Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

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SIMULATION OF FECAL COLIFORM CONCENTRATIONS

IN THE CHICAGO WATERWAY SYSTEM UNDER

UNSTEADY FLOW CONDITIONS

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July 2005

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TECHNICAL REPORT # 16

SIMULATION OF FECAL COLIFORM CONCENTRATIONS IN THE CHICAGO WATERWAY SYSTEM UNDER UNSTEADY FLOW CONDITIONS

SUBMITTED TO

The Metropolitan Water Reclamation District of Greater Chicago

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ABSTRACT

Based on the results of the Use Attainability Analysis for the Chicago Area Waterways (CAWs), bacterial water quality does not meet the General Use standards. For mitigation of excessive fecal coliform levels, the Illinois Environmental Protection agency has requested that the Metropolitan Water Reclamation District of Greater Chicago (District) evaluate disinfection measures at the water reclamation plants.

The main purpose of this study was to develop and calibrate a fecal coliform simulation model for the Chicago Waterway System (CWS). The developed model was intended to assist the District in evaluating disinfection strategies at the existing water reclamation plants and/or combined sewer overflows in the study area. A simple first-order fecal coliform decay model was added to the flow-water quality model DUFLOW developed for the CWS in a previous study done by Marquette University.

Monthly grab samples were available to calibrate the model at several locations along the river system. Therefore, a new concept of model parameter estimation was developed in this study based on historical data analysis. The application of this concept in model calibration allowed satisfactory results at almost all considered locations to be obtained. The verification of the model for different periods confirmed furthermore that the model is suitable to reproduce fecal coliform dynamics in the CWS during dry weather flow conditions as well as during rainstorm events.

In this study, data on fecal coliform concentrations resulting from combined sewer overflows during rainstorm events were not available. Therefore, assumptions were made based on the data available for Milwaukee and on engineering judgment. The calibration and verification of the model during high flow periods confirmed the validity of these assumptions. Consequently, the developed fecal coliform model can be applied as an effective tool to evaluate potential disinfection measures.

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INTRODUCTION

1.1 Problem definition

In 2003, the Illinois Environmental Protection Agency (IEPA), selected Camp, Dresser and McKee (CDM) to perform an Use Attainability Analysis (UAA) for the Chicago Area Waterways (CAWs). The UAA study was required because the portions of the CAWs that are designated as "Secondary Contact" waters do not meet the goals of the Clean Water Act.

The CAWs study area includes the Chicago Waterway System, the Calumet River, The Grand Calumet River, and Lake Calumet. In addition to commercial navigation, these waterways are also used for recreational activities such as boating and fishing.

The National Pollution Discharge Elimination System (NPDES) permits reissued by the IEPA in 2002 for the Calumet, North Side, and Stickney water reclamation plants (WRPs) required that the Metropolitan Water Reclamation District of Greater Chicago (District) participate in and support the UAA study for the Chicago Waterway System (CWS). The District's water quality monitoring data and those from other several sources were collected and analyzed by CDM. The analysis showed that chemical water quality in the CAWs meet the Illinois Pollution Control Board (IPCB) standards most of the time. Bacterial water quality does not meet the General Use standards. However, the waterways are currently classified as Secondary Contact and Indigenous Aquatic Life, with the exception of the North Shore Channel upstream of the North Side WRP, the Chicago River Main Stem, and the Calumet River from Lake Michigan to the O'Brien Lock and dam which are designated as General Use.

The current Secondary Contact use designation does not include body contact recreation such as swimming or water-skiing. Based on CDM's assessment of water quality in the CAWs and on federal bacterial criteria (EPA, 1986), the IEPA has proposed three recreational use designations:

- Whole Body Contact Recreation: protects for prolonged and intimate contact uses such as swimming and water skiing.
- Limited Contact Recreation: protects for incidental body contact such as recreational boating, wading, or fishing

- Recreational Navigation: protects for non-contact activities such as commercial and pleasure boating.

A geometric mean of E.coli standards was assigned for each of the above-mentioned use as follows: 126, 1030, and 2740 CFU/100 ml, respectively. Analysis of available fecal coliform and E. coli data for the Chicago WRP effluent and in the CWS done by CTE/AECOM and Limno-Tech (CTE team) has found a 1:1 ratio between these bacteria. More fecal coliform data are available than E. coli data, therefore, a model capable of simulating fecal coliform concentrations can be more reliably developed and can assist in evaluating future compliance with E. coli standards.

Based upon a review of current recreational use of the CAWs, the Stakeholders Adisory Committee (SAC) formed by the IEPA determined that the proposed Limited Contact Recreation use would be appropriate for all of the waterways, except for the Chicago Sanitary and Ship Canal. The proposed Recreation Navigation use would be appropriate for the Chicago Sanitary and Ship Canal.

For mitigation of fecal coliform problems in the CWS, the IEPA has requested that the District evaluate disinfection measures at the three large WRPs Calumet, North Side, and Stickney. A computer model (DUFLOW) for the simulation of water quality in the CWS during unsteady flow conditions was already developed by Marquette University (Shrestha and Melching, 2003; Alp and Melching, 2004). In order to provide modeling support to the District to evaluate the effects of possible disinfection measures on fecal coliform and related E. coli counts in the CWS, Marquette University prepared a proposal to add a fecal coliform simulation routine to the DUFLOW water quality model of the CWS. This proposal has been approved and the project was extended to include modeling of fecal coliform in the CWS so that disinfection or other fecal coliform reduction alternatives can be evaluated.

1.2 Objectives

The specific objectives of this project can be defined as follows:

(1) Development, calibration and verification of a fecal coliform model for the Chicago Waterway System.

(2) Providing modeling support to the District to evaluate the effects of fecal coliform removal methods on counts in the Chicago Waterway System.

1.3 Outline of the report

This report is divided into 4 chapters. Following this introductory chapter, a general overview of fecal coliform modeling and the implementation of fecal coliform process simulation in the DUFLOW model is given in Chapter 2. A detailed description of the application of the model to the CWS also is given in this chapter.

Chapter 3 presents the calibration and verification of the DUFLOW model to the available measurements. Flow analysis and the concept of estimating the fecal coliform decay rate based on statistical data analysis are included in this Chapter. The calibration of the fecal coliform model for the period July 12 to September 15, 2001, is discussed in addition to the model verification for the periods September 2 to November 10, 2001, May 1 to September 29, 2002, September 11 to December 30, 1998, and February 5 to May 24, 1999. Additionally, this Chapter presents and discusses model calibration and verification results for the rainstorm events in 2001 and 2002. Based on these results, an average fecal coliform concentration is recommended to be used as representative to combined sewer overflow (CSO) bacterial loads in the project area. Finally, conclusions are given in Chapter 4.

Chapter 2
FECAL COLIFORM MODELING

2.1 Introduction

Fecal coliforms are relatively harmless microorganisms that live in the digestive system of human beings and other warm-blooded animals. In general, these bacteria are natural and aid in the digestion of food when they are in the body. The fecal coliform bacteria themselves do not necessarily cause illness. However, pathogenic organisms are associated with fecal coliform bacteria, and these organisms can result in disease in human beings or other warm-blooded animals.

High concentrations of fecal coliform bacteria in aquatic environments (greater than 200 CFU/100 ml) indicate that the water has been contaminated with the fecal material of man or other animals. Pathogens or disease producing bacteria or viruses can exist in fecal material and may cause waterborne diseases. Disease problems that can be contracted in water with high fecal coliform counts include typhoid fever, gastroenteritis, hepatitis A, dysentery, cholera, and others. The presence of fecal contamination is an indicator that a potential health risk exists for individuals exposed to this water.

Potential sources of fecal coliform contamination include both point source and nonpoint source contributions. The primary sources of point source bacterial contamination is sewage-treatment-plant outfalls and CSOs. Nonpoint sources include agricultural-animal waste, application of manure and biosolids to fields, urban runoff, failed septic systems, wildlife waste, etc. Fecal coliform bacteria considerably increase after rainfall events. Heavy rainfall results in washing of fecal matter from the land surfaces in addition to overflows from sewage collection systems. Due to the first-flush effect, the first part of a storm causes substantial fecal contamination in receiving waters.

In the CWS, the main sources of bacteria during dry weather flow are the Calumet, North Side, and Stickney WRPs. It should be noted that all the WRPs currently meet their National Pollutant Discharge Elimination System (NPDES) limits. However, during wet weather flow, bacteria results from a large number of CSOs in the CWS drainage area and overshadows the bacteria from the three WRPs. CSOs contribute high bacterial loads but for short periods of time and at randomly distributed intervals. This "impulse" type load requires particular attention during mathematical modeling and impact assessment of varying storms on the transient bacterial concentration.

2.2 Decay of fecal coliform

After discharge to a water body, fecal coliform decay is dominated by several factors such as sunlight, temperature, salinity, sedimentation, resuspention, predation, aftergrowth, etc. A broad review of these factors can be found in Bowie et al. (1985). Generally, a simple first-order kinetics decay model is used to characterize the change of coliform population in rivers or streams:

$$C_t = C_0 e^{-kt} \tag{2.1}$$

Where C_t the concentration of fecal coliform at time t (CFU/100 ml), C_0 is the initial concentration of fecal coliform at the outfall (CFU/100 ml), k is the loss rate (die-off) constant (1/day), and t is the exposure time (day). In this simple model, the overall net loss rate k is used as a measure of bacterial kinetics. Typically, k is considered as a function of temperature. In many modeling cases, the use of this simple model is justified by the fact that the uncertainty in the input loads is considerably high so that the use of a very detailed kinetic structure would be impractical.

When input loads are known with a degree of certainty, a complex model incorporating salinity, solar radiation, settling and temperature factors can be used. Of the various formulations for calculating the decay rate that incorporates these factors, that of Mancini (Mancini, 1978, Thomann and Mueller, 1987, p. 237) frequently used:

$$k = \frac{(0.8 + 0.006 P_{SW})}{24} 1.07^{T-20} + \frac{\alpha I_0(t)}{K_e H}\left[1 - \exp(-K_e H)\right] + F_p \frac{v_s}{H} \tag{2.2}$$

where P_{SW} is the percent seawater (%), T is the temperature (°C), α is a proportionality constant, $I_0(t)$ is the surface solar radiation (cal/cm^2.h), H is the water depth (m), K_e is the vertical light extinction coefficient (1/m), F_p is fraction of the bacteria attached to particles, and v_s is the settling velocity of particulate bacterial forms (m/day). For a variety of situations, the simple exponential die-away or decay of coliforms (i.e. equation 2.1) is a good representation of real data. This equation shows that the downstream distribution of fecal coliform bacteria will drop exponentially and asymptotically approach zero. The slope of a semi-logarithmic plot of C_t versus t represents the decay rate k. This allows estimation of the in-stream loss rate k from measurements at various downstream locations.

As the flow moves downstream from a discharge point (e.g., WRPs, CSOs) the rate of bacterial die-away often decreases because as time goes on only more resistant organisms remain. Thus, the value of k often decreases for reaches farther downstream from the WRPs (Thomann and Mueller, 1987, p. 239-241).

2.3 Implementation of fecal coliform process simulation in the DUFLOW model

Two predefined eutrophication models are included in DUFLOW; EUTROF1 and EUTROF2. The first one is a relatively simple model based on the EUTRO4 model from WASP4 developed by the U.S. Environmental Protection Agency (Ambrose et al., 1988). It includes the cycling of nitrogen, phosphorous, and oxygen. The growth of one phytoplankton species also is simulated. The interactions between the sediment and the overlying water column are not explicitly included in the model. This model is suitable to study the short term behaviour of a system (e.g., impact of a discharge on the oxygen dynamics). EUTROF2 is more appropriate where long term behaviour of a system is of interest. In this model, three algal species are included and interactions between the sediment and the overlying water column are taken into consideration. EUTROF2 was selected to simulate water quality variables in the CWS (Alp and Melching, 2004).

EUTROF2 in its original version does not include a fecal coliform decay process. However, taking into account that DUFLOW has an open model structure that allows modellers to include any water-process description, it was feasible to add a fecal coliform routine to EUTROF2. The first-order decay model expressed by the Equation 2.1 is used to describe the die-off of coliforms in the CWS. Since re-growth generally is neglected, no growth terms are included in the model.

2.4 Application of the DUFLOW model to the CWS

The DUFLOW model (DUFLOW, 2000) was used to represent flow and water quality in the CWS. In the DUFLOW model, the CWS is divided into 36 elements, each of which is limited by two nodes. In total the model includes 36 nodes and 36 elements or sections. The DUFLOW model network of the CWS is shown in Figure 2.1. About 216 measured cross sections at different points along the river were used to describe the geometry of the river.

Discharges and pollutant loads coming from different sources are given at the model nodes and schematization points. The schematization points are extra points on a section between two nodes for which output can be generated. One or more discharge points at which discharges and pollutant loads in or out of the network occur can be connected to the schematization points. The DUFLOW model network of the CWS includes about 50 discharge points and 58 schematization points.

WRPs, CSOs, CSO pumping stations, and tributaries are the main sources of fecal coliform contamination in the CWS. An overview of the DUFLOW model input data (discharges and fecal coliform concentrations) is given in the following sections.

2.5 Model input data

2.5.1 Water Reclamation Plants

Flow data were available from the District for each of four WRPs that discharge to the CWS. Hourly discharge data were available for the North Side, Stickney, and Calumet WRPs. Daily discharge data were available for the Lemont WRP.

These WRP data were used as model flow input for the periods during which the fecal coliform model is calibrated and verified. (i.e. 07/12/2001-09/15/2001, 09/02/2001-11/10/2001, 05/01/2002-09/29/2002, 09/11/1998-12/30/1998, 02/05/1999-05/24/1999).

Fecal coliform concentration in the treatment plants effluents were available on a weekly basis (i.e. about four or five measurements a month) for the period August 3, 1998 to July 26, 1999 and for the period July 1, 2001 to September 30, 2002. These measurements were used in the DUFLOW model to represent the bacterial loads from the WRPs. Table 2.1 lists the mean, maximum, and minimum values of fecal concentration in the WRPs effluents for the two periods of measurement previously mentioned.

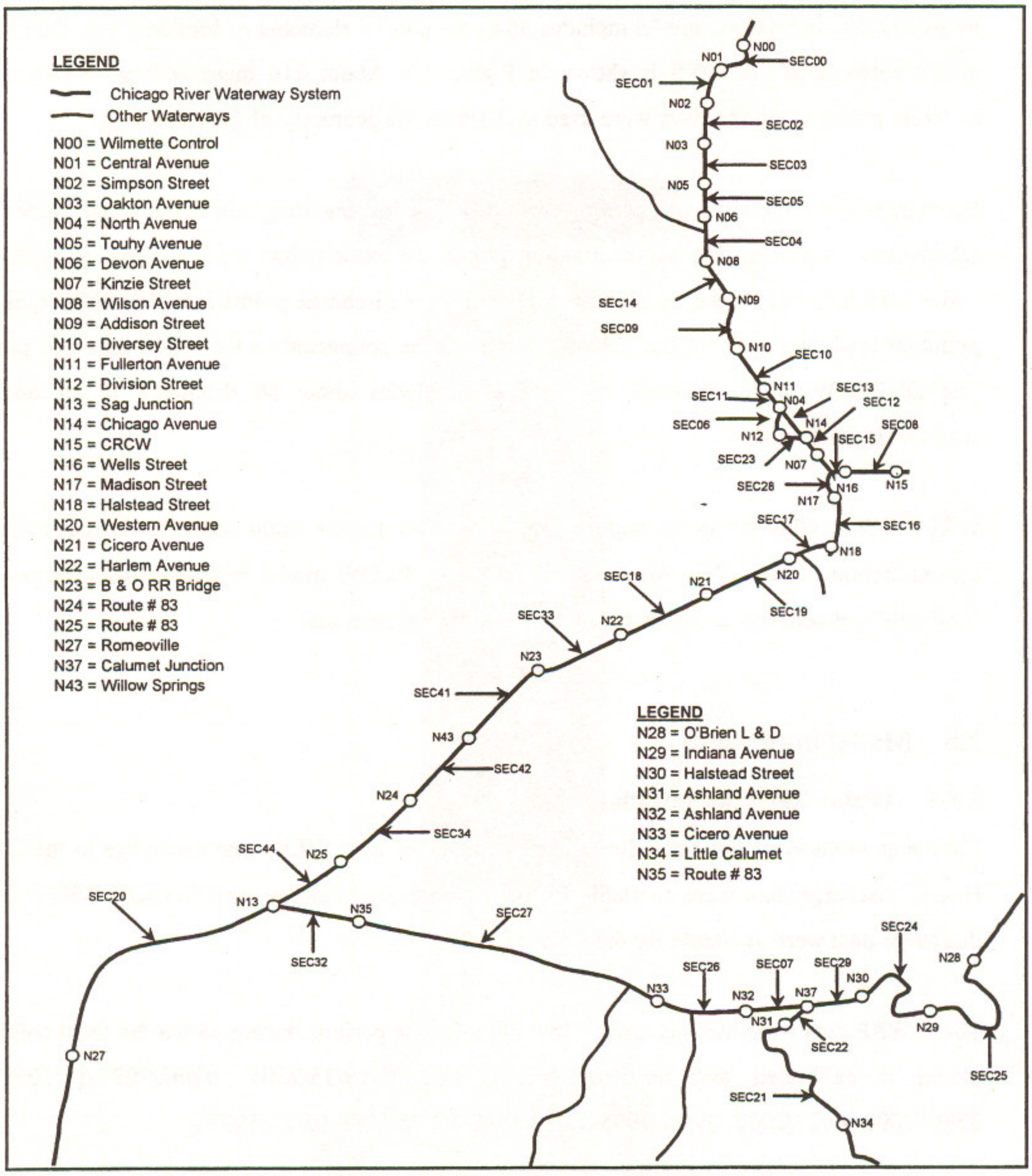

Figure 2.1 Schematic representation of the DUFLOW model network of the Chicago Waterway System.

