Evaluation of Methods to Reduce Backflows from the Chicago Waterway System to Lake Michigan

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ABSTRACT

A detailed study of seven historic backflow from the Chicago Waterway System (CWS) to Lake Michigan events (including the 2nd and 4th largest since 1965) was done to evaluate changes in waterway operation procedures to determine if backflows could be avoided or reduced in volume. The study applied a dynamic-wave simulation model to the CWS at a 15-minute time step combining measured inflows for the major tributaries, combined sewer overflow (CSO) pump stations, and water reclamation plants with simulated gravity CSO flows computed by the U.S. Army Corps of Engineers. The simulated CSO inflows were confirmed against a detailed mass balance approach for four storms and the peak flows from the two approaches were found to be remarkably similar. It was found that the hydraulic capacity limitations of the Chicago Sanitary and Ship Canal (CSSC) prevented changes in operations at the Lockport Powerhouse and Controlling Works from substantially reducing backflows. The maximum discharge through the CSSC is around 19,500 cfs whereas inflows may peak at 40,000 to 50,000 cfs and flows cannot drain away fast enough to avoid having to allow backflows to Lake Michigan. These backflows cannot be avoided until the reservoirs of the Tunnel and Reservoir Plan (TARP) are completed.

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.

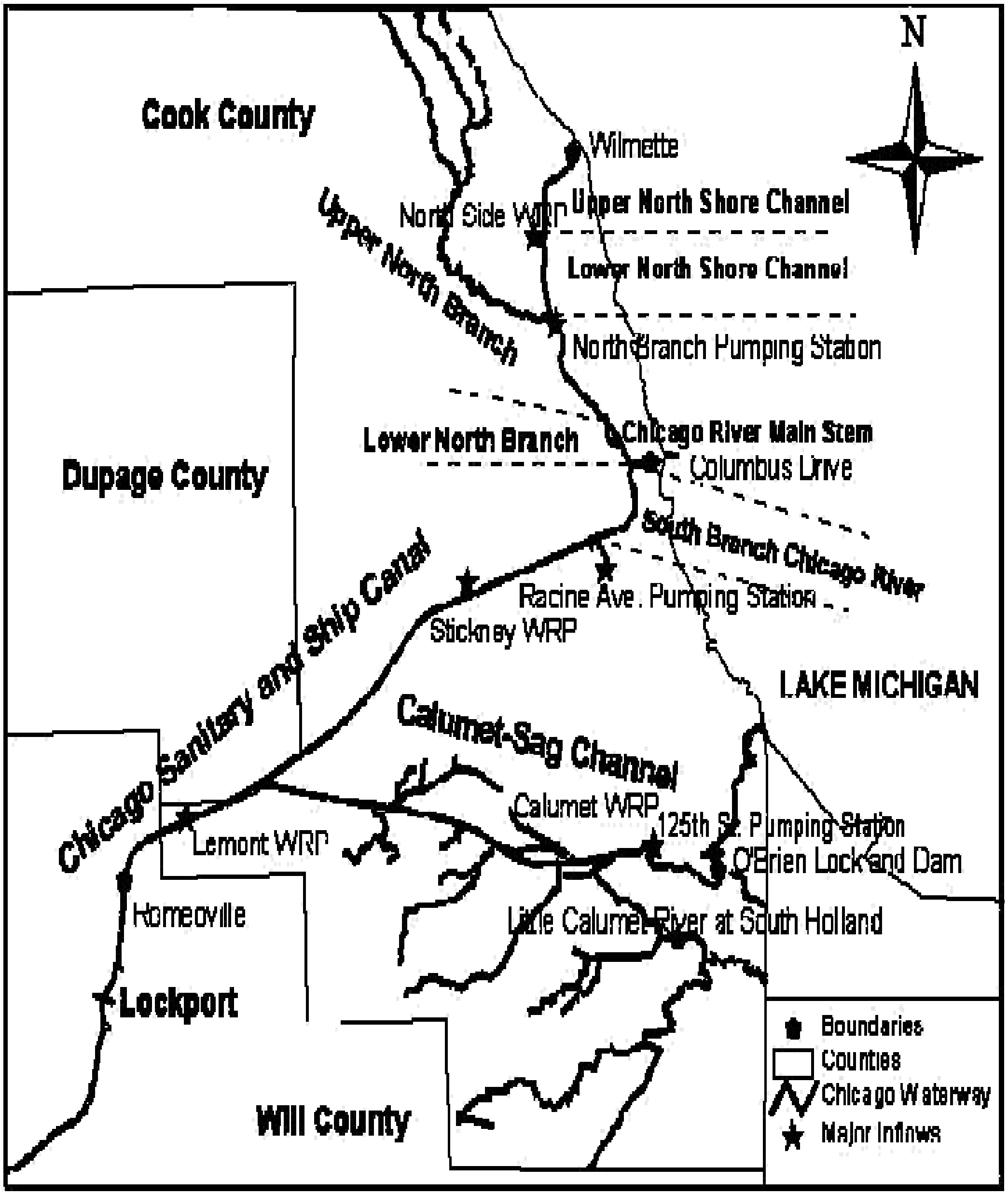

Figure 1. Schematic diagram of the Calumet and the Chicago River Systems.

Minimizing the occurrence of backflows of storm runoff and sewage to Lake Michigan through the lakefront sluice gates and locks is a high priority for the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC). Backflows can potentially affect the water supply of Chicago, the accessibility of beaches to the public, and the general environment of Lake Michigan. Since the O'Brien Lock and Dam were completed in 1965 forty-nine storms have 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 on-line for a pre-TARP rate of 1.5 per year and a post-TARP rate of 0.73 per year. The decrease in frequency of backflows reflects the reduction in flood flows resulting from the TARP tunnels. However, the volumes of the backflows since 1990 have been large with 6 of the 10 largest backflow volumes from 1965 to 2007 occurring since 1990 (Table 1). The objective of this study is to evaluate 7 historic backflow events (1997-2002) to see if changes in operation procedures at the Lockport Powerhouse and Controlling Works can avoid or reduce the volume of backflows.

