Institute for Urban Environmental Risk Management

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TECHNICAL REPORT # 19

EVALUATION OF PROCEDURES TO PREVENT FLOW REVERSALS TO LAKE MICHIGAN FROM THE CHICAGO WATERWAY SYSTEM

SUBMITTED TO
The Metropolitan Water Reclamation District of Greater Chicago

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CHAPTER 1 - INTRODUCTION

The Chicago Waterway System (CWS) is composed of the Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag Channel, North Shore Channel (NSC), lower portion of the North Branch Chicago River (NBCR), South Branch Chicago River (SBCR), Chicago River Main Stem, and Little Calumet River (North). 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 (CSOs), 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.

The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) has been facing a number of difficult management issues including flow reversals of storm runoff and sewage to Lake Michigan through the lakefront sluice gates and locks. Flow reversals can potentially affect the water supply of the City of Chicago, the accessibility of beaches to the public, and the general environment of Lake Michigan. Thus, it is a high priority for the MWRDGC to avoid such flow reversals. Since the O'Brien Lock and Dam was completed in 1965 there have been 48 storms that caused the MWRDGC to open the sluice gates or locks at the lakefront and allow water to flow to Lake Michigan. Thirty two of these occurred before 1986 when the first of the Tunnel and Reservoir Plan (TARP) tunnels went online for a pre-TARP flow reversal rate of 1.5 per year and a post-

TARP rate of 0.73 per year. The decrease in frequency of flow reversals events from 1.5 per year to 0.73 per year reflects the effectiveness of the TARP tunnels in reducing flood flows. However, the volumes of the flow reversals since 1990 has been very large with 6 of the 10 largest (post O'Brien Lock and Dam) flow reversals volumes occurring since 1990 including the 1st, 3rd, and 4th largest flow reversal volumes (Table 1.1). This indicates that changes in operation procedures at the Lockport Powerhouse and Controlling Works should be considered to reduce the volume of flow reversals to Lake Michigan. The objective of this study is to evaluate historic flow reversal events to determine if improved operation procedures at Lockport could avoid or reduce the volume of flow reversals.

Table 1.1 Volume of flow reversal events (in million gallons) from 1990-present.

Date	O'Brien	CRCW	Wilmette	Total
8/23-24/07			224.0	224.0
8/22/02		1296.4	455.4	1751.8
10/13/01			90.7	90.7
8/31/01			75.3	75.3
8/02/01		883.1	139.9	1023.0
6/13/99			9.7	9.7
8/16-17/97		402.0	157.0	559.0
2/20-22/97	1458.0	1947.0	774.0	4179.0
7/17-18/96	1032.0	519.0		1551.0
11/27-28/90	224.0	86.0	154.0	464.0
8/17-18/90			9.5	9.5
5/9-10/90		208.0	289.0	497.0

In this study, 7 historic flow reversal events (1997-2002) were analyzed to determine if changes in operation schemes for the gates at Lockport could have eliminated or minimized the volume of the flow reversals to Lake Michigan. If changes in gate operations could reduce flow reversals, development of a flood forecasting could be beneficial. The development of a complete flood forecasting scheme and gate operation guidelines would require relating rainfall timing and volume to water levels in the CWS and may involve consideration of rainfall forecasts. Thus, this project should be considered a first step to see if detailed hydraulic modeling can aid the MWRDGC in establishing procedures to minimize the number and volume of flow reversal events.

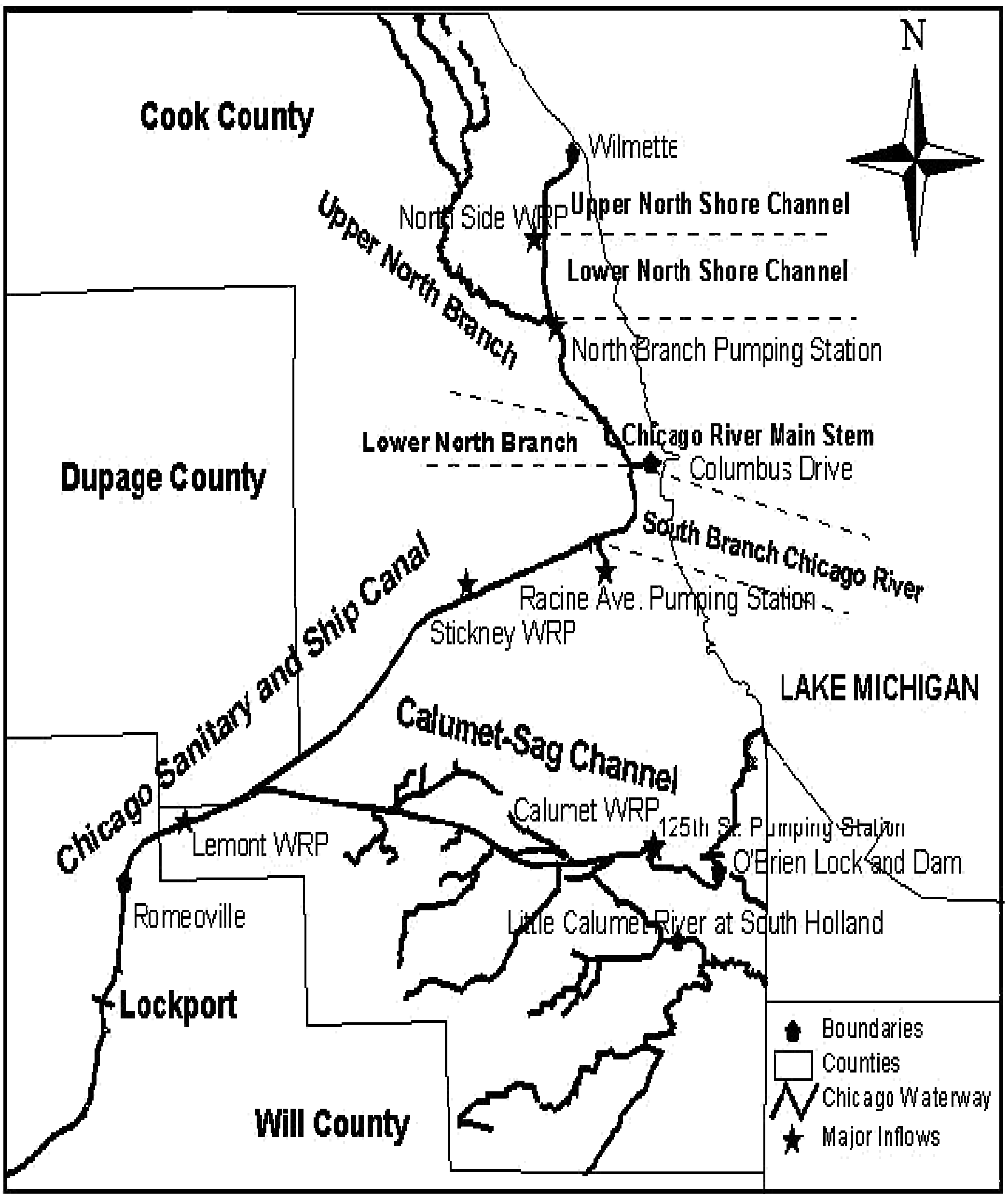


Figure 1.1 Schematic diagram of the Calumet and the Chicago River Systems

CHAPTER 2 - HYDRAULIC MODEL VERIFICATION

2.1 Introduction

The DUFLOW (DUFLOW, 2000) unsteady-flow model for the CWS was calibrated and verified by the Institute for Urban Environmental Risk Management, Marquette University in 2003. Marquette University successfully applied the DUFLOW water quality model to the CWS for several purposes: i) Alp and Melching (2004) used the DUFLOW model to investigate the possible effects of a change in navigational water level requirements and the navigation make-up diversion of water from Lake Michigan during storm events, ii) Neugebauer and Melching (2005) developed a method to verify the calibrated DUFLOW model under uncertain storm loads, and iii) Manache and Melching (2005) applied the DUFLOW model to simulate fecal coliform concentrations in the CWS under unsteady flow conditions.

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). Shrestha and Melching (2003) calibrated the model 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 Chicago River Controlling Works (CRCW) and O'Brien Lock and Dam upstream boundaries. For the evaluation of the flow reversal events, the DUFLOW model was extended from Romeoville to the Lockport Controlling Works (3 miles downstream from Romeoville and 2.2 miles upstream of the Lockport Power House and Lock) where the MWRDGC records hourly water-surface elevation data and the water-surface elevation was used at the Lockport Controlling Works as the downstream boundary condition for the model. The model was run at a 15-min. time step and measured and simulated water-surface values were compared for a 60-min. time interval. Assumptions, data used, and results are presented in the following sections.

2.2 Hydraulic Data used for the Model Input

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 [discontinued in 2003]

iii) The North Shore Channel at Maple Avenue (near the Wilmette Pumping Station) [discontinued September 2003]

The data from the Chicago River Main Stem at Columbus Drive, the Calumet River at the O'Brien Lock and Dam, and the North Shore Channel at Maple Avenue gages were used as the primary flow versus time (5-minute) upstream boundary conditions for the unsteady-flow model. Water-surface elevation versus time data (on a 1-hr basis) from the MWRDGC gage on the CSSC at the Lockport Controlling Works were used for the downstream boundary condition. Because of missing data, for the February 1997 and June 1999 simulations, daily estimated USGS flows were used at the O'Brien Lock and Dam and Wilmette, respectively. For the 1997 simulations, simulated discharge values were used at Wilmette boundary condition. Simulated flow reversal volumes at Wilmette were compared with the volume of flow reversal estimated by the MWRDGC as listed in Table 2.1. The simulated flow reversal volumes are reasonably close to MWRD estimates, therefore, simulated flows were used at Wilmette upstream boundary.

Table 2.1 Simulated and MWRDGC flow reversal volumes (in million gallons) at Wilmette for 1997 events

Wilmette	MWRD	Simulated Flow Reversal
2/20-22/1997	774	767
8/16/1997	157	225

During the flow reversal events, MWRDGC estimated the volume of flow reversal. In order to compare the volume of flow reversal estimates of the USGS and MWRDGC, two sets of simulations were run and the water-surface elevations for each simulations were compared with the measured values. The first set of simulations were done with the MWRDGC flow reversal volume estimates and the second set of simulations were done with the USGS flow reversal volume. It was observed that simulations with the flow reversal volume estimated by the MWRDGC resulted in better estimates. Since USGS flow reversal volumes were significantly lower than MWRDGC flow reversal volumes, just during flow reversal events, USGS flows were multiplied by the numbers given in Table 2.2 to match the MWRDGC flow reversal volume estimates. This approach is reasonable because the USGS never made a discharge measurement during a flow reversal with which they could properly calibrate their acoustic velocity meter gages at the Lakefront structures (Jim Duncker, USUS, personal commun., 2007)

Table 2.2 Ratio of volume of flow reversal estimates (MWRD/USGS)

	MWRDGC/USGS Ratio		
Date	**Columbus**	**O'Brien**	**Wilmette**
8/22/02	95.2	-	8.4
8/2/2001	1.8	-	22.6
8/31/2001	-	-	-
10/13/2001	-	-	1.8
2/20-22/1997	1.2	2.7	

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 three Water Reclamation Plants (WRPs)—North Side, Stickney, and Calumet. In addition, flows discharged to the CWS at three CSO pumping stations—North Branch, Racine Avenue, and 125th Street—were estimated from operating logs of these stations. 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 NBCR is measured just upstream of its confluence with the NSC at the USGS gage at Albany Avenue.

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. Hourly flows from all 3 pumping stations were estimated from pump operation records of on and off times and the rated capacity of the various pumps and then input to the model.

There are nearly 240 CSOs in the modeled portion of the CWS drainage area. Since it is practically difficult to introduce all CSO locations in the modeling, 28 representative CSO locations were identified and their locations are shown in Figure 2.1. In the original calibrated model (Shrestha and Melching, 2003), the volume of CSO was determined from the system wide flow balance and water level measurements at Romeoville, and flow distribution was done on the basis of drainage area for each of the representative locations.

In this study, simulated combined sewer overflow (CSO) flows were obtained from the U.S. Army Corps of Engineers (Corps), which are calculated on an annual basis on an hourly time step in support of the Lake Michigan Diversion Accounting. Detailed discussion of the Corps models (a combination of the Hydrological Simulation program-Fortran, Special Contribution Area Loading Program, and Tunnel Network Model) is given in Espey et al. (2004). In 1990, the Corps established a new network of 25 precipitation gages throughout the Chicago area. The CSO flows simulated on the basis of data from these gages are considered more accurate than the flows simulated on the basis of an earlier network of 13 precipitation gages. The new precipitation gage network and the extensive portions of the TARP system in operation are the primary reasons for evaluating flow reversal events from 1997 to 2002. Also lack of hourly WRP flows prior to 1997 limited this study to events beginning in 1997.

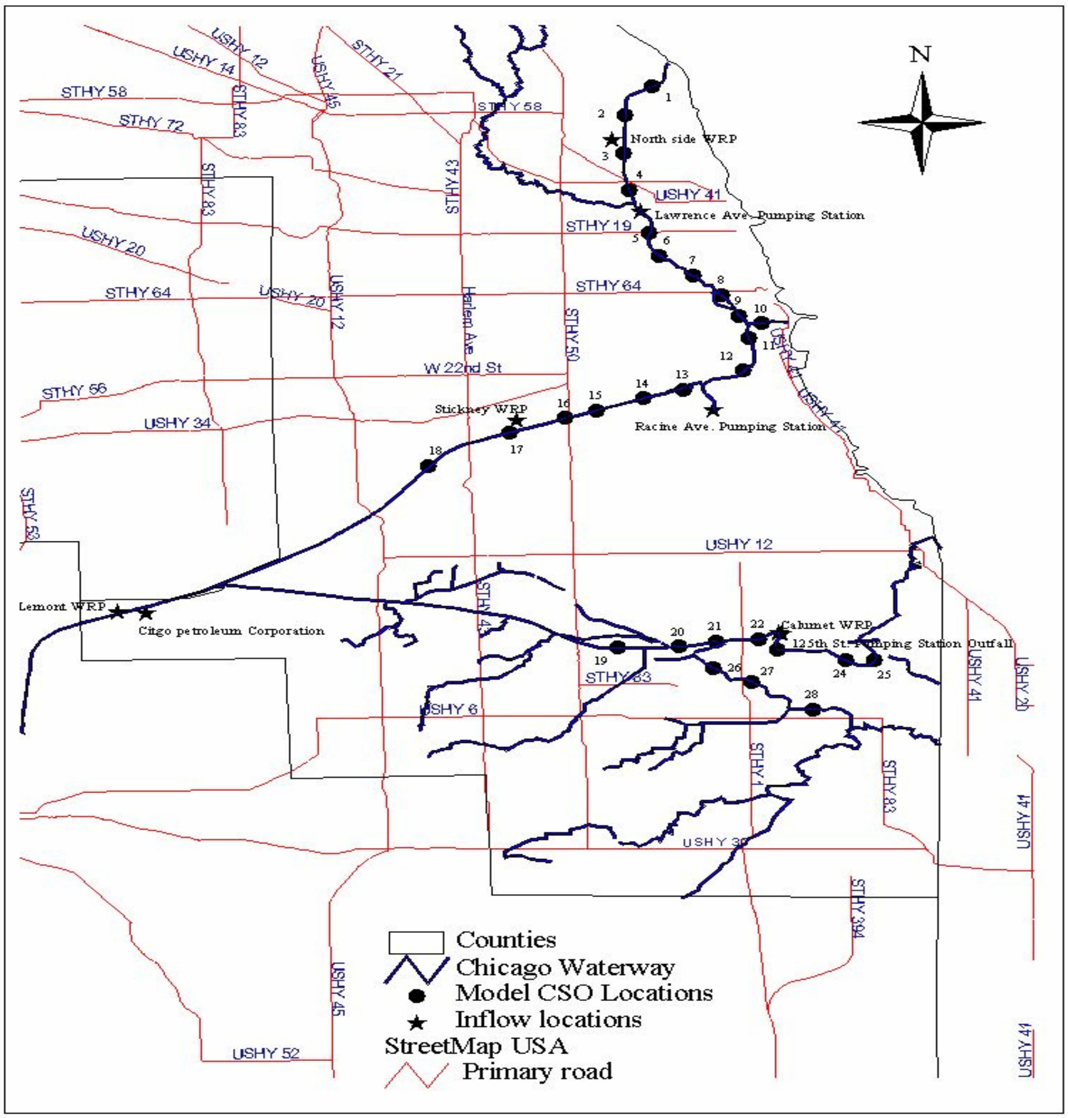


Figure 2.1 Locations of the 28 representative combined sewer overflows (CSOs) used in this study (note: The location of the Citgo Petroleum plant is shown above, the inflow location in the model and in reality is downstream from the Lemont WRP.)

