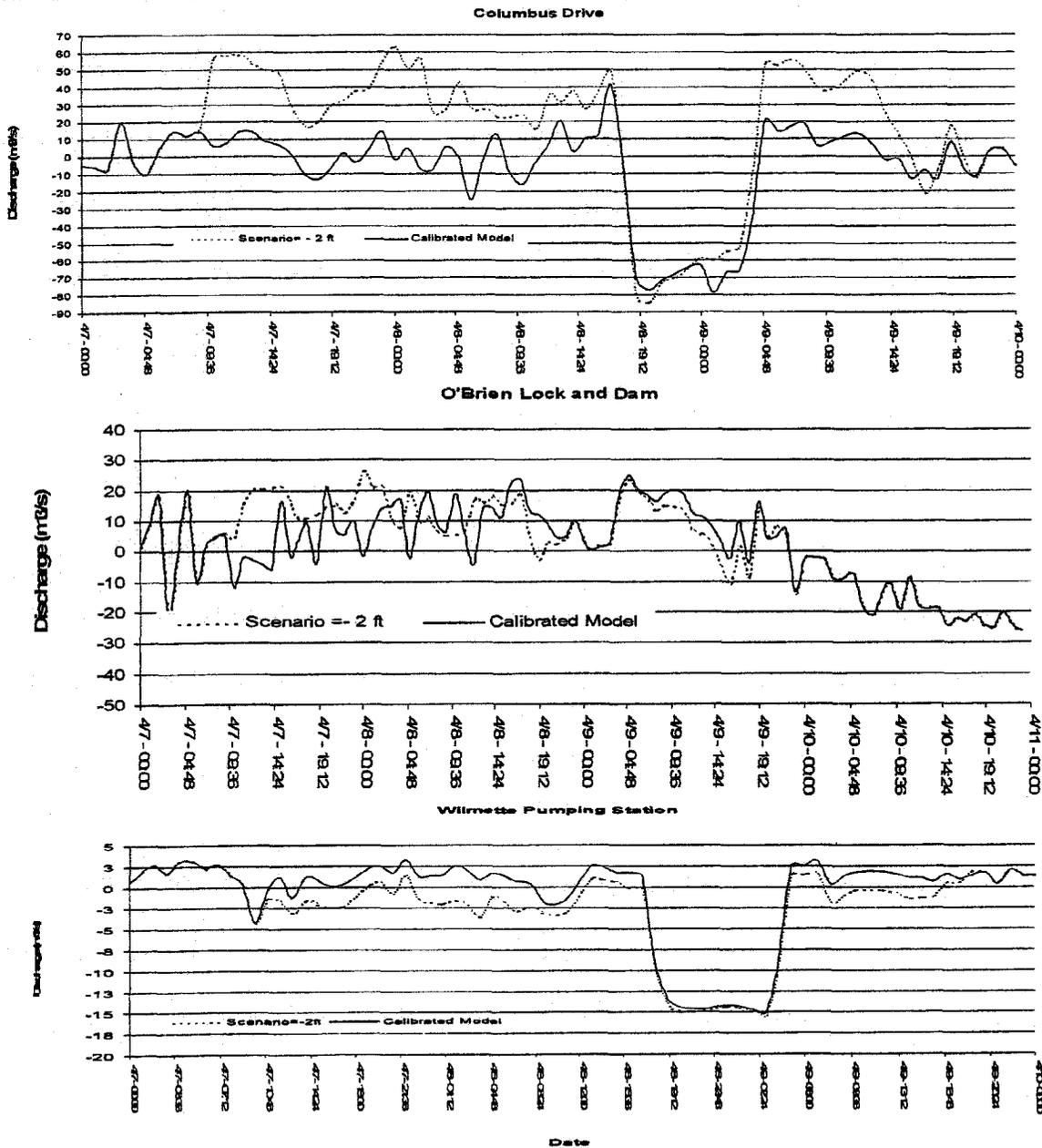
There are two significant limitations to this comparison. First, if the upstream boundary conditions were changed relative to the observed case, the observed downstream boundary condition also would change. Therefore, using the observed downstream boundary condition with the hypothetical upstream boundary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

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

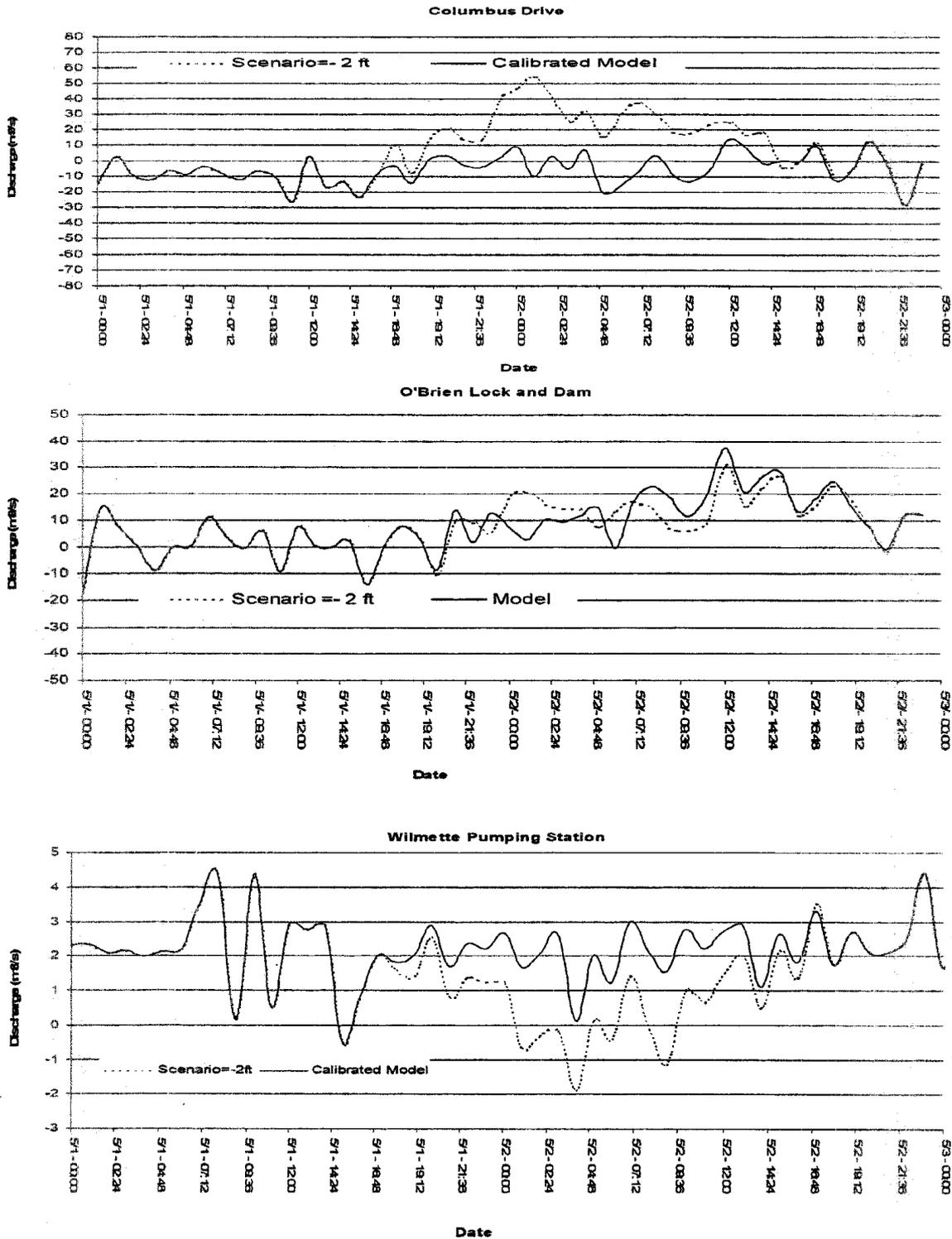
The changes in flow at the lake front controlling structures resulting from maintaining water-surface elevations at or above -2 ft CCD are listed in Table 4.1 for the April 7-9 and May 1-3 periods. The changes in flows for these periods also are shown in Figure 4.2 and 4.3.

**Table 4.1.** Comparison of flows at the lake front controlling structures simulated with the measured water-surface elevations (calibrated model) and the water-surface elevations held at -2 ft City of Chicago Datum (scenario = -2ft)

|           |                                | Columbus      |                  | O'Brien       |                  | Wilmette      |                  |
|-----------|--------------------------------|---------------|------------------|---------------|------------------|---------------|------------------|
|           |                                | Scenario=-2ft | Calibrated Model | Scenario=-2ft | Calibrated Model | Scenario=-2ft | Calibrated Model |
| April 7-9 | Average<br>(m <sup>3</sup> /s) | 16.6          | -7.7             | 9.5           | 7.9              | -3.1          | -1.4             |
| May 1-3   |                                | 20.5          | -2.7             | 13.2          | 13.8             | 1.0           | 2.1              |



**Figure 4.2** Comparison of flows at the lake front controlling structures simulated with the measured water-surface elevations (calibrated model) and the water-surface elevations held at -2 ft City of Chicago Datum (scenario = -2ft) for April 7-9, 2002



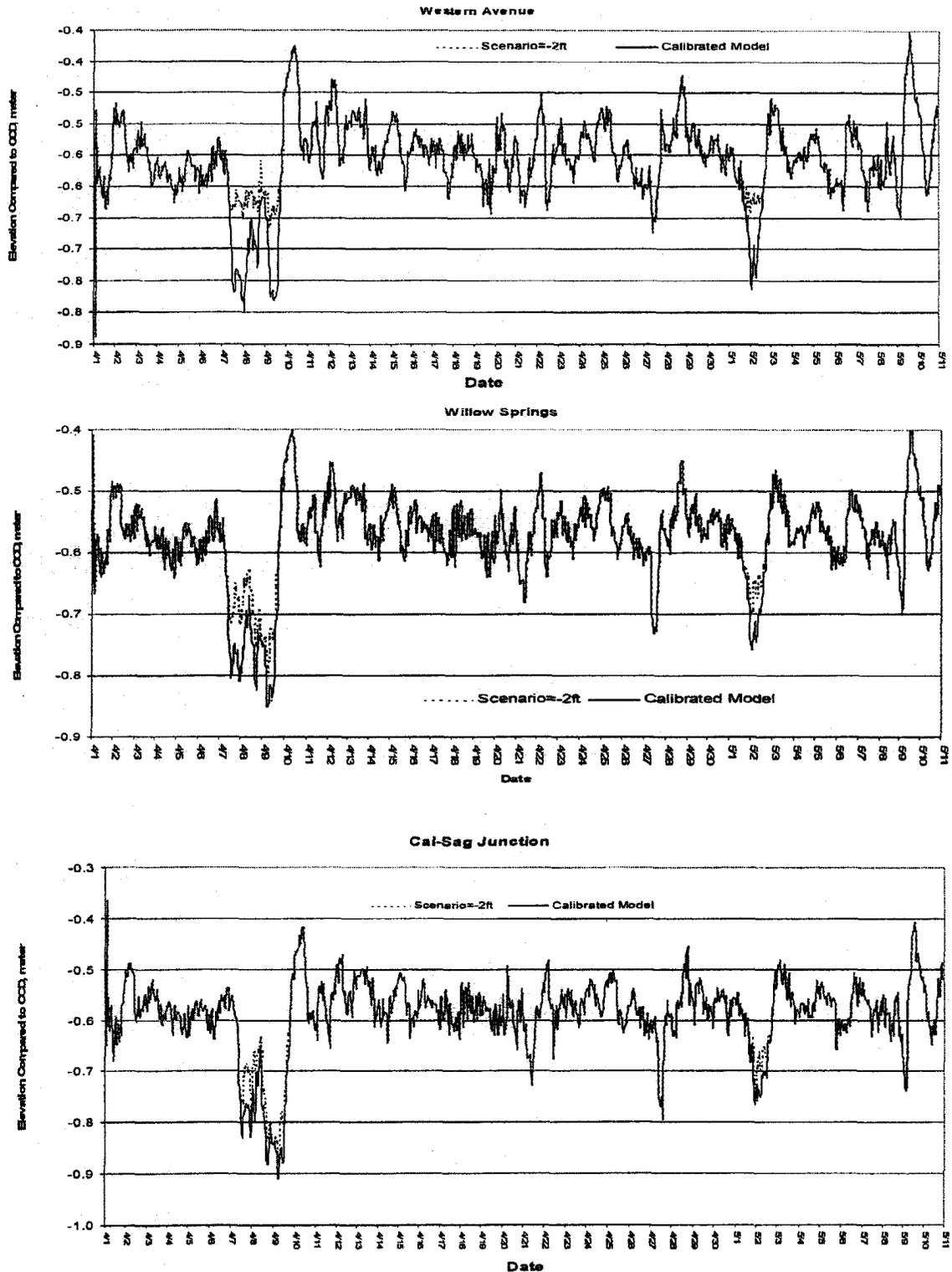
**Figure 4.3.** Comparison of flows at the lake front controlling structures simulated with the measured water-surface elevations (calibrated model) and the water-surface elevations held at -2 ft City of Chicago Datum (scenario = -2ft) for May 1-3, 2002

The negative flows at Columbus Drive and Wilmette in Table 4.1 and at all lake front boundaries at various times in Figures 4.2 and 4.3 require some explanation. At O'Brien Lock and Dam during storm periods negative flows computed by the model actually represent flows moving upstream on the Grand Calumet River as discussed in detail by Shrestha and Melching (2003). Negative flows (i.e. out of the system, towards Lake Michigan) computed for Columbus Drive and Wilmette and at O'Brien Lock and Dam in non-storm periods have no physical explanation. They basically result from the imbalance between inflows to the CWS and outflows from the CWS at Romeoville. That is, if the inflows to the CWS in a particular period are greater than the measured outflows at Romeoville during this period, the flow at the lake front boundaries is reduced relative to measured values and may become negative to preserve conservation of mass in the hydraulic computations done by DUFLOW. Within DUFLOW the comparison between inflows and outflows accounts for the travel time between the various inflow points and Romeoville.