Table 2.1 The arithmetic mean, maximum, and minimum weekly fecal coliform concentrations in CFU/100 ml in the Water Reclamation Plant (WRP) effluent.

	North Side WRP	Stickney WRP	Lemont WRP	Calumet WRP
	August 3, 1998 to July 26, 1999			
Mean	12490	18332	31136	15117
Maximum	46000	81000	270000	54000
Minimum	860	2200	800	100
	July 1, 2001 to September 30, 2002			
Mean	20481	15349	36709	11370
Maximum	74000	75000	380000	71000
Minimum	1000	2000	1500	1800

2.5.2 Pumping stations and combined sewer overflows

During wet weather flows, the CWS receives substantial fecal coliform bacteria loads from three CSO pumping stations; Racine, North Branch, and 125th Street, in addition to the loads from nearly 200 CSOs in the CWS drainage area. In the DUFLOW model, these nearly 200 CSOs were represented by 28 locations (Alp and Melching, 2004). The estimation of total CSOs volume and its time distribution for each of the 28 locations was done based on the method mentioned in Section 3.2.3 of Shrestha and Melching (2003). Discharges from the CSO pumping stations were estimated from pump operation records.

Since no bacteriological data on discharges from CSOs were available for the study area, fecal coliform input concentrations to the DUFLOW model were estimated. Data for CSOs in Milwaukee after its deep tunnel system went into operation were obtained from the Milwaukee Metropolitan Sewerage District (MMSD) and analyzed. Figure 2.2 shows the non exceedance probability for the Milwaukee CSO fecal coliform concentration data. The median value of the sampling data for the period 2001-2004 is considered as representative of fecal coliform concentration at the pumping stations and CSOs. This value is about 170,000 CFU/100 ml. A similar modeling effort is being done to simulate fecal coliform concentrations in the water courses, harbor, and near shore Lake Michigan in the Milwaukee area. In this modeling effort, the geometric mean of CSO fecal coliform concentrations of 160,000 CFU/100 ml is being used (Recktenwalt et al., 2004). This further supports the use of 170,000 CFU/100 ml in the simulation of the CWS.

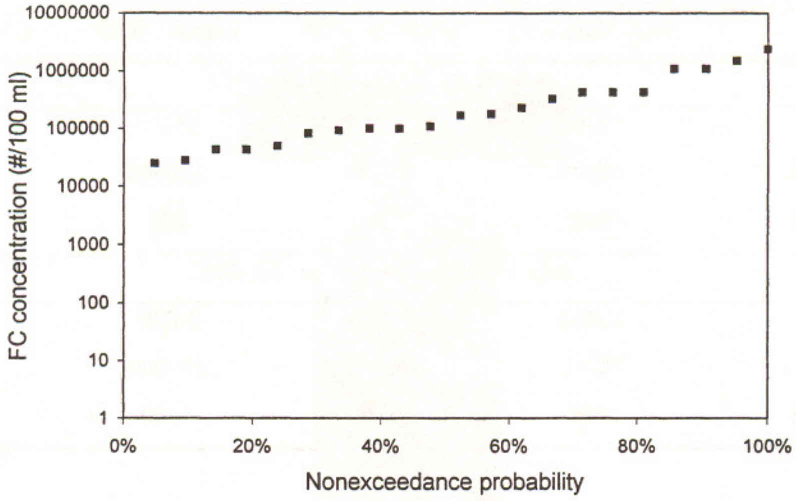

Figure 2.2 Nonexcedance probability for the Milwaukee CSO fecal coliform concentration data.

Monthly fecal coliform data at Archer Avenue (South Fork South Branch Chicago River) were available for the period 2001-2004. This sampling site is located downstream from the Racine Avenue Pumping Station. The comparison between the dates when the fecal coliform samples were taken at Archer Avenue and the dates of Racine Avenue Pump operation, showed that only one sample was taken on the same date as the pump operations. This date corresponds to the rainstorm of October 13, 2001, during which reversals to lake Michigan occurred at Wilmette. The concentration of fecal coliforms on that date was about 1,300,000/100ml.

The value of fecal coliform concentration measured at Archer Avenue during the rainstorm event of October 13, 2001 was to close to the 90th percentile of the sampled fecal coliform data for Milwaukee, that is, 1,100,000 CFU/100 ml (see Figure 2.2). This outcome supports the assumption that the 90th percentile of fecal coliform bacteria for Milwaukee is a good representation of fecal coliform concentrations in the CSOs during rainstorm events. Consequently, this value will be used for model calibration during wet weather flows as discussed in Sections 3.10 and 3.11.

2.5.3 Tributaries

Flow measurements at a 15-minute time interval were available for two tributaries to the Cal-Sag Channel, Tinley Creek near Palos Park and Midlothian Creek at Oak Forest. These flow data are used as model input at these two locations. Available flow measurements for the Grand Calumet River at Hohman Avenue are tributary input to the Little Calumet River (north). For the North Branch Chicago River, a 15-minute flow data at Albany Avenue were used as hydraulic input to the DUFLOW model.

For ungaged tributaries to the CWS (i.e. Mill Creek, Stoney Creek West, Cal-Sag Watershed East, Navajo Creek, Stoney Creek East, Des Plaines Watershed, Calumet Union Ditch, and Cal-Sag Watershed West), flow data were estimated from the Midlothian Creek data based on drainage area ratios relative to the total Midlothian Creek drainage area. The estimation of flow for ungaged tributaries was extensively explained in Shrestha and Melching (2003).

Historical fecal coliform concentration data available at Burnham Avenue on the Grand Calumet River (1990-2003) and at Albany Avenue on the North Branch Chicago River (2000-2003), were used as input for these two tributaries. For ungaged tributaries, The available data on fecal coliform concentration for the locations that are not affected by WRPs or CSOs were analyzed. These locations include County Line Road on Middle Fork North Branch Chicago River (Metropolitan Water Reclamation District (MWRD) sampling location #31), County Line Road on Buffalo Creek (MWRD sampling location #12), Higgins Road on Salt Creek (MWRD sampling location #79), Wentworth Avenue on the Little Calumet River (MWRD sampling location #52), and Joe Orr Road on Thorn Creek (MWRD sampling location #54). The location of these sites is shown in Figure 2.3.

The analysis of historical data of fecal coliform concentrations that are taken on the same date at the five previously mentioned sites for the period 1990-2003 (about 120 samples) has shown that the average concentration varies from about 2,000 CFU/100 ml for Salt Creek and Buffalo Creek to about 15,000 CFU/100 ml for Thorn Creek and the Little Calumet River (Table 2.2). Taking into account that the Middle Fork North Branch Chicago, Buffalo Creek and Salt Creek are located in the northern part of the Chicago area while Thorn Creek is located in the southern region of the Chicago area where most of the ungaged tributaries are located, and, considering the difference in land use and activities between theses regions, it was assumed that Thorn Creek data can be considered as representative of the concentrations coming from ungaged tributaries.

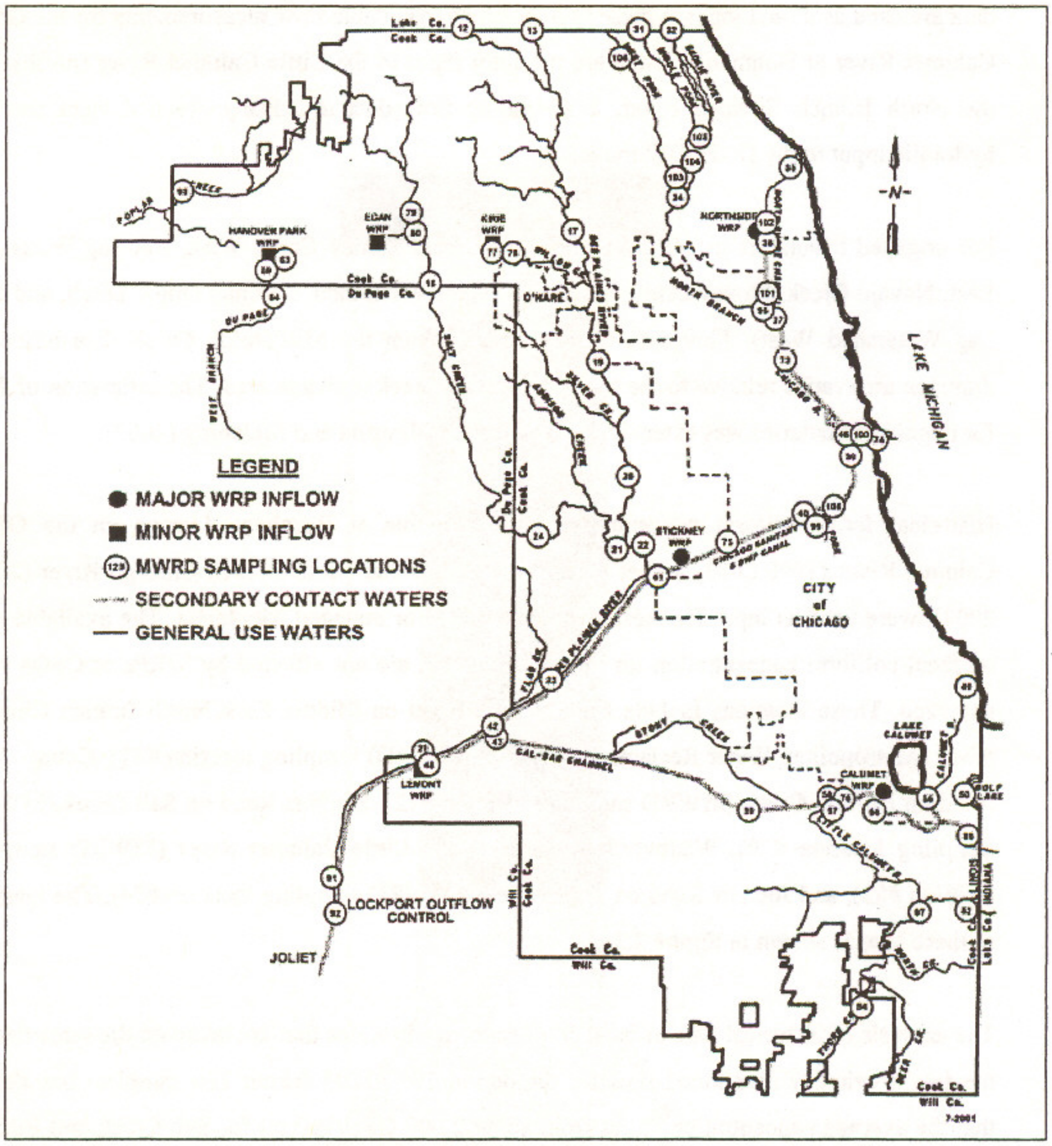

Figure 2.3 Ambient water quality monitoring locations in 2001 (after Abedin et al., 2002).

Table 2.2 Summary statistics of fecal coliform concentrations in CFU/100 ml at sampling locations that are not affected by water reclamation plants or combined sewer overflows.

	Number of samples	Middle Fork North Branch	Little Calumet River	Thorn Creek	Buffalo Creek	Salt Creek
Average	120	6673	12476	15016	2458	1679
Median	120	1500	2000	2800	320	99.5
STDV	120	24100	47688	36971	11360	5384

The monthly median values of fecal coliform concentration at Joe Orr Road on Thorn Creek (Figure 2.4) were used as input to the DUFLOW model for all ungaged tributaries (i.e. Mill Creek, Stoney Creek West, Cal-Sag Watershed East, Navajo Creek, Stoney Creek East, Des Plaines Watershed, Calumet Union Ditch, and Cal-Sag Watershed West).

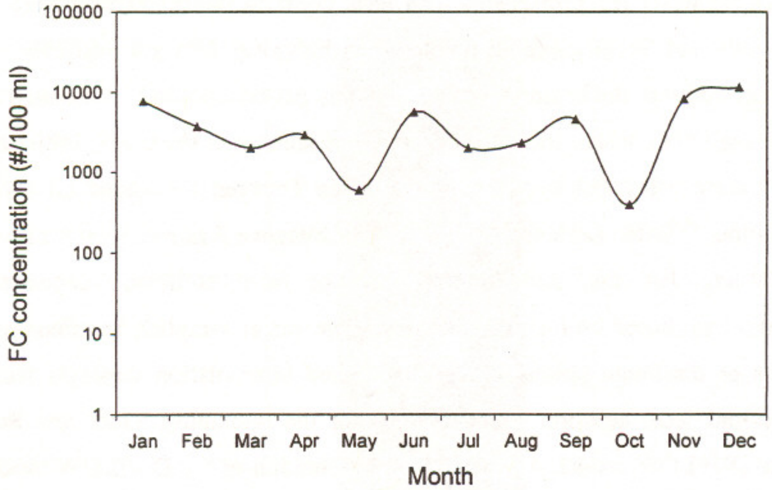

Figure 2.4 Monthly variation of median fecal coliform concentration at Joe Orr Road on Thorn Creek for 1990-2003.

2.5.4 Boundaries and initial conditions

The upstream flow boundary conditions for the DUFLOW model were measured hourly water levels at Maple Avenue near the Wilmette Pumping Station, O'Brien Lock and Dam, Columbus Drive near the Chicago River Controlling Works (CRCW), and continuous (every 15 minutes) discharge data at South Holland on the Little Calumet River. The downstream flow boundary conditions were measured discharges (every 15 minutes) at Romeoville.

The monthly historical fecal coliform measurements (1990-2003) at Lockport Forebay (MWRD sampling location #92, Figure 2.3) and 130th Street (MWRD sampling location #55, Figure 2.3) are used as representative of the boundary conditions at Romeoville and O'Brien Lock and Dam, respectively.

The fecal coliform boundary conditions at South Holland on the Little Calumet were estimated based on a mass balance between monthly historical data (2001-2003) at 170th Street on Thorn

Creek (MWRD sampling location #97, Figure 2.3) and Wentworth Avenue on the Little Calumet River (MWRD sampling location #52, Figure 2.3). Taking into account the quality of Lake Michigan water, fecal coliform boundary conditions at the Wilmette Pumping Station and the CRCW at Columbus Drive were set to zero.

Initial values for water level, discharge, and fecal coliform concentrations were input at each DUFLOW node and Schematization point. When historical data are available, the measured values corresponding to the beginning of a simulation period were used. Cumulative flows were computed at the points where tributaries or WRPs discharge to the CWS. Initial conditions for water levels were estimated by linear interpolation between the gaged sites (i.e. Wilmette Pumping Station, O'Brien Lock and Dam, CRCW, Lawrence Avenue, Western Avenue, Willow Springs, Cal-Sag Junction, and Romeoville). For fecal coliform concentrations, initial conditions were set based on the available measurements at sampling locations represented by model nodes or discharge points. Mass balance and interpolation concepts were applied to derive the initial fecal coliform concentrations for the remaining nodes and Schematization points of the DUFLOW model. A schematic representation of the DUFLOW model input from different sources is shown in Figure 2.5.