Table 1. Flow volume of backflow events (in million gallons) from 1990 to 2007.

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

HYDRAULIC MODEL DESCRIPTION AND VERIFICATION

The DUFLOW (2000) unsteady-flow model for the CWS was calibrated and verified by the 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). 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 backflow events, the DUFLOW model was extended from Romeoville to the Lockport Controlling Works, LCW, (3 miles downstream from Romeoville and 2.2 miles upstream of the Lockport Power House, LPH, and Lock). The model was run at a 15-min. time step and measured and simulated stage values were compared for a 60-min. time interval. Assumptions, data used, and results are presented in the following subsections.

Measured inflows, outflows, and water-surface elevations. During the study period the USGS operated 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 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 LCW were used for the downstream boundary condition.

During the backflow events, MWRDGC estimated the volume of backflows and the USGS measured them with acoustic velocity meter (AVM) gages. It was found that simulations with the volume of backflows estimated by MWRDGC resulted in better water-surface elevation estimates in the CWS than simulations using the USGS measurements. Thus, just during backflow events USGS flows were adjusted to match the MWRDGC backflow volume estimates. This approach is reasonable because the USGS never made discharge measurements during a backflow with which the AVM gages could be properly calibrated at the Lakefront structures (Jim Duncker, USGS, personal commun., 2007).

The data from the USGS gage of the Little Calumet River (South) at South Holland provide a flow versus time upstream boundary condition for the model. Two tributaries to the Calumet-Sag Channel are gaged by the USGS, Tinley Creek near Palos Park and Midlothian Creek at Oak Forest. The USGS gage on the Grand Calumet River at Hohman Avenue at Hammond, IN measures flow on a tributary of 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.