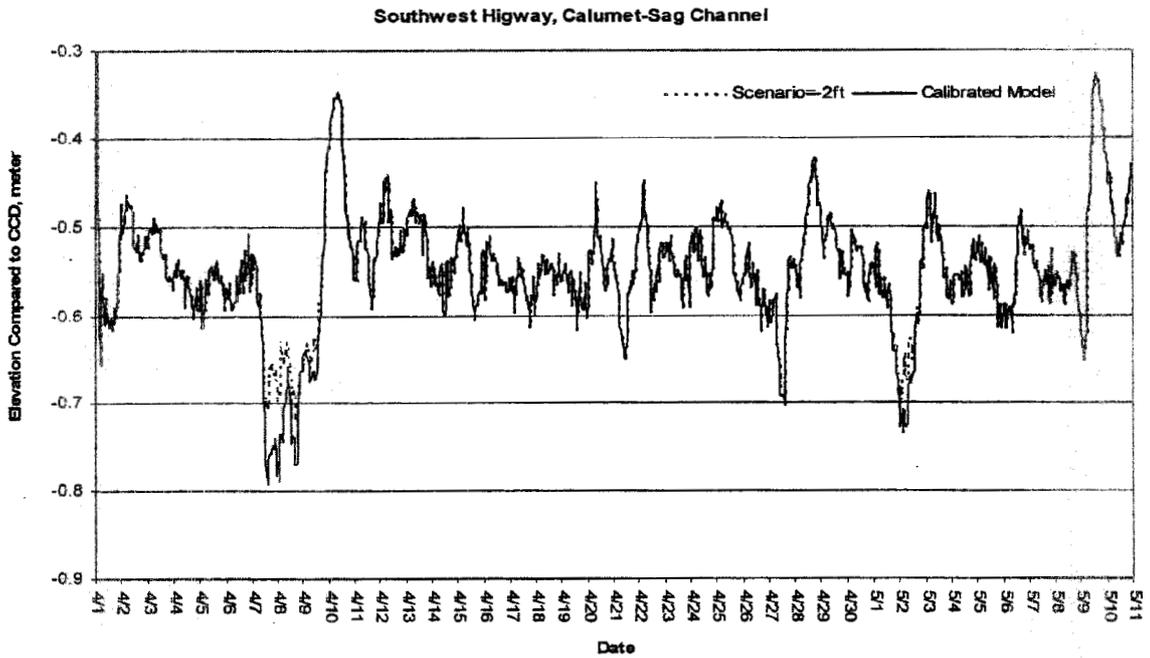
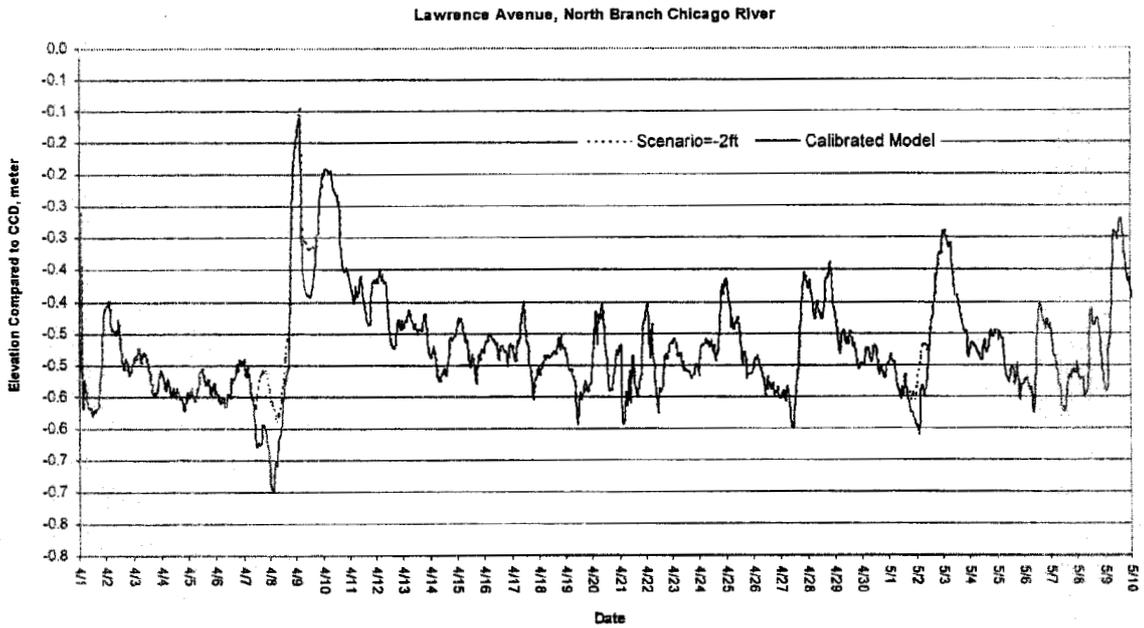
For the April 7-9 storm, the flow increased  $24.3 \text{ m}^3/\text{s}$  at Columbus Drive and  $1.6 \text{ m}^3/\text{s}$  at O'Brien Lock and Dam, and decreased  $1.7 \text{ m}^3/\text{s}$  at the Wilmette Pumping Station for a total increase of  $24.2 \text{ m}^3/\text{s}$  (855 cfs) because of maintaining the  $-2 \text{ ft}$  CCD water-surface elevation. The duration of the increase is only 63 hrs, and, thus, the total volume of increase is  $5,488,000 \text{ m}^3$ . For the May 1-3 storm, the flow increased  $23.2 \text{ m}^3/\text{s}$  at Columbus Drive and decreased  $1.1$  and  $0.6 \text{ m}^3/\text{s}$  at the Wilmette Pumping Station and O'Brien Lock and Dam, respectively, for a total increase of  $21.5 \text{ m}^3/\text{s}$  (759 cfs) because of maintaining the  $-2 \text{ ft}$  CCD water-surface elevation. The duration of the increase is

only 28 hrs, and, thus, the total volume of increase is 2,167,000 m<sup>3</sup>. The decrease in flow at O'Brien Lock and Dam for the May 1-3 period when the water depth is maintained at -2 ft CCD probably results from an increase in water-surface elevation at Sag Junction that limits/slows the flow coming through the Calumet-Sag Channel. The low navigation make up flow at O'Brien Lock and Dam relative to CRCW probably results because flow from the Little Calumet River (south) more quickly refills the Calumet-Sag Channel and Little Calumet River (north) than local inflows refill the Chicago River main stem.

The increase in water-surface elevation at the lake front also increases the water-surface elevations throughout the CWS. Figure 4.4 and 4.5 show the increase in water-surface elevation resulting from holding the water-surface elevation at the lake front boundaries at or above -2 ft CCD for the CSSC and the North Branch and Calumet-Sag Channel, respectively. Most notable are the increases in water-surface elevation on the North Branch Chicago River at Lawrence Avenue (Figure 4.5). This increase indicates the cause of reduced flows at the Wilmette Pumping Station and the backflow of water into the North Shore Channel.



**Figure 4.4** Comparison of water-surface elevations on the Chicago Sanitary and Ship Canal simulated with the measured water-surface elevations (calibrated model) and the water surface elevations held at -2 ft City of Chicago Datum (Scenario = -2ft)



**Figure 4.5** Comparison of the water-surface elevations of the North Branch Chicago River and Calumet-Sag Channel simulated with measured water-surface elevations (calibrated model) and the water-surface elevations held at -2 ft City of Chicago Datum (scenario = -2ft)

Figures showing the difference between DO concentrations simulated with water-surface elevations held at -2 ft CCD and with the measured water-surface elevations over the full study period for each continuous DO monitoring location are shown in Appendix D. These time series of differences yield three interesting results.

- 1) On the CSSC from the Baltimore and Ohio Railroad to Romeoville, the increased water-surface elevation scenario initially results in lower DO concentrations at the beginning of the April 7-9 and May 1-3 storms. This results because the increased gradient from the lake front to Romeoville causes the poorer quality water discharged from the Stickney WRP and CSOs during the storm to move downstream more quickly initially depressing the DO concentration. After this initial period the higher quality Lake Michigan water reaches these locations and the DO concentration increases relative to the simulation with the measured water-surface elevations at the lake front.
- 2) For most locations, the difference in DO concentrations between the two scenarios is nearly zero except during and immediately after the storms for which the upstream boundary conditions were changed.
- 3) For the downstream reaches of the CSSC from the Baltimore and Ohio Railroad to Romeoville the positive effect on DO concentrations because of increased diversion lasted around one week after the event for the April 7-9 storm. Thus, for these locations, in order to compute the full effect of the increased diversion on DO concentrations for the May 1-3 storm, the simulation period was extended to May 10.

Table 4.2 lists the average change in DO concentration resulting for the April 7-9, 2002, and May 1-3, 2002, storms comparing the simulation holding water-surface elevations at the lake front at or above -2 ft CCD with the simulation using the observed water-surface elevations. The sequence of DO concentration increases moving down the South Branch to the CSSC and Romeoville was completely expected. The highest increase in inflows from Lake Michigan is at the CRCW and this inflow makes up a substantial portion of the flow at Jackson Boulevard. Thus, Jackson Boulevard has the largest increase in DO concentration. The increase in DO is reduced at Cicero Avenue because of the dilution effects on the Racine Avenue Pumping Station flows, and the DO increase is further reduced downstream from the Stickney WRP (Baltimore and Ohio Railroad to Route 83) because of dilution. Finally, the DO increase is reduced even more downstream from Sag-Junction because of the dilution effects from the Calumet-Sag Channel. The change in DO concentration is much smaller for the May 1-3 storm compared to the April 7-9 storm because its increase in Lake Michigan water withdrawal was 40% of the increase for the April 7-9 storm.

**Table 4.2** Average change in DO concentration in milligrams per liter over the period affected by the April 7-9 and May 1-3 storms comparing the simulation holding water-surface elevations at the lake front at or above -2 ft City of Chicago Datum with the simulation using observed water-surface elevations at the lake front

| Location                       | Average Change in DO (mg/L) |               | River Mile | Water Course                    |
|--------------------------------|-----------------------------|---------------|------------|---------------------------------|
|                                | April 7-9-Storm             | May 1-3 Storm |            |                                 |
| Linden Street                  | -1.8                        | -0.5          | 49.8       | North Shore Channel             |
| Simpson Street                 | -1                          | -0.6          | 48.5       | North Shore Channel             |
| Main Street                    | -0.8                        | -1.0          | 46.5       | North Shore Channel             |
| Addison Street                 | -0.1                        | -0.1          | 40.3       | North Branch Chicago River      |
| Fullerton Avenue               | -0.1                        | -0.1          | 38.4       | North Branch Chicago River      |
| Division Street                | -0.1                        | -0.1          | 36.3       | North Branch Chicago River      |
| Kinzie Street                  | -0.6                        | -0.3          | 34.8       | North Branch Chicago River      |
| Jackson Boulevard              | 1.7                         | 0.4           | 34         | South Branch Chicago River      |
| Cicero Avenue                  | 0.7                         | 0.2           | 26.3       | Chicago Sanitary and Ship Canal |
| Baltimore and Ohio Railroad    | 0.5                         | 0.1           | 21.3       | Chicago Sanitary and Ship Canal |
| Route 83                       | 0.5                         | 0.1           | 13.1       | Chicago Sanitary and Ship Canal |
| River Mile 11.6                | 0.3                         | 0.1           | 11.6       | Chicago Sanitary and Ship Canal |
| Romeoville                     | 0.3                         | 0             | 5.2        | Chicago Sanitary and Ship Canal |
| O'Brien Lock and Dam           | -0.1                        | 0.1           | 36         | Calumet River                   |
| Conrail Railroad               | 0                           | 0             | 34.4       | Little Calumet River (North)    |
| Central and Wisconsin Railroad | 0.1                         | 0             | 31.6       | Little Calumet River (North)    |
| Halsted Street                 | 0.1                         | 0             | 29.1       | Little Calumet River (North)    |
| Division Street                | 0.2                         | 0             | 27.6       | Calumet-Sag Channel             |
| Kedzie Avenue                  | 0.1                         | 0             | 26.1       | Calumet-Sag Channel             |
| Cicero Avenue                  | 0.1                         | 0             | 24         | Calumet-Sag Channel             |
| Harlem Avenue                  | 0                           | 0             | 20.7       | Calumet-Sag Channel             |
| Southwest Highway              | 0                           | 0             | 19.7       | Calumet-Sag Channel             |
| Route 83                       | 0.1                         | 0             | 13.3       | Calumet-Sag Channel             |

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

Since less lake water is withdrawn from Wilmette for the scenario holding water-surface elevation at or above -2 ft CCD, locations on the North Shore Channel showed

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

## **Chapter 5 - CONCLUSIONS AND RECOMMENDATIONS**

An unsteady water-quality model for the Chicago Waterway System (CWS) has been calibrated to assist water-quality management and planning decision making. An extensive set of flow, stage, and water-quality data have been used for verification of the previously calibrated hydraulic model and for calibration of the unsteady-flow water-quality model for the CWS for the period of April 1 to May 4, 2002.