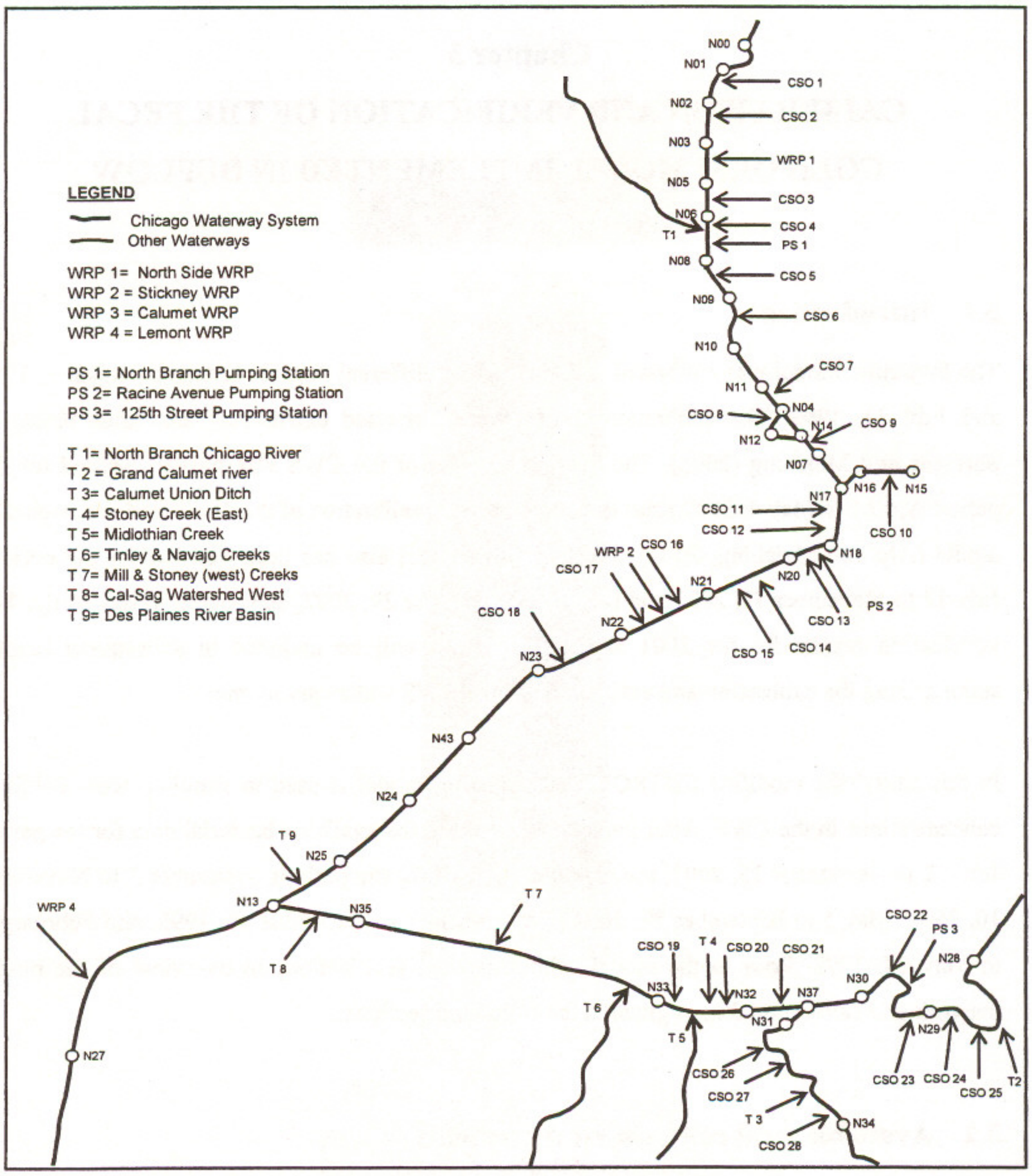

Figure 2.5 Schematic representation of the DUFLOW model input from different sources of fecal coliform. (note: WRP= Water reclamation Plant, CSO= representative combined sewer overflow location).

Chapter 3

CALIBRATION AND VERIFICATION OF THE FECAL COLIFORM MODEL IMPLEMENTED IN DUFLOW

3.1 Introduction

The hydraulic model was calibrated and verified for different periods between August 1, 1998 and July 31, 1999. The calibration results were discussed extensively and documented in Shrestha and Melching (2003). The hydraulic model of the CWS was further verified for the period April 1 to May 4, 2002 prior to the preliminary calibration of the developed water-quality model (Alp and Melching, 2004). The hydraulic model also has been verified for the periods July 12 to November 10, 2001 and May 5 to September 29, 2002, considered in this study. The verification results for the 2001 and 2002 periods will be included in subsequent reports summarizing the calibration and verification of the CWS water-quality model.

In this study, the modified EUTROF2 water-quality model is used to simulate fecal coliform concentrations in the CWS. After model calibration to the available bacterial data for the period July 12 to September 15, 2001, the model is verified for the periods September 2 to November 10, 2001, May 5 to September 29, 2002 , September 11 to December 30, 1998, and February 5 to May 24, 1999. Prior to the model calibration and verification, an overview of the model network and calibration data is given in the following sections.

3.2 Available fecal coliform measurements

Monthly fecal coliform data for the CWS and other rivers in the region are available for the period 1990-2003. These data were provided by the District for 66 sampling sites. Forty two of the sampling sites are located in the study area and sixteen were included as calibration locations in the DUFLOW model (i.e. nodes 3, 5, 8, 10, 16, 17, 20, 21, 22, 25, 29, 30, 31, 32, 33, and 35 on Figure 2.1 and Figure 2.5). The District fecal coliform sampling sites, sampling periods, and the number of samples are listed in Table 3.1. The location of all available sampling sites is shown in Figure 2.3.

Table 3.1 The Metropolitan Water Reclamation District of Greater Chicago fecal coliform sampling sites, sampling periods, and number of samples.

Location Code	Sampling site	Waterway system	Notes	Period of record		Number of samples
12	County Line Rd.	Buffalo Creek	3	01/22/90	04/05/04	153
43	Route 83	Cal-Sag Channel	1	01/08/90	04/26/04	166
58	Ashland Ave.	Cal-Sag Channel	1	01/08/90	04/26/04	160
59	Cicero Ave.	Cal-Sag Channel	1	01/08/90	04/26/04	169
49	Ewing Avenue	Calumet River	2	05/07/90	04/26/04	113
55	130th Street	Calumet River	2	01/08/90	04/26/04	161
56	Indiana Ave.	Little Calumet River (north)	1	02/05/90	04/26/04	158
74	Lake Shore Drive	Chicago River	2	01/16/90	04/19/04	161
100	Wells Street	Chicago River	1	03/19/01	04/19/04	35
41	Harlem Ave.	Chicago Sanitary & Ship Canal	1	01/16/90	04/19/04	169
75	Cicero Ave.	Chicago Sanitary & Ship Canal	1	01/16/90	04/19/04	172
40	Damen Avenue	Chicago Sanitary & Ship Canal	2	01/10/00	04/19/04	24
42	Route 83	Chicago Sanitary & Ship Canal	1	01/16/90	04/19/04	168
48	Stephen Street	Chicago Sanitary & Ship Canal	2	01/16/90	04/19/04	170
92	Lockport Forebay	Chicago Sanitary & Ship Canal	1	01/20/00	04/26/04	223
107	Western Avenue	Chicago Sanitary & Ship Canal	1	03/19/01	12/16/02	22
13	Lake-Cook Road	Des Plaines River	3	01/22/90	04/05/04	166
17	Oakton St.	Des Plaines River	3	01/22/90	04/05/04	153
19	Belmont Ave.	Des Plaines River	3	01/22/90	04/05/04	168
20	Roosevelt Road	Des Plaines River	3	01/22/90	04/05/04	163
22	Ogden Ave.	Des Plaines River	3	01/22/90	04/05/04	161
23	Willow Springs Rd.	Des Plaines River	3	01/22/90	04/05/04	160
29	Lemont Stephen St.	Des Plaines River	3	01/22/90	04/05/04	166
91	Material Service Road	Des Plaines River	3	01/20/00	04/05/04	129
93	Jefferson Street, Joliet	Des Plaines River	3	01/20/00	12/27/01	100
94	Empress Casino	Des Plaines River	3	01/20/00	12/27/01	102
95	I-55	Des Plaines River	3	02/03/00	10/04/01	70
63	Longmeadow Lane	Du Page River	3	01/22/90	10/25/99	105
64	Lake St.	Du Page River	3	01/22/90	11/22/99	117
86	Burnham Avenue	Grand Calumet River	2	01/08/90	04/26/04	162
77	Elmhurst Rd.	Higgins Creek	3	01/22/90	04/05/04	148
78	Wille Rd.	Higgins Creek	3	01/22/90	04/05/04	167
76	Halsted Street	Little Calumet River (north)	1	01/08/90	04/26/04	162
52	Wentworth Ave.	Little Calumet River (south)	2	01/08/90	04/26/04	159
57	Ashland Avenue	Little Calumet River (south)	1	02/05/90	04/26/04	155
31	Lake-Cook Road	Middle Fork North Branch	2	02/14/90	04/12/04	147
34	Dempster St.	North Branch Chicago River	2	01/16/90	04/12/04	165
37	Wilson Ave.	North Branch Chicago River	1	01/16/90	04/12/04	168
46	Grand Ave.	North Branch Chicago River	2	01/16/90	04/12/04	166
73	Diversey Parkway	North Branch Chicago River	1	01/16/90	04/12/04	172
96	Albany Avenue	North Branch Chicago River	2	07/17/00	04/12/04	43
104	Glenview Road	North Branch Chicago River	2	03/12/01	04/12/04	26
35	Central Ave.	North Shore Channel	1	02/14/90	04/12/04	136
36	Touhy Ave.	North Shore Channel	1	01/16/90	04/12/04	170
101	Foster Avenue	North Shore Channel	2	03/12/01	04/12/04	38
102	Oakton Street	North Shore Channel	1	03/12/01	04/12/04	35
90	Route 19	Poplar Creek	3	01/22/90	04/05/04	147
18	Davon Ave.	Salt Creek	3	01/22/90	04/05/04	169
21	First Ave.	Salt Creek	3	01/22/90	04/01/02	141
24	Wolf Road	Salt Creek	3	01/22/90	04/05/04	161
79	Higgins Rd.	Salt Creek	3	01/22/90	04/05/04	144
80	Arlington Hts. Rd.	Salt Creek	3	01/22/90	04/05/04	167
109	Brookfield Avenue	Salt Creek	3	07/01/02	04/05/04	19
32	Lake-Cook Road	Skokie River	2	01/16/90	04/12/04	146
105	Frontage Road	Skokie River	2	03/12/01	04/12/04	38
39	Madison St.	South Branch Chicago River	1	01/16/90	04/19/04	162

40	Damen Ave.	South Branch Chicago River	2	01/16/90	12/13/99	116
108	Loomis Street	South Branch Chicago River	2	04/16/01	04/19/04	37
99	Archer Avenue	Bubbly Creek	2	03/19/01	04/19/04	38
54	Joe Orr Road	Thorn Creek	2	01/08/90	04/26/04	158
97	170th Street	Thorn Creek	2	03/26/01	04/26/04	36
63	Longmeadow Lane	West Branch Du Page River	3	03/27/00	05/05/03	14
64	Lake Street	West Branch Du Page River	3	01/24/00	04/05/04	50
89	Walnut Lane	West Branch Du Page River	3	01/22/90	04/05/04	170
110	Springinsguth Road	West Branch DuPage River	3	03/01/04	04/05/04	2
30	Lake-Cook Road	West Fork North Branch Chicago River	2	01/16/90	02/13/01	66
103	Golf Road	West Fork North Branch Chicago River	2	03/12/01	04/12/04	31
106	Dundee Road	West Fork North Branch Chicago River	2	03/12/01	04/12/04	18
50	Wolf Lake Burnham Ave.	Wolf Lake Burnham Ave.	2	01/08/90	04/26/04	171

1= Sampling site included in the DUFLOW model; 2= Sampling site located in the study area; 3= Sampling site outside the CWS.

The measurements at the sixteen sampling sites included in the DUFLOW model were used for model calibration and verification for the simulation periods mentioned in Section 3.1. The analysis of the measurements at the sampling sites included in DUFLOW found that the samples were taken on common days for the sites located on the North Shore Channel and the North Branch Chicago River. Similarly, fecal coliform samples were taken on common days for the sites located on the Chicago Sanitary and Ship Canal, and on other common days for the sites located on the Cal-Sag Channel and Little Calumet River. The percentage of common days of measurements at each sampling site relative to a reference site located on the same river section is listed in Table 3.2. For the sites located on the North Shore Channel and the North Branch Chicago River, about 98% of the samples at Touhy Avenue, 84% of the samples at Central Avenue, 100% of the samples at Oakton Street, and 99% of the samples at Wilson Avenue were taken on the same days of those taken at Diversey Avenue. Similar results can be seen in Table 3.2 for the other River sections. Based on this data analysis, reliable values of the fecal coliform decay rate were identified throughout the CWS and used for model calibration as will comprehensively discussed in Section 3.4.

Table 3.2 The percentage of common days of measurements at each sampling site relative to a reference site.

Waterway system	Reference sampling site	Considered sampling site	Percentage of common sampling days
North Shore Channel & North Branch Chicago River	Diversey Avenue	Touhy Avenue	98%
		Central Avenue	84%
		Oakton Street	100%
		Wilson Avenue	99%
South Branch & Chicago Sanitary and Ship Canal	Cicero Avenue	Madison Street	100%
		Western Avenue	100%
		Harlem Avenue	100%
		Route # 83	100%
Little Calumet River & Cal-Sag Channel	Cicero Avenue	Halsted Street	99%
		Ashland Avenue (Calumet)	100%
		Indiana Avenue	100%
		Route # 83	100%
		Ashland Avenue (Cal-Sag)	99%

3.3 Flow data analysis

A suitable representation of the river flow frequency regime is an essential component for many hydrological applications including water-quality management. Because fecal coliform data were available on a monthly basis at almost all sampling sites on the CWS except for Lockport Forebay where weekly data were available, it was necessary to examine whether the flows during the days of fecal coliform bacteria sampling are representative to the flow regime of the CWS.

Based on the historical daily flows available for the North Shore Channel at Wilmette, North Branch Chicago River at Albany Avenue, Chicago River at Columbus Drive, Calumet River below O'Brien Lock and Dam, Little Calumet River at South Holland, and Chicago Sanitary and Ship Canal at Romeoville, flow duration curves were developed with all available daily flows during the fecal coliform sampling period and with the flows measured on the dates of fecal coliform sampling at the nearest sampling site (i.e. Touhy Avenue, Albany Avenue, Lake Shore Drive, Ewing Avenue, Wentworth Avenue, and Lockport Forebay, respectively). The flow-duration curves for the six previously mentioned discharge measurement sites are presented in Figures 3.1 and 3.2. A good match is obtained between the flow duration curves representing all daily flows and those that are measured on the dates of fecal coliform sampling at each considered location. It can, thus, be concluded that the CWS flow regime is well represented during the days of bacterial monitoring.

3.4 Estimation of fecal coliform decay rate

In general, the value of the fecal coliform decay rate k should be determined by calibration for the various sections of the CWS. In this study, a new concept is established to determine this parameter based on historical data analysis. Taking into account that the in-stream samples were taken on common days at the sites located on a particular reach of the river system as described in Section 3.2, the variation in fecal coliform concentration between two successive locations should follow the first-order decay model expressed by the Equation 2.1 (i.e. $C_t = C_0 e^{-kt}$). In this equation, C_t and C_0 represent the concentration of fecal coliform at the downstream and upstream locations, respectively.