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 lakefront control structures and at Lockport and for the tributary flows. Data collected by the MWRDGC for the discharges from different WRPs also were used.

Boundary Locations:

a. Chicago River at Columbus Drive (USGS flow adjusted for reversals)
b. North Shore Channel at Wilmette (Maple Avenue) (USGS flow adjusted for reversals)
c. Calumet River at O'Brien Lock and Dam (USGS flow adjusted for reversals)
d. Little Calumet River (South) at South Holland (Cottage Grove Avenue) (USGS flow)
e. CSSC at Lockport (downstream boundary) (MWRDGC water-surface elevation)

The major flows into the CWS have been identified as follows:

a. North Side Water Reclamation Plant (MWRDGC flow)
b. Stickney Water Reclamation Plant (MWRDGC flow)
c. Calumet Water Reclamation Plant (MWRDGC flow)

and the minor flows into the CWS are from:

a. North Branch Chicago River at Albany Avenue (USGS flow)
b. Racine Avenue Pumping Station (MWRDGC flow)
c. North Branch Pumping Station (MWRDGC flow)
d. 125th Street Pumping Station (MWRDGC flow)

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

f. Midlothian Creek (USGS flow)

g. Grand Calumet River (USGS flow)

h. Mill+Stony Creek (West)*

i. Stony Creek (East)*

j. Des Plaines River Basin*

k. Calumet Union Ditch*

l. Cal-Sag Watershed West*

m. 28 CSO locations (Corps simulated flow)

* These flows were estimated based on Midlothian Creek flows

2.3 Channel Geometry and Roughness Coefficient

The channel geometry is represented as a series of 231 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 listed in Table 4.2 of Shrestha and Melching (2003).

2.4 Model Verification

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 elevations recorded at Columbus Drive, O'Brien Lock and Dam, Wilmette, Lawrence Avenue. Western Avenue, Willow Springs Road, Southwest Highway and Sag Junction by the MWRDGC and at Romeoville by the USGS were used for model verification. Details of the calibration and the verification results are given in Alp and Melching (2006), Neugebauer and Melching (2005) and Shrestha and Melching (2003). In the following section details of the verification results for the flow reversal events are given.

2.5 Results of the Hydraulic Verification-Flow Reversal Events

In order to evaluate the flow reversal events, the DUFLOW model was used for the following simulation periods:

February 1 - March 30, 1997

August 1 - September 30, 1997

June 1 - June 30, 1999

July 1- November 10, 2001

August 1 – September 23, 2002

The comparison of measured and simulated water-surface elevations at various locations used in the model verification during flow reversal events are shown in Figures 2.2-2.8.

Statistical analysis listed in Tables 2.3-2.7 show that difference between the measured and simulated stages are all below 10 % relative to the depth (where depth is measured relative to the thalweg of the channel) of the water for 90% of the values except for 2001 simulations at Wilmette and Lawrence Avenue. These high percentages of small errors and close agreement between the simulated and the measured water-surface elevations especially during flow reversal events at the boundaries indicate an excellent hydraulic verification of the model. The excellent results at CRCW and the good results at Wilmette (for all periods except 2001) indicate the model is suitable to evaluate the ability of changes in gate operations at Lockport to reduce the need for flow reversals.

Table 2.3. Correlation coefficient and percentage of the hourly water-surface elevations for which the error in simulated versus measured elevations relative to the depth of flow (measured from the thalweg of the channel) is less than the specified percentage for February 1-March 30, 1997

Location	Correlation Coefficient	Percentage		
		<±2% of D	**<±5% of D**	**<±10% of D**
Wilmette (NSC)	1.00	100	100	100
CRCW (Chicago River Main Stem)	0.86	92	98	99
O'Brien Lock and Dam (Calumet River)	0.79	87	95	99
Lawrence Avenue (NBCR)	-	-	-	-
Western Avenue (CSSC)	0.86	93	98	99
Willow Springs (CSSC)	0.80	95	98	100
Southwest Highway (Sag Channel)	0.74	50	91	96
Calumet-Sag Junction	0.71	93	99	99
Romeoville (CSSC)	0.96	96	99	100

Table 2.4 Correlation coefficient and percentage of the hourly water-surface elevations for which the error in simulated versus measured elevations relative to the depth of flow (measured from the thalweg of the channel) is less than the specified percentage for August 1- September 30, 1997

Location	Correlation Coefficient	Percentage		
		<±2% of D	<±5% of D	<±10% of D
Wilmette (NSC)	0.98	95	96	100
CRCW (Chicago River Main Stem)	0.96	97	100	100
O'Brien Lock and Dam (Calumet River)	-	-	-	-
Lawrence Avenue (NBCR)	-	-	-	-
Western Avenue (CSSC)	-	-	-	-
Willow Springs (CSSC)	0.92	99	100	100
Southwest Highway (Sag Channel)	0.84	59	100	100
Calumet-Sag Junction	0.80	99	100	100
Romeoville (CSSC)	0.94	97	100	100

Table 2.5 Correlation coefficient and percentage of the hourly water-surface elevations for which the error in simulated versus measured elevations relative to the depth of flow (measured from the thalweg of the channel) is less than the specified percentage for June 1-June 30, 1999

Location	Correlation Coefficient	Percentage		
		<±2% of D	<±5% of D	<±10% of D
Wilmette (NSC)	0.79	20	77	95
CRCW (Chicago River Main Stem)	0.63	89	97	100
O'Brien Lock and Dam (Calumet River)	0.49	94	100	100
Lawrence Avenue (NBCR)	0.64	6	39	90
Western Avenue (CSSC)	0.62	91	97	100
Willow Springs (CSSC)	0.63	94	99	100
Southwest Highway (Sag Channel)	-	-	-	-
Calumet-Sag Junction	0.78	96	99	100
Romeoville (CSSC)	0.93	95	100	100

Table 2.6 Correlation coefficient and percentage of the hourly water-surface elevations for which the error in simulated versus measured elevations relative to the depth of flow (measured from the thalweg of the channel) is less than the specified percentage for July 1, November 9, 2001

Location	Correlation Coefficient	Percentage		
		<±2% of D	<±5% of D	<±10% of D
Wilmette (NSC)	0.81	0	4	75
CRCW (Chicago River Main Stem)	0.82	87	99	100
O'Brien Lock and Dam (Calumet River)	0.69	97	100	100
Lawrence Avenue (NBCR)	0.65	8	48	83
Western Avenue (CSSC)	0.84	94	99	100
Willow Springs (CSSC)	0.78	97	99	100
Southwest Highway (Sag Channel)	0.77	84	99	100
Calumet-Sag Junction	0.80	98	99	100
Romeoville (CSSC)	0.96	95	100	100

Table 2.7 Correlation coefficient and percentage of the hourly water-surface elevations for which the error in simulated versus measured elevations relative to the depth of flow (measured from the thalweg of the channel) is less than the specified percentage for August 1-September, 23, 2002

Location	Correlation Coefficient	Percentage		
		<±2% of D	<±5% of D	<±10% of D
Wilmette (NSC)	0.83	1	44	94
CRCW (Chicago River Main Stem)	0.91	90	99	100
O'Brien Lock and Dam (Calumet River)	0.66	99	99	100
Lawrence Avenue (NBCR)	0.86	14	43	96
Western Avenue (CSSC)	0.91	98	99	100
Willow Springs (CSSC)	-	-	-	-
Southwest Highway (Sag Channel)	0.85	67	99	100
Calumet-Sag Junction	0.88	100	100	100
Romeoville (CSSC)	0.94	95	100	100

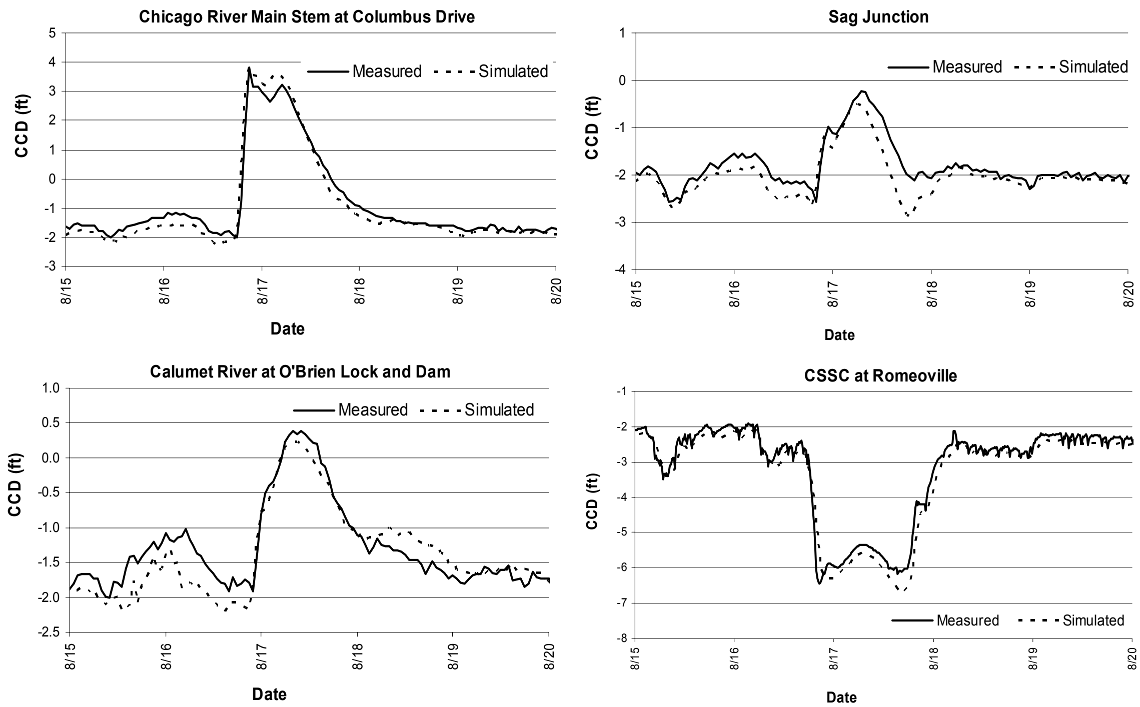


Figure 2.2 Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for August 15-August 20, 1997

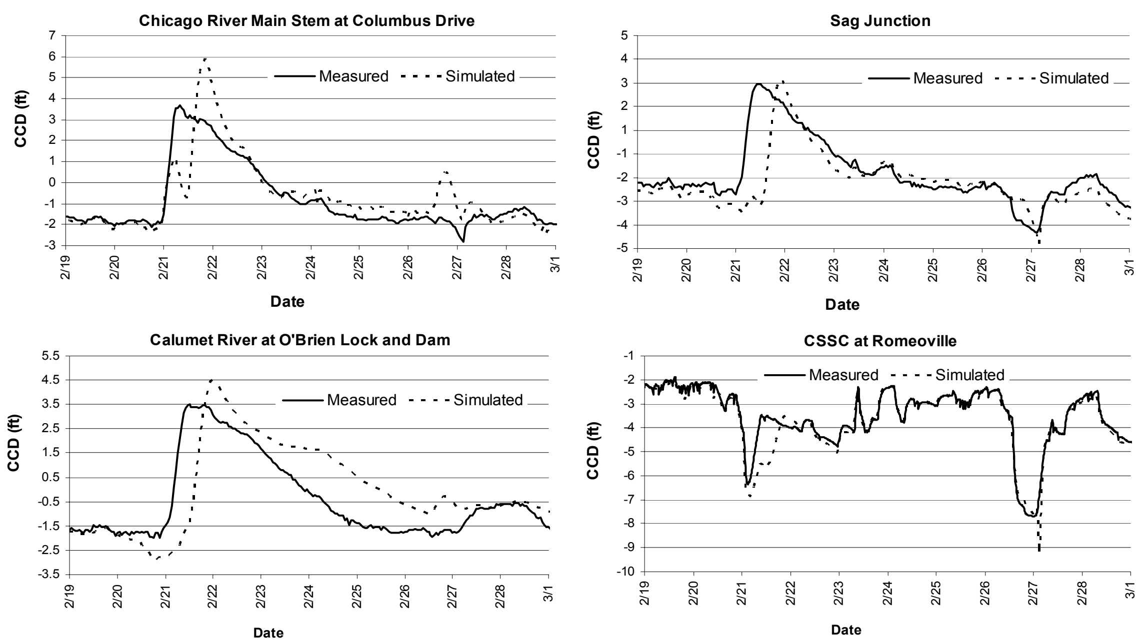


Figure 2.3 Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for February 19-March 1, 1997

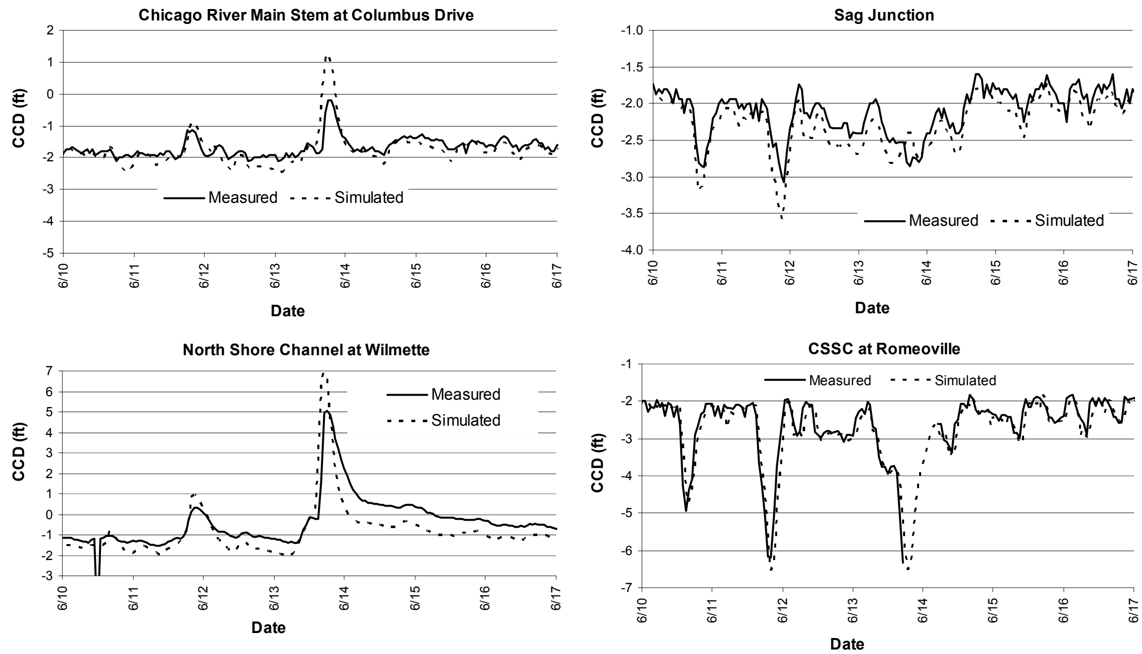


Figure 2.4 Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for June 6-June17, 1999