First, hydraulic verification of the previously calibrated hydraulic model (Shrestha and Melching, 2003) was done. Water-surface elevation data at two new stations were used to test the power of the model, and it was observed that model could predict water levels at all locations with a high accuracy (one to two percent error relative to depth).

Boundary conditions, water reclamation plants, SEPA stations, in-stream aeration stations, tributaries, CSOs, and pumping stations input constituents to the CWS. The water-quality model was calibrated using monthly grab sample data at 18 locations and hourly dissolved oxygen (DO) and temperature data at 24 locations all collected by the MWRDGC. The model was run at a 15-min. time step for the period of April 1 to May 4, 2002. Primarily hourly measured and simulated DO concentrations were compared.

Except for locations close to the boundaries (i.e. upstream of WRPs), the simulated DO concentrations agreed well with the observed concentrations. The calibration results showed that reaction rate constants are low during the simulation period and the most of

the variations in DO result from hydraulic behavior of the system. This result is similar to previous experience with QUAL2EU applied to the CWS (CDM, 1992).

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

The model then was applied to evaluate the effect of a change in navigational water levels on the water quality in the CWS. In anticipation of a significant rainfall-runoff event, the MWRDGC draws down the Chicago Sanitary and Ship Canal (CSSC) at Lockport. Drawing down the canal allows more storage within the canal and increases water velocities to more quickly move flood water out of the canal system. The Code of Federal Regulations requires that the water-surface elevation at the lake front be maintained at or above -2 ft CCD at all times. If a storm fails to occur or is smaller than anticipated, the MWRDGC must divert water from Lake Michigan (“navigation make up water”). In order to reduce diversions from Lake Michigan allowing water surface elevations at the lake front down to -3 ft CCD during or after storms is being evaluated. On April 7-9 and May 1-2, 2002, the MWRDGC was allowed to draw the water-surface elevation at the lake front below -2 ft CCD to determine effects on navigation, water quality, and other features. In order to examine the effect of navigation makeup water at

the lake front structures on water-quality in the CWS, water-surface elevations below -2 ft CCD at the boundaries were set to -2 ft and then DO concentrations were simulated and compared to the results of simulation using measured water-surface elevations at the lake front. The results showed that for the April 7-9 and May 1-3 storms navigation make up water savings of 5,488,000 and 2,167,000 m<sup>3</sup>, respectively, could occur by allowing water levels less than -2 ft CCD. These volumes translate to 8.57 cfs over an entire year. The results also showed that dissolved oxygen concentrations increased on average by 0.3 mg/L and 0.0 mg/L at Romeoville because of navigation make up water at Columbus Drive in the April 7-9 and May 1-3 storm events, respectively. Because of higher temperatures that reduce DO saturation concentrations and increase biological activity, the effects of the proposed change in regulations related to water-surface elevations in the CWS and the resulting decrease navigation make-up flows on water quality in the summer might be higher than for the April 7-9 storm event.

For future studies, the calibrated model should be verified with new data sets collected during summer and fall periods. Since April is a relatively cold month, all reaction constants are low and bio-chemical activities are at a minimum level. Therefore, in order to use the model for possible summer month scenarios, it has to be verified (and/or recalibrated) with a summer time data set. Combined sewer overflow and wet weather concentrations are very important during storm events. Volumetric CSO loads were distributed based on the contributing area and DO concentration was assumed to be 6.5 mg/L for CSOs in the calibrated model. Detailed CSO volume and water-quality analysis would improve the power of the model.

## REFERENCES CITED

Abedin, Z., Knafl, G., Sawyer, B., Tata, P., and Lue-Hing, C., 1999, 1996 Annual Summary Report Water Quality Within the Waterways System of the Metropolitan Water Reclamation District of Greater Chicago, Metropolitan Water Reclamation District of Greater Chicago, *Department of Research of Development Report No. 99-12*, Chicago, IL.

Ambrose, R.B., et al., 1988, WASP4, A Hydrodynamic and Water Quality Model—Model Theory, User's Manual, and Programmer's Guide, U.S. Environmental Protection Agency, *EPA/600/3-87-039*, Athens, GA.

Butts, T.A., Shackleford, D.B., and Bergerhouse, T.R., 1999, Evaluation of Reaeration Efficiencies of Sidestream Elevated Pool Aeration (SEPA) Stations, *Illinois State Water Survey Contract Report 653*, Champaign, IL.

Butts, T.A., Shackleford, D.B., and Bergerhouse, T.R., 2000, Sidestream Elevated Pool Aeration (SEPA) Stations: Effect on Instream Dissolved Oxygen, *Illinois State Water Survey Contract Report 2000-02*, Champaign, IL.

Camp, Dresser, & McKee, 1992, *Water Quality Modeling for the Greater Chicago Waterway and Upper Illinois River Systems, Main Report*, Chicago, IL.

Committee on Sanitary Engineering Research, 1960, Solubility of Atmospheric Oxygen in Water, *Journal of the Sanitary Engineering Division, ASCE*, V. 86, no. (4), p. 41-53.

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

Hey, D.L., Dreher, D.W., and Trybus, T.W., 1980, NIPC Chicago Waterways Model: Verification/Recalibration, Northeastern Illinois Planning Commission Technical Report, Chicago, IL.

Hydrocomp, Inc., 1979a, Chicago Sanitary and Ship Canal Hydrologic Calibration, Report to the Northeastern Illinois Planning Commission, Areawide Clean Water Planning Water Quality Evaluation.

Hydrocomp, Inc., 1979b, Chicago River, Sanitary and Ship Canal, Calumet Sag Channel Basin, Report to the Northeastern Illinois Planning Commission, Areawide Clean Water Planning Water Quality Evaluation.

Novotny, V. and Olem, H., 1994, *Water Quality: Prevention, Identification, and Management of Diffuse Pollution*, Van Nostrand Reinhold, New York.

O'Connor, D.J. and Dobbins, W.E., 1958, The Mechanism of Reaeration in Natural Streams, *Transactions, ASCE*, V. 123, no. 2934, p. 641-684.

Polls, I. Washington, B., and Lue-Hing, C., 1982, Improvements in Dissolved Oxygen Levels by Artificial In-Stream Aeration in Chicago Waterways, Metropolitan Sanitary District of Greater Chicago, *Department of Research and Development Report No. 82-16*, Chicago, IL.

Shrestha, R.L. and Melching, C.S., 2003, Hydraulic Calibration of an Unsteady Flow Model for the Chicago Waterway System, *Technical Report 14*, Institute of Urban Environmental Risk Management, Marquette University, Milwaukee, WI, and Metropolitan Water Reclamation District of Greater Chicago, *Department of Research and Development Report No. 03-18*, Chicago, IL.

# APPENDIX-A Eutrophication Model EUTROF2

## DUFLOW v2.0

```

/*
/* Hans Aalderink
/*
/* Wageningen Agricultural University
/* Department of Nature Conservation
/* Water Quality Management Section
/* P.O. BOX 8080
/* 6700 DD Wageningen
/* The Netherlands
/*
/* November 1992
/*
/* EUTROF2L.MOD: linear equations for the estimation of the
/* secchi depth and the extinction coefficient
/*
/* G. Blom en J. Icke, July 1997
/*

water      SSW      [ 8.00]    g/m3      ;Suspended solids concentration water column
water      TIPW     [ 0.70]    g-P/m3    ;Inorganic P water column
water      TOPW     [ 0.20]    g-P/m3    ;Organic P water column
water      TONW     [ 1.200]   g-N/m3    ;Organic N water column
water      NH4W     [ 1.000]   g-N/m3    ;Ammonia N water column
water      O2W      [ 7.00]    g-O2/m3   ;Oxygen water column
water      BODW     [ 5.00]    g-O2/m3   ;BOD water column
water      A1       [ 0.000]   g-C/m3    ;Algal biomass species 1
water      A2       [ 0.000]   g-C/m3    ;Algal biomass species 2
water      A3       [ 0.000]   g-C/m3    ;Algal biomass species 3
water      NO3W    [ 3.00]    g-N/m3    ;Nitrate N water column
water      DET      [ 1.00]    g/m3      ;Detritus concentration

bottom     TIPB     [ 0.10]    g-P/m3    ;Inorganic P sediment
bottom     TOPB     [ 0.10]    g-P/m3    ;Organic P sediment
bottom     TONB     [ 1.00]    g-N/m3    ;Organic N sediment
bottom     NH4B     [ 1.00]    g-N/m3    ;Ammonia N sediment
bottom     O2B      [ 0.00]    g-O2/m3   ;Oxygen sediment
bottom     BODB     [ 20.00]   g-O2/m3   ;BOD sediment
bottom     AB       [ 0.000]   g-C/m3    ;Total algal biomass sediment
bottom     NO3B    [ 3.000]   g-N/m3    ;Nitrate N sediment

parm       Is1      [40.000]   W/m2      ;Optimal light intensity species 1
parm       Is2      [40.000]   W/m2      ;Optimal light intensity species 2
parm       Is3      [40.000]   W/m2      ;Optimal light intensity species 3
parm       achlc1   [30.000]   ug Chl/mg C ;Chlorophyll to Carbon ratio species 1
parm       achlc2   [30.000]   ug Chl/mg C ;Chlorophyll to Carbon ratio species 2
parm       achlc3   [30.000]   ug Chl/mg C ;Chlorophyll to Carbon ratio species 3
parm       umax1    [ 2.000]   1/day     ;Maximum growth rate species 1
parm       umax2    [ 2.000]   1/day     ;Maximum growth rate species 2
parm       umax3    [ 2.000]   1/day     ;Maximum growth rate species 3
parm       kres1    [ 0.100]   1/day     ;Respiration rate species 1
parm       kres2    [ 0.100]   1/day     ;Respiration rate species 2
parm       kres3    [ 0.100]   1/day     ;Respiration rate species 3
parm       kdie1    [ 0.200]   1/day     ;Die-off rate species 1
parm       kdie2    [ 0.200]   1/day     ;Die-off rate species 2
parm       kdie3    [ 0.200]   1/day     ;Die-off rate species 3
parm       tra1     [ 1.040]   -         ;Temperature coefficient die-off species 1
parm       tra2     [ 1.040]   -         ;Temperature coefficient die-off species 2
parm       tra3     [ 1.040]   -         ;Temperature coefficient die-off species 3
parm       Tcs1     [25.000]   oC        ;Critical temperature species 1
parm       Tcs2     [25.000]   oC        ;Critical temperature species 2
parm       Tcs3     [25.000]   oC        ;Critical temperature species 3
parm       Tos1     [20.000]   oC        ;Optimal temperature species 1
parm       Tos2     [20.000]   oC        ;Optimal temperature species 2
parm       Tos3     [20.000]   oC        ;Optimal temperature species 3
parm       kn1      [ 0.010]   g-N/m3    ;Nitrogen monod constant species 1
parm       kn2      [ 0.010]   g-N/m3    ;Nitrogen monod constant species 2
parm       kn3      [ 0.010]   g-N/m3    ;Nitrogen monod constant species 3