Hourly flow data are available from the MWRDGC for the treated effluent discharged to the CWS by each of the three Water Reclamation Plants—North Side, Stickney, and Calumet. In addition, hourly flows discharged to the CWS at three CSO pumping stations—North Branch, Racine Avenue, and 125th Street—were estimated from operation logs and rated pump capacities for these stations.

Estimation of flow for ungaged tributaries and combined sewer overflows. Flows on Midlothian Creek were used to estimate flows on ungaged tributaries on an area-ratio basis as was done in the model calibration (Shrestha and Melching, 2003).

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. In this study, simulated CSO flows were obtained from the U.S. Army Corps of Engineers (Corps), which are calculated on an annual basis in support of the Lake Michigan Diversion Accounting. Detailed discussion of the Corps models (a combination of the Hydrological Simulation Program-Fortran, Special Contributing Area Loading Program, and Tunnel Network Model) is given in Espey et al. (2004). The flow simulations are driven by precipitation data from a network of 25 precipitation gages throughout the Chicago area established by the Corps in 1990.

Channel geometry and roughness coefficient. The channel geometry is represented as a series of 231 measured cross sections. The DUFLOW model uses Chezy's roughness coefficient, C, to calculate hydraulic resistance. The calibrated C values vary between 6 and 60 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).

Model verification. Although flows in the various branches of the CWS are not measured, water-surface elevation data recorded at different locations were used for calibration and verification of the model. The water-surface elevations recorded at Columbus Drive, O'Brien Lock and Dam, Wilmette, 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 order to evaluate the backflow events, the DUFLOW model was applied for the following simulation periods:

February 1 - March 30, 1997
August 1 - September 30, 1997
June 1 - June 30, 1999
July 1- November 9, 2001
August 1 – September 23, 2002

As an example of the output, Table 2 lists the statistical analysis for July 1 to November 9, 2001 of the difference between the measured and simulated stages. It can be seen that the errors are below 10 % relative to the depth (where depth is measured from the thalweg of the channel) of the water for all of the values except for 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 backflow events at the boundaries indicate an excellent hydraulic verification of the model. Similar results for the other simulation periods are presented in Alp and Melching (2008).

Table 2. 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.

July 1-November 9, 2001		Percentage		
Location	Correlation Coefficient	<±2% of D	<±5% of D	<±10% of D
Wilmette	0.81	0	4	75
Chicago River Controlling Works	0.82	87	99	100
O'Brien Lock and Dam	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 (Cal-Sag)	0.77	84	99	100
Sag Junction	0.80	98	99	100
Romeoville (CSSC)	0.96	95	100	100

EVALUATION OF OPERATION SCHEMES FOR LOCKPORT GATES

Actual operation schemes for the Lockport Gates. Records for 1998-2002 of the opening of the LPH pit gates and LCW sluice gates were obtained from the MWRDGC. These were compared with the measured water-surface elevations at the LCW to establish typical water-surface elevations for various combinations of gate openings. There are 9 LPH pit gates and 7 LCW sluice gates. Comparison of the water-surface elevations at LCW with the various gate openings for the selected storms are detailed in Alp and Melching (2008). The MWRDGC gradually opens the pit gates at the LPH when a larger storm is anticipated and LCW sluice gates are also opened when higher discharges and water-surface elevations are observed. When the 9 LPH pit gates are open, water-surface elevation at the LCW goes down to -5.9 ft CCD on average and when all the gates (LPH and LCW) are open, water-surface elevation goes down to -9.3 ft CCD on average. Different combinations of gate operations result in water-surface elevations ranging from -4 ft CCD to -9.3 ft CCD on average.