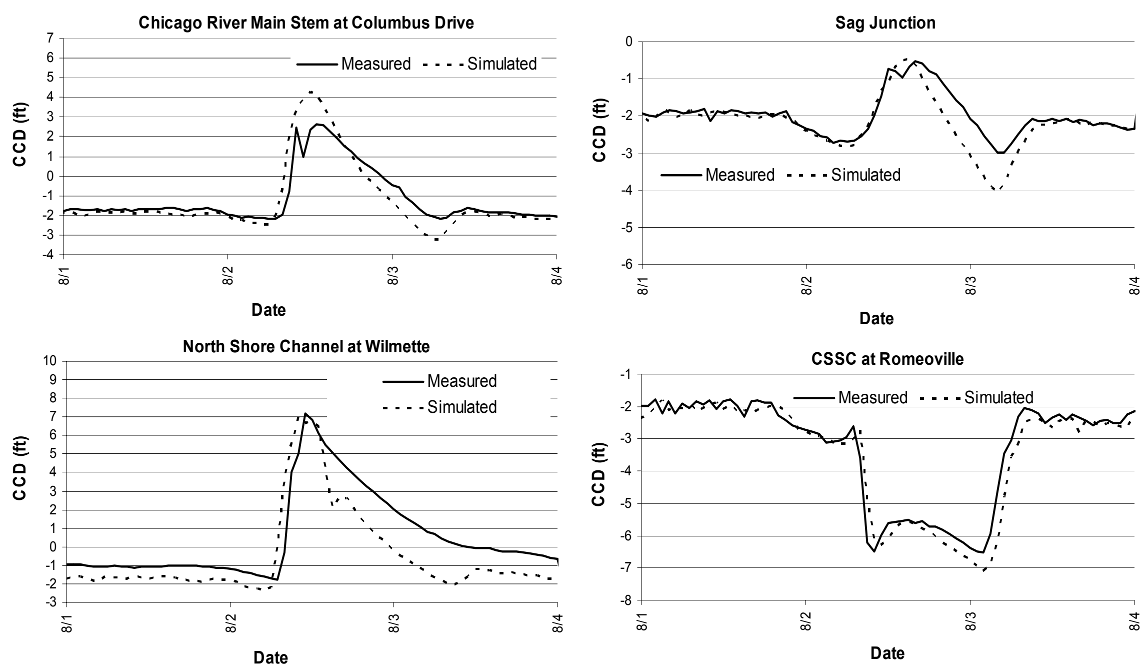


Figure 2.5 Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for August 1-August 4, 2001

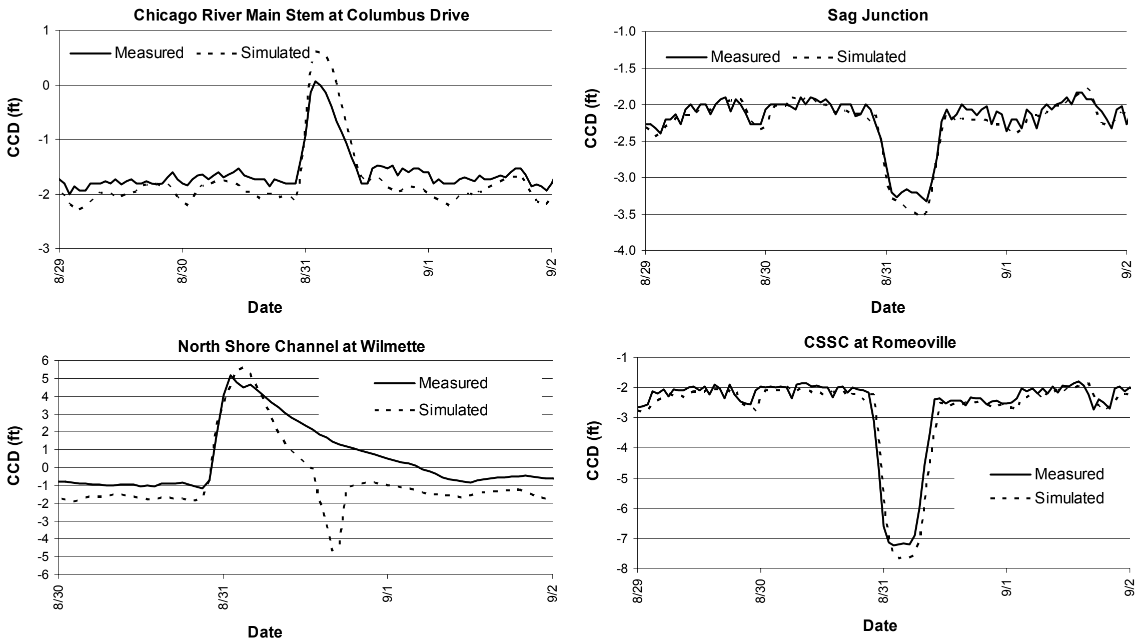


Figure 2.6 Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for August 29-September 2, 2001

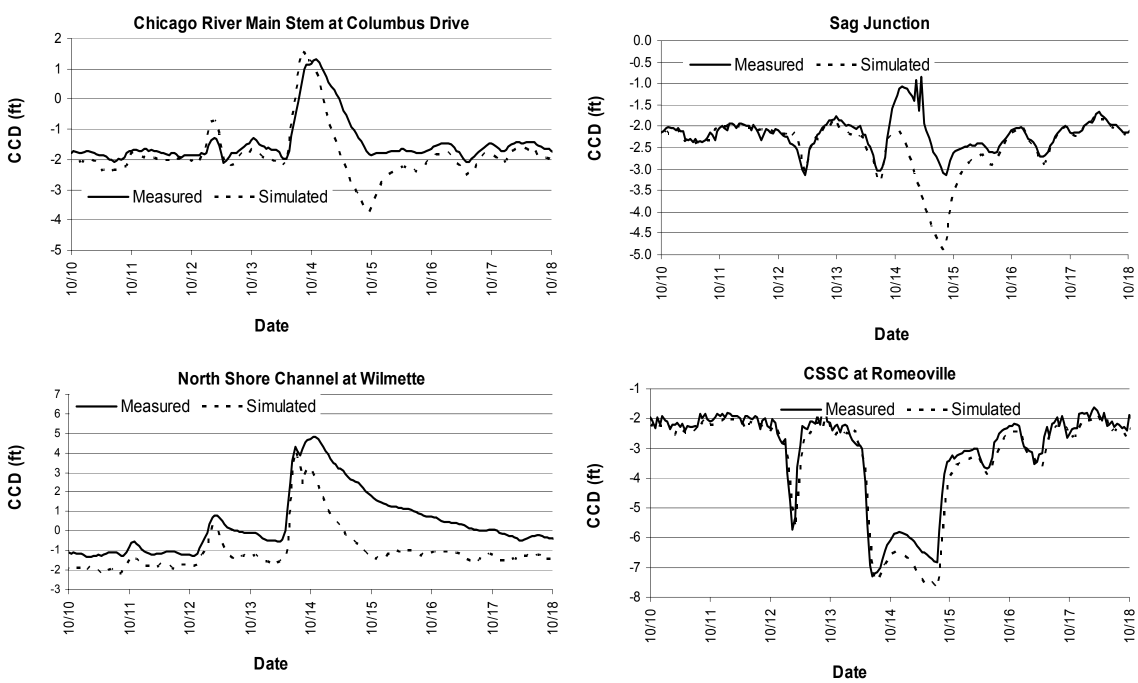


Figure 2.7 Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for October 10-October 18, 2001

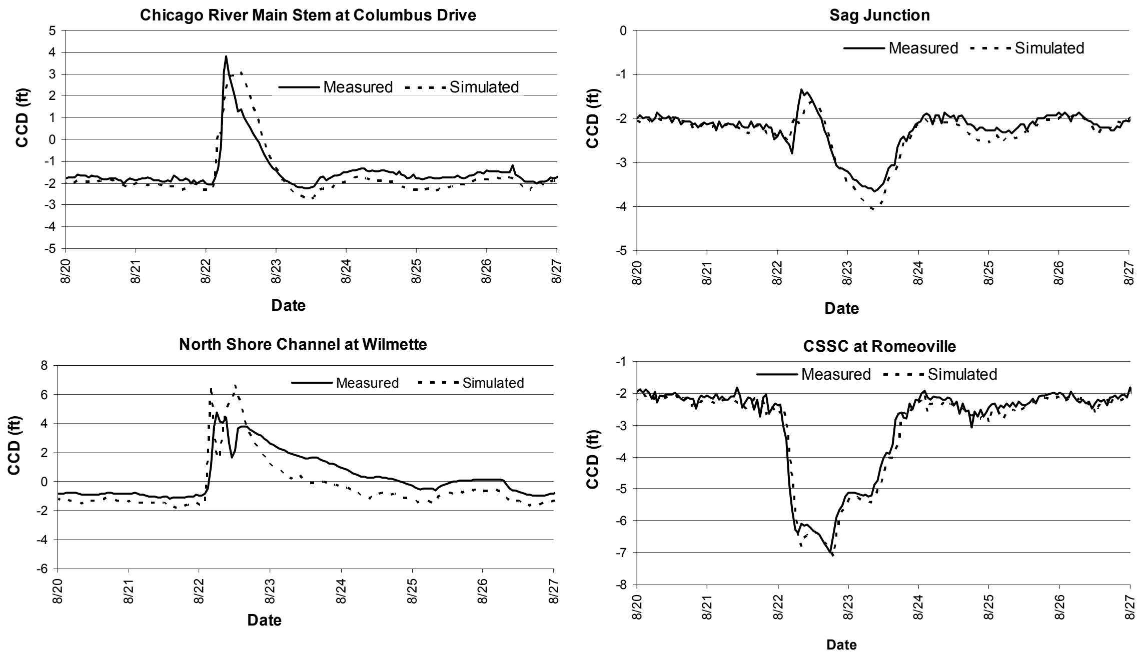


Figure 2.8 Comparison of measured and simulated water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Waterway System for August 20-August 27, 2002

CHAPTER 3 - EVALUATION OF OPERATION SCHEMES FOR THE GATES AT LOCKPORT

3.1 Introduction

During periods of extreme storm runoff, when necessary, sluice gates at Wilmette, CRCW and/or O'Brien Lock and Dam are opened to lower high water elevations in the Chicago Waterway System at the lakefront. The MWRDGC opens the gates at the lakefront to reverse the flow of canal water to Lake Michigan when the water-surface elevations at the lakefronts reach the following maximum allowable levels (MWRDGC, 2007):

Wilmette	: +4.50/+5.00 ft CCD (CCD = City of Chicago Datum)
CRCW	: +3.00/+3.50 ft CCD
O'Brien	: +3.00/+3.50 ft CCD

The first number refers to the water levels at which the MWRDGC will open the gates if the water-surface elevation of the canal is rising rapidly and the MWRDGC anticipates that water-surface elevation will most likely exceed the second number if left unchecked. If the canal is rising slowly, the MWRDGC waits until the canal level gets to the second number before the gates are opened.

The waterway elevations listed in Table 3.1 are in force for navigational purposes in the CWS during periods immediately preceding and throughout storm runoff unless the elevation of Lake Michigan is less than -1.8 ft CCD. In the following sections, results of the simulations regarding the operational schemes for the gates at Lockport to prevent flow reversals to Lake Michigan are presented. The water-surface elevations of the downstream boundary condition at Lockport are lowered to reflect the opening of more gates and changes in the timing of gate openings at Lockport. The goal is to observe if gate operation could be changed such that water-surface elevations remain at or above -3 ft CCD and -4 ft CCD at the CRCW and Sag Junction, respectively, as per the navigational water levels in Table 3.1, and that peak water-surface elevations do not exceed the levels requiring flow reversal to Lake Michigan.

Table 3.1 Wet Weather Limits on Waterways Elevations for navigational purposes (after MWRDGC, 2007)

	Lower Limit (ft CCD)	Upper Limit (ft CCD)	Ideal Level (ft CCD)
Chicago River Controlling Works	-3.0	-0.50	-3.0
O'Brien Lock and Dam	-3.0	-0.50	-3.0
Calumet-Sag Junction	-4.0	-1.8	-4.0
Lockport Controlling Works	-10.0	-2.0	-10.0

3.2 1998-2002 Actual Operation Schemes for the Gates at the Lockport

Past records on the opening of the Lockport Powerhouse (LPH) pit gates and Lockport Controlling Works (LCW) sluice gates were obtained between 1998-2002 from the MWRDGC and these were compared with the measured water-surface elevations at LCW to establish typical water-surface elevations for various combinations of gate openings. There are total of 9 LPH pit gates and 7 LCW sluice gates. Comparison of the water surface elevations at the LCW with the various gate openings for selected storms are shown in Figure 3.1. Summaries of gate operations and corresponding water-surface elevations at LCW are listed in Tables 3.2-3.4. The MWRDGC gradually opens the gates at the Lockport Power House when a larger storm is anticipated and LCW sluice gates are also opened when higher discharges are observed. When 9 LPH gates are open, the water-surface elevation at LCW goes down to -5.9 ft CCD on average and when all the gates (LPH and LCW) are open, the water-surface elevation at Lockport goes down to -9.3 ft CCD on average. Different combinations of gate operations result in water-surface elevations at LCW ranging from -4 ft CCD to -9.3 ft CCD on average as listed in Table 3.3.