```

|      |        |          |           |   |
|------|--------|----------|-----------|---|
| parm | kp1    | [ 0.005] | g-P/m3    | ;Phosphorus monod constant species 1                  |
| parm | kp2    | [ 0.005] | g-P/m3    | ;Phosphorus monod constant species 2                  |
| parm | kp3    | [ 0.005] | g-P/m3    | ;Phosphorus monod constant species 3                  |
| parm | Vsa1   | [ 0.001] | m/day     | ;Settling velocity species 1                          |
| parm | Vsa2   | [ 0.001] | m/day     | ;Settling velocity species 2                          |
| parm | Vsa3   | [ 0.001] | m/day     | ;Settling velocity species 3                          |
|      |        |          |           |   |
| parm | Vss    | [ 1.00]  | m/day     | ;Fall velocity suspended solids                       |
| parm | POR    | [ 0.90]  | -         | ;Sediment porosity                                    |
| parm | RHO    | [1200.0] | kg/m3     | ;Density suspended solids                             |
| parm | HB     | [ 0.02]  | m         | ;Depth of sediment top layer                          |
|      |        |          |           |   |
| parm | KpipW  | [ 0.01]  | m3/g SS   | ;Partition constant P water column                    |
| parm | KpipB  | [0.0001] | m3/g SS   | ;Partition constant P sediment                        |
| parm | fdpoW  | [ 0.00]  | -         | ;Fraction DOP water coloumn                           |
| parm | fdpoB  | [ 0.00]  | -         | ;Fraction DOP sediment                                |
| parm | TIPLB  | [ 0.05]  | g/m3      | ;Inorganic P lower sediment layer                     |
| parm | TOPLB  | [ 0.01]  | g/m3      | ;Organic P lower sediment layer                       |
| parm | fporg  | [ 0.80]  | -         | ;Fraction organic P released by respiration           |
| parm | apc    | [ 0.025] | mgP/mgC   | ;Phosphorus to Carbon ratio                           |
|      |        |          |           |   |
| parm | fdnoW  | [ 0.00]  | -         | ;Fraction dissolved organic N water column            |
| parm | fdnoB  | [ 0.00]  | -         | ;Fraction dissolved organic N sediment                |
| parm | TONLB  | [ 1.00]  | g-N/m3    | ;Organic N lower sediment layer                       |
| parm | fnorg  | [ 0.80]  | -         | ;Fraction organic N released by respiration           |
| parm | anc    | [ 0.25]  | mgN/mgC   | ;Nitrogen to Carbon ratio                             |
|      |        |          |           |   |
| parm | NH4LB  | [ 1.00]  | g-N/m3    | ;Ammonia N lower sediment layer                       |
| parm | Kmn    | [ 0.025] | g-N/m3    | ;Ammonia preference constant                          |
| parm | tnit   | [ 1.080] | -         | ;Temperature coefficient nitrification                |
| parm | Kno    | [ 0.100] | mg-O2/m3  | ;Oxygen half sat. constant nitr.                      |
|      |        |          |           |   |
| parm | NO3LB  | [ 3.000] | g-N/m3    | ;Nitrate lower sediment layer                         |
| parm | Kden   | [ 0.100] | 1/day     | ;Denitrification rate constant water column           |
| parm | tden   | [ 1.040] | -         | ;Temperature coefficient denitrification water column |
| parm | Kdno   | [ 0.500] | g-N/m3    | ;Oxygen half sat. constant denitrification            |
| parm | KdenB  | [ 0.050] | 1/day     | ;Denitrification rate constant sediment               |
| parm | tdenB  | [ 1.040] | -         | ;Temperature ceoefficient denitrification sediment    |
|      |        |          |           |   |
| parm | O2LB   | [ 0.0]   | g/m3      | ;Oxygen lower sediment layer                          |
| parm | Krmin  | [ 0.1]   | m/day     | ;Minimum oxygen mass transfer coefficient             |
| parm | trea   | [ 1.024] | -         | ;Temperature coefficient reaeration                   |
| parm | aoc    | [ 2.67]  | g-O2/g-C  | ;Oxygen to Carbon ratio                               |
|      |        |          |           |   |
| parm | BODLB  | [ 20.00] | g/m3      | ;BOD lower sediment layer                             |
| parm | tbod   | [ 1.04]  | -         | ;Temperature coefficient oxidation water column       |
| parm | fdbodW | [ 1.00]  | -         | ;Fraction dissolved BOD water column                  |
| parm | fdbodB | [ 0.00]  | -         | ;Fraction dissolved BOD sediment                      |
| parm | Kbodo  | [ 2.00]  | g/m3      | ;Oxygen half sat constant oxidation                   |
| parm | KbodB  | [ 0.05]  | 1/day     | ;Anaerobic decomposition rate BOD sediment            |
| parm | tbodB  | [ 1.04]  | -         | ;Temperature coefficient anaerobic BOD decomposition  |
|      |        |          |           |   |
| parm | KdaB   | [ 0.01]  | 1/day     | ;Anaerobic decay algae sediment                       |
| parm | tdaB   | [ 1.040] | -         | ;Temperature coefficient algal decay sediment         |
|      |        |          |           |   |
| parm | KminB  | [0.0004] | 1/day     | ;Anearobic decomposition rate                         |
| parm | tminB  | [1.080]  | -         | ;Temperature coefficient anaerobic decomposition      |
| parm | Kmin   | [0.1000] | 1/day     | ;Decomposition rate organic matter water column       |
| parm | tmin   | [1.0400] | -         | ;Temperature coefficient decomposition                |
|      |        |          |           |   |
| parm | ma     | [ 1.884] | g alg/g C | ;Biomass to Carbon ratio algae                        |
| parm | E0     | [0.627]  | m-1       | ;Background extinction                                |
| parm | Eads   | [0.0498] | -         | ;Contribution of yellow substance to extinction       |
| parm | Ealg   | [0.0209] | m-1mg-1m3 | ;Contribution of algae to extinction                  |
| parm | Edet   | [0.0490] | m-1g-1m3  | ;Contribution of detritus to extinction               |
| parm | Ess    | [0.0253] | m-1g-1m3  | ;Contribution of suspended solids to extinction       |

```

parm      Sd0      [3.31]      m      ;Background secchi depth
parm      Sdads    [0.0107]     -      ;Contribution of gelbstoff to inverse secchi
depth
parm      Sdalg    [0.0111]     m-lmg-lm3 ;Contriution of algae to inverse secchi depth
parm      Sddet    [0.0636]     m-lg-lm3 ;Contribution of detritus to inverse secchi
depth
parm      Sdsss    [0.0606]     m-lg-lm3 ;Contribution of suspended solids to inverse
secchi depth

```

```

xt      Fres      [ 5.00]      g/m2,day ;Resuspension flux
xt      T          [ 0 ]      oC      ;Temperature
xt      Ia        [187.90]     W/m2     ;Average light intensity
xt      L          [ 13.94]     hour     ;Day length
xt      Ads        [ 8.5]      m-1      ;Adsorption at 380 nm
xt      Edif       [0.0002]     m2/day   ;Diffusive exchange
xt      Kbod       [ 0.15]     1/day    ;Oxidation rate constant BOD water column
xt      Knit       [0.1000]     1/day    ;Nitrification rate constant

```

```

flow     Z          [ 8.00]      m      ;Depth
flow     As        [375.00]     m2     ;Flow area
flow     Q          [ 75.00]     m3/s   ;Flow

```

```

{
Atot=A1+A2+A3;

```

```

Kdif=Edif/HB;

```

```

mino=Kmin*tmin^(T-20);
minoB=KminB*tminB^(T-20);
minaB=KdaB*tdaB^(T-20);

```

```

k1(SSW)=-Vss/Z;
k0(SSW)=Fres/Z;
SSB=RHO*1000*(1-POR);
Fsed=Vss*SSW;
Vs=Fsed/(RHO*(1-POR)*1000);
Vr=Fres/(RHO*(1-POR)*1000);
Vsd=Vs-Vr;
Vsnet=(Fsed-Fres)/SSW;

```

```

Chla=achlc1*A1+achlc2*A2+achlc3*A3;

```

```

Etot= E0 + Ealg*Chla + Eads*Ads + Ess*SSW + Edet*DET;
Secchi=1/((1/Sd0) + Sdalg*Chla + Sdads*Ads + Sdsss*SSW + Sddet*DET);

```

```

alfa01=Ia/Is1;
alfall1=alfa01*exp(-1*etot*z);
alfa02=Ia/Is2;
alfal2=alfa02*exp(-1*etot*z);
alfa03=Ia/Is3;
alfal3=alfa03*exp(-1*etot*z);
f=L/24;
fl1=2.718*f*(exp(-1*alfall1)-exp(-1*alfa01))/(etot*z);
fl2=2.718*f*(exp(-1*alfal2)-exp(-1*alfa02))/(etot*z);
fl3=2.718*f*(exp(-1*alfal3)-exp(-1*alfa03))/(etot*z);
if (T>Tcs1)

```

```

{
ft1=0.;
}

```

```

else
{
beta1=(Tcs1-T)/(Tcs1-Tos1);
ft1=beta1*exp(1-beta1);
}

```

```

if (T>Tcs2)

```

```

{
ft2=0.;
}

```

```

else
{
beta2=(Tcs2-T)/(Tcs2-Tos2);

```

```

        ft2=beta2*exp(1-beta2);
    }
if (T>Tcs3)
{
    ft3=0.;
}
else
{
    beta3=(Tcs3-T)/(Tcs3-Tos3);
    ft3=beta3*exp(1-beta3);
}
DINW=NO3W+NH4W;
fdpW=1/(1+KpipW*SSW);
DIPW=fdpW*TIPW;
fn1=min(DIPW/(DIPW+kp1),DINW/(DINW+kn1));
fn2=min(DIPW/(DIPW+kp2),DINW/(DINW+kn2));
fn3=min(DIPW/(DIPW+kp3),DINW/(DINW+kn3));
Gr1=umax1*f11*ft1*fn1;
Gr2=umax2*f12*ft2*fn2;
Gr3=umax3*f13*ft3*fn3;
GrT=Gr1*A1+Gr2*A2+Gr3*A3;
Resp1=kdie1+kres1*tra1^(T-20);
Resp2=kdie2+kres2*tra2^(T-20);
Resp3=kdie3+kres3*tra3^(T-20);
RespT=Resp1*A1+Resp2*A2+Resp3*A3;
k1(A1)=Gr1-Resp1-Vsa1/Z;
k1(A2)=Gr2-Resp2-Vsa2/Z;
k1(A3)=Gr3-Resp3-Vsa3/Z;

k0(DET)=RespT*ma;
k1(DET)=-1*mino-Vsnet;

k1(AB)=-minaB;
k0(AB)=(Vsa1*A1+Vsa2*A2+Vsa3*A3)/HB;

fdpB=1/(1+KpipB*SSB);
DIPB=fdpB*TIPB/POR;
PIPW=(1-fdpW)*TIPW/SSW;
PIPB=(1-fdpB)*TIPB/SSB;
FipD=Kdif*(DIPB-DIPW);
FipS=Fsed*PIPW+Vs*POR*DIPW;
FipR=Fres*PIPB+Vr*POR*DIPB;
FipB=-Vsd*TIPB;
If (Vsd<0.0)
{
    FipB+=Vsd*TIPLB;
}
k0(TIPW)=mino*TOPW-GrT*apc+RespT*apc*(1-fporg)+(FipD-FipS+FipR)/Z;
k0(TIPB)=minoB*TOPB+(-FipD+FipS-FipR+FipB)/HB;

NH4I=NH4B/POR;
Fnh4D=Kdif*(NH4I-NH4W);
Fnh4S=Vs*POR*NH4W;
Fnh4R=Vr*POR*NH4I;
Fnh4B=-Vsd*NH4B;
If (Vsd<0.0)
{
    Fnh4B+=Vsd*NH4LB;
}
if (NO3W==0.0 && NH4W==0.0)
{
    pnh4=0.;
}
else
{
    pnh4=NH4W*NO3W/((kmn+NH4W)*(kmn+NO3W))+NH4W*kmn/((NH4W+NO3W)*(kmn+NO3W));
}
Nitr=Knit*tnit^(T-20)*O2W/(O2W+Kno);
k1(NH4W)=-Nitr;
k0(NH4W)=mino*TONW-anc*Pnh4*GrT+(1-fnorg)*anc*RespT+(Fnh4D-Fnh4S+Fnh4R)/Z;
k1(NH4B)=0;

```

```

k0 (NH4B) =minoB*TONE+ (-Fnh4D+Fnh4S-Fnh4R+Fnh4B) /HB;

NO3I=NO3E/POR;
Fno3D=Kdif*(NO3I-NO3W);
Fno3S=Vs*POR*NO3W;
Fno3R=Vr*POR*NO3I;
Fno3B=-Vsd*NO3B;
If (Vsd<0.0)
{
    Fno3B=+Vsd*NO3LB;
}
denitW=Kden*tnden^(T-20)*Kdno/(Kdno+O2W);
denitB=KdenB*tndenB^(T-20);
kl(NO3W)=-denitW;
k0(NO3W)=nitr*NH4W-anc*(1-pnh4)*GrT+(Fno3D-Fno3S+Fno3R)/Z;
kl(NO3B)=-denitB;
k0(NO3B)=(-Fno3D+Fno3S-Fno3R+Fno3B)/HB;

DOPW=fdpoW*TOPW;
DOPB=fdpoB*TOPB/POR;
POPW=(1-fdpoW)*TOPW/SSW;
POPB=(1-fdpoB)*TOPB/SSB;
FopD=Kdif*(DOPB-DOPW);
FopS=Fsed*POPW+Vs*POR*DOPW;
FopR=Fres*POPB+Vr*POR*DOPB;
FopB=-Vsd*TOPB;
If (Vsd<0.0)
{
    FopB=+Vsd*TOPLB;
}
kl(TOPW)=-mino;
k0(TOPW)=fporG*RespT*apc+(FopD-FopS+FopR)/Z;
kl(TOPB)=-minoB;
k0(TOPB)=apc*minaB*AB+(-FopD+FopS-FopR+FopB)/HB;

DONW=fdnoW*TONW;
DONB=fdnoB*TONB/POR;
PONW=(1-fdnoW)*TONW/SSW;
PONB=(1-fdnoB)*TONB/SSB;
FonD=Kdif*(DONB-DONW);
FonS=Fsed*PONW+Vs*POR*DONW;
FonR=Fres*PONB+Vr*POR*DONB;
FonB=-Vsd*TONB;
If (Vsd<0.0)
{
    FonB=+Vsd*TONLB;
}
kl(TONW)=-mino;
k0(TONW)=fnorg*RespT*anc+(FonD-FonS+FonR)/Z;
kl(TONB)=-minoB;
k0(TONB)=anc*minaB*AB+(-FonD+FonS-FonR+FonB)/HB;

DBODW=fdbodW*BODW;
DBODB=fdbodB*BODE/POR;
PBODW=(1-fdbodW)*BODW/SSW;
PBODB=(1-fdbodB)*BODE/SSB;
FbodD=Kdif*(DBODB-DBODW);
FbodS=Fsed*PBODW+Vs*POR*DBODW;
FbodR=Fres*PBODB+Vr*POR*DBODB;
FbodB=-Vsd*BOCB;
If (Vsd<0.0)
{
    FbodB=vsd*BODLB;
}
oxidW=Kbod*tbod^(T-20)*O2W/(O2W+Kbodo);
oxidB=KbodB*tbodB^(T-20);
kdieT=Kdie1*A1+Kdie2*A2+kdie3*A3;
XCONV=1-exp(-5*kbod);
kl(BODW)=-oxidW;
k0(BODW)=(kdieT*apc-5/4*32/14*denitW*NO3W)*XCONV+(FbodD-FbodS+FbodR)/Z;