Simulation of the Lockport Gate Operation Procedures. Four sets of simulations representing various Lockport gate operation procedures were evaluated and throughout the text some abbreviations explained below are used to describe the simulations:

i) *Before CSO*: Lockport Gates are open 6 to 12 hrs before CSO to bring the water level down to -3, -5, or -7 ft CCD at the LCW and the water level is kept higher than -3 and -4 ft CCD at CRCW and Sag Junction, respectively, as required by navigational regulations. When CSO starts, actual gate operations and LCW water-surface elevations are used. During the backflow event, upstream boundaries are set to zero discharge to see how high the water could rise.

ii) *During CSO*: Gates are open 6 to 12 hrs during CSO event to bring the water level down to -9 ft CCD at the LCW and the water-surface elevation is kept higher than -3 and -4 ft CCD at CRCW and Sag Junction, respectively. Prior to the CSO events, actual gate operations and LCW water-surface elevations are used. During the backflow events, upstream boundaries are set to zero discharge.

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

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

Simulation Results. The results of the *"Before CSO"* simulations reflecting hypothetical gate operations to prevent backflows were compared with the *Baseline* simulations. In these simulations, water-surface elevations were lowered at the LCW while maintaining minimum allowable water-surface elevations at CRCW and Sag

Junction. Outcomes of the simulations show that lowering the water-surface elevations at Lockport to -3 to -5 ft CCD for 6 hours before the CSO event do not provide enough storage for the CSOs in the CWS to prevent backflows. The effect of lowering water-surface elevations at Lockport decreases as locations farther from Lockport are considered with reductions at CRCW ranging from negligible to 0.56 ft and at Wilmette from negligible to 0.43 ft. Even though this practice helps to lower the water-surface elevations in the CWS before the CSO events, the peak water-surface elevations during CSO events are far higher than the levels at which backflows to Lake Michigan are necessary.

In the *"No limit"* simulations, the downstream boundary condition at the LCW was lowered to -5 to -7 ft CCD for an extended 12 hour period before the CSO event and water-surface elevations were allowed to be lower than minimum water-surface elevations limits at CRCW and Sag Junction. Decreases in the peak water-surface elevations of 0.32 to 1.18 ft resulted at Wilmette and decreases on the order of 1.5 ft resulted at CRCW for the events resulting in backflows. However, at both locations peak water-surface elevations were not low enough to prevent backflows to Lake Michigan for all events except October 13, 2001 at Wilmette. Figure 2 shows the water-surface elevation reductions for the *"No limit"* simulations for the August 2, 2001 event, which had the largest decrease at Wilmette among the 7 storms. Similar figures for all storms and scenarios are included in Alp and Melching (2008).