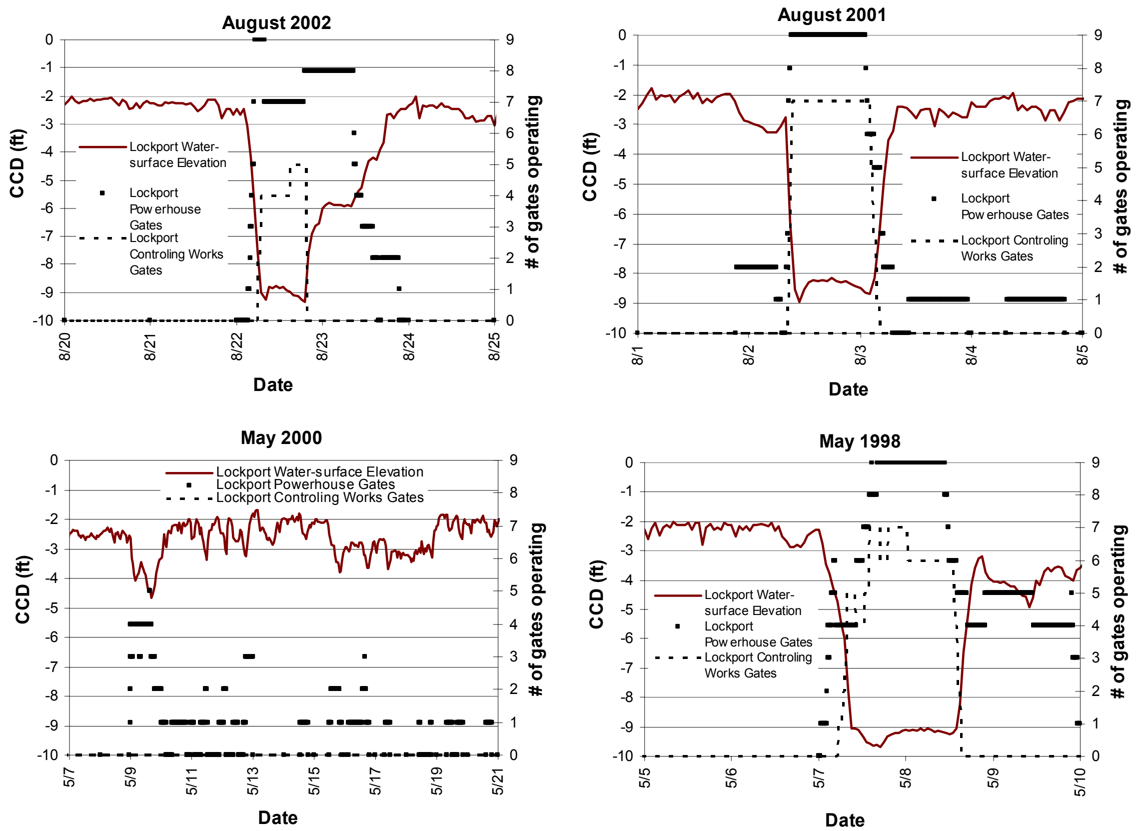


Figure 3.1 Comparison of the water-surface elevations at the Lockport Controlling Works with the various gate openings for selected storms

Table 3.2 Average water-surface elevations at the Lockport Controlling Works for various Lockport Powerhouse Pit Gate openings

Only Lockport Powerhouse Gates	Average Water-Surface Elevation (CCD ft)
2	-3.6
3	-4.1
4	-4.5
5	-4.5
6	-6.2
7	-*
8	-5.7
9	-5.9

* -: no case occurred between 1998 and 2002

Table 3.3 Average water-surface elevations at the Lockport Controlling Works for various combinations of gate openings

Lockport Powerhouse Gates	Average Number of Lockport Controlling Works Gates	Average Water-surface Elevation (CCD ft)
1	3	-5.4
2	-	-
3	1	-6.7
4	4	-7.8
5	2	-6.7
6	3	-8.3
7	5	-9.0
8	5	-9.0
9	7	-9.3

Table 3.4 Average water-surface elevations at the Lockport Controlling Works for various gate openings (all gates included)

All Gates (Powerhouse+ Controlling Works)	Average Water-Surface Elevation (CCD ft)
2	-3.6
3	-4.1
4	-4.6
5	-4.7
6	-6.3
7	-6.8
8	-7.2
9	-7.8
10	-9.1
11	-8.7
12	-9.2
13	-8.4
14	-9.0
15	-9.2
16	-9.4

3.3 Evaluation of the Lockport Gates Operation Procedures

In this section the 7 flow reversal events that occurred between 1997 and 2002 are evaluated to see if improved gate operation schemes can prevent flow reversals to Lake Michigan. Four sets of simulations representing various Lockport gate operation procedures were done and throughout the text some abbreviations explained in the following points will be used to explain the simulations:

i) *Before CSO*: Lockport Gates are open 6 to 12 hrs before CSO starts to bring the water-surface elevation down to -5, -7, or -9 ft CCD at the LCW but still keeping the water-surface elevation higher than -3.0 and -4.0 ft CCD at CRCW and Sag Junction, respectively. When CSO starts, actual gate operations and LCW water-surface elevations are used in the simulation. During the flow reversal event, upstream boundaries are set to zero discharge allowing the water-surface elevation to rise as high as necessary. Before and after the flow reversal event the USGS flows are used at the upstream boundaries.

ii) *During CSO*: Gates are open 6 to 12 hrs during the CSO event to bring the water level down to -9 ft CCD at the LCW but still keeping the water-surface elevation higher than -3.0 and -4.0 ft CCD at CRCW and Sag Junction, respectively. Prior the CSO events, actual gate operations and LCW water-surface elevations are used in the simulations. During the flow reversal events, upstream boundaries are set to zero discharge.

iii) *No limit*: Lockport Gates are open 6 to 12 hrs before the CSO event to bring the water level down to -5, -7, or -9 ft CCD at the LCW without considering the lower water-surface elevation limits at CRCW and Sag Junction. When CSO starts, actual gate operations and LCW water-surface elevations are used in the simulations. During the flow reversal event, upstream boundaries are set to zero discharge.

iv) *Baseline*: During the flow reversal events, upstream boundaries are set to zero discharge.

Results of the simulations are given in Sections 3.3.1-3.3.7 and a general discussion of the results is presented in Chapter 4.

3.3.1 February 20-22, 1997

The February 20-22, 1997 event caused the largest flow reversal volume among the events in this study and the highest flow reversal volume was observed at the CRCW with 1,947.0 million gallons of flow reversal volume. Different gate operation schemes were tried and results (Figure 3.2) showed that if the water-surface elevation at the LCW is kept at -5 ft CCD for 6 hr prior the CSO event, allowable minimum water-surface elevations for wet weather conditions listed in Table 3.1 can be maintained throughout the CWS. Figure 3.2 also shows the results of simulations reflecting gate-opening schemes for lowering the water-surface elevations at the LCW to -9 ft CCD for 12 hr during the CSO event. Since actual and simulated gate operations for *During CSO* are very close to each other, similar values are obtained for both *During CSO* and *Baseline* simulations. As can be seen in Figure 3.3 water-surface elevations go below the allowable values at CRCW and Sag Junction when water-surface elevations at the LCW are allowed to go down to -7 CCD for 12 hr before the CSO event starts. Both Figure 3.2 and Figure 3.3 show that lowering the water-surface elevations at Lockport before the CSO event starts has little or no effect on water-surface elevation at Columbus Drive and Wilmette when water-surface elevations reach to peak values.

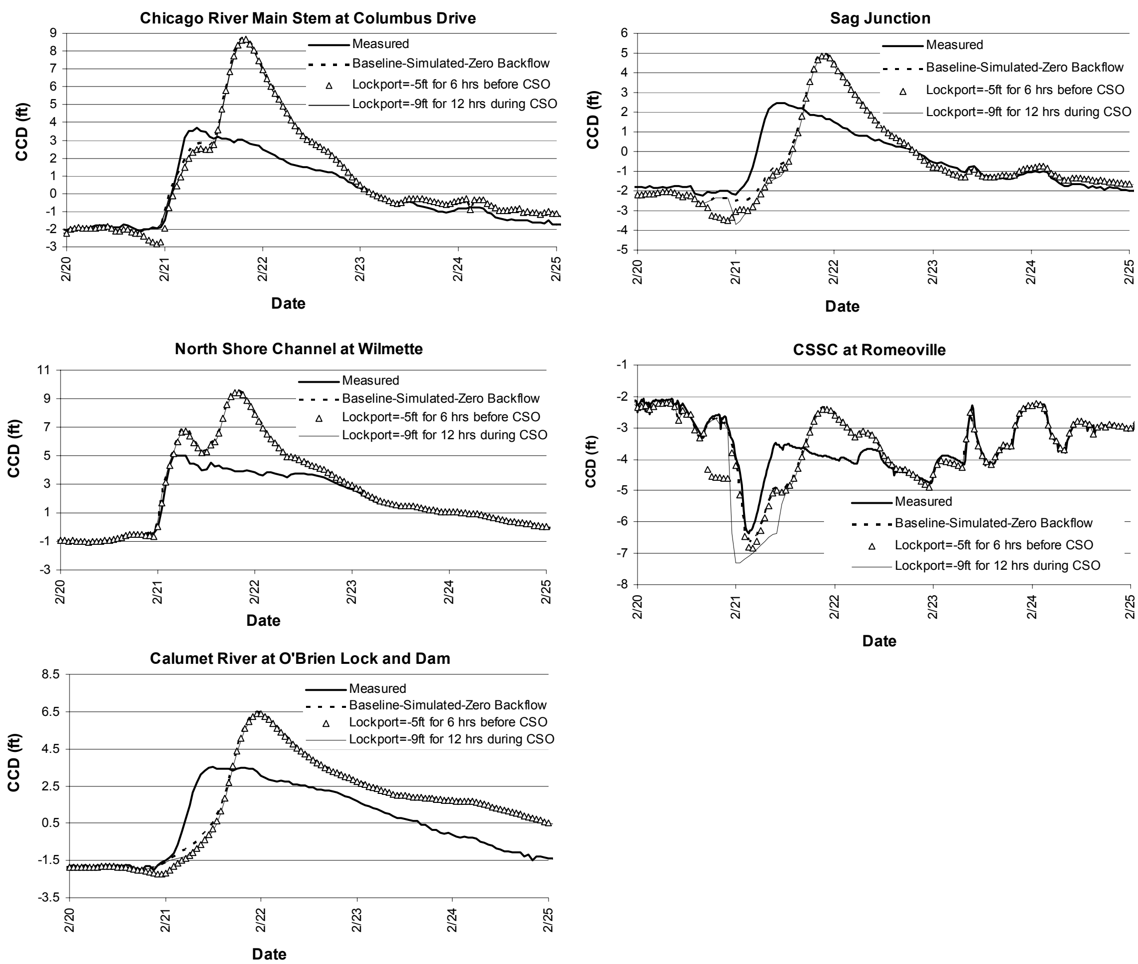


Figure 3.2 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for simulations reflecting various gate operations at Lockport for February 20-25, 1997

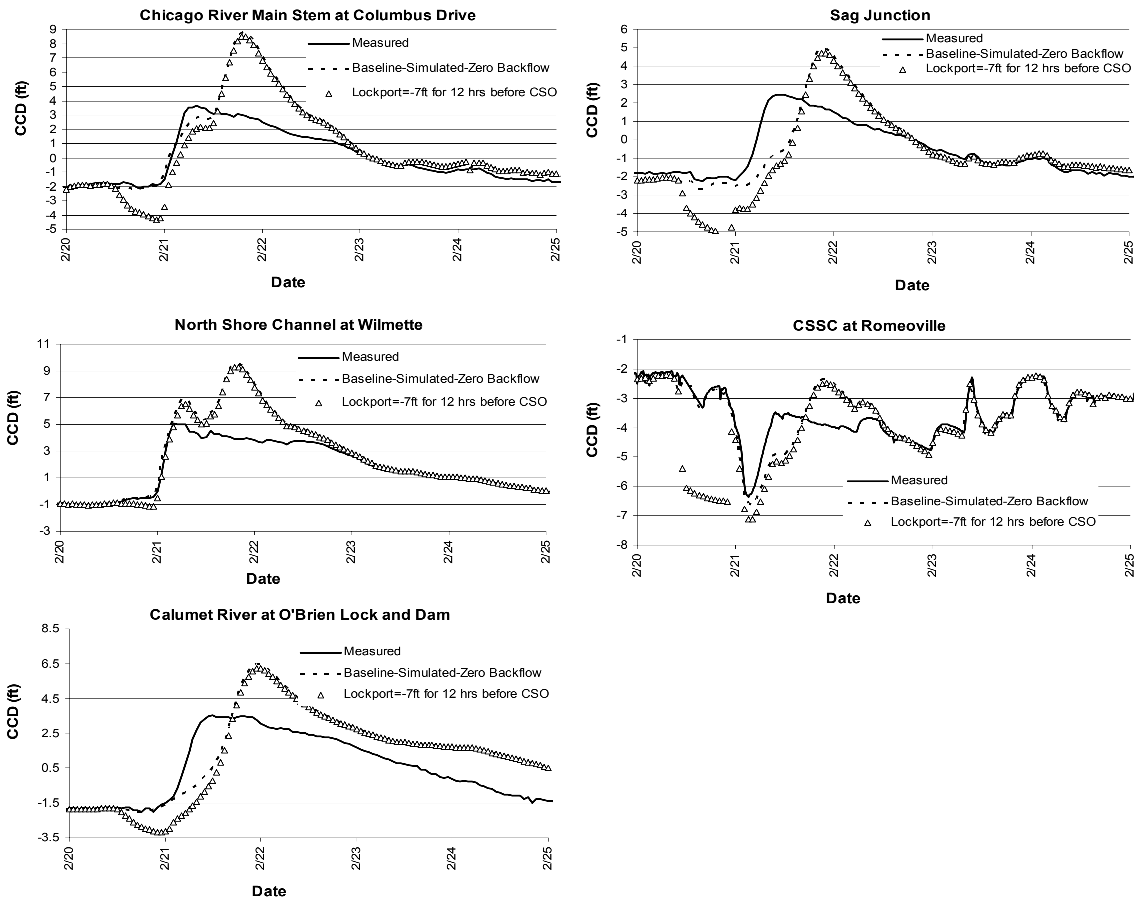


Figure 3.3 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for "*No Limit"* simulations for February 20-25, 1997

3.3.2 August 16-17, 1997

The August 16-17, 1997 flow reversal event was one of the 2 flow reversal events that occurred in 1997 and caused 559.0 million gallons of flow to Lake Michigan. Different gate operation schemes were tried and results (Figure 3.4) showed that if the water-surface elevations at the LCW is kept at -5 ft CCD for 6 hr prior the CSO event, allowable minimum water-surface elevations for wet weather conditions can be maintained throughout the CWS. Figure 3.4 also shows the results of simulations reflecting gate-opening schemes for lowering the water-surface elevations at the LCW to -9 ft CCD for 12 hr during the CSO event. As can be seen in Figure 3.5 water-surface elevations go below the allowable values at CRCW and Sag Junction when water-surface elevations at the LCW are allowed to go down to -7 ft CCD for 12 hr before the CSO event starts. The peak water-surface elevations at Columbus Drive and Wilmette decreased from 5.97 and 6.81 ft CCD, respectively, to 5.41 and 6.39 ft CCD, respectively by lowering the downstream boundary condition at the LCW to -5 ft CCD for 6 hr prior the CSO event. In the *No Limit* simulation (Figure 3.5), the peak water-surface elevations at Columbus Drive and Wilmette decreased from 5.97 and 6.81 ft CCD, respectively, to 4.47 and 5.79 ft CCD, respectively, by lowering the downstream boundary condition at the LCW to -7 ft CCD for 12 hr prior the CSO event. Even though the *No Limit* simulation provides more than a 1 ft drop in water-surface elevations at the upstream boundaries, this practice causes violation of minimum allowable navigational water-surface elevation requirements in the CWS. Both Figure 3.4 and Figure 3.5 show that lowering the water-surface elevations at Lockport before the CSO event starts provides some relief at the upstream boundaries but still this practice is not enough to prevent a flow reversal.