Frequency analysis of the historical fecal coliform data was carried out for every two successive sampling sites on the CWS. Graphical representation of this analysis is given in Figures 3.3-3.5 for the 17 sampling sites included in the DUFLOW model. As can be clearly seen from these figures, a decrease in fecal coliform concentration is apparent from Touhy Avenue to Wilson Avenue to Diversey Avenue to Madison Street. Similarly between Harlem Avenue and Route # 83 on the Chicago Sanitary and Ship Canal (CSSC), and from Halstead Avenue to Ashland Avenue to Cicero Avenue to Route # 83 on the Little Calumet River (north) and Cal-Sag Channel. However, for the other locations such as from Central Avenue to Oakton Avenue to Touhy Avenue, an increase of fecal coliform concentrations is noticed between upstream and downstream locations. Similarly between Cicero Avenue and Harlem Avenue on the CSSC and between Indiana Avenue and Halsted Street on the Little Calumet River (north). The increase in fecal coliform bacteria concentration from upstream to downstream at these locations can be explained by the presence of the WRPs between these locations (e.g., The North Side WRP between Oakton Avenue and Touhy Avenue, the Stickney WRP between Cicero Avenue and Harlem Avenue, and the Calumet WRP between Indiana Avenue and Halsted Street) that overshadows the decay process occurring between the upstream site and the WRP discharge point. Further, because of bi-directional flow in the upper North Shore Channel, the effluent from the North Side WRP elevates fecal coliform concentrations at Oakton Avenue relative to Central Avenue.

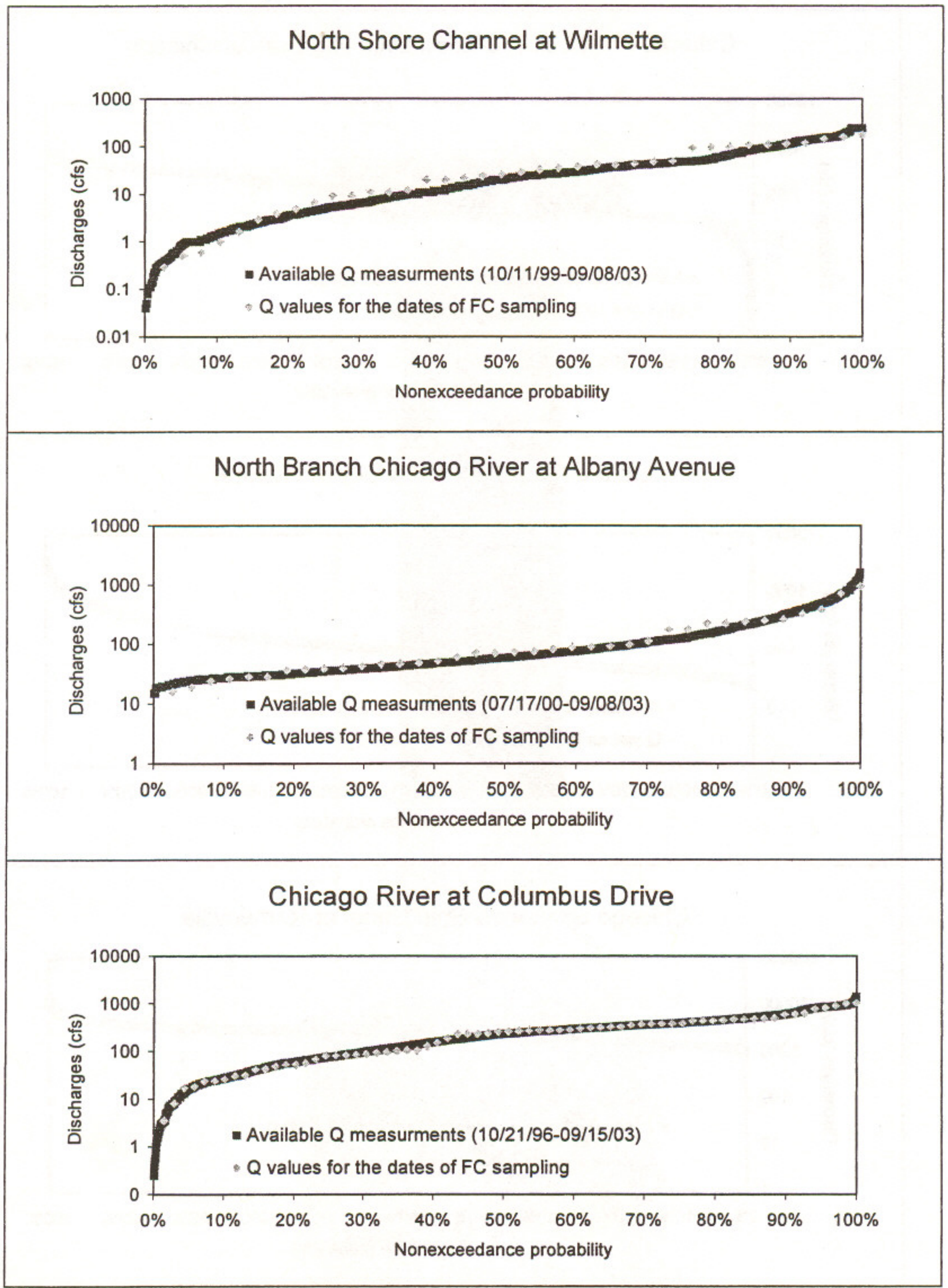

Figure 3.1 Flow duration curves at Wilmette, Albany Avenue, and Columbus Drive (All daily flows vs. daily flows measured on the dates of fecal coliform sampling).

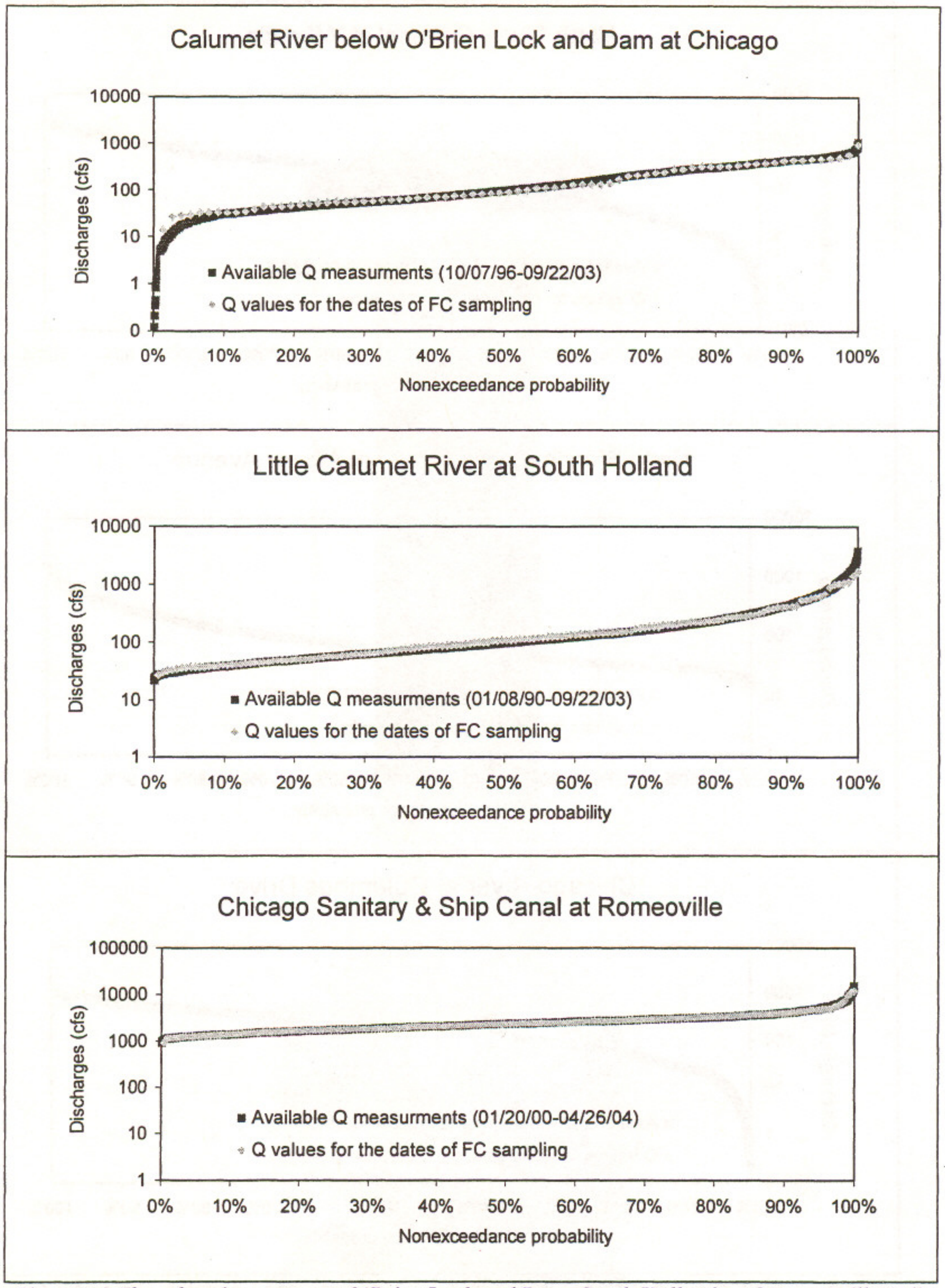

Figure 3.2 Flow duration curves at O'Brien Lock and Dam, South Holland, and Romeoville (All daily flows vs. daily flows measured on the dates of fecal coliform sampling).

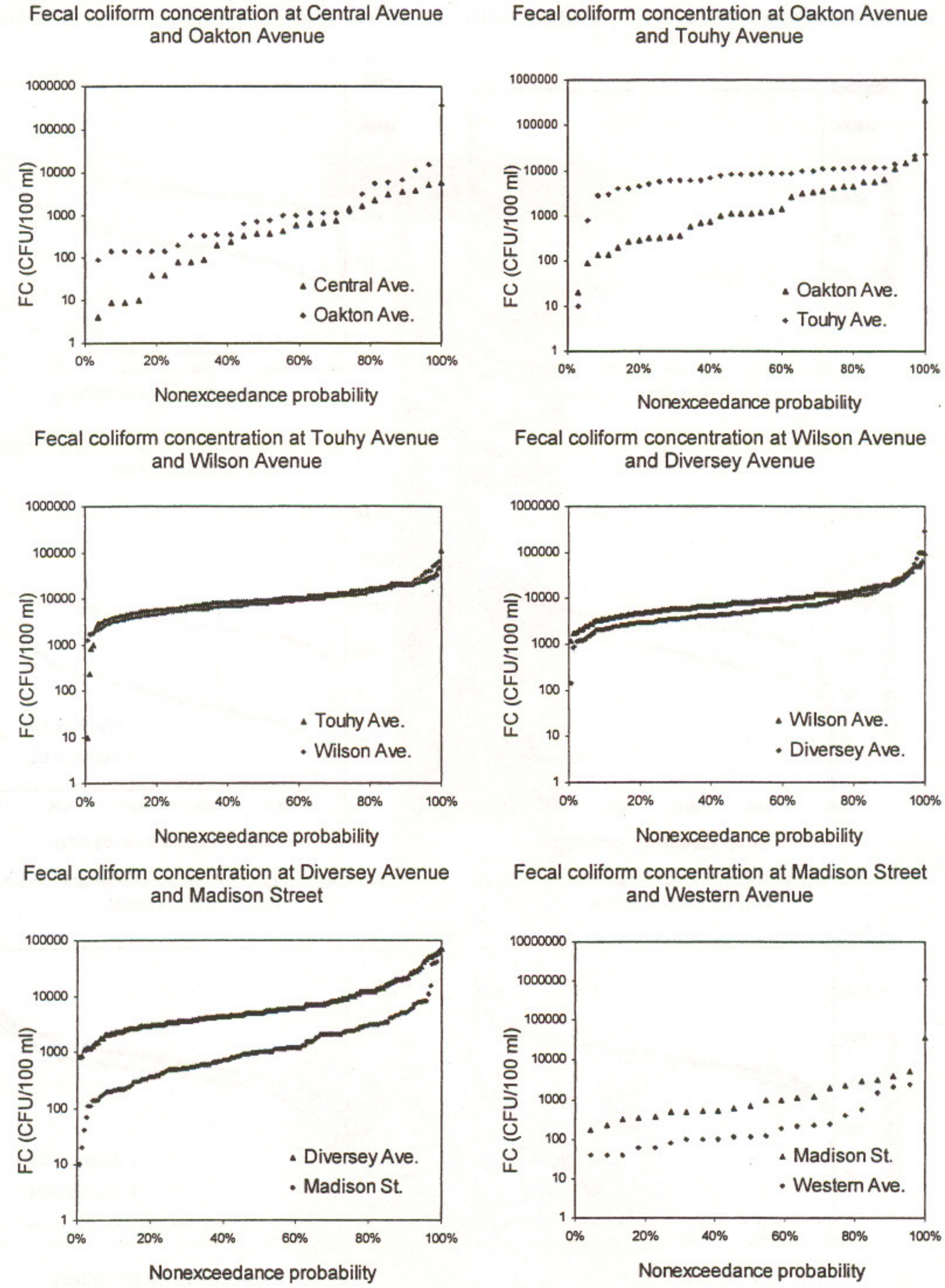

Figure 3.3 Nonexceedence probability distribution of fecal coliform concentrations at Central Avenue, Oakton Avenue, Touhy Avenue, Wilson Avenue, Diversey Avenue, Madison Street, and Western Avenue.

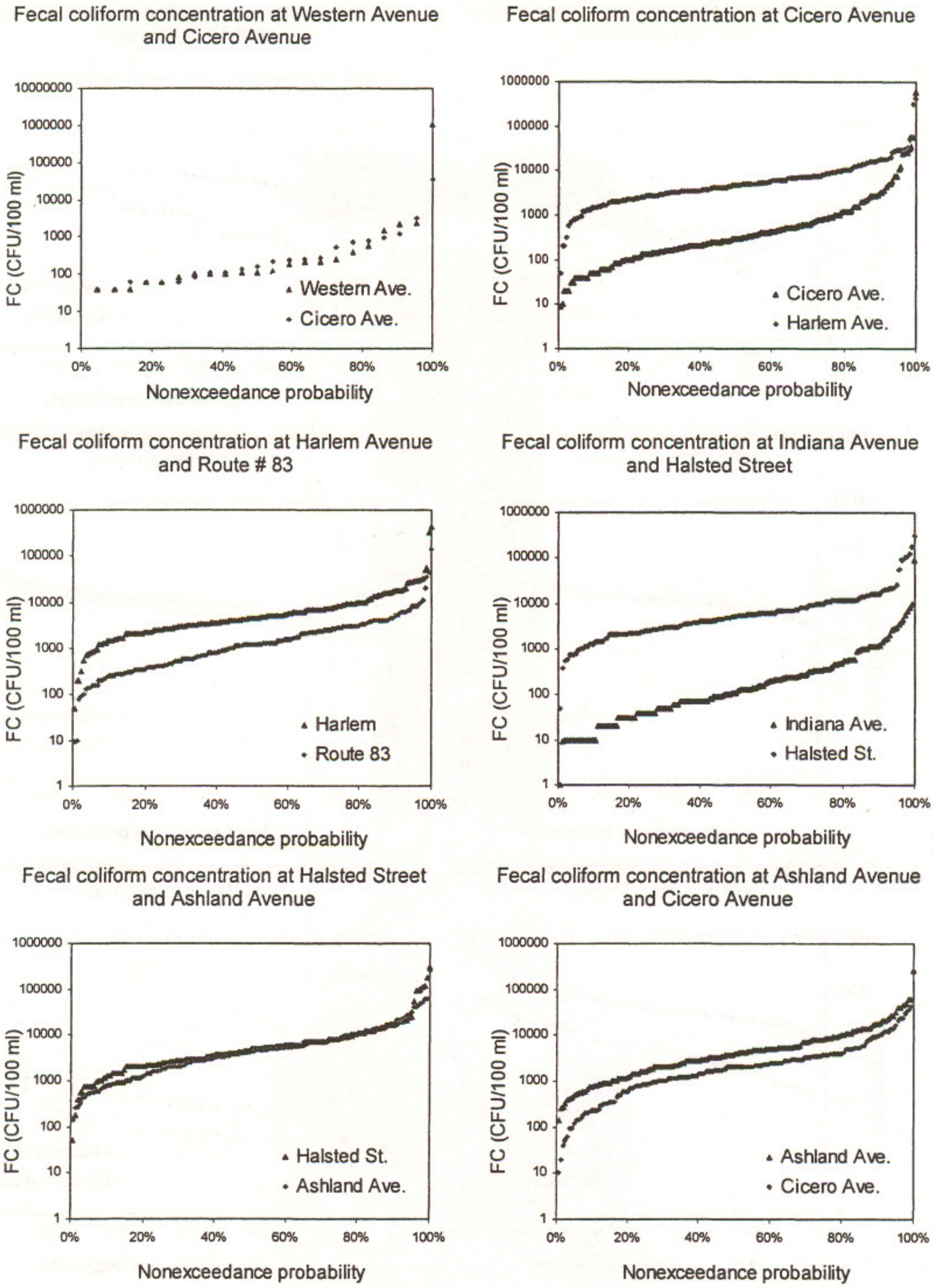

Figure 3.4 Nonexceedence probability distribution of fecal coliform concentrations at Western Avenue, Cicero Avenue (CSSC), Harlem Avenue, Route # 83, Indiana Avenue, Halsted Street, Ashland Avenue, and Cicero Avenue (Cal-Sag).