```

```

k1(BODB)=-oxidB;
k0(BODB)=+(aoc*minaB*AB-5/4*32/14*denitB*NO3B)*XCONV+(-FbodD+FbodS-FbodR+FbodB)/HB;

O2I=O2B/POR;
Fo2D=Kdif*(O2I-O2W);
Fo2S=Vs*POR*O2W;
Fo2R=Vr*POR*O2I;
Fo2B=-Vsd*O2b;
If (Vsd<0.0)
  {
    Fo2B+=Vsd*O2LB;
  }
u=ABS(Q/As);
kmas=(3.94*u^0.5*z^(-1.5))*trea^(t-20);
if (kmas<krmin)
  {
    kmas=krmin;
  }
kre=kmas/z;
cs=14.5519-0.373484*t+0.00501607*t*t;
k1(O2W)=-kre;
k0(O2W)=kre*cs-oxidW*BODW/XCONV-64/14*nitr*NH4W-32/12*(RespT-
kdieT)+GrT*(32/12+48/14*anc*(1-pnh4)*NO3W)+(Fo2D-Fo2S+Fo2R)/Z;
k0(O2B)=(-oxidB*BODB)/XCONV+(-Fo2D+Fo2S-Fo2R+Fo2B)/HB;
}

```

## APPENDIX-B Daily DO loads from SEPA and Aeration Stations

Table B.1 Daily DO loads from SEPA and Aeration Stations (g/s)

| Date       | SEPA3 | SEPA4 | SEPA5 | Webster Avenue | Devon Avenue |
|------------|-------|-------|-------|----------------|--------------|
| 04/01/2002 | 12.67 | 10.73 | 0.00  | 0.00           | 0.00         |
| 04/02/2002 | 10.95 | 9.83  | 0.00  | 29.13          | 7.29         |
| 04/03/2002 | 11.68 | 8.45  | 0.00  | 0.00           | 1.39         |
| 04/04/2002 | 11.94 | 9.63  | 0.00  | 5.93           | 3.88         |
| 04/05/2002 | 12.20 | 9.57  | 0.00  | 0.00           | 0.00         |
| 04/06/2002 | 12.68 | 8.94  | 0.00  | 13.46          | 3.71         |
| 04/07/2002 | 12.30 | 9.12  | 0.00  | 11.06          | 0.00         |
| 04/08/2002 | 12.38 | 9.27  | 0.00  | 10.30          | 6.88         |
| 04/09/2002 | 13.17 | 11.22 | 0.00  | 27.30          | 21.21        |
| 04/10/2002 | 13.47 | 13.09 | 0.00  | 0.00           | 1.41         |
| 04/11/2002 | 13.67 | 12.83 | 0.00  | 0.00           | 0.66         |
| 04/12/2002 | 14.88 | 12.64 | 0.00  | 0.00           | 0.00         |
| 04/13/2002 | 16.46 | 13.38 | 3.46  | 22.16          | 0.00         |
| 04/14/2002 | 11.10 | 14.05 | 8.71  | 12.91          | 4.33         |
| 04/15/2002 | 15.31 | 13.65 | 9.60  | 24.84          | 7.91         |
| 04/16/2002 | 14.76 | 12.65 | 9.34  | 19.37          | 17.07        |
| 04/17/2002 | 16.43 | 12.00 | 9.10  | 27.00          | 21.23        |
| 04/18/2002 | 18.74 | 12.54 | 8.19  | 30.98          | 17.91        |
| 04/19/2002 | 14.76 | 12.26 | 7.65  | 25.67          | 17.79        |
| 04/20/2002 | 16.90 | 12.88 | 6.93  | 25.36          | 25.88        |
| 04/21/2002 | 17.15 | 16.48 | 9.97  | 36.61          | 23.54        |
| 04/22/2002 | 16.52 | 15.30 | 12.21 | 15.41          | 9.35         |
| 04/23/2002 | 17.06 | 13.16 | 10.08 | 24.98          | 8.18         |
| 04/24/2002 | 15.70 | 12.72 | 7.55  | 6.93           | 22.89        |
| 04/25/2002 | 14.89 | 11.69 | 6.84  | 30.02          | 20.05        |
| 04/26/2002 | 16.28 | 11.56 | 7.08  | 8.14           | 14.01        |
| 04/27/2002 | 14.79 | 13.40 | 7.87  | 36.56          | 32.17        |
| 04/28/2002 | 12.69 | 12.42 | 9.40  | 33.38          | 27.29        |
| 04/29/2002 | 14.41 | 11.81 | 8.50  | 14.25          | 24.09        |
| 04/30/2002 | 14.57 | 12.66 | 7.92  | 17.04          | 15.15        |
| 05/01/2002 | 16.06 | 13.32 | 9.58  | 20.68          | 19.78        |
| 05/02/2002 | 16.43 | 12.37 | 9.48  | 22.24          | 28.17        |
| 05/03/2002 | 15.53 | 11.70 | 8.79  | 0.00           | 5.86         |
| 05/04/2002 | 15.97 | 10.07 | 8.26  | 0.00           | 20.54        |

## **APPENDIX-C Initial Conditions**

Initial conditions are given in Table C.1. Starting from upstream boundaries, initial conditions for discharge (1<sup>st</sup> measurement of the simulation period) were introduced at the each node by adding the cumulative flow as tributaries or treatment facilities enter to the system. Water level data provided by the MWRDGC (Lawrence Avenue, Southwest Highway, Western Avenue, Willow Spring, Cal-Sag Junction) and USGS (boundary conditions) were used to set initial conditions for water level at the each node by doing interpolation. Calculation nodes and sections are given in Figure C.1 It was observed that effect of hydraulic initial conditions are negligible since it takes just a few a hours to converge. Initial conditions for the water quality variables were introduced based on the water quality measurements provided by MWRDGC at several sampling locations. Default DUFLOW EUTROF2 sediment concentrations were used as initial conditions.

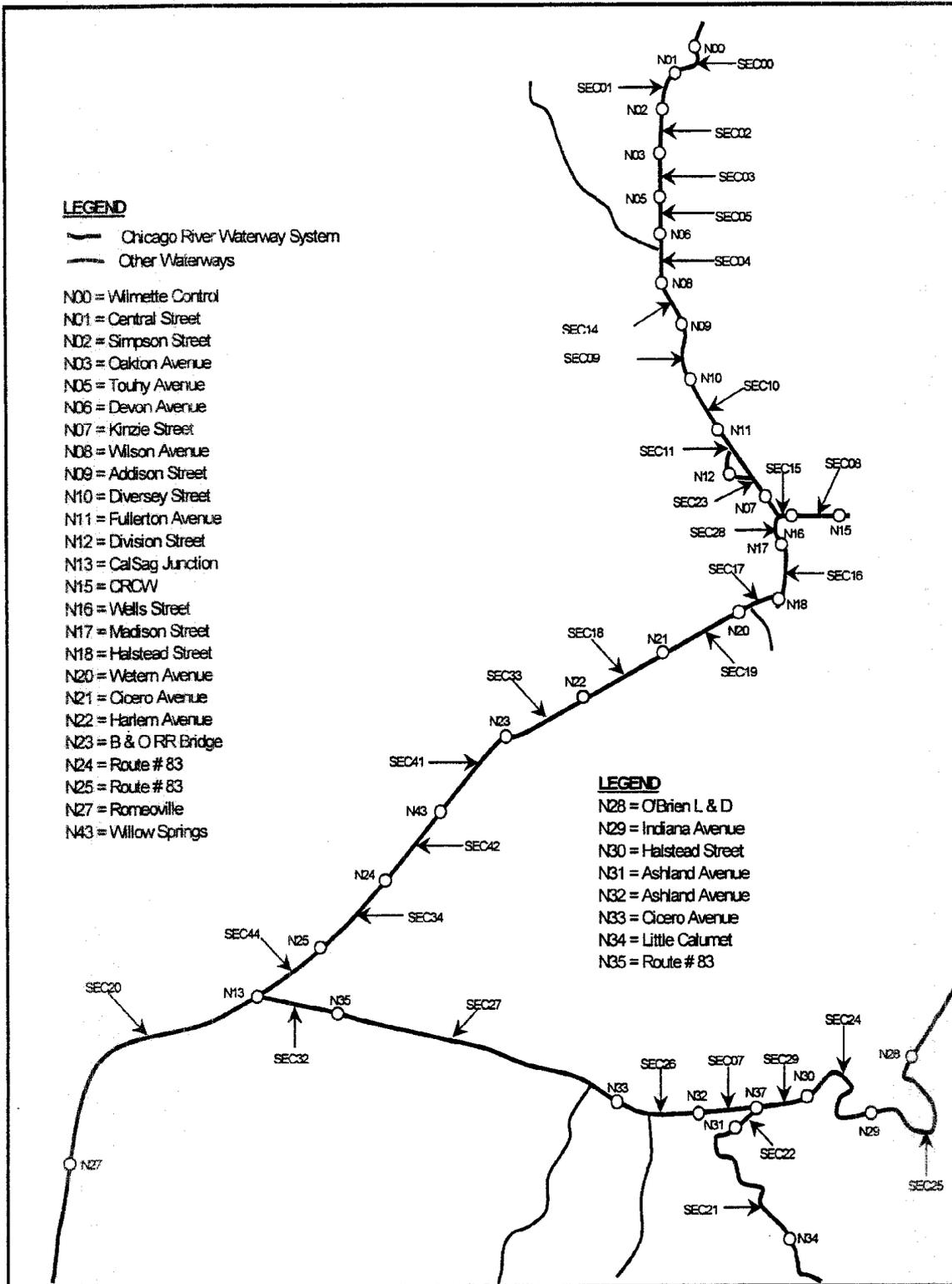


Figure C.1 Calculation nodes sections for the Chicago Waterway System

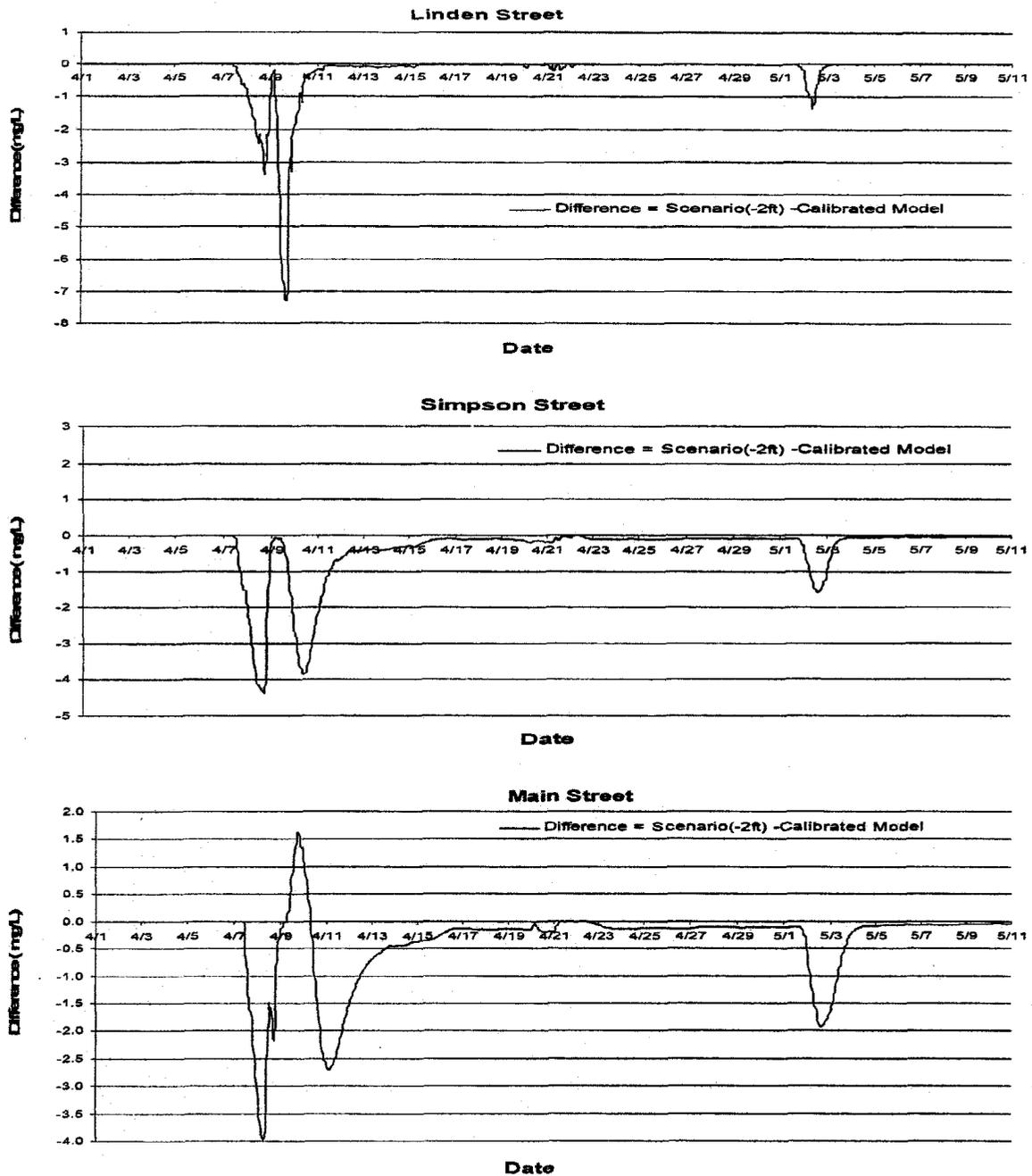
**Table C.1** Initial conditions used in DUFLOW model