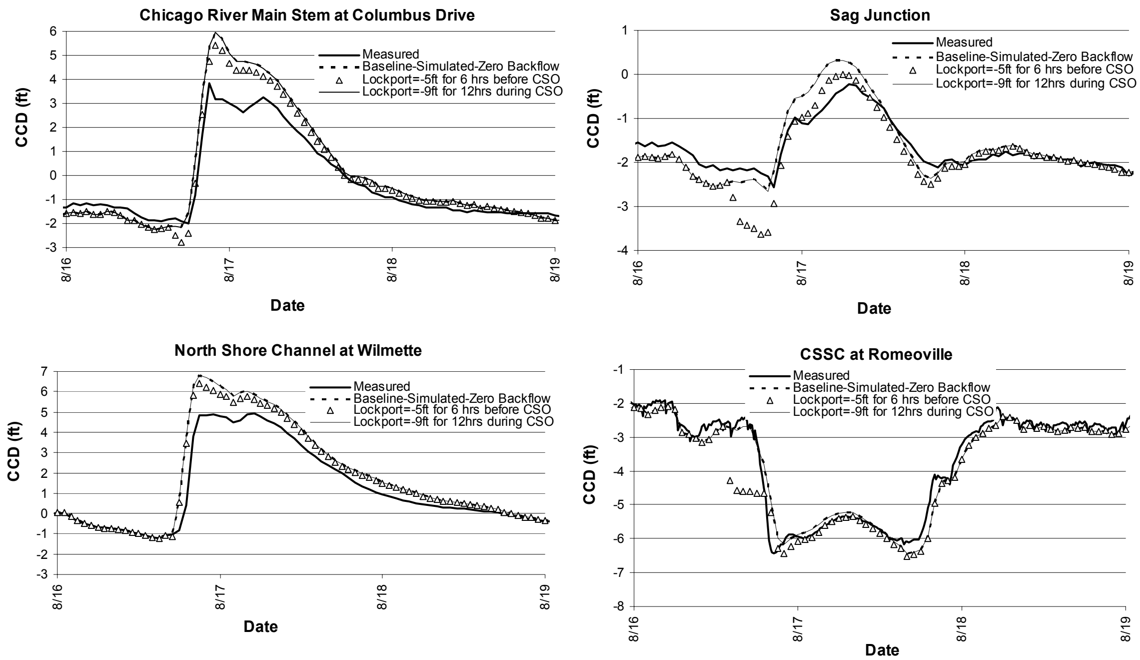


Figure 3.4 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for simulations reflecting various gate operations at Lockport for August 16-19, 1997

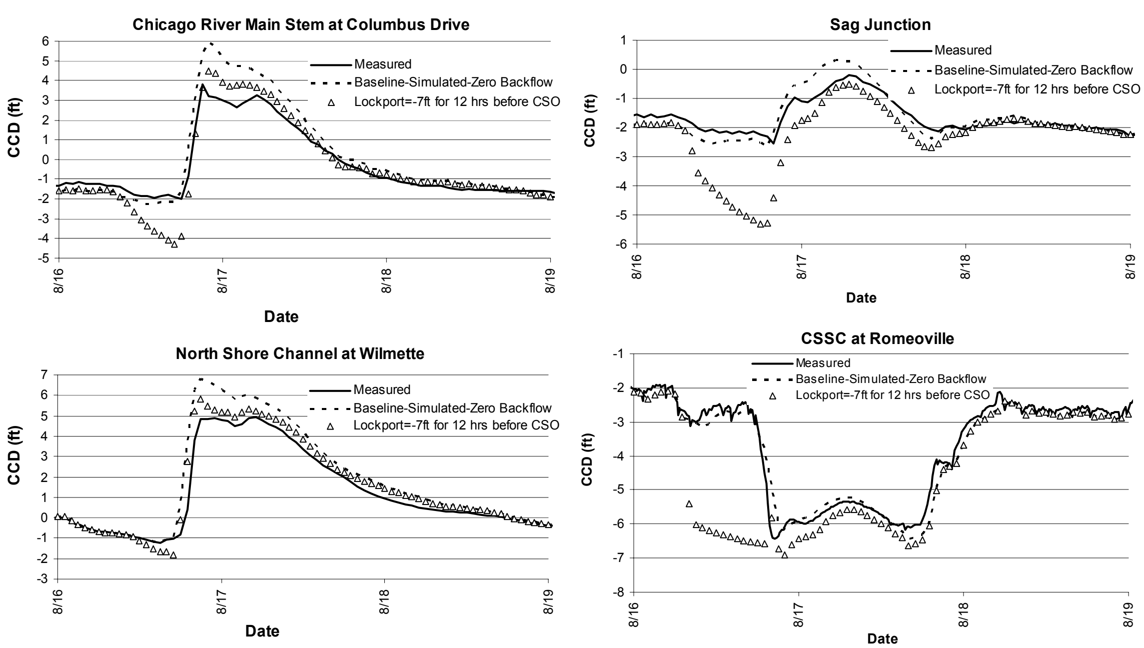


Figure 3.5 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for "*No Limit*" simulations for August 16-19, 1997

3.3.3 June 13, 1999

The June 13, 1999 flow reversal event was the smallest reversal flow event between 1997 and 2002 with 9.7 million gallons of flow reversal. Different gate operation schemes were tried and results (Figure 3.6) showed that if the water-surface elevation at the LCW is kept at -3 ft CCD for 6 hr prior the CSO event, allowable minimum water-surface elevations for wet weather conditions can be maintained throughout the CWS. Figure 3.6 also shows the results of simulations reflecting gate-opening schemes for lowering the water-surface elevations at Lockport to -9 ft CCD for 6 hrs during the CSO event. As can be seen in Figure 3.7 water-surface elevations go below the allowable minimum water-surface elevations at CRCW and Sag Junction when the water-surface elevations at the LCW are allowed to go down to -7ft CCD for 12 hr before the CSO event starts. The June 13, 1999 event caused a flow reversal just at Wilmette and lowering the downstream boundary condition at the LCW to -3 ft CCD for 6 hours prior the CSO event has an insignificant effect on the peak water-surface elevations at Wilmette. In the *No Limit* simulation (Figure 3.7), the peak water-surface elevations at Columbus Drive and Wilmette decreased from 1.29 and 7.27 ft CCD, respectively, to 0.75 and -6.95 ft CCD, respectively, by lowering the downstream boundary condition at the LCW to -7 ft CCD for 12 hr prior the CSO event. Even the *No Limit* simulation does not provide enough decrease in peak water-surface elevations at Wilmette to prevent flow to Lake Michigan.

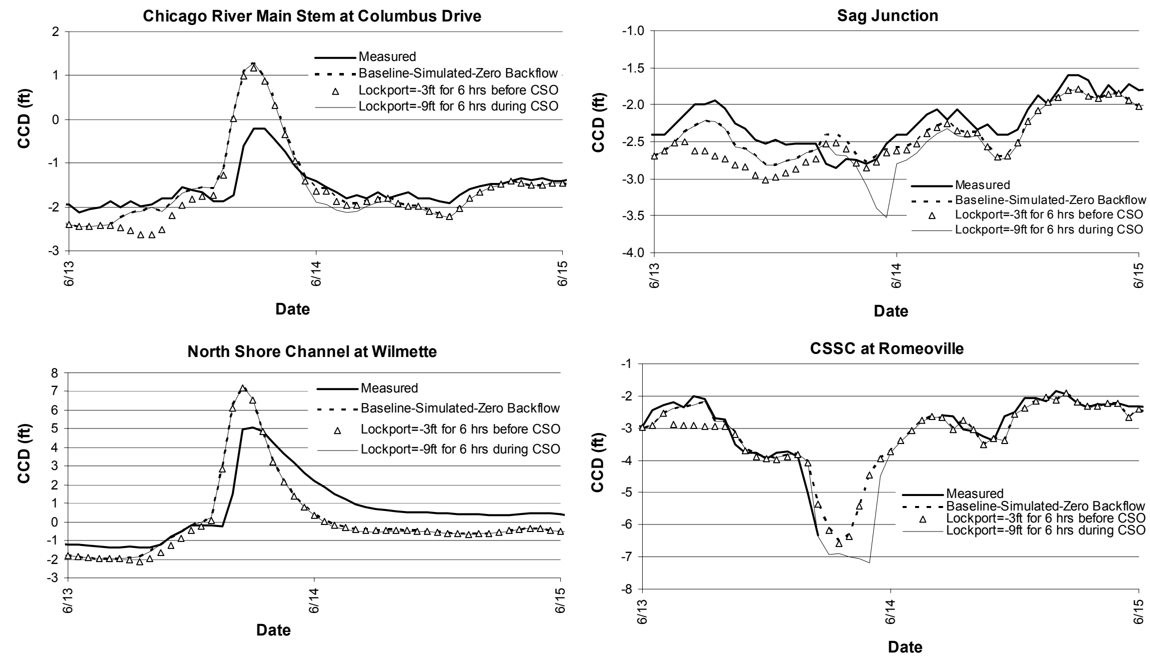


Figure 3.6 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for simulations reflecting various gate operations at Lockport for June 13-15, 1999

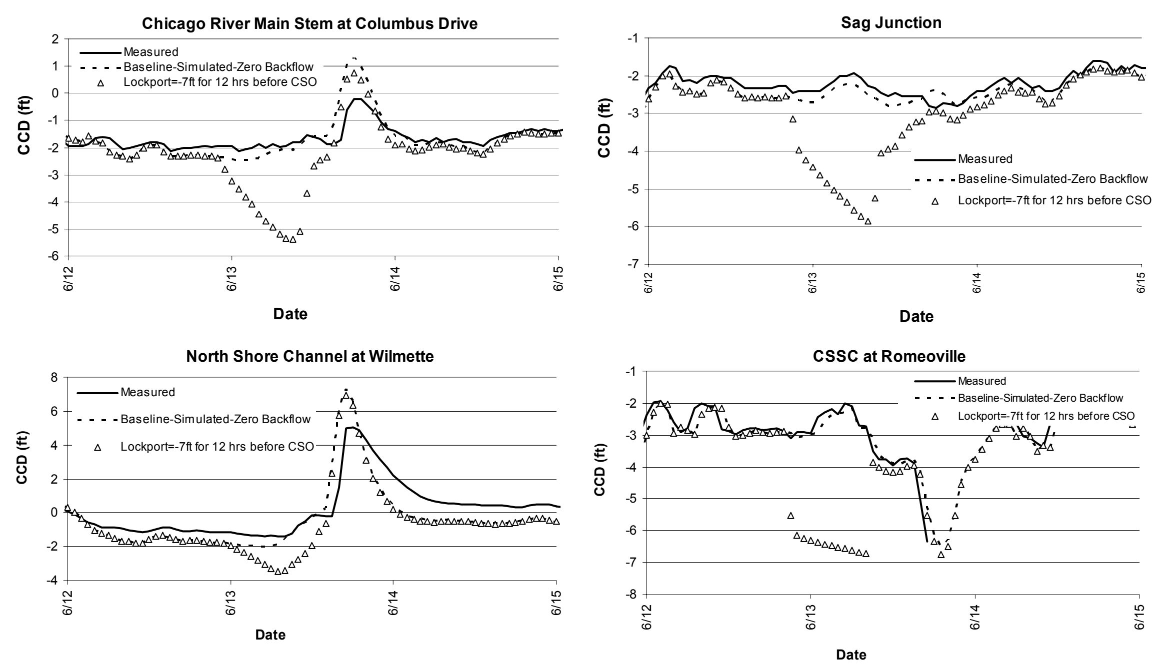


Figure 3.7 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for "*No Limit*" simulations for June 13-15, 1999

3.3.4 August 2, 2001

There were 3 flow reversal events in 2001 and the August 2, 2001 event caused the largest flow reversal volume with the total of 1,023.0 million gallons. Different gate operation schemes were tried and results (Figure 3.8) showed that if the water-surface elevation at the LCW is kept at -5 ft CCD for 6 hr prior the CSO event, allowable minimum water-surface elevations for wet weather conditions can be maintained throughout the CWS. Figure 3.8 also shows the results of simulation reflecting gate-opening schemes to lower the water-surface elevations at the LCW to -9 ft CCD for 12 hr during the CSO event. The peak water-surface elevations at Columbus Drive and Wilmette decreased from 6.59 and 8.40 ft CCD, respectively, to 6.08 and 7.97 ft CCD, respectively, by lowering the downstream boundary condition at Lockport to -5 ft CCD for 6 hr prior the CSO event. In the *No Limit* simulation (Figure 3.9), the peak water-surface elevations at Columbus Drive and Wilmette decreased from 6.59 and 8.40 ft CCD, respectively, to 5.14 and 7.22 ft CCD, respectively by lowering the downstream boundary condition at Lockport to -7 ft CCD for 12 hr prior the CSO event. Both Figure 3.8 and Figure 3.9 show that lowering the water-surface elevations at the LCW before the CSO event is not enough to prevent flow to Lake Michigan.

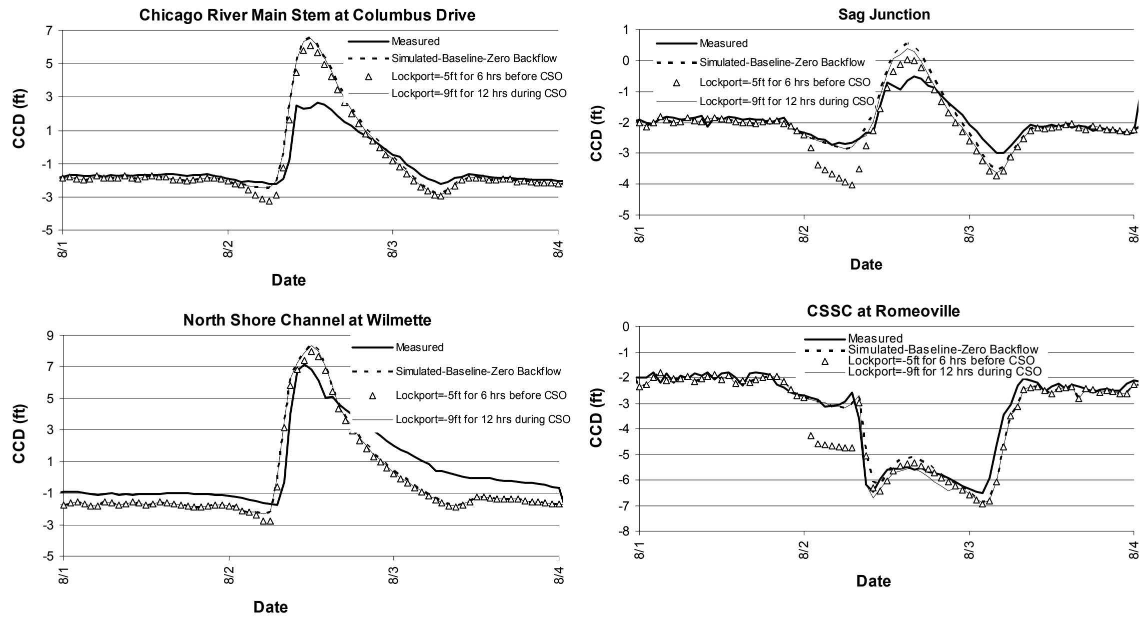


Figure 3.8 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for simulations reflecting various gate operations at Lockport for August 1-4, 2001

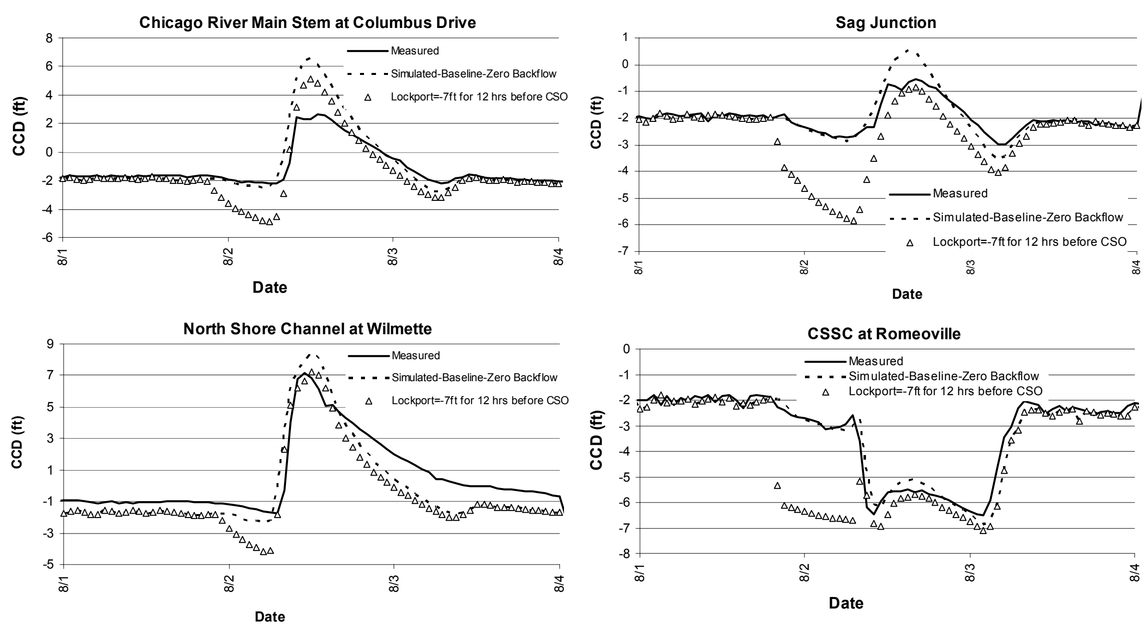


Figure 3.9 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for "*No Limit*" simulations for August 1-4, 2001

3.3.5 August 31, 2001

The August 31, 2001 flow reversal event caused a total of 75.3 million gallons of flow reversal volume. Different gate operation schemes were tried and results (Figure 3.10) showed that if the water-surface elevation at the LCW is kept at -3 ft CCD for 6 hr prior the CSO event, allowable minimum water-surface elevations for wet weather conditions can be maintained throughout the CWS. The peak water-surface elevation at Wilmette is 5.62 ft CCD for the *Baseline* simulation and lowering the downstream boundary condition at LCW to -3 ft CCD for 6 hr prior the CSO event has an insignificant effect on the peak water-surface elevation at Wilmette. In the *No Limit* simulation (Figure 3.11), the peak water-surface elevations at Columbus Drive and Wilmette decreased from 0.58 and 5.62 ft CCD, respectively, to -1.64 and 4.84 ft CCD, respectively by lowering the downstream boundary condition at Lockport to -7 ft CCD for 12 hr prior the CSO event. Both Figure 3.8 and Figure 3.9 show that lowering the water-surface elevations at Lockport before the CSO event does not provide enough storage in the CWS to prevent flow to Lake Michigan. Since gate operation scheme of *During CSO* simulation is very close to the actual gate operations, *Baseline* and *During CSO* simulations resulted in very close water-surface elevations.