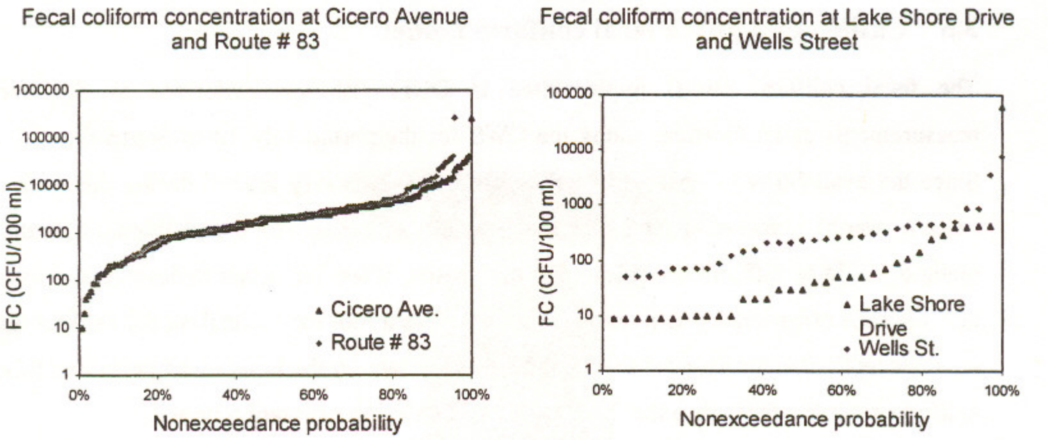

Figure 3.5 Nonexceedence probability distribution of fecal coliform concentrations at Cicero Avenue (Cal-Sag), Route # 83 (Cal-Sag), Lake Shore Drive, and Wells Street.

In order to derive k between two successive locations from equation 2.1, the travel time should be first identified. Given that the travel time is not explicitly computed in DUFLOW, a slight modification of the EUTROF2 code has been made to include this variable as an explicit model output. The mean value of the travel time between every two consecutive locations was computed based on the model run for period July 12 to September 15, 2001. The mean and median values of the fecal coliform decay rate k were computed for every section as follows:

$$k = \frac{\ln\left(\frac{C_0}{C_t}\right)}{t} \tag{3.1}$$

where C_t and C_0 are the fecal coliform concentrations having the same probability of exceedance (quantile) at the downstream and upstream locations (CFU/100 ml), t is the mean travel time between upstream and downstream locations (day). The computed mean and median decay rate values are given in Table 3.3. The negative decay rate values obtained for certain sections express the increase of fecal concentration while moving downstream due to the effect of the WRPs previously mentioned. Similar mean decay rate values were also obtained when Equation 3.1 is applied on the paired data of fecal coliform concentrations collected at two successive sampling locations on the same date.

3.5 Calibration of the fecal coliform model

The fecal coliform model implemented in DUFLOW was calibrated to the available measurements at 16 locations along the CWS for the period July 12 to September 15, 2001. Since the availability of observed fecal coliform data was very limited during this period (one value a month), it was obvious that reasonable calibration based on the traditional trial and error method would be difficult to achieve. For that reason, it was important to develop and validate a new concept of parameter estimation (Section 3.4) as a tool for rational model calibration. This new concept parameterizes the fecal coliform decay rate on the basis of 14 years monthly fecal coliform samples rather than the three samples taken in the calibration period.

Table 3.3 Estimated decay rate for fecal coliform based on historical data analysis.

Sampling Site (Upstream)	Sampling Site (Downstream)	Waterway	Travel time (day)	Computed decay rate Mean (1/day)	Median (1/day)	Estimated decay rate (1/day)
Central Avenue	Oakton Street	North Shore	0.57	-2.10	-1.50	0.8
Oakton Street	Touhy Avenue	North Shore	0.22	-7.10	-8.90	0.8
Touhy Avenue	Wilson Avenue	North Branch	0.24	0.16	0.46	0.2
Wilson Avenue	Diversey	North Branch	0.25	1.60	1.60	1.6
Diversey	Madison Street	South Branch	1.12	1.60	1.50	1.6
Madison Street	Western Avenue	CSSC	1.42	0.98	1.20	1.6
Western	Cicero Avenue	CSSC	1.09	0.03	-0.12	0.2
Cicero Avenue	Harlem Avenue	CSSC	0.71	-3.60	-3.9	0.2
Harlem Avenue	Route # 83	CSSC	1.61	0.90	0.80	0.9
Indiana Avenue	Halsted Street	Little	1.46	-2.50	-2.60	0.8
Halsted Street	Ashland Avenue	Cal-Sag	1.72	0.10	0.06	0.1
Ashland	Cicero Avenue	Cal-Sag	1.30	0.60	0.60	0.6
Cicero Avenue	Route # 83	Cal-Sag	2.97	0.57	0.64	0.6

In this study, model calibration was done in two steps. In the first step, a model run was performed with a bacteria decay rate of about 0.8 reported in the literature (Thomann and Mueller, 1987, p. 235). This value was considered for all the river sections. In the second step, a model run was performed with the estimated decay rate parameter for each river section (i.e. column 5 of Table 3.3). Between Madison Street and Western Avenue the upstream value of 1.6 was used rather than the computed mean of 0.98 because of the limited data at Western Avenue.

Similarly, the computed mean of 0.03 between Western Avenue and Cicero Avenue was increased to 0.2 because of the limited data at Western Avenue. Other differences between the computed mean and estimated decay rate (i.e. column 5 vs. column 7 of Table 3.3) is that the computed decay rate values were replaced by the literature value (i.e. k=0.8) for the sections near the river boundaries (Central Avenue-Oakton Street, Oakton Street-Touhy Avenue, and Indiana Avenue-Halsted Street) or by the computed value of the preceding section as is the case for Cicero Avenue-Harlem Avenue (i.e. k=0.2).

Figures 3.6-3.10 show the calibration results obtained from the two model runs at 16 locations on the CWS for the period July 12 to September 15, 2001. As can be seen from Figures 3.6-3.10, the use of the estimated decay rate values based on historical data analysis allows a good match between observed and simulated fecal coliform concentrations to be obtained for almost all the locations with a few model runs. This can be clearly seen for the locations Madison Street, Western Avenue, and Cicero Avenue on the CSSC.

At Indiana Avenue, Ashland Avenue (Little Calumet River (south)), and Wells Street, however, a difference between the measurements and the simulated concentrations is noticed. Since no historical data were available at the upstream node O'Brien lock and dam for Indiana Avenue, the concept of parameter estimation from historical data could not be applied upstream of Indiana Avenue. Taking into account that the river hydraulics for these sections were also difficult to calibrate due to the uncertainty in the hydraulic data (see discussion of boundary flow hydraulic balance in Shrestha and Melching (2003)), it is therefore, difficult to get good calibration results with the literature value of the decay rate considered for these particular sections. Similar problems in obtaining good calibrations in the upper North Shore Channel, Chicago River main stem, and the Little Calumet River (north) upstream from the Calumet WRP for the dissolved oxygen model were found and discussed extensively in Alp and Melching (2004).

During the calibration process, the DUFLOW model was run with the following computational setup:

- Hydraulic calculation time step: 15 minutes
- Fecal coliform calculation time step: 15 minutes
- Model output (i.e. fecal coliform concentration): 1 day

With these run parameters, one simulation run for the calibration period (i.e. July 12 to September 15, 2001) takes about 8 minutes on a Pentium 4, 2.08 GHz computer.

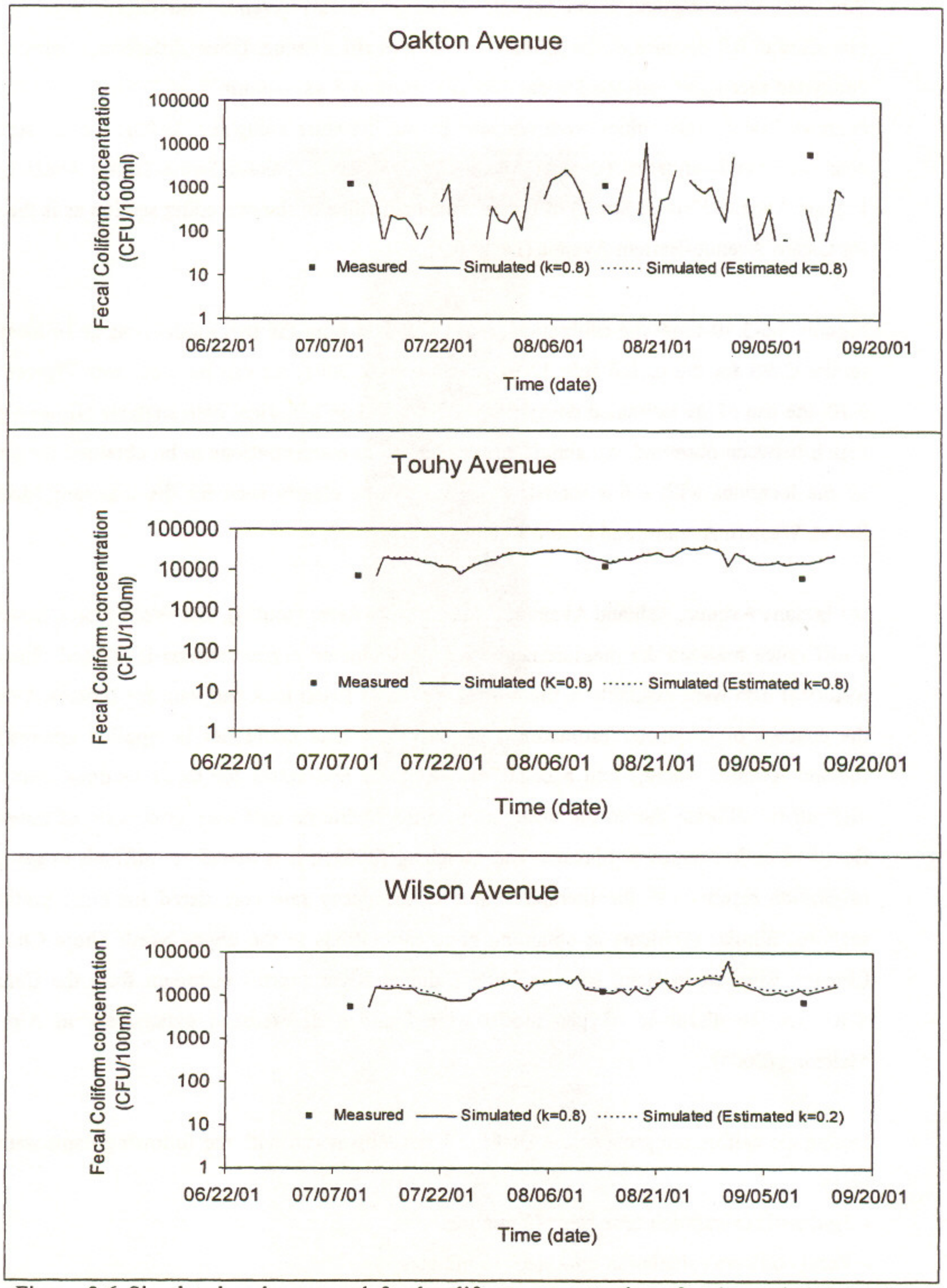

Figure 3.6 Simulated and measured fecal coliform concentrations for the period July 12 to September 15, 2001, for various locations along the North Shore Channel and North Branch Chicago River.

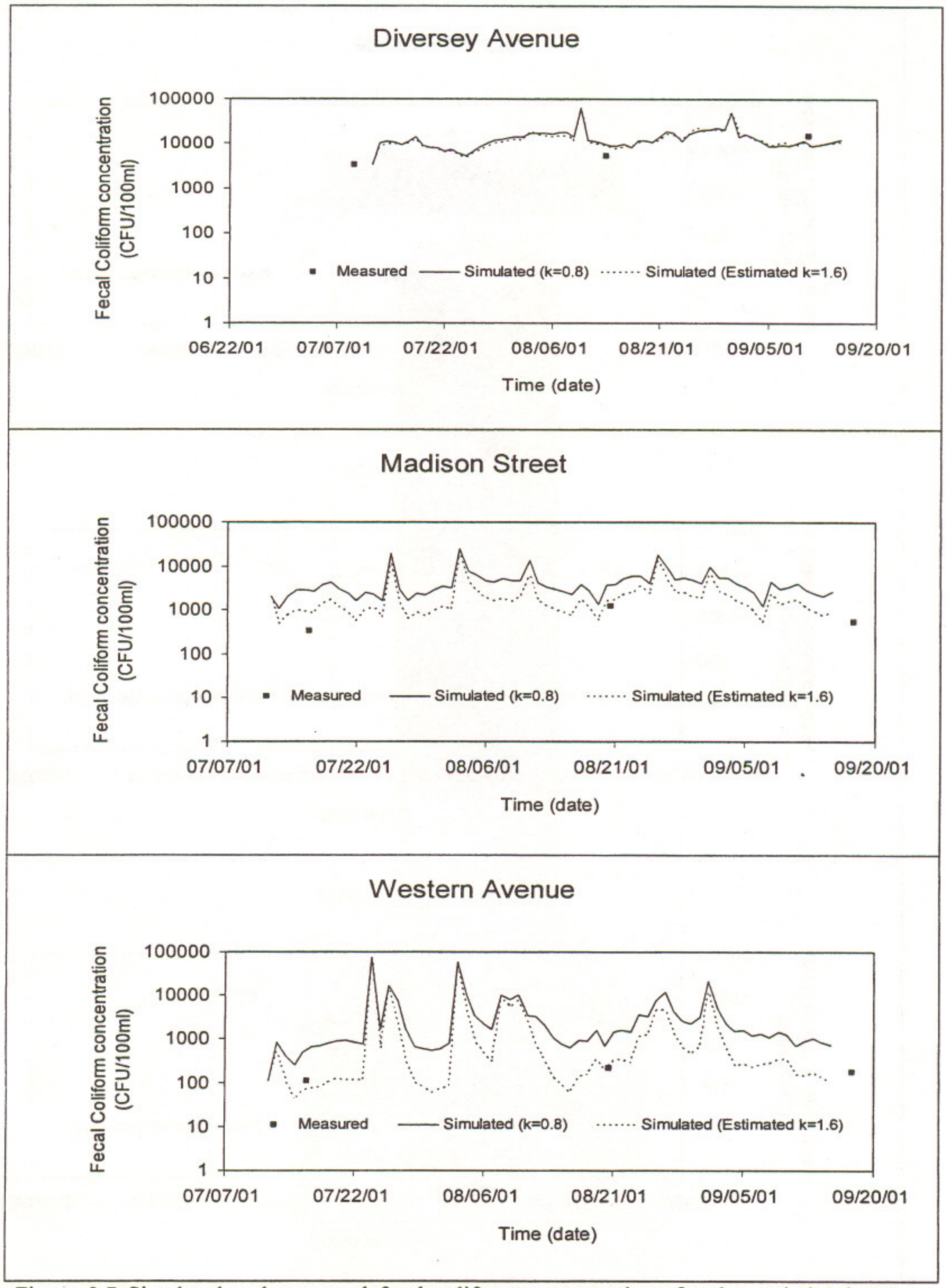

Figure 3.7 Simulated and measured fecal coliform concentrations for the period July 12 to September 15, 2001, for various locations along the North Branch Chicago River, South Branch Chicago River, and Chicago Sanitary and Ship Canal.