|                  | Discharge | Level   | a1  | a2   | a3   | ab | bods | bods | det | nh4s | nh4w | no3s | no3w | o2s | o2w  | ssw | tips | tipw | tons | tonw | tops | topw |
|------------------|-----------|---------|-----|------|------|----|------|------|-----|------|------|------|------|-----|------|-----|------|------|------|------|------|------|
| SEC00000 - begin | 1.27      | -0.367  | 3   | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.4  | 3    | 0.5  | 0   | 2    | 15  | 0.1  | 0.1  | 1    | 0.6  | 0.1  | 0.05 |
| SEC00000 - end   | 1.27      | -0.3825 | 3   | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.4  | 3    | 0.5  | 0   | 2    | 15  | 0.1  | 0.1  | 1    | 0.6  | 0.1  | 0.05 |
| SEC00001 - begin | 1.27      | -0.3825 | 3   | 0.15 | 0.15 | 0  | 20   | 5    | 1   | 1    | 0.6  | 3    | 0.5  | 0   | 2    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.05 |
| SEC00001 - end   | 1.27      | -0.3961 | 3   | 0.15 | 0.15 | 0  | 20   | 5    | 1   | 1    | 0.6  | 3    | 0.5  | 0   | 0    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.05 |
| SEC00002 - begin | 1.27      | -0.3961 | 2   | 0.15 | 0.15 | 0  | 20   | 5    | 1   | 1    | 0.6  | 3    | 2    | 0   | 0    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.05 |
| SEC00002 - end   | 1.27      | -0.4349 | 2   | 0.15 | 0.15 | 0  | 20   | 5    | 1   | 1    | 0.6  | 3    | 2    | 0   | 1    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.05 |
| SEC00005 - begin | 12.57     | -0.4601 | 2.3 | 0.15 | 0.15 | 0  | 20   | 7    | 1   | 1    | 1.4  | 3    | 6    | 0   | 4    | 15  | 0.1  | 0.05 | 1    | 1.6  | 0.1  | 0.2  |
| SEC00005 - end   | 12.57     | -0.4794 | 2.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 6    | 0   | 4    | 15  | 0.1  | 0.05 | 1    | 1.6  | 0.1  | 0.2  |
| SEC00014 - begin | 15.03     | -0.5227 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00014 - end   | 15.03     | -0.5294 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00009 - begin | 15.03     | -0.5294 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00009 - end   | 15.03     | -0.5351 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00010 - begin | 15.03     | -0.5351 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00010 - end   | 15.03     | -0.5387 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00011 - begin | 15.03     | -0.5387 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00011 - end   | 15.03     | -0.5495 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 5    | 0   | 6.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00016 - begin | 21.09     | -0.5604 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3.5  | 0   | 5.3  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00016 - end   | 21.09     | -0.57   | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3.5  | 0   | 6    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00019 - begin | 21.09     | -0.5851 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3.5  | 0   | 6    | 15  | 0.1  | 0.6  | 1    | 1.2  | 0.1  | 0.2  |
| SEC00019 - end   | 21.09     | -0.6021 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3.5  | 0   | 6    | 15  | 0.1  | 0.6  | 1    | 1.2  | 0.1  | 0.2  |
| SEC00033 - begin | 53.73     | -0.6186 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 6    | 0   | 6.7  | 15  | 0.1  | 0.6  | 1    | 1.2  | 0.1  | 0.2  |
| SEC00033 - end   | 53.73     | -0.6273 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 6    | 0   | 5.5  | 15  | 0.1  | 0.6  | 1    | 1.2  | 0.1  | 0.2  |
| SEC00034 - begin | 53.73     | -0.6505 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 6    | 0   | 5.5  | 15  | 0.1  | 0.6  | 1    | 1.2  | 0.1  | 0.2  |
| SEC00034 - end   | 53.73     | -0.6505 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 6    | 0   | 5.5  | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00008 - begin | 6.06      | -0.5689 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 11.9 | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00008 - end   | 21.09     | -0.5602 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 8    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00021 - begin | 3.89      | 0.3261  | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 8    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00021 - end   | 4.05      | -0.3251 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 8    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00022 - begin | 4.05      | -0.3251 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 8    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00022 - end   | 23.93     | -0.5432 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 7    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00029 - begin | 19.88     | -0.5449 | 2   | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 4.5  | 0   | 7    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00029 - end   | 23.93     | -0.5432 | 2   | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 4.5  | 0   | 7    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00007 - begin | 23.93     | -0.5432 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 8    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |
| SEC00007 - end   | 23.93     | -0.5414 | 0.3 | 0.15 | 0.15 | 0  | 20   | 4    | 1   | 1    | 0.6  | 3    | 3    | 0   | 8    | 15  | 0.1  | 0.05 | 1    | 1.2  | 0.1  | 0.2  |

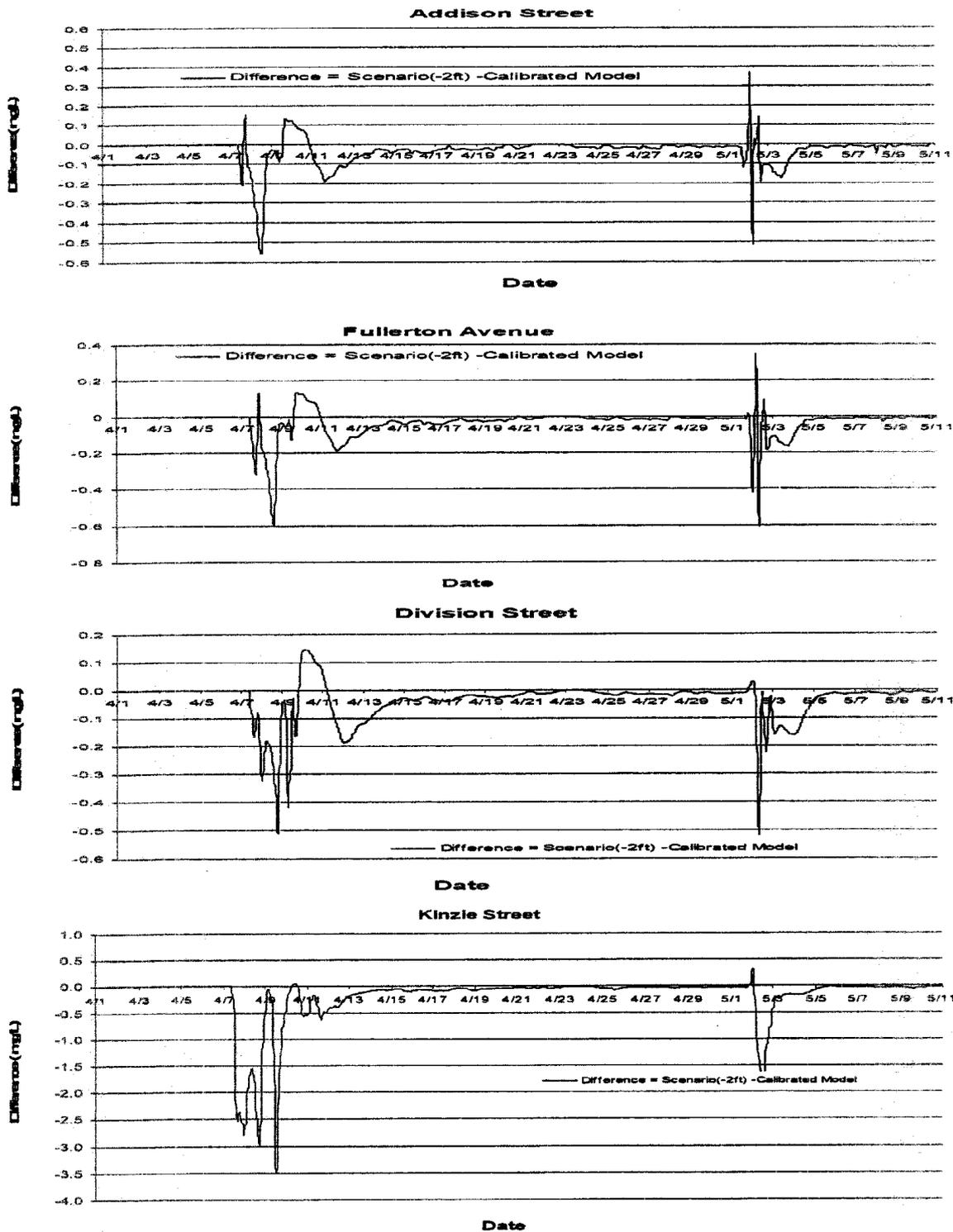
|                  |       |         |     |      |      |   |    |   |   |   |     |   |     |   |     |    |     |      |   |     |     |     |
|------------------|-------|---------|-----|------|------|---|----|---|---|---|-----|---|-----|---|-----|----|-----|------|---|-----|-----|-----|
| SEC00032 - begin | 24.6  | -0.4898 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 9.8 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00032 - end   | 78.57 | -0.6505 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 9.8 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00025 - begin | 6.06  | -0.5689 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 12  | 15 | 0.1 | 0.25 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00025 - end   | 6.23  | -0.5529 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 1.5 | 0 | 8   | 15 | 0.1 | 0.25 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00041 - begin | 53.73 | -0.6273 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 1.5 | 0 | 6.5 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00041 - end   | 53.73 | -0.6505 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 6   | 0 | 6.5 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00042 - begin | 53.73 | -0.6505 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 6   | 0 | 6.5 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00042 - end   | 53.73 | -0.6505 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 6   | 0 | 6.5 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00044 - begin | 53.73 | -0.6505 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 6   | 0 | 5.5 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00044 - end   | 78.57 | -0.6505 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 6   | 0 | 5.5 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00003 - begin | 1.27  | -0.4349 | 0.3 | 0.15 | 0.15 | 0 | 20 | 7 | 1 | 1 | 1.4 | 3 | 6   | 0 | 1   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.4 |
| SEC00003 - end   | 12.57 | -0.4601 | 0.3 | 0.15 | 0.15 | 0 | 20 | 7 | 1 | 1 | 1.4 | 3 | 6   | 0 | 6.8 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.4 |
| SEC00004 - begin | 12.57 | -0.4794 | 0.3 | 0.15 | 0.15 | 0 | 20 | 6 | 1 | 1 | 0.9 | 3 | 5   | 0 | 6.8 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00004 - end   | 15.03 | -0.5227 | 0.3 | 0.15 | 0.15 | 0 | 20 | 6 | 1 | 1 | 0.9 | 3 | 5   | 0 | 6.1 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00015 - begin | 6.06  | -0.5689 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3.5 | 0 | 8   | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00015 - end   | 21.09 | -0.5604 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3.5 | 0 | 7   | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00017 - begin | 21.09 | -0.57   | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3.5 | 0 | 6   | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00017 - end   | 21.09 | -0.5851 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3.5 | 0 | 6   | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00018 - begin | 21.09 | -0.6021 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 6.5 | 0 | 6   | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00018 - end   | 53.73 | -0.6186 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 6.5 | 0 | 6.7 | 15 | 0.1 | 0.6  | 1 | 1.2 | 0.1 | 0.2 |
| SEC00020 - begin | 78.57 | -0.6505 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 5.5 | 0 | 6.5 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00020 - end   | 78.88 | -0.6672 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 5.5 | 0 | 6.5 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00024 - begin | 6.23  | -0.5529 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 2.5 | 0 | 8   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00024 - end   | 19.88 | -0.5449 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 2.5 | 0 | 7   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00026 - begin | 23.93 | -0.5414 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 8   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00026 - end   | 24.14 | -0.5271 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 8   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00027 - begin | 24.14 | -0.5271 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 8   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00027 - end   | 24.6  | -0.5495 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 9.8 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00023 - begin | 15.03 | -0.5517 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 6.5 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00023 - end   | 15.03 | -0.5567 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 6.5 | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00028 - begin | 15.03 | -0.5567 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 8   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |
| SEC00028 - end   | 21.09 | -0.5504 | 0.3 | 0.15 | 0.15 | 0 | 20 | 4 | 1 | 1 | 0.6 | 3 | 3   | 0 | 8   | 15 | 0.1 | 0.05 | 1 | 1.2 | 0.1 | 0.2 |