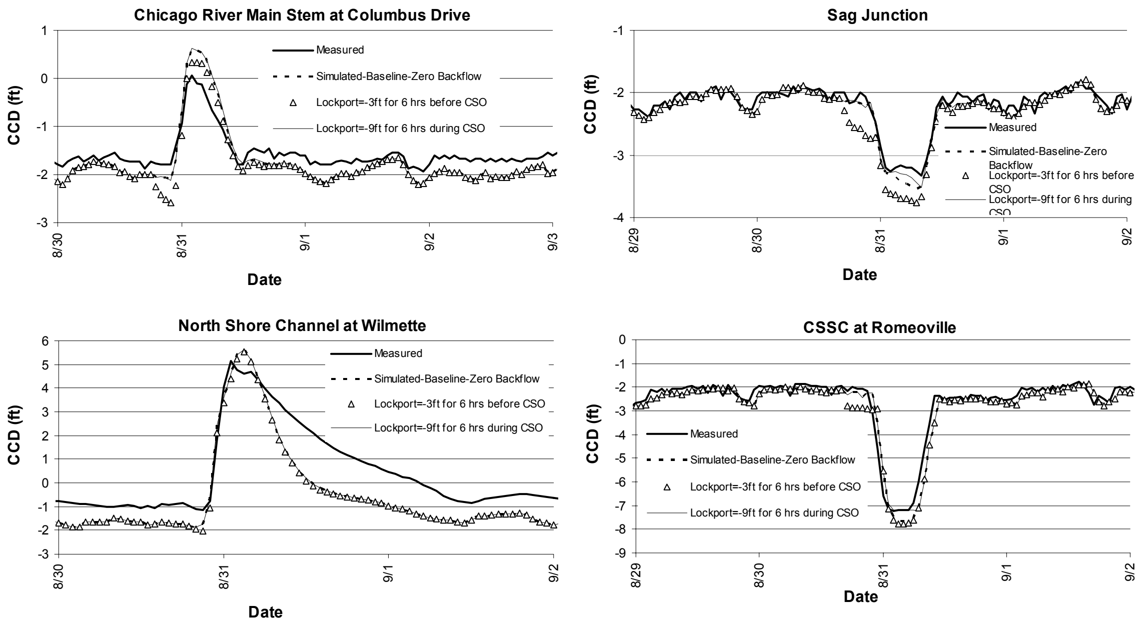


Figure 3.10 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for simulations reflecting various gate operations at Lockport for August 30-September 2, 2001

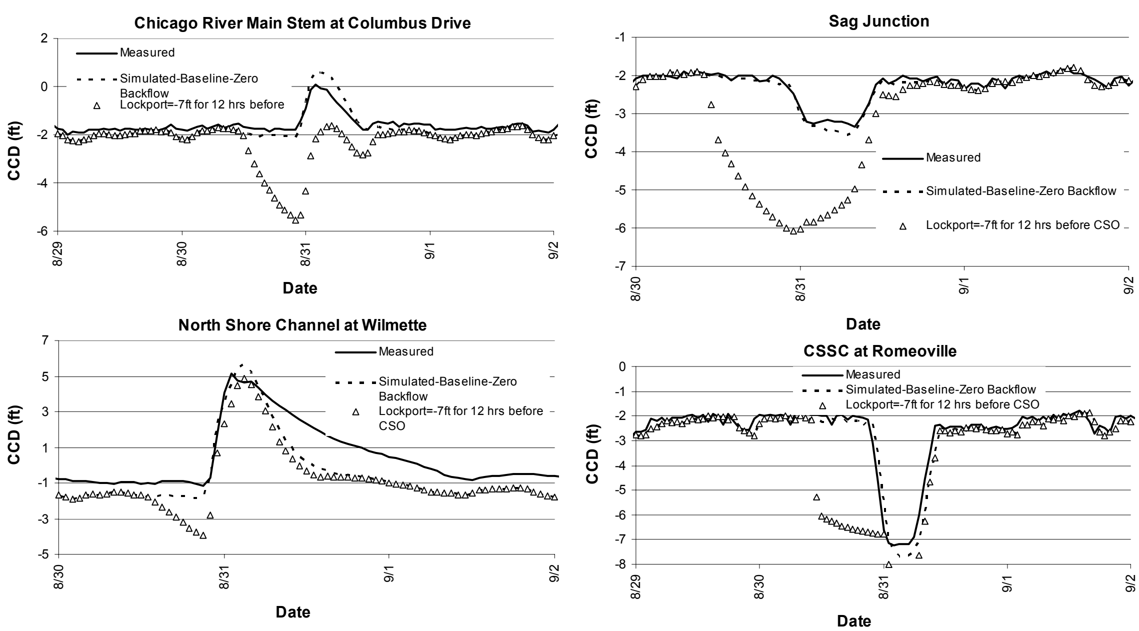


Figure 3.11 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for "*No Limit*" simulations for August 29-September 2, 2001

3.3.6 October 13, 2001

The October 13, 2001 flow reversal event caused a total of 90.7 million gallons of flow reversal volume. As can be seen in Figure 3.12 when the water-surface elevation at the LCW is kept at -3 ft CCD for 6 hr prior the CSO event, allowable minimum water-surface elevations can be maintained throughout the CWS. In the *No Limit* simulation (Figure 3.13), the peak water-surface elevations at Columbus Drive and Wilmette decreased from 1.77 and 4.95 ft CCD, respectively, to 0.46 and 4.23 ft CCD, respectively by lowering the downstream boundary condition at Lockport to -7 ft CCD for 12 hr prior the CSO event. Figure 3.12 shows that the flow reversal can not be prevented if the water-surface elevation at LCW is lowered before the CSO but navigational water-surface elevations are maintained. However, Figure 3.13 shows that if the allowable navigational water-surface elevations at Columbus Drive and Sag Junction were relaxed prior to storms, this flow reversal to Lake Michigan could have been avoided. Such a policy is risky because if the storm turned out to be small substantial navigation make-up water would have to be taken from Lake Michigan. Since the gate operation scheme of *During CSO* simulation is very close to the actual gate operations, *Baseline* and *During CSO* simulations resulted in very close water-surface elevations.

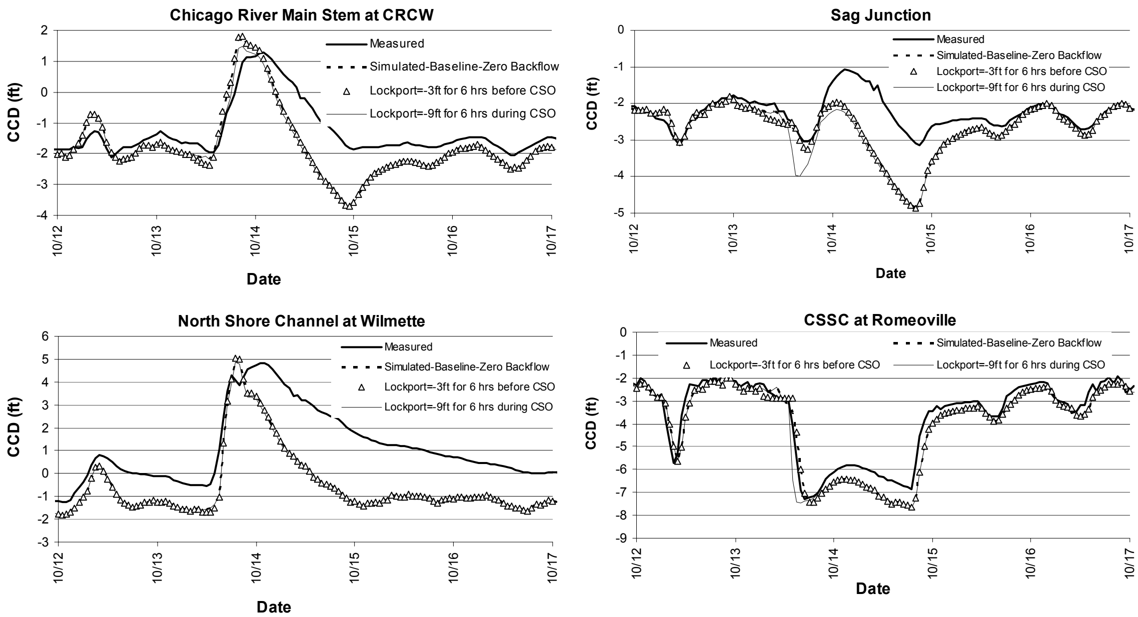


Figure 3.12 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for simulations reflecting various gate operations at Lockport for October 12-17, 2001

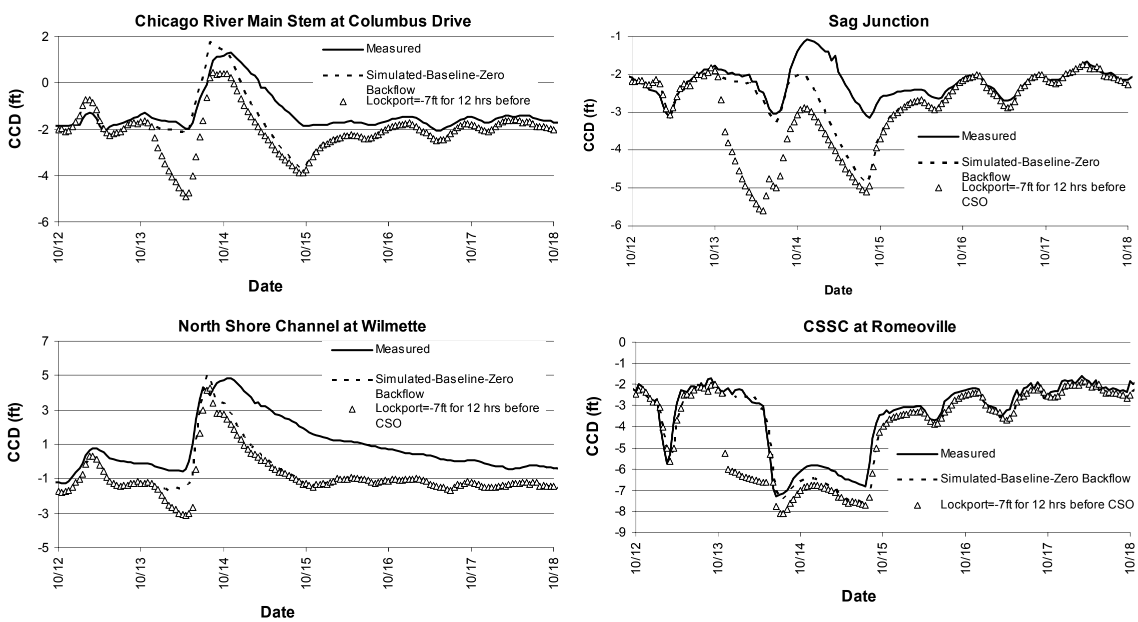


Figure 3.13 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for "*No Limit*" simulations for October 12-18, 2001

3.3.7 August 22, 2002

The August 22, 2002 flow reversal event caused a total of 1,751.8 million gallons flow reversal volume, the second largest flow reversal event between 1990 and 2007. In the *Before CSO* simulation, the water-surface elevations at the LCW are kept at -3 ft CCD for 6 hr prior the CSO event in order to meet allowable minimum water-surface elevations throughout the CWS (Figure 3.14). Both Figure 3.14 and Figure 3.15 show that lowering the water-surface elevations at Lockport before the CSO event starts does not provide enough storage in the CWS to prevent flow reversals at the upstream boundaries. In the *No Limit* simulation (Figure 3.15), the peak water-surface elevations at Columbus Drive and Wilmette decreased from 6.82 and 10.55 ft CCD (*Baseline* simulation), respectively, to 5.21 and 9.57 ft CCD, respectively, by lowering the downstream boundary condition at the LCW to -7 ft CCD for 12 hr prior to the CSO event. Since the gate operation scheme of *During CSO* simulation is very close to the actual gate operations, *Baseline* and *During CSO* simulations resulted in very close water-surface elevations.

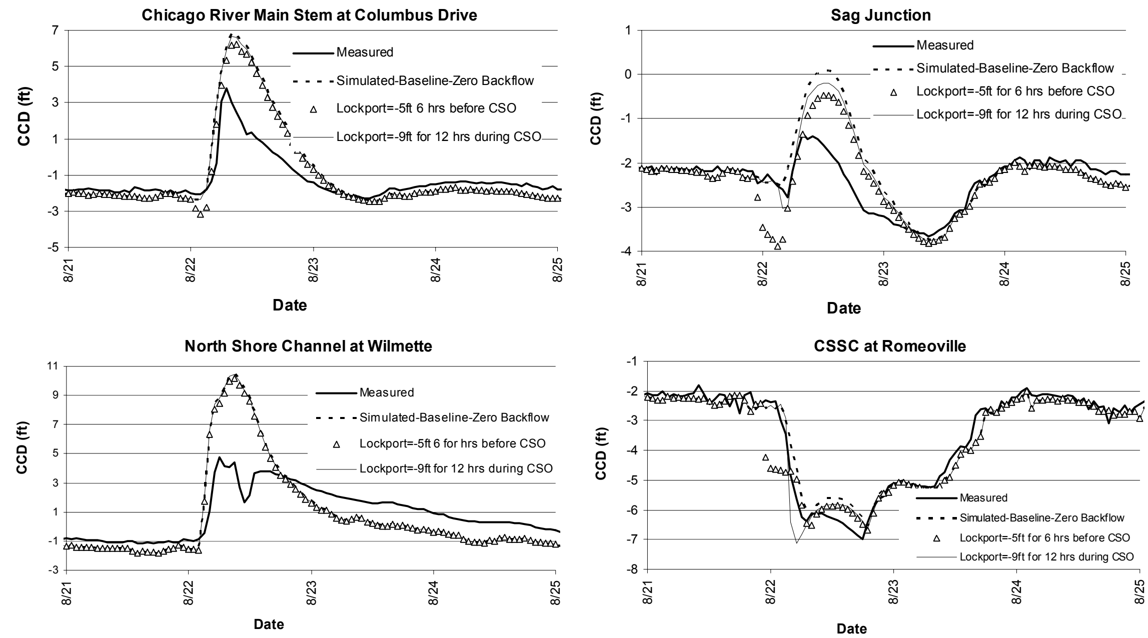


Figure 3.14 Water-surface elevations at different location in the Chicago Water System for simulations reflection various gate operations at the Lockport for August 21-25, 2002