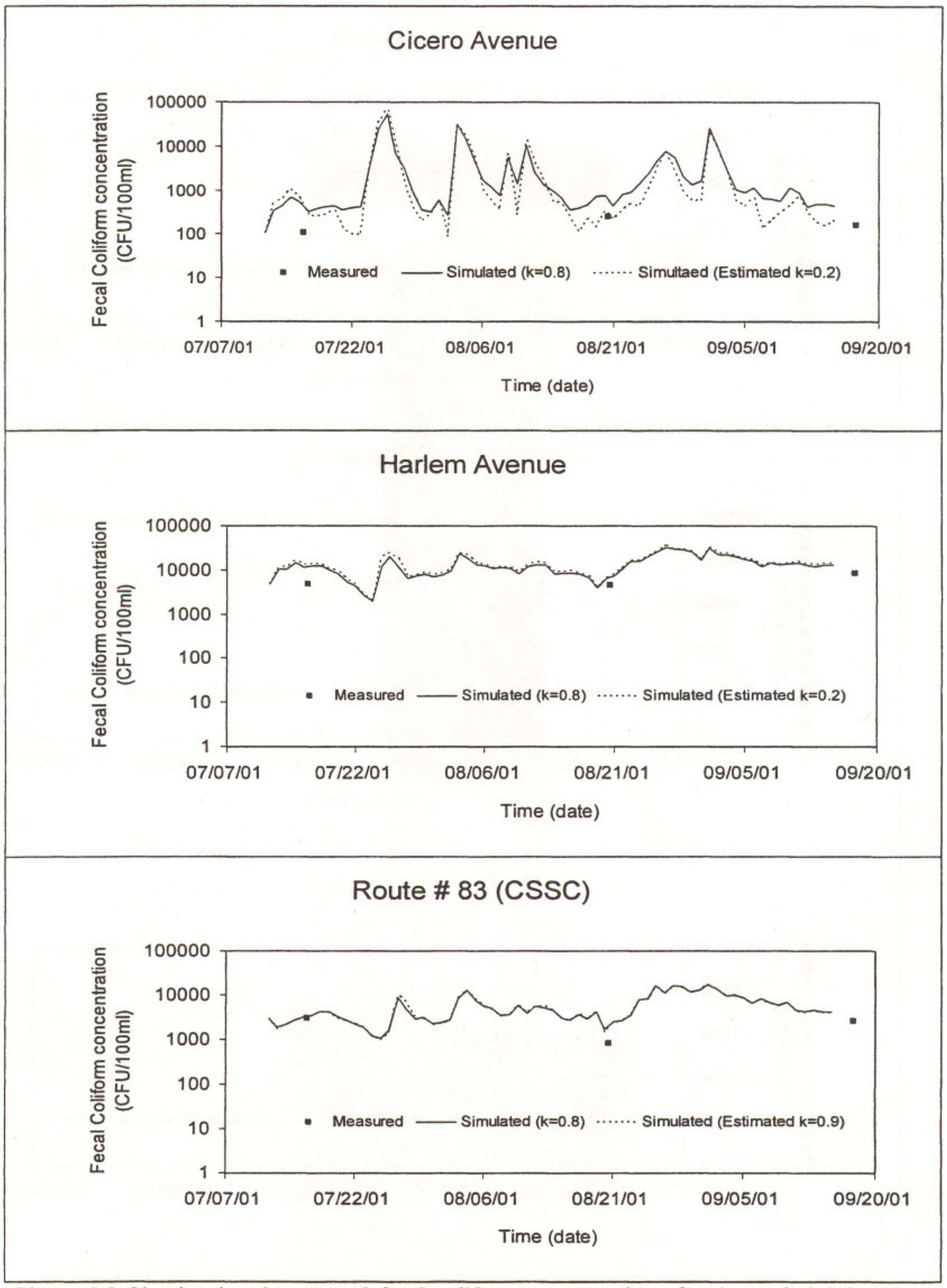

Figure 3.8 Simulated and measured fecal coliform concentrations for the period July 12 to September 15, 2001, for various locations along the Chicago Sanitary and Ship Canal.

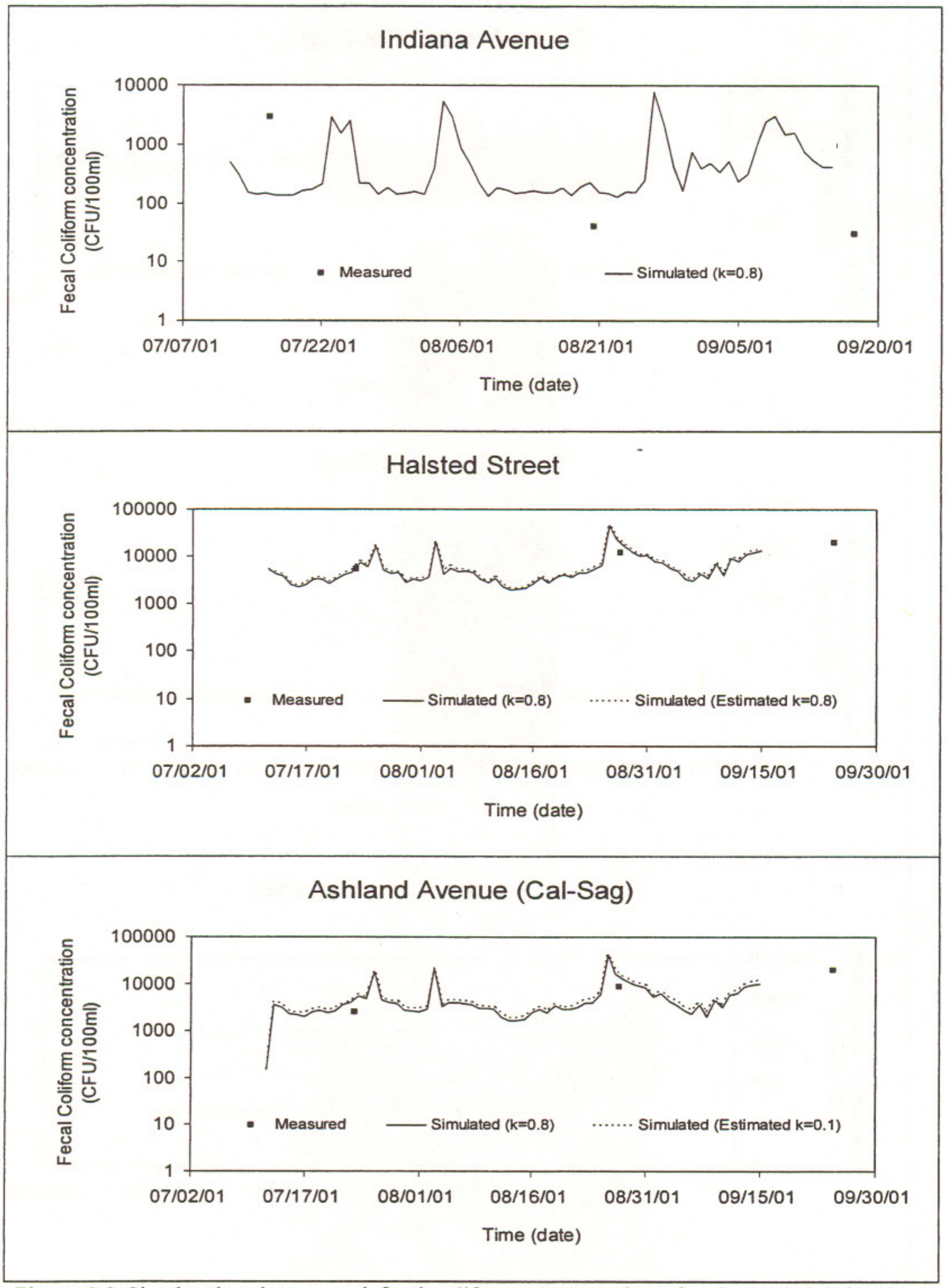

Figure 3.9 Simulated and measured fecal coliform concentrations for the period July 12 to September 15, 2001, for various locations along the Little Calumet River (north) and Calumet-Sag Channel.

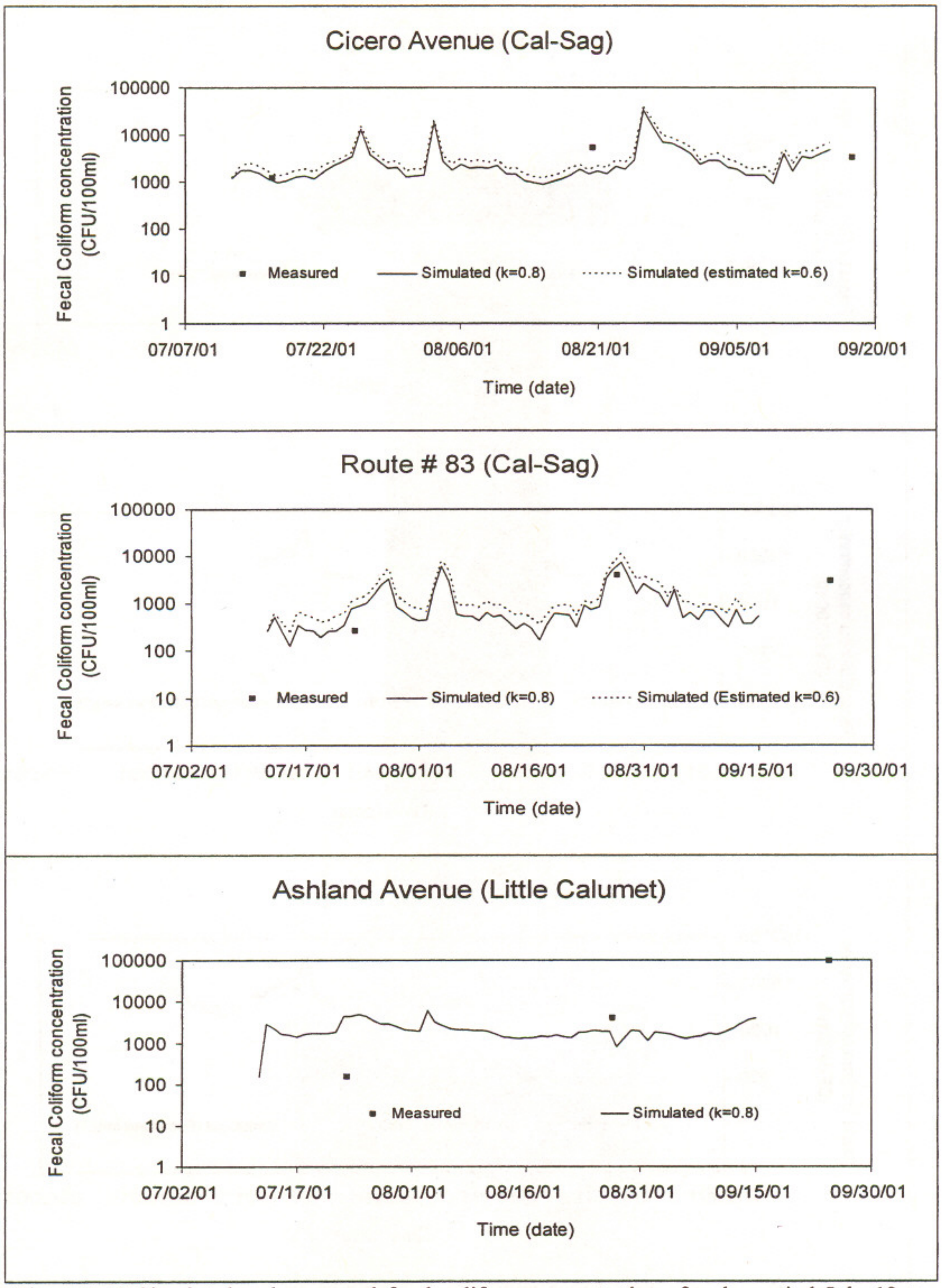

Figure 3.10 Simulated and measured fecal coliform concentrations for the period July 12 to September 15, 2001, for various locations along the Calumet-Sag Channel and Little Calumet River (south).

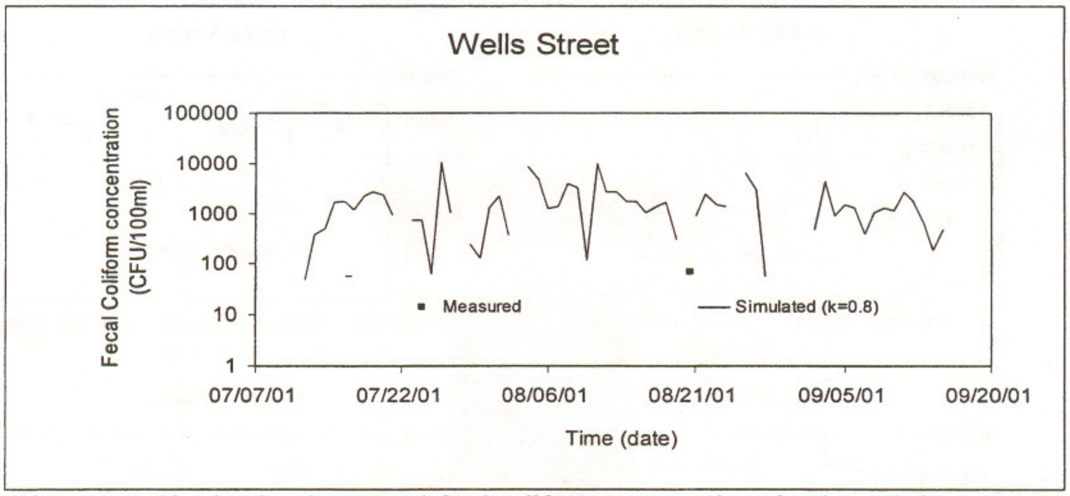

Figure 3.11 Simulated and measured fecal coliform concentrations for the period July 12 to September 15, 2001, for Wells Street on the Chicago River main stem.

3.6 Model verification for the period 09/02/2001-11/10/ 2001

After model calibration to the available bacterial data for the period July 12 to September 15, 2001, the model is verified for the periods September 2 to November 11, 2001, May 5 to September 29, 2002 , September 11 to December 30, 1998, and February 5 to May 24, 1999. Model verification results for the period September 2 to November 11, 2001 are illustrated in Figures 3.12 and 3.13. These plots clearly demonstrate that a good match between simulated and observed fecal coliform concentrations is still present at most of the sites mentioned in the previous section. For Indiana Avenue and Ashland Avenue (Little Calumet River (south)), the difference between measured and simulated fecal coliform concentrations is expected. For reasons explained in the previous section. Due to the uncertainty of hydraulic data, the verification results should be similar to the calibration results. The verification results obtained at these two locations confirm, to certain extent, that the model calibration is acceptable. If the verification results at these two locations were different from those obtained for the calibration period (i. e. good match is obtained for the verification period), then, the adequacy of the calibrated model would be questionable. In the verification results, Wells Street was excluded from the 16 considered points due to the lack of fecal coliform measurements for the verification period.