\* w = water; s = sediment

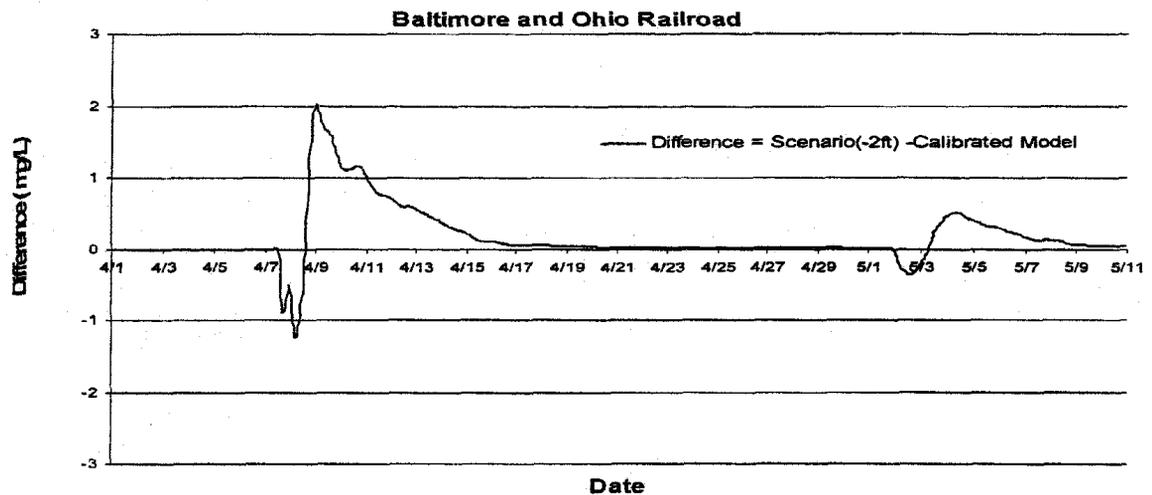
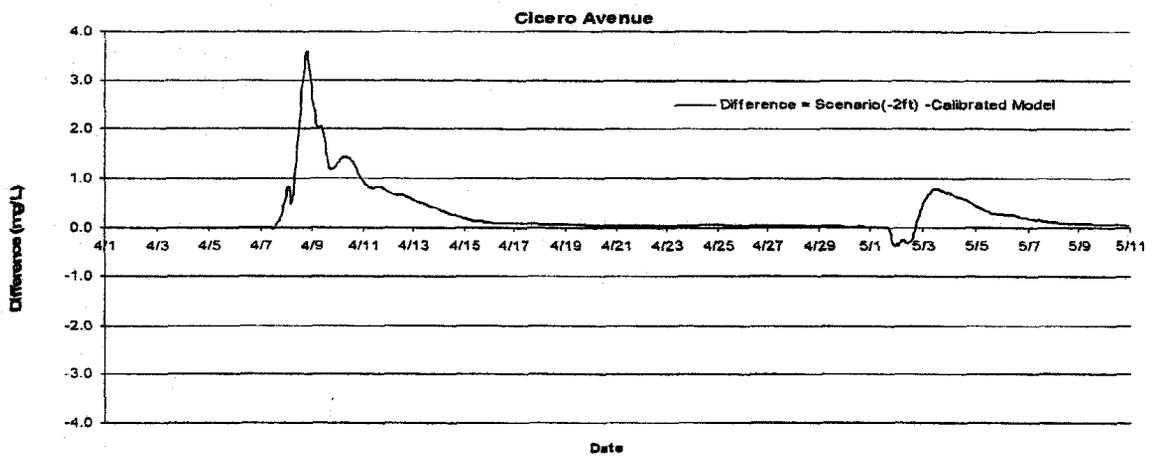
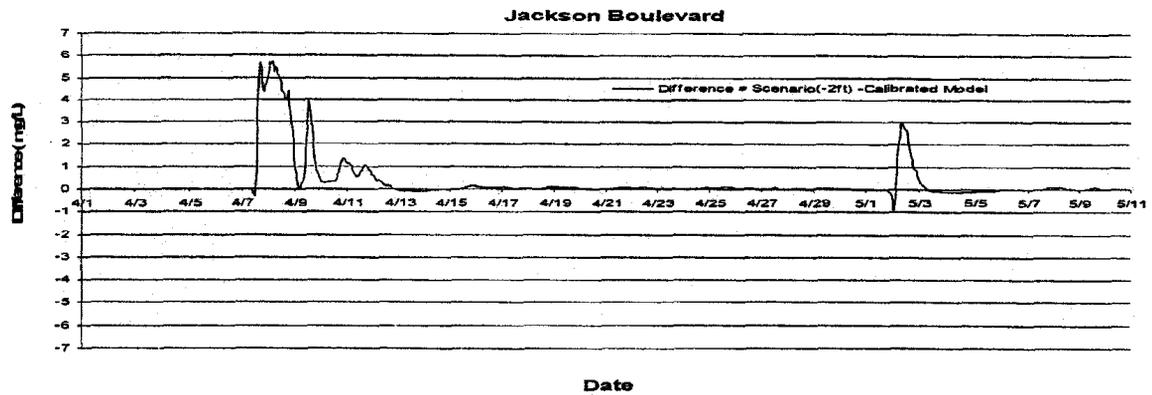
**APPENDIX-D** Difference dissolved oxygen concentration between the scenario where water-surface elevations are held at or above -2ft City of Chicago Datum at the lakefront and the scenario where measured water surface elevations at the lakefront are used



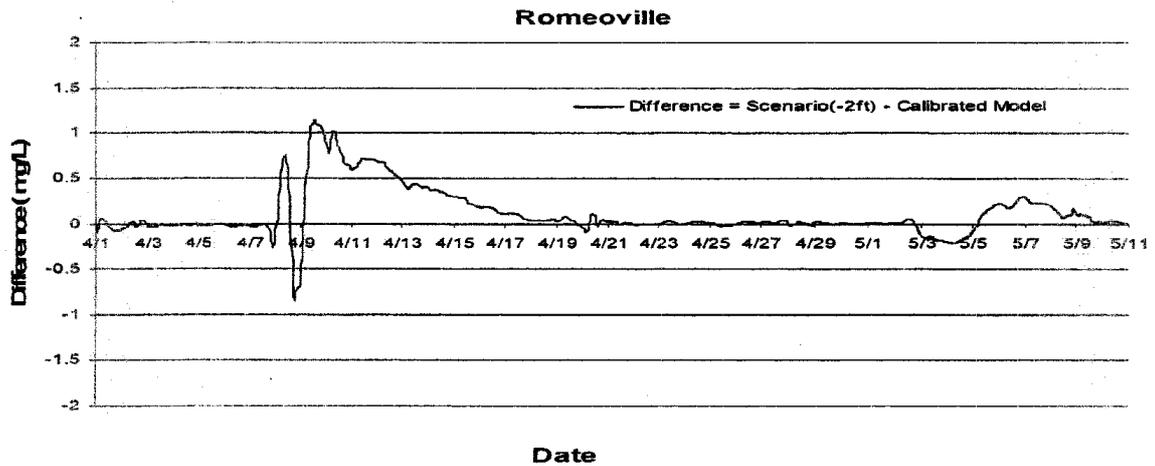
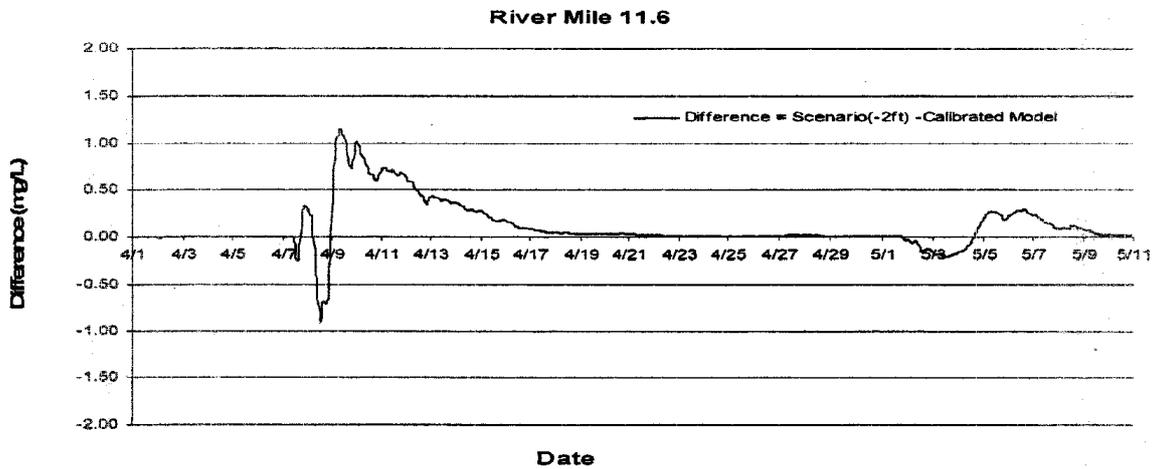
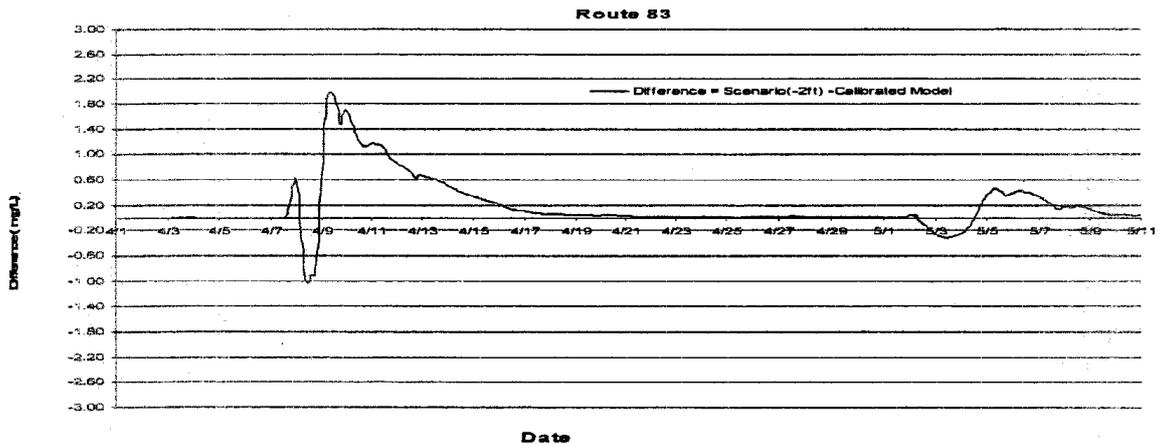
**Figure D.1** Difference in dissolved oxygen concentrations resulting when water-surface elevations at the lakefront are held at or above -2 ft City of Chicago Datum (scenario=-2 ft) relative to those resulting when measured water-surface elevations (calibrated model) are used in the simulation for locations on the North Shore Channel



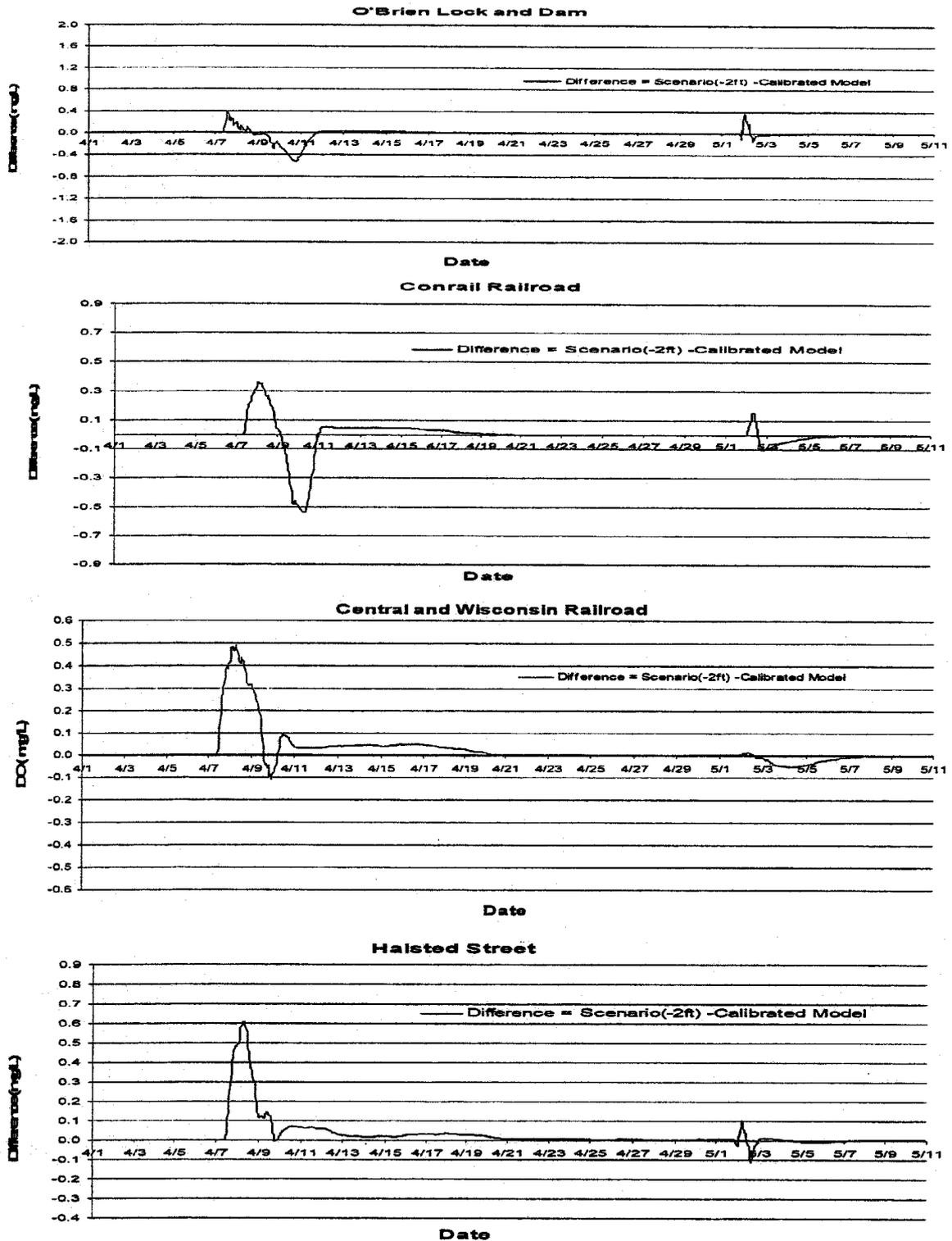
**Figure D.2** Difference in dissolved oxygen concentrations resulting when water-surface elevations at the lakefront are held at or above -2 ft City of Chicago Datum (scenario=-2 ft) relative to those resulting when measured water-surface elevations (calibrated model) are used in the simulation for locations on the North Branch Chicago River