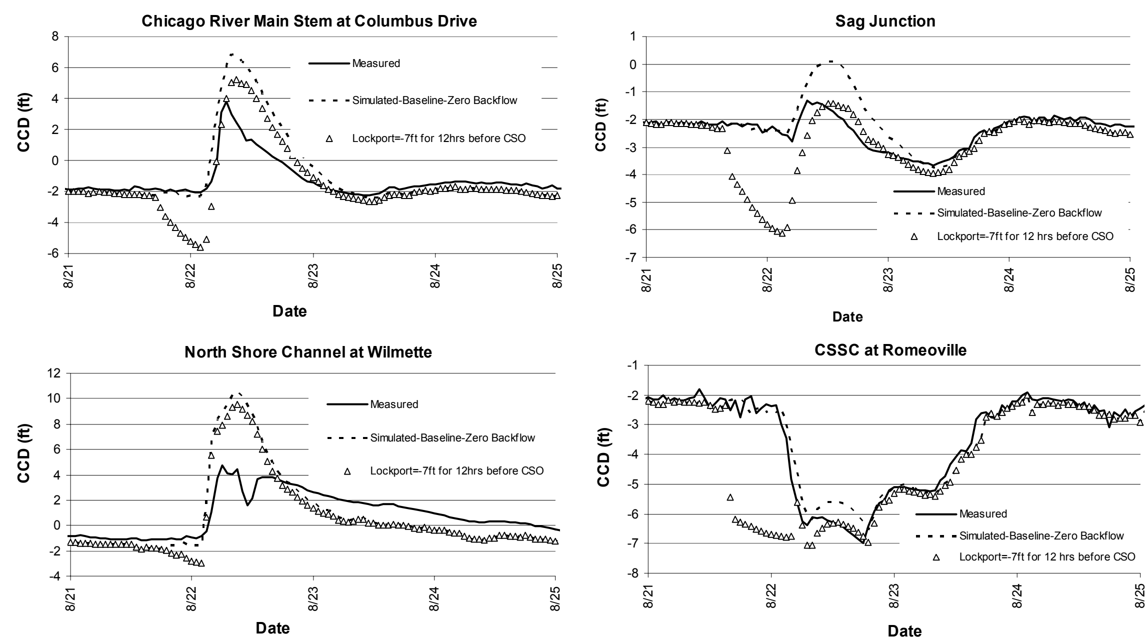


Figure 3.15 Water-surface elevations relative to the City of Chicago Datum (CCD) at different locations in the Chicago Water System for "*No Limit*" simulations for August 21-25, 2002

CHAPTER 4 - DISCUSSIONS AND CONCLUSIONS

In this study, 7 flow reversal events that occurred between 1997 and 2002 were analyzed to determine if operation schemes for the gates at Lockport could have eliminated or minimized the volume of the flows to Lake Michigan for these events. The results of the simulations reflecting various gate operations between 1997 and 2002 are presented in Chapter 3.

The results of the simulations reflecting hypothetical gate operations to prevent flow reversals were compared with the *Baseline* simulations in which zero discharge has been assumed during flow reversal events. In these simulations, water-surface elevations were lowered to maintain minimum allowable water-surface elevations in the CWS. Outcomes of the simulations show that lowering the water-surface elevations at the LCW to -3 to -5 ft CCD for 6 hr before the CSO event do not provide enough storage for the CSOs in the CWS to prevent flow reversals. The effect of lowering water stages at Lockport decreases as locations farther from Lockport are considered and is almost negligible at Wilmette. Even though this practice lowers the water-surface elevations in the CWS before the CSO events, the peak water-surface elevations during CSO events are insignificantly affected by lowering the water-surface elevations before the CSO events.

In subsequent runs, the downstream boundary condition at the LCW were lowered upto -5 to -7 ft CDD for an extended 12 hr period before the CSO event and water-surface elevations were allowed to be lower than minimum navigational water-surface elevations limits. Even though a 0.3 to 1.0 ft decrease in the peak water-surface elevations at CRCW and Wilmette resulted, peak water-surface elevations were not low enough to prevent flow reversals to the Lake Michigan for all events except for October 13, 2001.

In the last set of simulations, water-surface elevations were allowed to go down to -9.0 ft CCD at the LCW to increase the water-surface slope and flow rate in the CSSC just as water-surface create storage for the CSOs during flow reversal events. Since, in the actual case (*Baseline*), all Lockport gates were open and water-surface elevations were allowed to decreased to -9 ft CCD, these simulations resulted in very close numbers to *Baseline* simulations results.

In order to understand the general lack of effectiveness of the various simulated changes in gate operations at Lockport in reducing water-surface elevations at the lakefront boundaries, a comparison of the inflows to and outflows from the CWS was done. The measured and estimated inflows as summarized in Section 2.2.3 were summed on an hourly basis for each flow reversal event and are compared with the measured outflows at Romeoville in Figures 4.1-4.7. For the February 20-22, 1997 event (Figure 4.1) the peak inflow is nearly 50,000 cubic feet per second (cfs) while the measured peak outflow was 19,466 cfs (the highest flow ever measured at the Romeoville gage). This comparison shows that with the inflow being up to 30,000 cfs higher than the outflow for several hours the storage space created by lowering the CWS is quickly filled and the CSSC and/or NSC and NBCR are not capable of draining the CWS fast enough to avoid flow reversals at the CRCW and Wilmette, respectively, despite changed gate operations at

Lockport. Figures 4.2-4.7 show similar results for the other 6 flow reversal events. For example, for the August 16-17, 1997 event the peak inflow was nearly 45,000 cfs whereas the peak outflow was 16,150 cfs (Figure 4.2); for the August 2, 2001 event the peak inflow was around 45,000 cfs and the peak outflow was 15,479 cfs (Figure 4.4); for the August 31, 2001 event the peak inflow was around 16,500 cfs and the peak outflow was 13,786 cfs (Figure 4.5); and for the August 22, 2002 event the peak inflow exceeded 35,000 cfs and the peak outflow was 17,984 cfs.

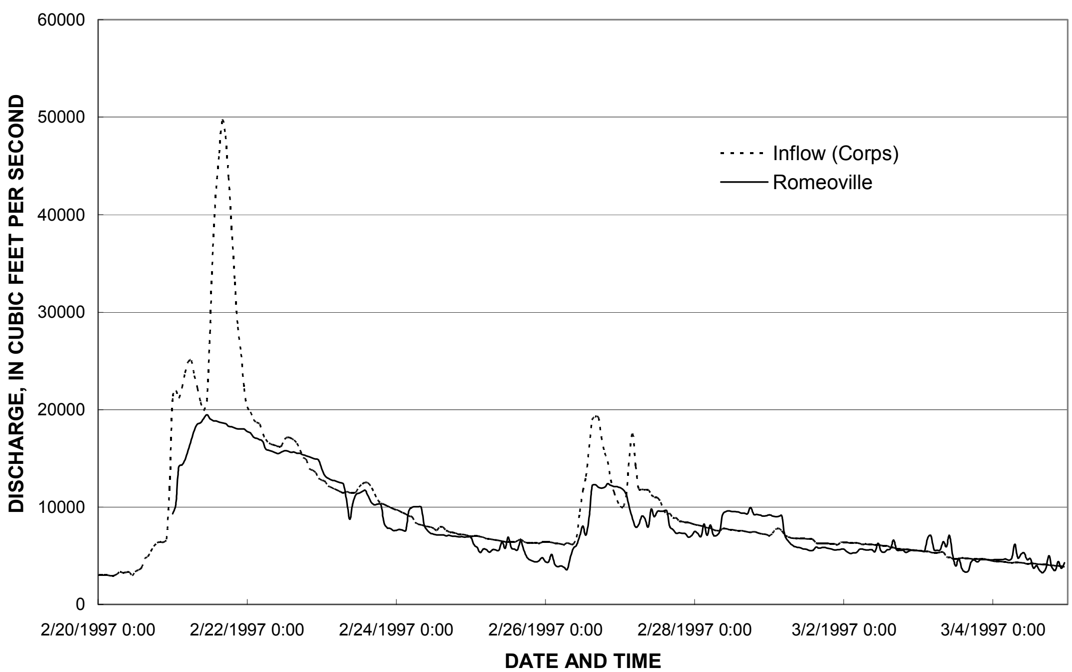


Figure 4.1 Measured and estimated inflow to the Chicago Waterway System and measured outflow at Romeoville, IL, for February 20 to March 4, 1997.

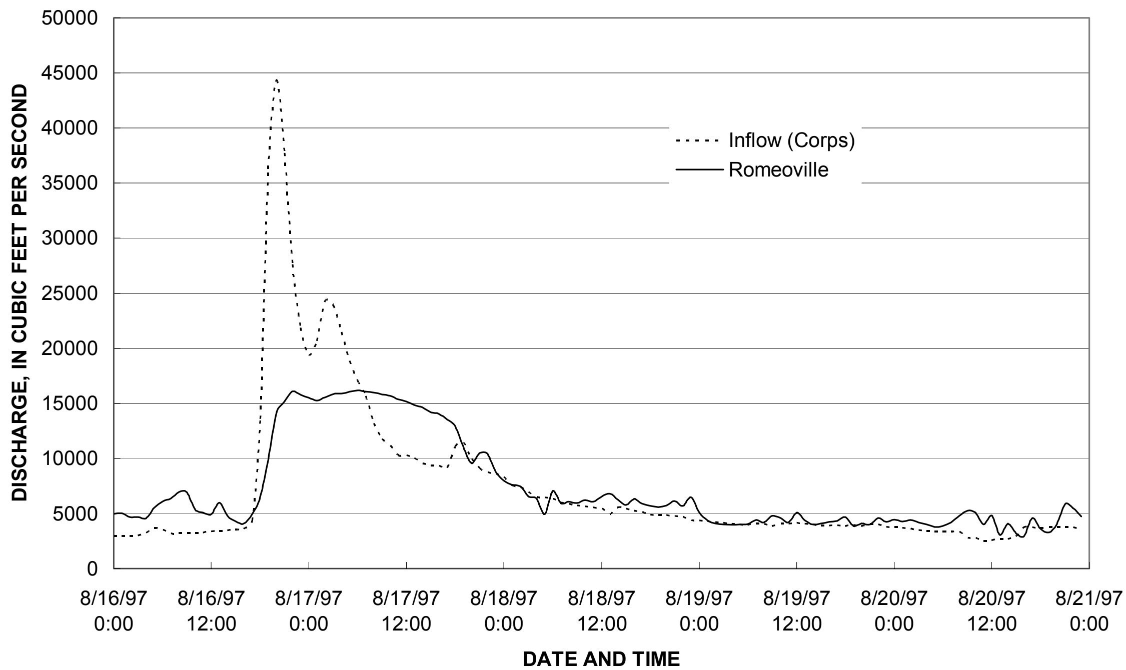


Figure 4.2 Measured and estimated inflow to the Chicago Waterway System and measured outflow at Romeoville, IL, for August 16 to 20, 1997.

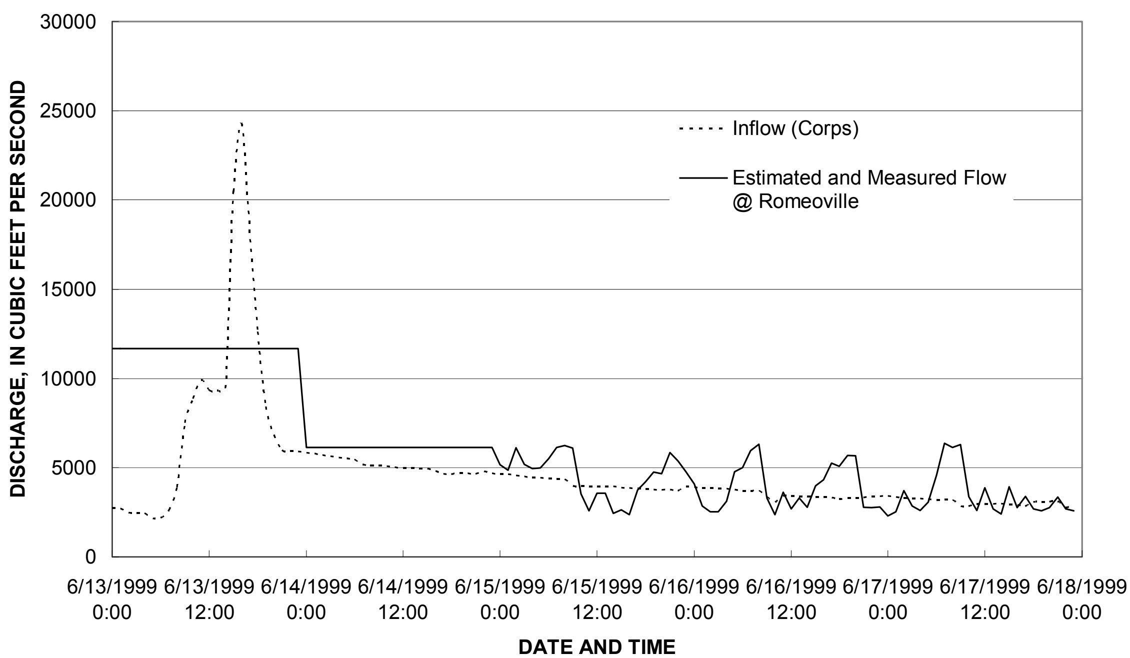


Figure 4.3 Measured and estimated inflow to the Chicago Waterway System and measured and estimated outflow at Romeoville, IL, for June 13 to 17, 1999.

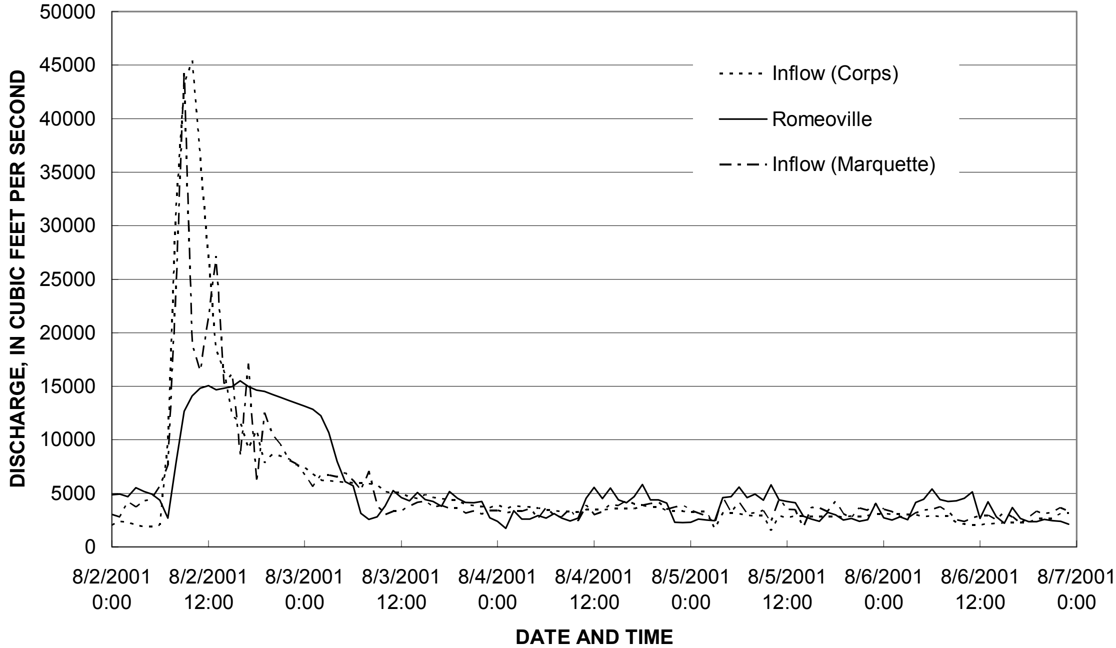


Figure 4.4 Measured and estimated inflow to the Chicago Waterway System and measured outflow at Romeoville, IL, for August 2 to 6, 2001.