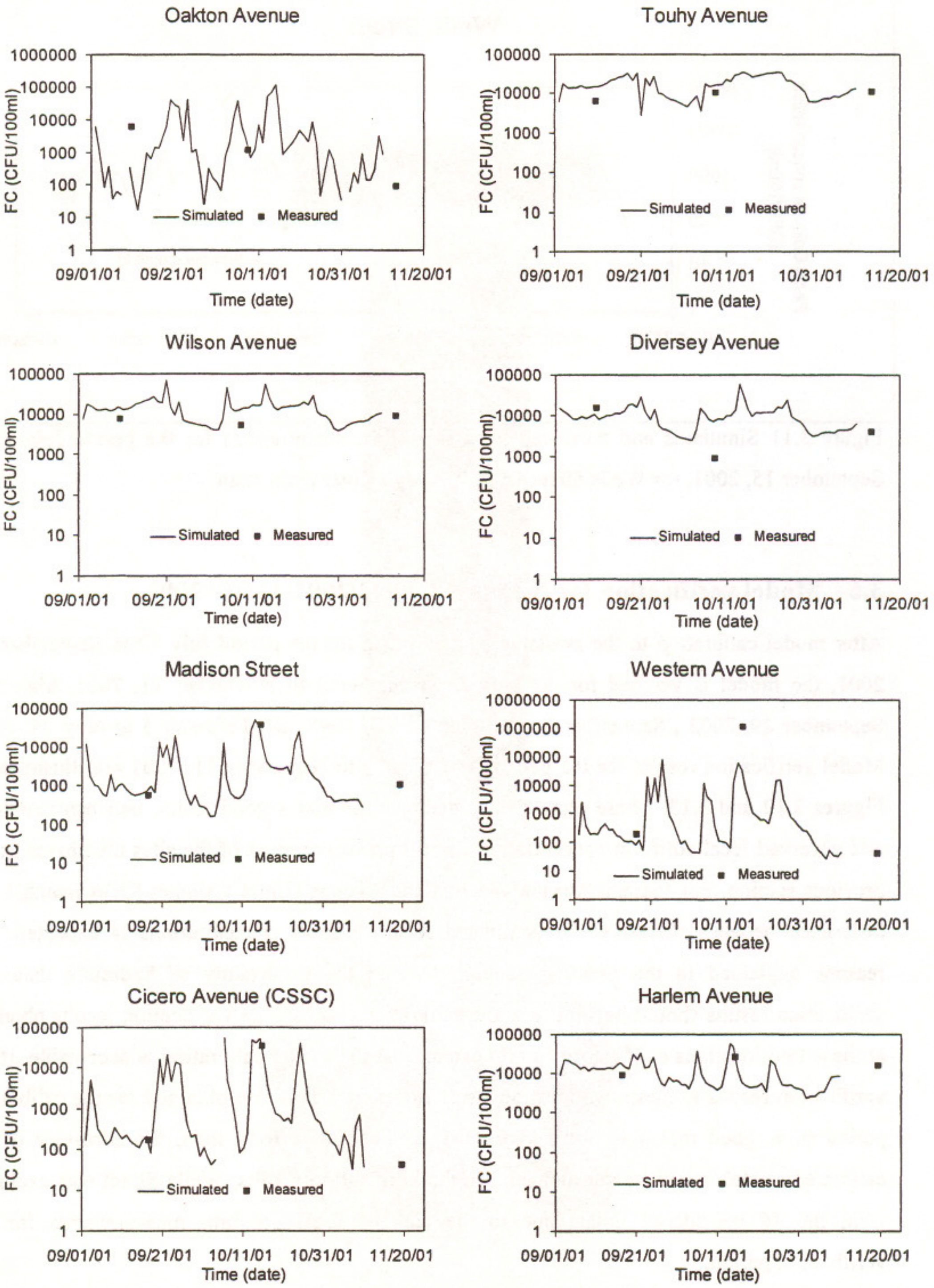

Figure 3.12 Simulated and measured fecal coliform concentrations for the period September 2 to November 10, 2001, for various locations along the North Shore Channel, North Branch Chicago River, South Branch Chicago River, and Chicago Sanitary and Ship Canal.

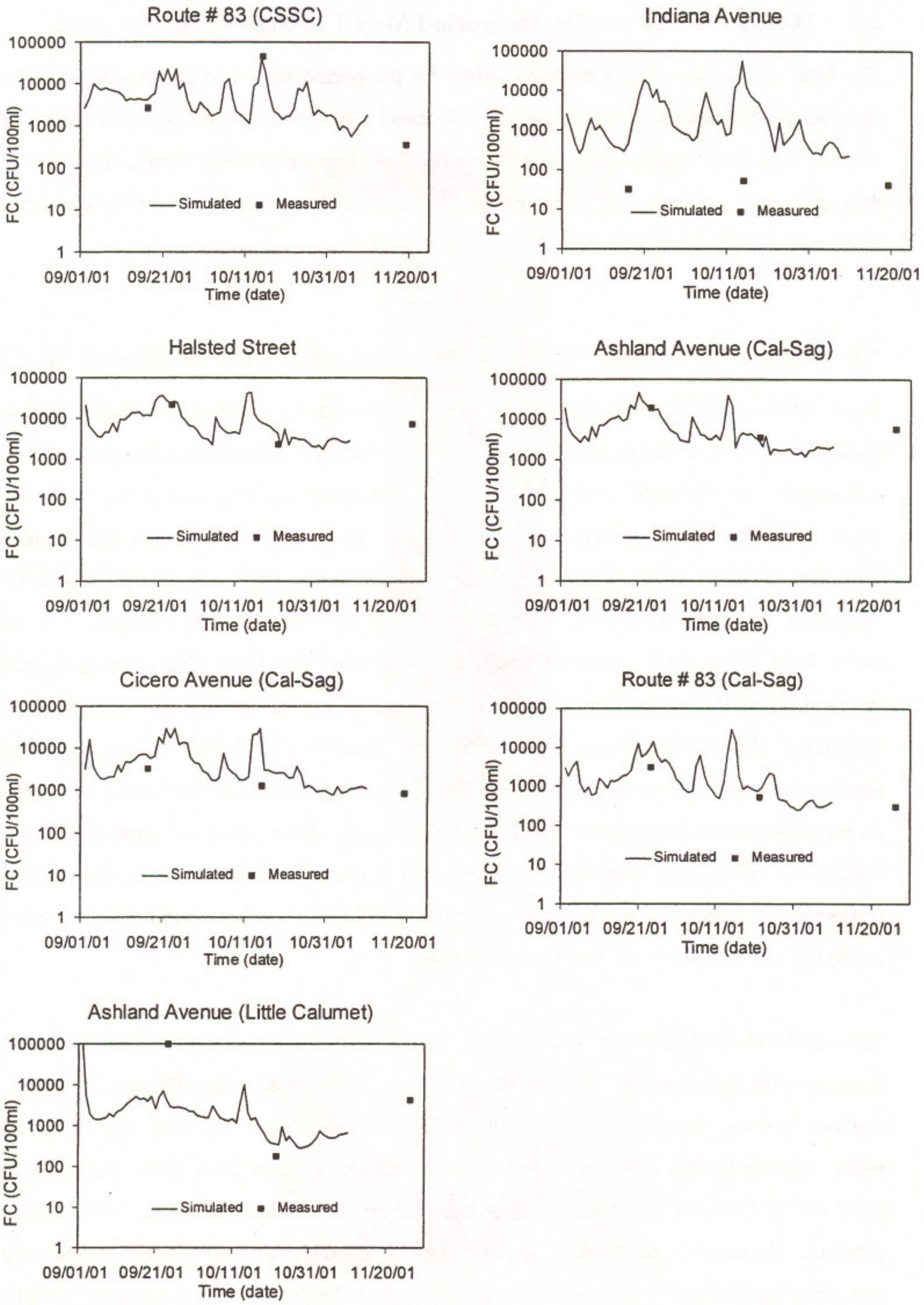

Figure 3.13 Simulated and measured fecal coliform concentrations for the period September 2 to November 10, 2001, for various locations along the Chicago Sanitary and Ship Canal, Little Calumet River (north), and Calumet-Sag Channel.

3.7 Model verification for the period May 1 to September 29, 2002

The fecal coliform model is further verified for the period May 1 to September 29, 2002. The simulation was performed for the considered period with the same computational time steps (see Section 3.5). The comparison between the fecal coliform simulation results and the observed data at the 16 considered sites (Figures 3.14 and 3.15) showed that the model adequately represents the fecal coliform decay process in the CWS.

3.8 Model verification for the period September 11 to December 30, 1998

Since the model verification reported in the previous sections (Sections 3.6 and 3.7) covers the periods from May to November, it was necessary to perform additional verification of the model that covers other periods of the year because recreational use is proposed for the CWS from March 1 to November 30. Hydraulic calibration of the DUFLOW model was done for six different periods in 1998 and 1999 (Shrestha and Melching, 2003): August 1 to August 15 1998; September 11 to December 31, 1998; January 7 to February 4, 1999; February 5 to May 25, 1999; May 27 to June 13, 1999; and, July 22 to July 29, 1999. Therefore, supplementary verification of the model was carried out for two of the six previously mentioned periods: September 11 to December 30, 1998 and February 5 to May 24, 1999. The choice of these two periods was supported by the fact that the other remaining periods were so short that only one or no measurements were available to check the adequacy of the calibrated model. Moreover, the model was sufficiently verified for the summer and the fall period and, thus, it would be more convenient to check the model under completely different weather conditions (i.e. winter and spring) as is the case for the two selected periods.

The simulated fecal coliform concentration for the period September 11 to December 30, 1998 together with the observed data are plotted for the considered sites (Figures 3.16 and 3.17). Oakton Avenue, Western Avenue, and Wells Street were not included due to the lack of measured data for the considered period. It can be clearly seen from these results that a very good match between the model output and the measured fecal coliform concentration was obtained. Moreover, it can be noticed that the peak and the minimum concentrations were quite well represented by the model confirming the model validity to simulate bacterial die-off in the CWS.

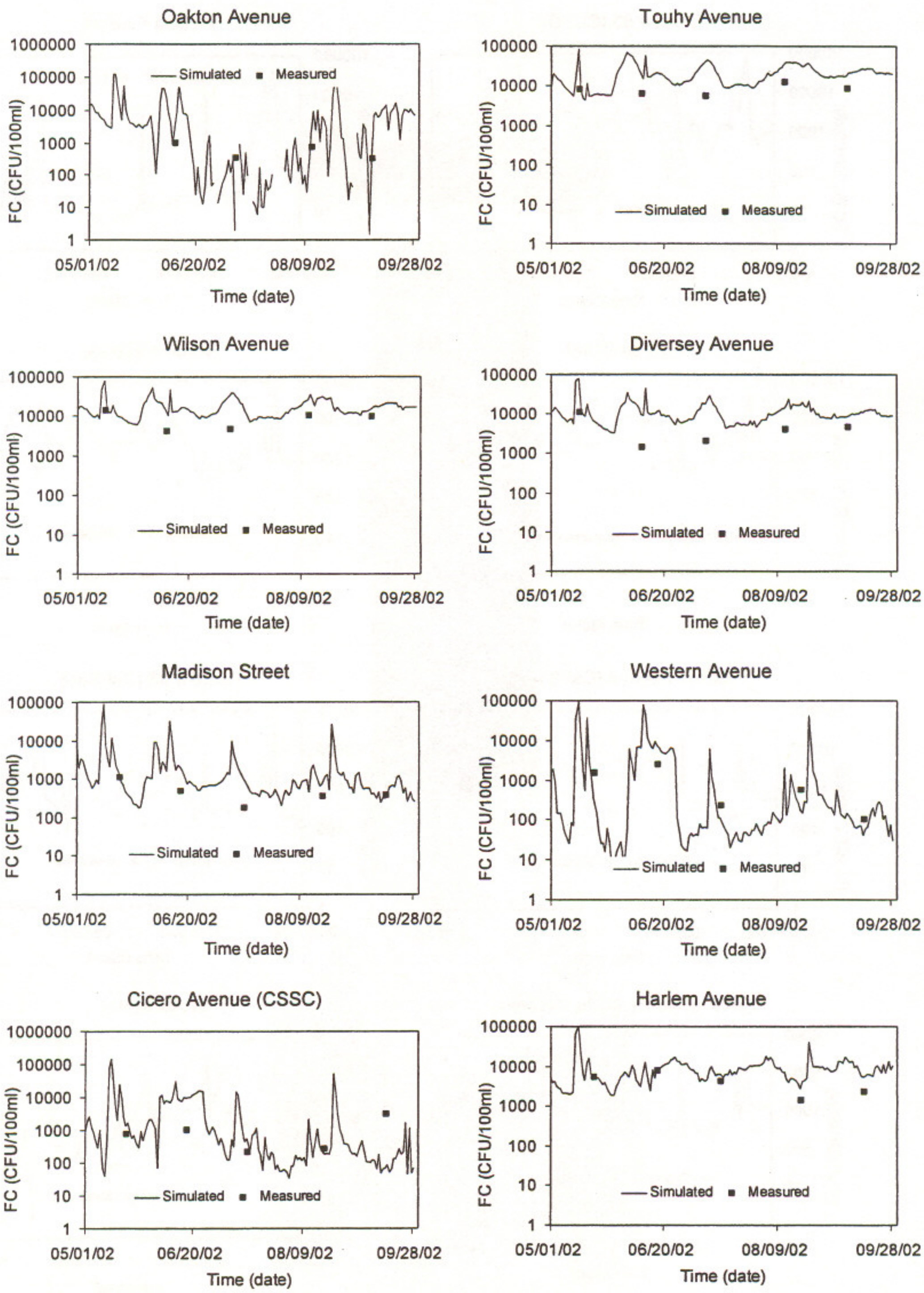

Figure 3.14 Simulated and measured fecal coliform concentrations for the period May 1 to September 29, 2002, for various locations along the North Shore Channel, North Branch Chicago River, South Branch Chicago River, and Chicago Sanitary and Ship Canal.

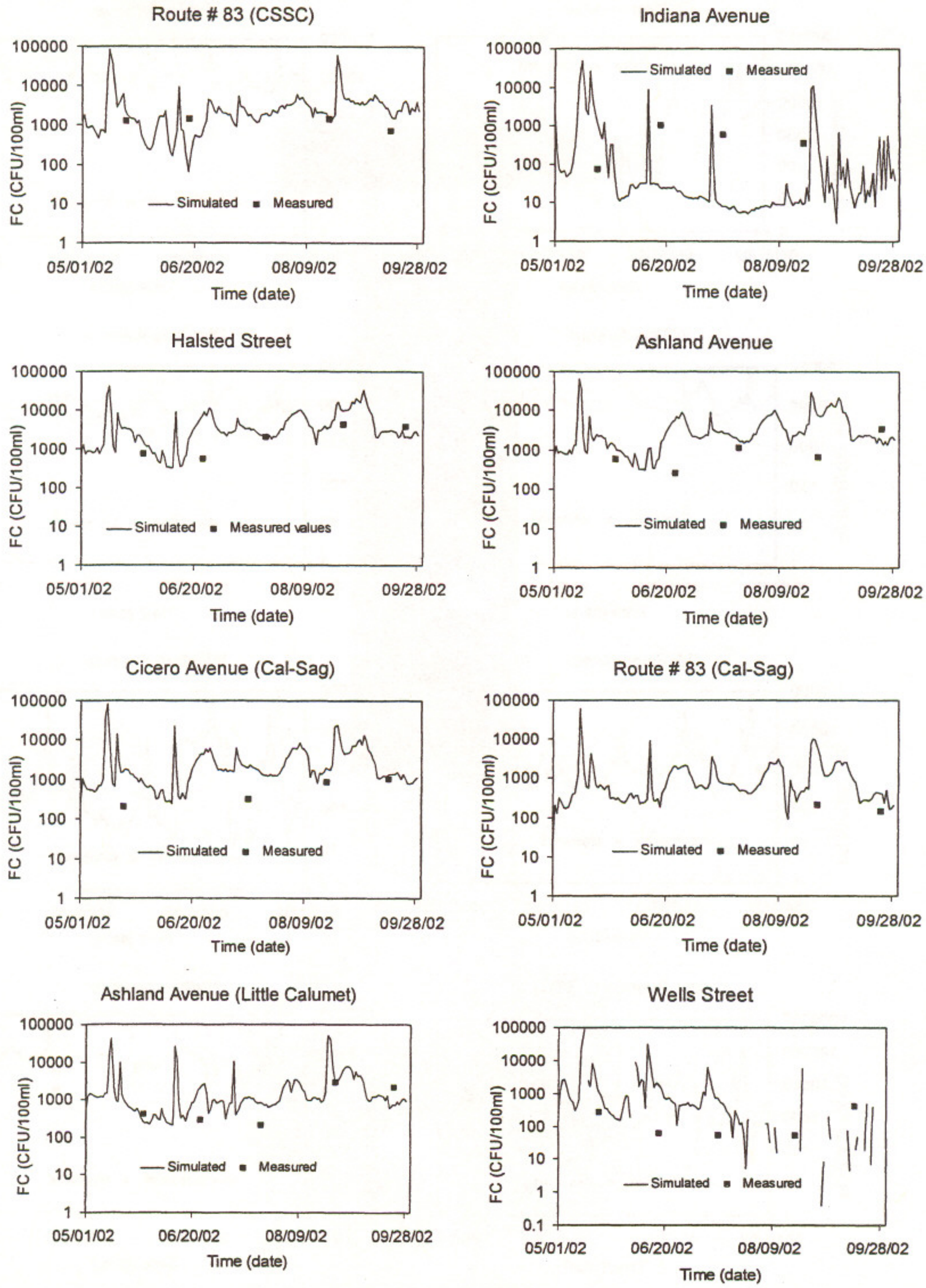

Figure 3.15 Simulated and measured fecal coliform concentrations for the period May 1 to September 29, 2002, for various locations along the Chicago Sanitary and Ship Canal, Little Calumet River (north and south), Calumet-Sag Channel, and Chicago River main stem.