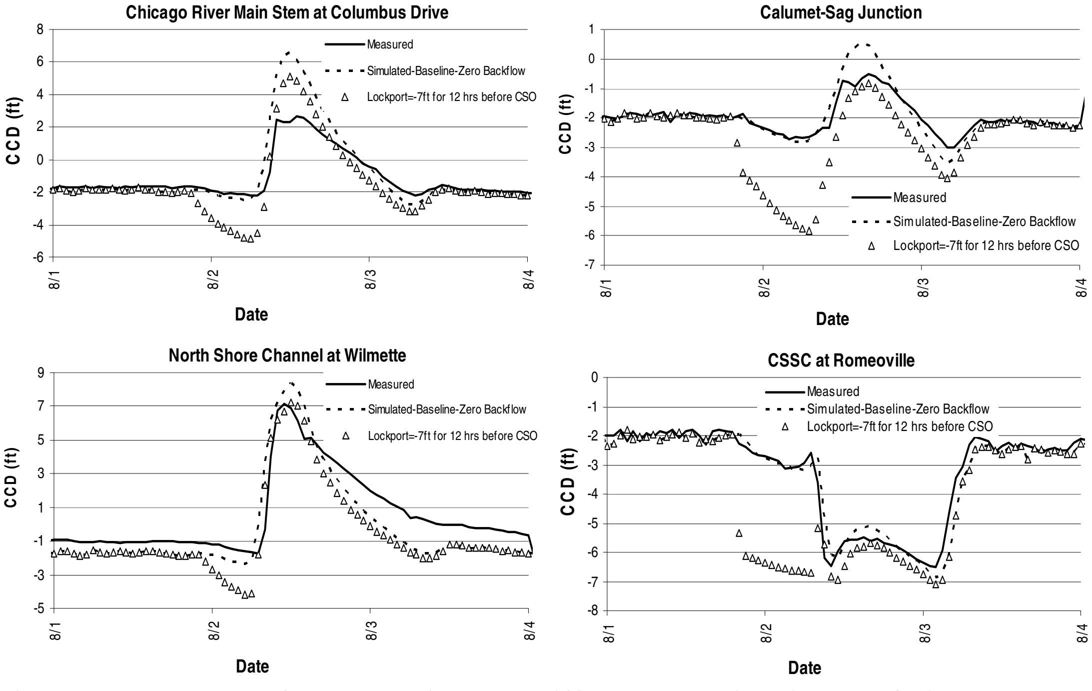

Figure 2. Water-surface elevations at different location in the Chicago Water System for "*No Limit*" simulations for August 1-4, 2001.

In the last set of simulations, water-surface elevations were allowed to go down to -9.0 ft CCD at Lockport to increase the water-surface slope and flow rate in the CSSC just as CSO starts during backflow events. Since, in the actual case (*Baseline*), all Lockport gates were open and water-surface elevations were allowed to decrease to -9 ft CCD, these simulations resulted in very close peak water-surface elevations to the *Baseline* simulation results.

Inflow-Outflow Comparison. In order to understand the 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 were summed on an hourly basis for each backflow event and the summation is compared with the measured outflows at Romeoville in Figure 3 for the August 2, 2001 event. For this event, the peak inflow is nearly 45,000 cubic feet per second (cfs) while the measured peak outflow was 15,479 cfs. 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 backflows at the CRCW and Wilmette, respectively, despite changed gate operations at Lockport. Similar results for the other 6 backflow events are shown in Alp and Melching (2008).

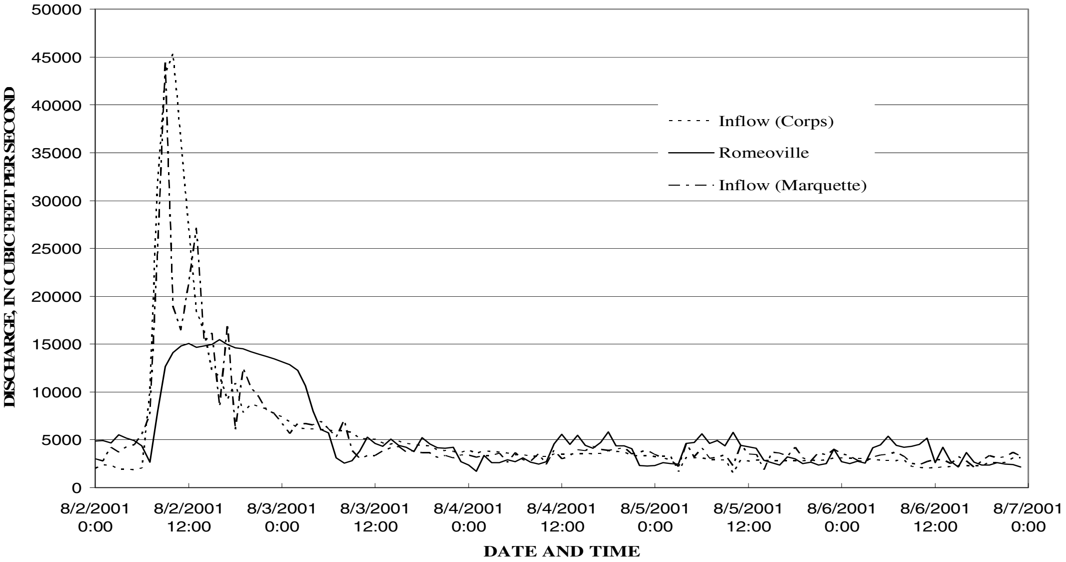

Figure 3. Measured and estimated inflow to the Chicago Waterway System and measured outflow at Romeoville, IL, for August 2 to 6, 2001.