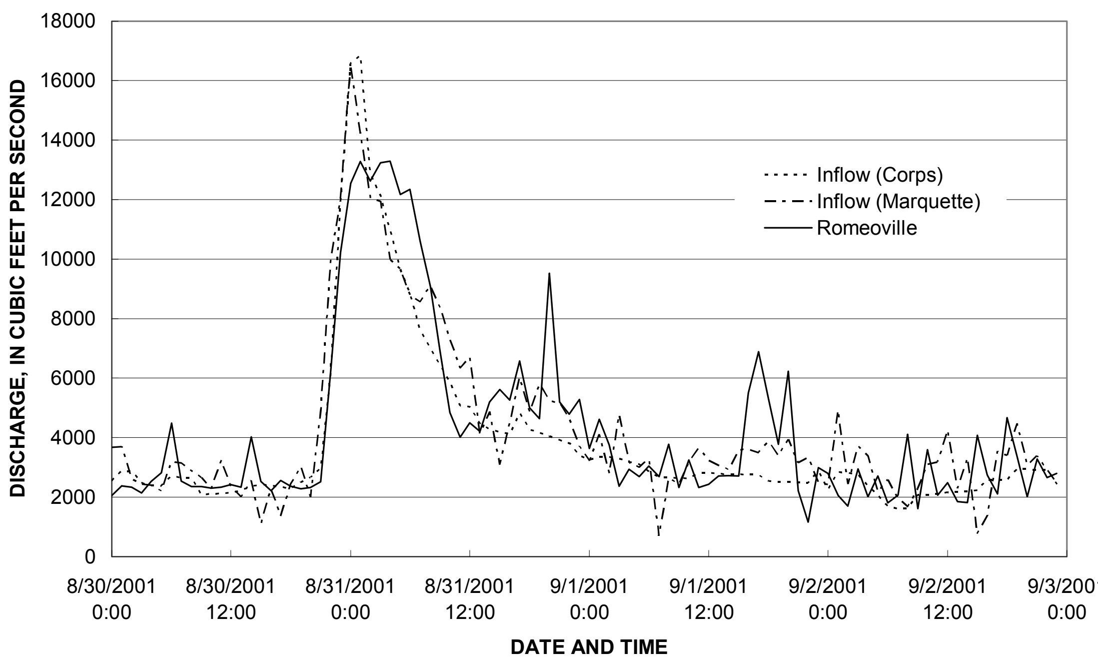


Figure 4.5 Measured and estimated inflow to the Chicago Waterway System and measured outflow at Romeoville, IL, for August 30 to September 2, 2001.

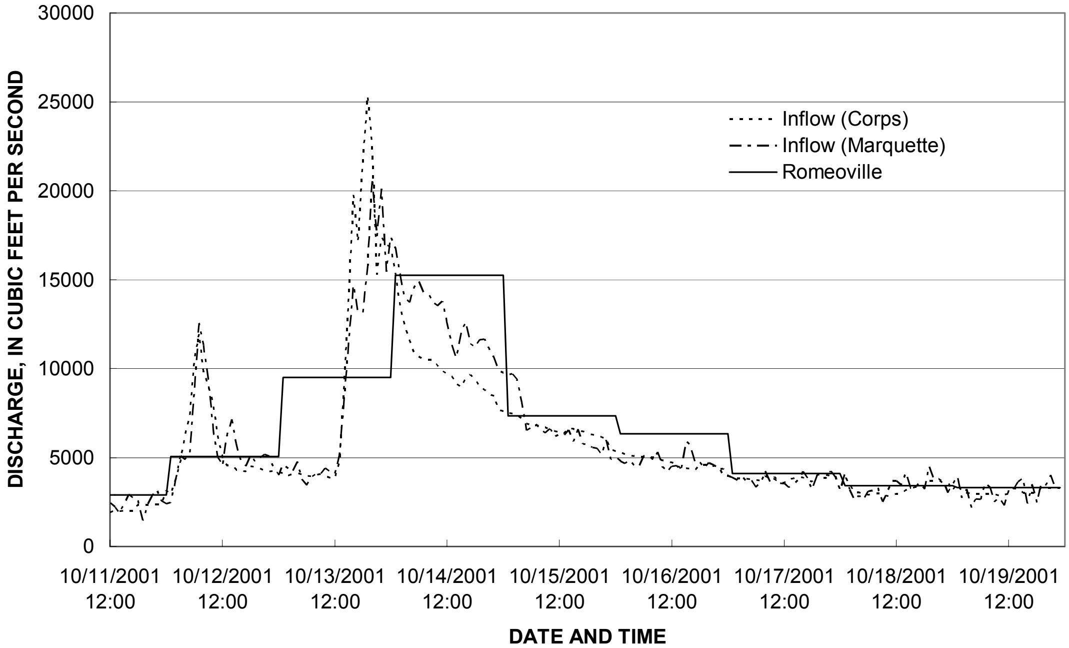


Figure 4.6 Measured and estimated inflow to the Chicago Waterway System and estimated outflow at Romeoville, IL, for October 11 to 19, 2001.

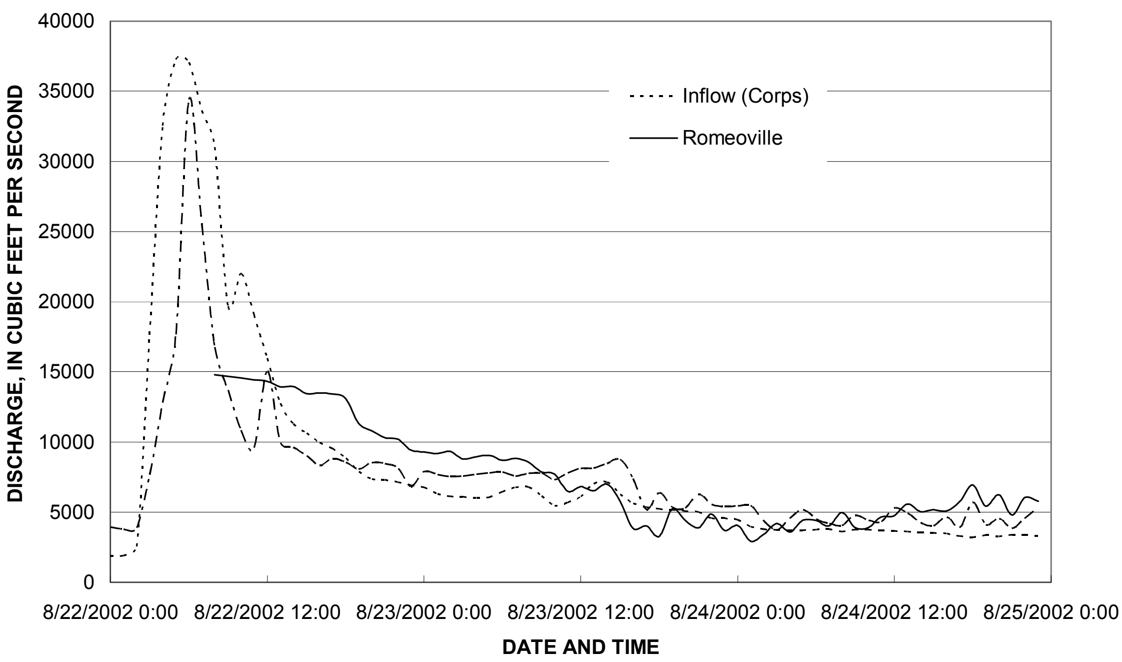
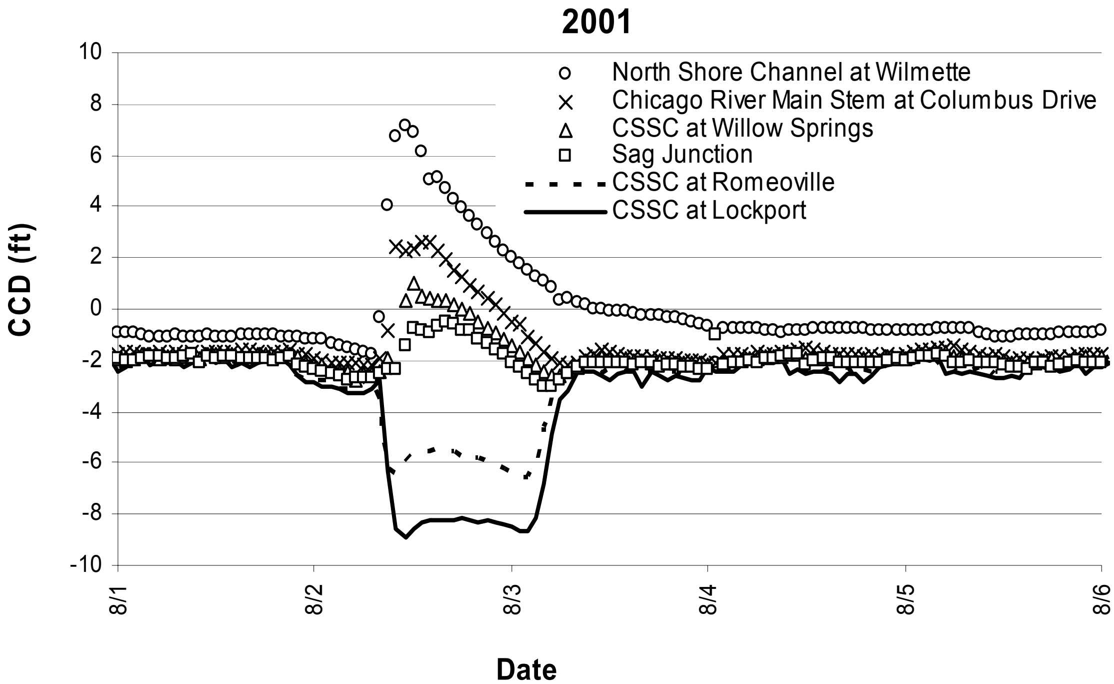


Figure 4.7 Measured and estimated inflow to the Chicago Waterway System and measured outflow at Romeoville, IL, for August 22 to 24, 2002.

It may be speculated that the inflows estimated by the Corps models are too high, and, thus, the inability of the CWS to drain away high storm flows is overstated in Figures 4.1-4.7 and in Chapter 3. Figures 4.4-4.7 also include the estimate of total inflows to the CWS based on Marquette University's original estimates of the gravity CSO flows. The Marquette estimates are based on the daily water balance for the CWS and the amount of gravity CSO flow and flow at the lakefront boundaries (where water-surface elevation boundary conditions were used in the model) needed to match measured water-surface elevations throughout the CWS (Shrestha and Melching, 2003). The peak inflows from the Corps models and Marquette estimates are very close within 2% for the August 2001 events, within 8% for the August 2002 event, and within 18% for the October 2001 event. Differences in volumes are greater, but in general, the agreement between the output of the Corps models and the Marquette estimates is good enough to conclude that during larger storms the inflows to the CWS overwhelm the drainage ability of the component channels of the CWS.

The measured water-surface elevations at different locations on the CWS for the two largest flow reversal events that occurred between 1990 and 2007 are shown in Figure 4.8 (measured water-surface elevations for the other 5 flow reversal events have similar patterns to those shown in Figure 4.8). As can be seen in Figure 4.8, the difference between the peak water-surface elevation at Wilmette and lowest water-surface elevation at the LCW can reach up to 16 ft during flow reversal events. Figure 4.8 also shows that measured water-surface elevations at the locations above Sag Junction are all higher than

-2.0 ft CCD even though minimum water-surface elevations at Romeoville and Lockport are around -6 and -9 ft CCD, respectively.



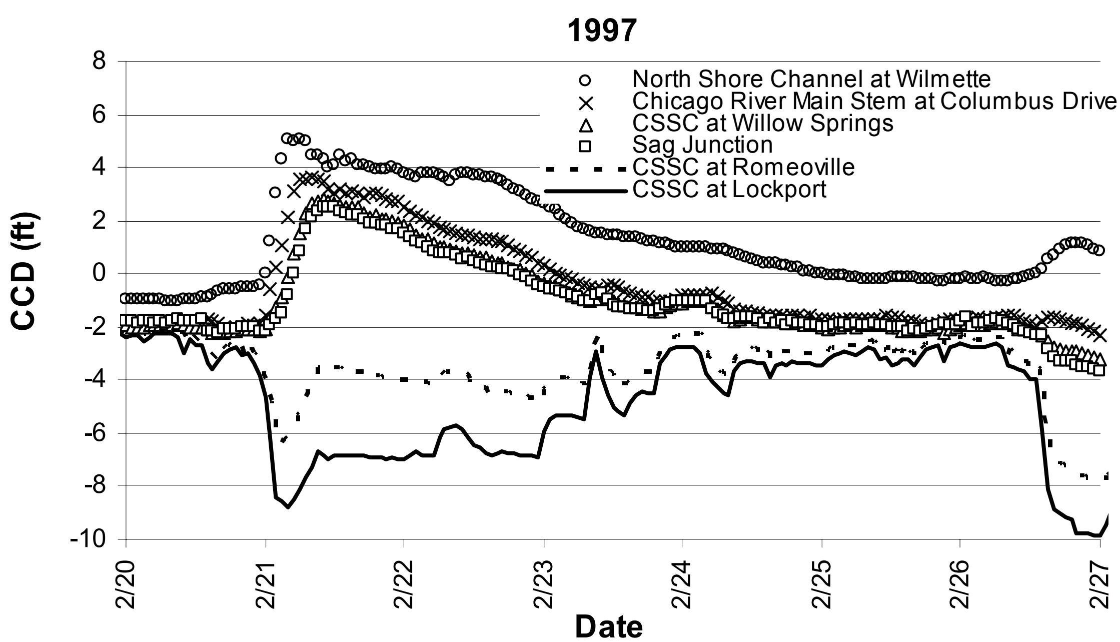


Figure 4.8 The measured water-surface elevations at different locations on the Chicago Waterway System for August 2, 2001 and February 20-22, 1997 flow reversal events.

For the February 1997 event the maximum difference in water-surface elevation between Wilmette and Columbus Drive (14 miles) and between Columbus Drive and Sag Junction (23.2 miles) is less than 2 ft, whereas the maximum difference in water-surface elevation between Sag Junction and the LCW (10.2 miles) is around 9 ft. For the August 2, 2001 event the maximum difference in water-surface elevation between Wilmette and Columbus Drive is around 5 ft, between Columbus Drive and Sag Junction is around 3 ft, and between Sag Junction and the LCW is around 8 ft. Thus, a large water-surface slope is present on the CSSC from Sag Junction to the LCW in order for this reach to transport the large storm flows coming from the upstream CSSC and Calumet-Sag Channel. The CSSC was not constructed anticipating the construction of the Calumet-Sag Channel, and the geometry of the CSSC is the same upstream and downstream of Sag Junction. Thus, a two lane highway of water is narrowed to one lane, causing water to back-up each of the two lanes (the upstream CSSC and Calumet-Sag Channel) resulting in low water-surface slopes and flow capacities. Thus, the inability of the CWS to drain high storm flows away from lakefront areas resulting in flow reversals can be seen in the records of the measured water-surface elevations.

In summary, changed operations of the gates at Lockport cannot prevent flow reversals to Lake Michigan because the flow capacity of the CWS is not large enough to drain away high storm flows. These high storm flows quickly fill storage space created by lowering the CWS by opening the gates at Lockport in anticipation of a large storm, and the water-surface elevations at the lakefront rise quickly to flood levels necessitating flow reversals. It is likely that the MWRDGC's policy of lowering the CWS in anticipation of storms may help avoid flow reversals for smaller storms, but this possibility was not explicitly evaluated in this study. Finally, there appears to be nothing that the MWRDGC can reasonably do to avoid future flow reversals until the reservoirs of the Tunnel and Reservoir Plan come on line and the volume of CSO flows is further reduced.

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