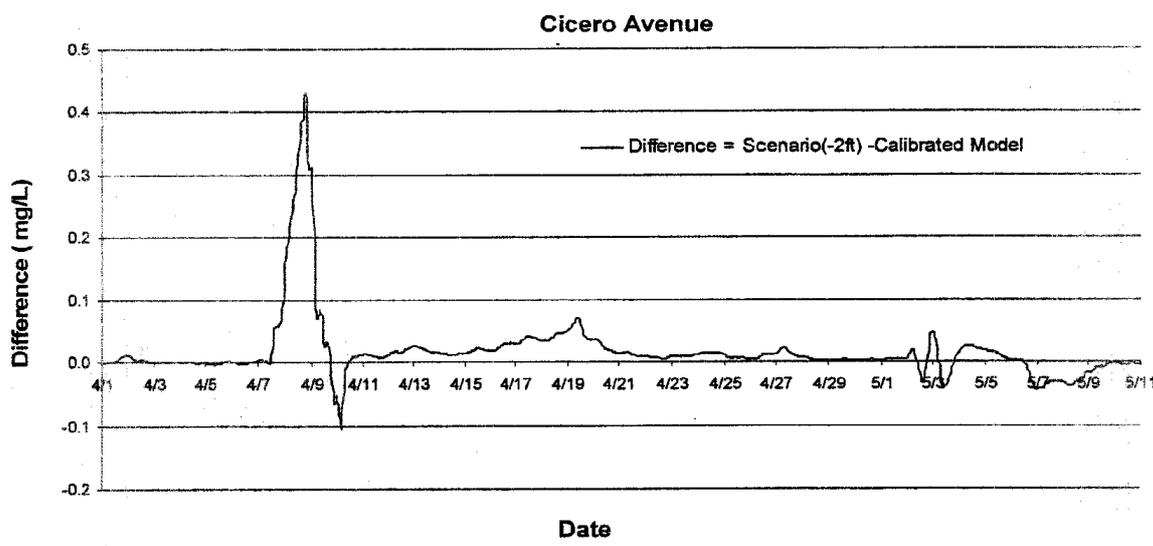
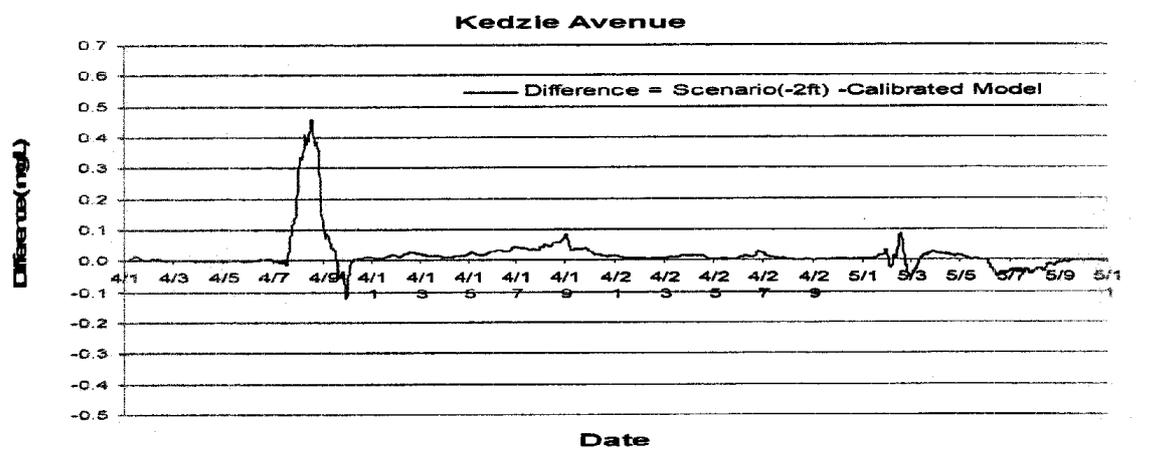
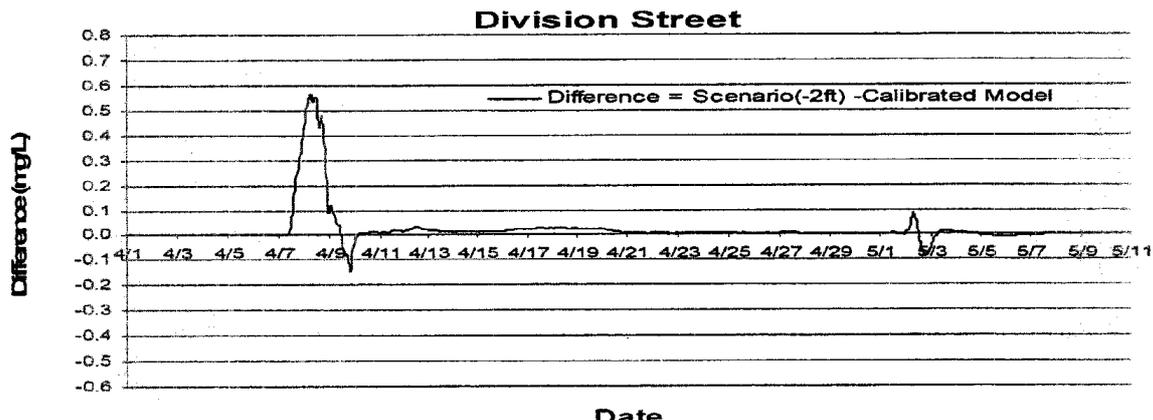
**Figure D.3** Difference in dissolved oxygen concentrations resulting when water-surface elevations at the lakefront are held at or above -2 ft City of Chicago Datum (scenario=-2 ft) relative to those resulting when measured water-surface elevations (calibrated model) are used in the simulation for locations on the South Branch Chicago River and the Chicago Sanitary and Ship Canal



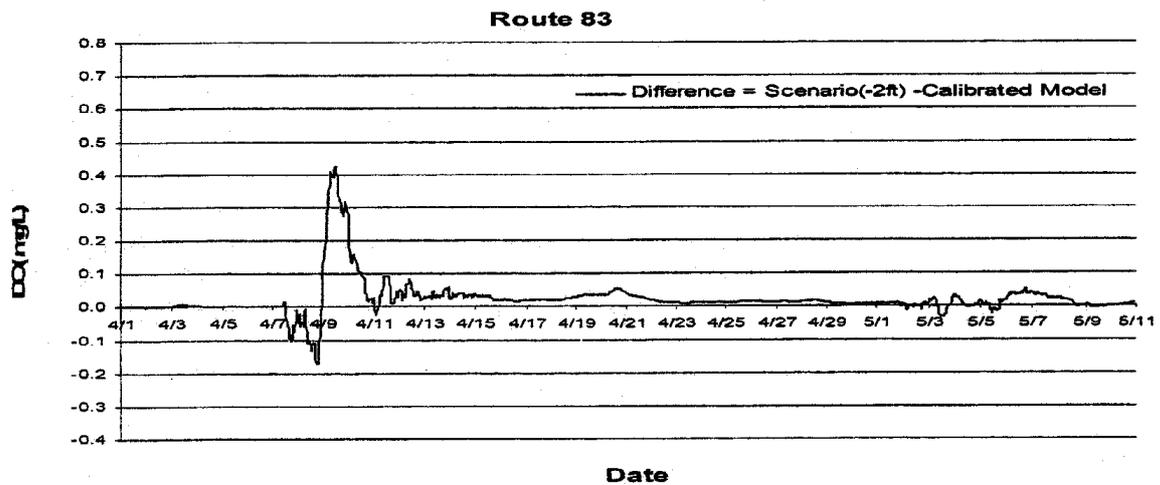
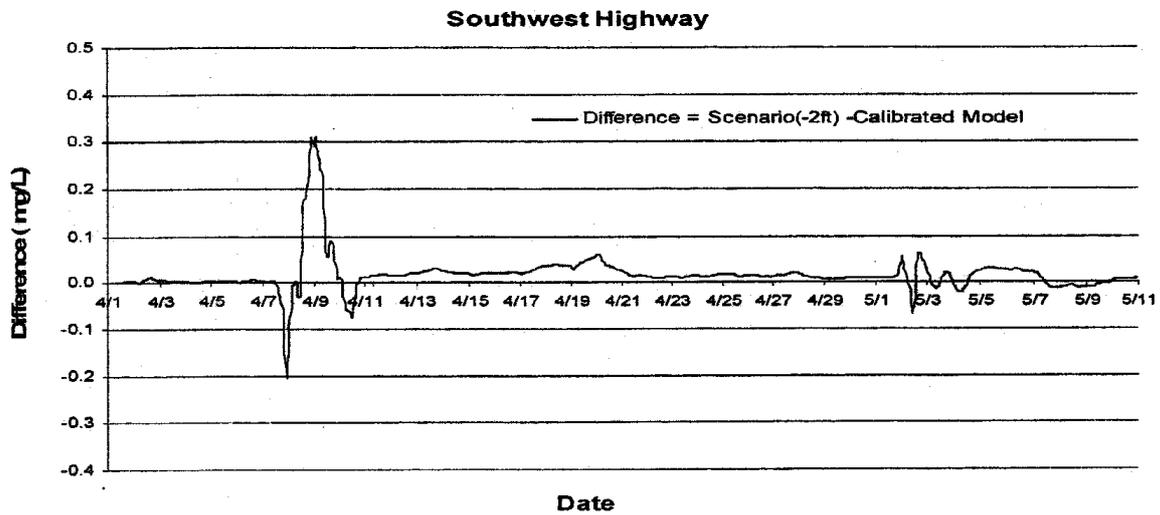
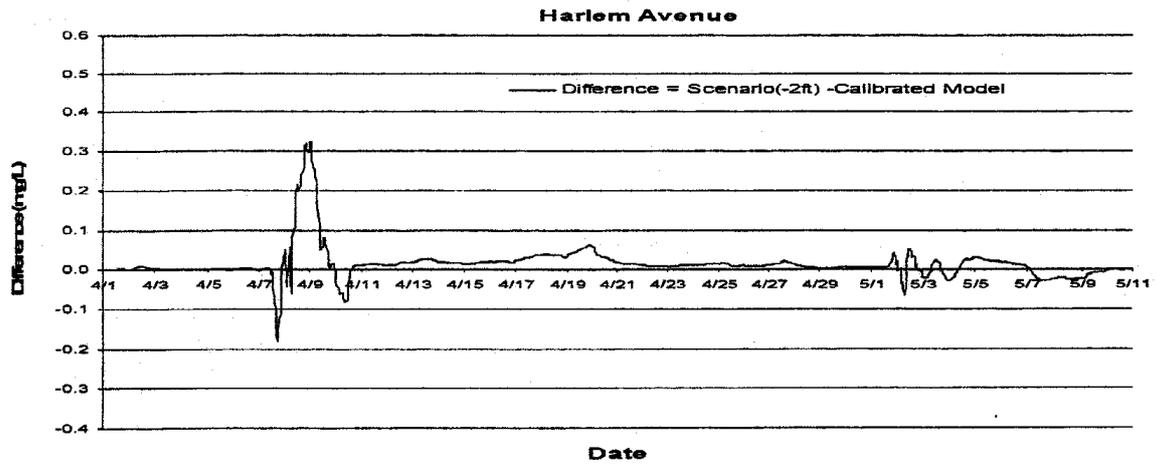
**Figure D.3 (cont.)** Difference in dissolved oxygen concentrations resulting when water-surface elevations at the lakefront are held at or above  $-2$  ft City of Chicago Datum (scenario= $-2$  ft) relative to those resulting when measured water-surface elevations (calibrated model) are used in the simulation for locations on the South Branch Chicago River and the Chicago Sanitary and Ship Canal



**Figure D.4** Difference in dissolved oxygen concentrations resulting when water-surface elevations at the lakefront are held at or above -2 ft City of Chicago Datum (scenario=-2 ft) relative to those resulting when measured water-surface elevations (calibrated model) are used in the simulation for locations on the Little Calumet (North)



**Figure D.5** Difference in dissolved oxygen concentrations resulting when water-surface elevations at the lakefront are held at or above -2 ft City of Chicago Datum (scenario=-2 ft) relative to those resulting when measured water-surface elevations (calibrated model) are used in the simulation for locations on the Calumet-Sag Channel



**Figure D.5 (cont.)** Difference in dissolved oxygen concentrations resulting when water-surface elevations at the lakefront are held at or above  $-2$  ft City of Chicago Datum (scenario= $-2$  ft) relative to those resulting when measured water-surface elevations (calibrated model) are used in the simulation for locations on the Calumet-Sag Channel