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 Figure 3. Figure 3 also includes 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 original 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 2, 2001 event. The peak flow also was within 2% for the August 31, 2001 event, within 8% for the August 2002 event, and within 18% for the October

2001 event (Alp and Melching, 2008). Differences in volumes are greater, but in general, the agreement between the output of the Corps models and the Marquette estimates is sufficient to conclude that during larger storms the inflows to the CWS overwhelm the drainage ability of the component channels of the CWS.

Measured Water-Surface Elevations. The measured water-surface elevations at different locations on the CWS for the August 2, 2001 event, the second largest backflow event that occurred between 1990 and 2007, are shown in Figure 4 (measured water-surface elevations for the other 6 flow reversal events have similar patterns to those shown in Figure 4). Figure 4 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.

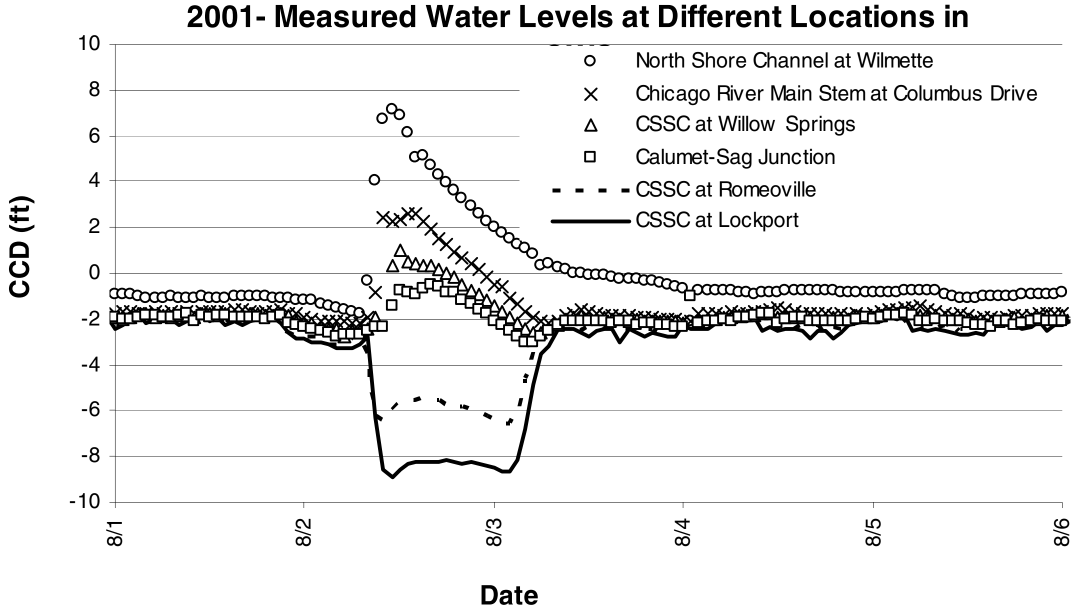

Figure 4. The measured water-surface elevations at different locations in the CWS for the August 2, 2001 backflow event.

For the August 2, 2001 event the maximum difference in water-surface elevation between Wilmette and Columbus Drive (14 mi) is around 5 ft, between Columbus Drive and Sag Junction (23.2 mi) is around 3 ft, and between Sag Junction and the LCW (10.2 mi) 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 backflows can be seen in the records of the measured water-surface elevations.

CONCLUSIONS

Changed operations of the gates at Lockport cannot prevent backflows 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 backflows. It is likely that the MWRDGC's policy of lowering the CWS in anticipation of storms may help avoid backflows 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 backflows until the reservoirs of TARP come on line and the volume of CSO flows is further reduced.

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