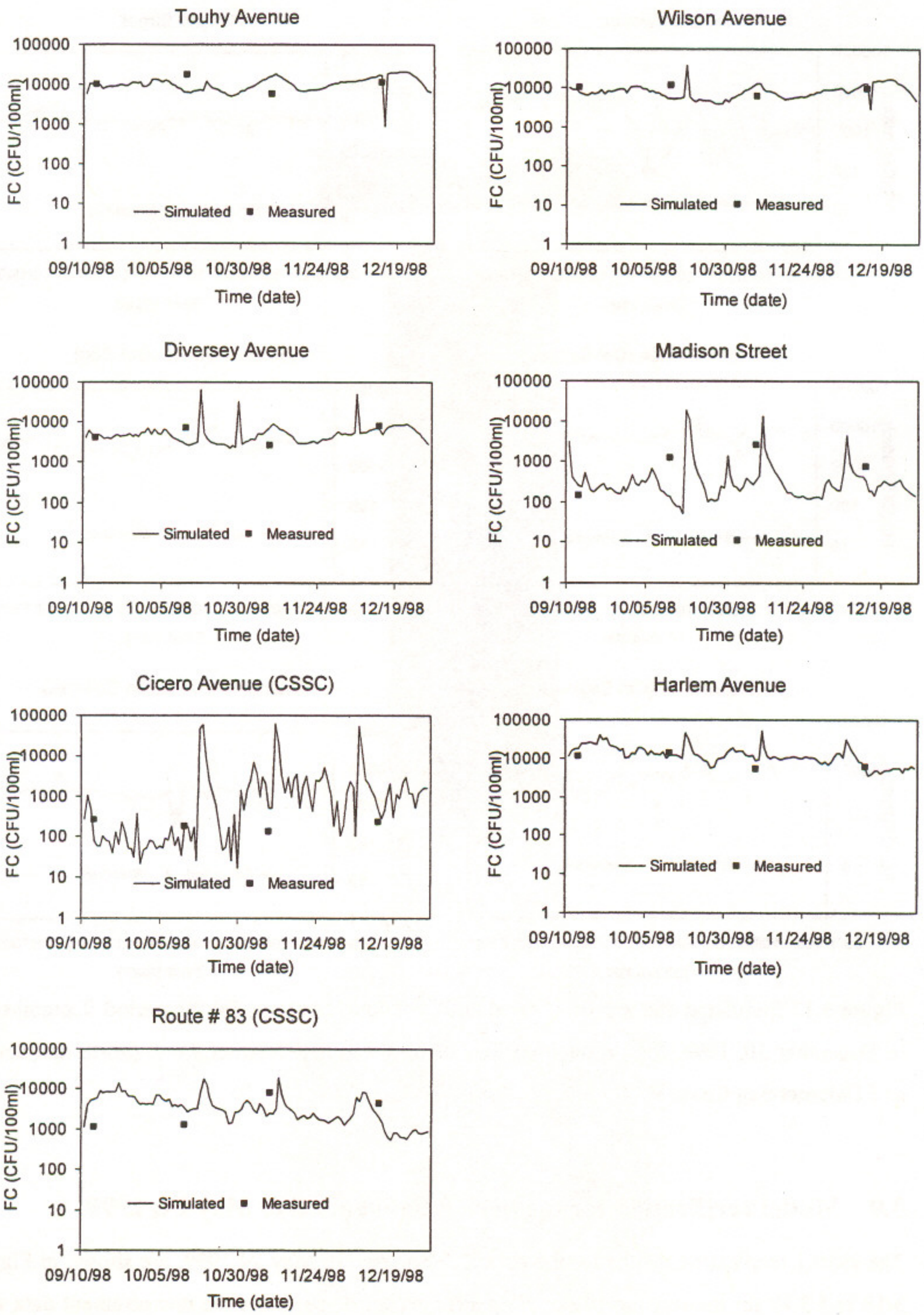

Figure 3.16 Simulated and measured fecal coliform concentrations for the period September 11 to December 30, 1998, for various locations along the North Shore Channel, North Branch Chicago River, South Branch Chicago River, and Chicago Sanitary and Ship Canal.

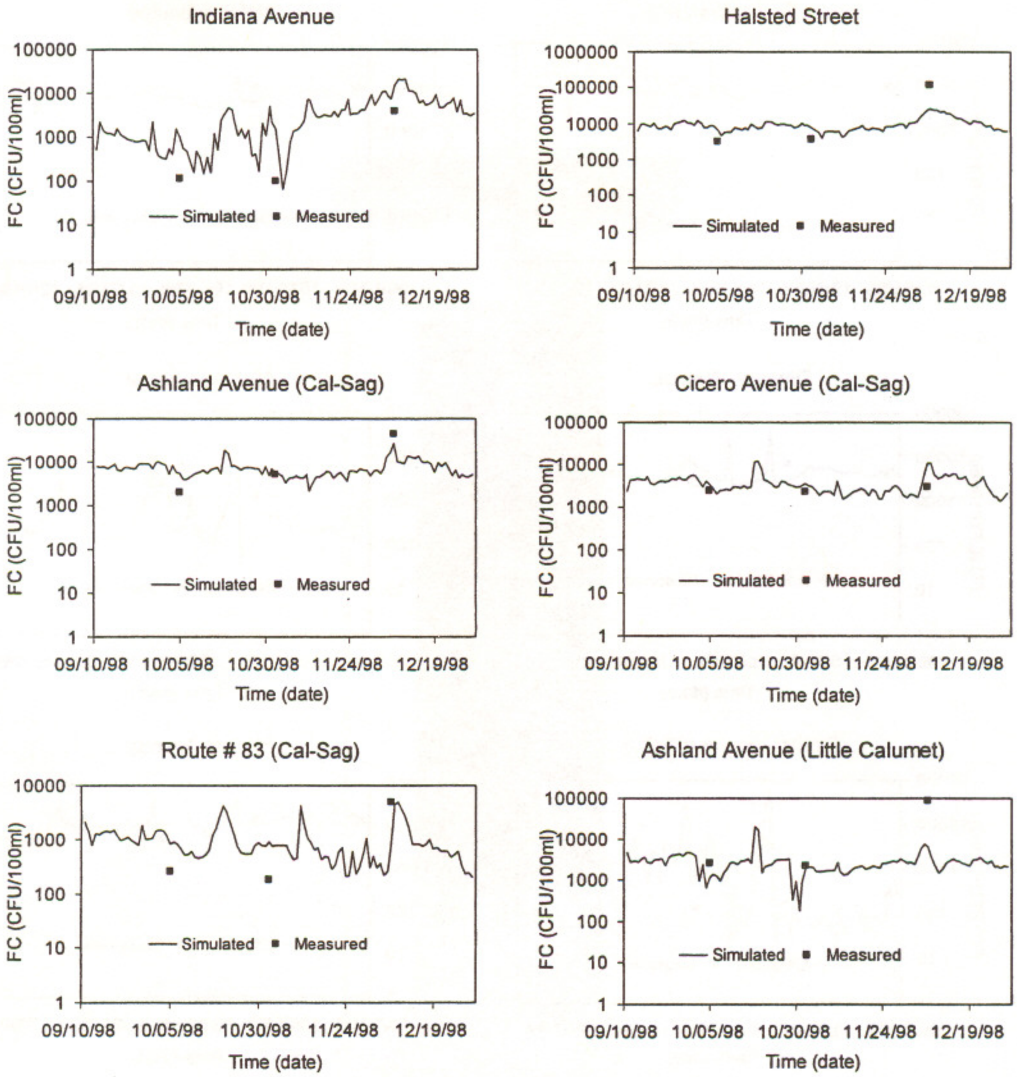

Figure 3.17 Simulated and measured fecal coliform concentrations for the period September 11 to December 30, 1998, for various locations along the Little Calumet River (north and south), and Calumet-Sag Channel.

3.9 Model verification for the period February 5 to May 24, 1999

The model verification results for the period February 5 to May 24,1999, are shown in Figures 3.18 and 3.19 for the considered sampling sites except those where the measurement data were lacking (i.e. Oakton Avenue, Western Avenue, and Halsted Street). As can be noticed, the match between observed and simulated values of fecal coliform concentration is as good (even slightly better) as those obtained with the other verification periods. With this outcome, it can be concluded that the calibrated model is suitable to simulate fecal coliform behavior in the CWS for any period of the year.

During the model calibration and verification described in the Sections 3.5-3.9, the fecal coliform concentration at the pumping stations and CSOs is considered equal to the median value of fecal coliform sampling data for Milwaukee (i.e. 170,000 CFU/100 ml). Therefore, it was necessary to investigate the validity of this estimated model input during rainstorm events. The following sections discuss extensively the calibration/verification of the fecal coliform model during high flow periods that resulted in flow reversals to Lake Michigan.

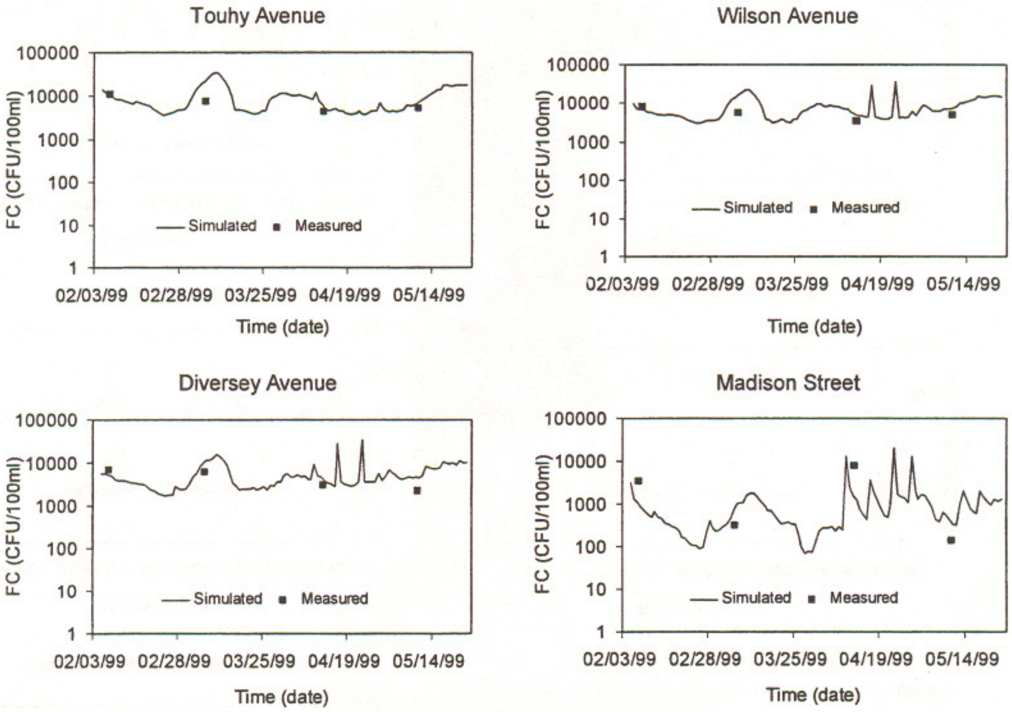

Figure 3.18 Simulated and measured fecal coliform concentrations for the period February 5 to May 24, 1999, for various locations along the North Shore Channel, North Branch Chicago River, and South Branch Chicago River.

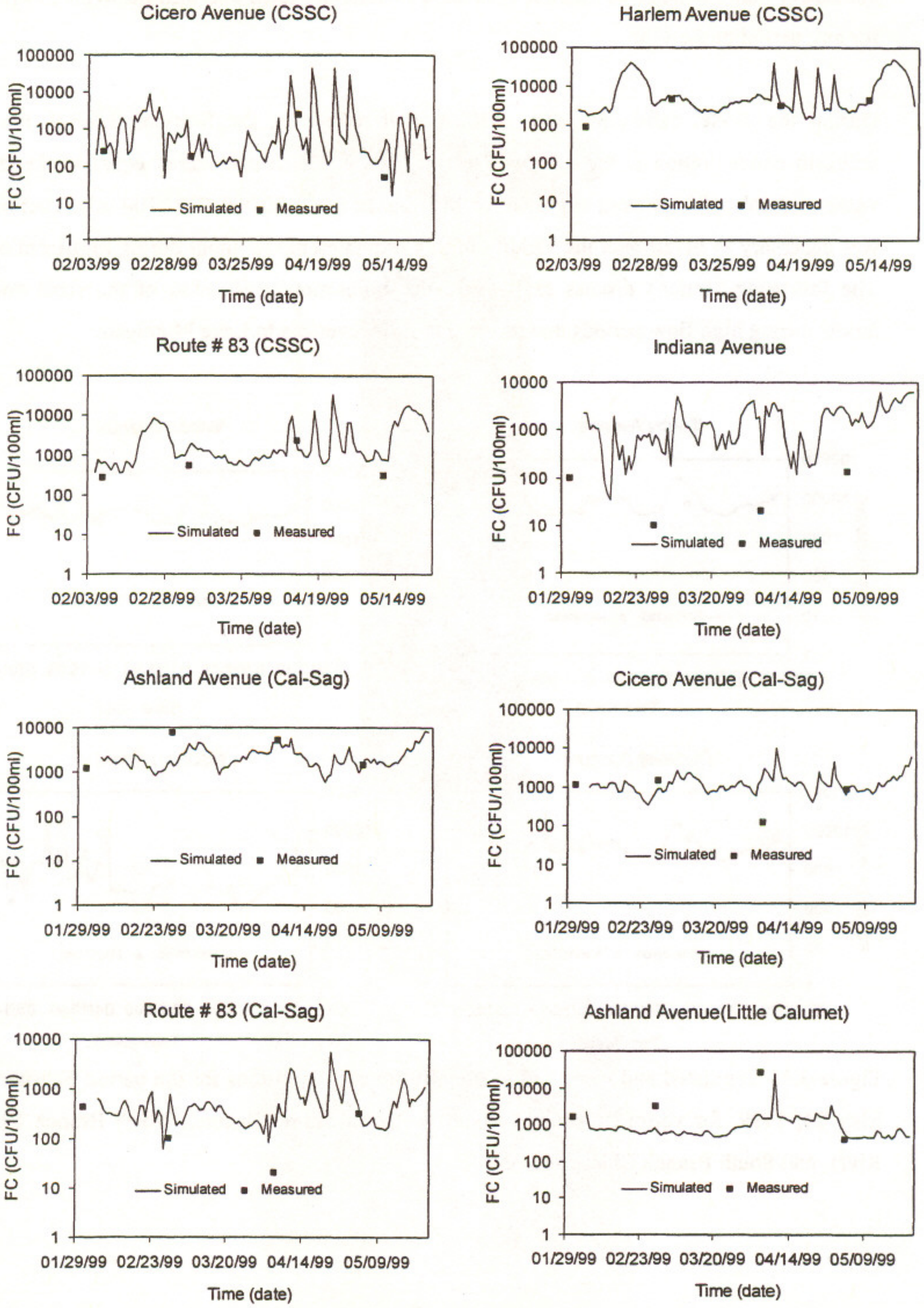

Figure 3.19 Simulated and measured fecal coliform concentrations for the period February 5 to May 24, 1999, for various locations along the Chicago Sanitary and Ship Canal, Little Calumet River (north and south), and Calumet-Sag Channel.

3.10 Model calibration during high flow periods in 2001

There were five severe rainstorms in 2001; July 25, August 2, August 25, and October 13 and 14. During these events, one or more pump stations were operated, and flow reversals of the Calumet River, North Shore Channel, and/or the Chicago River main stem at CRCW to Lake Michigan occurred. During periods of flow reversals to Lake Michigan, the District is required to intensively sample the quality of the water going into the Lake. These data facilitate evaluation of fecal coliform concentrations in CSOs.

During the two rainstorm events on July 25, the pump stations at 95th Street and 125th Street were operated discharging about 48.26 million gallons (MG) and 79.57 MG of CSOs into Howard Slip and the Calumet River, respectively. During the rainstorm event on August 2nd, the pump stations at 95th Street and 125th Street were operated discharging about 44.33 MG and 134.28 MG of CSOs into Howard Slip and the Calumet River, respectively. River reversal also occurred at CRCW and at Wilmette Harbor during which 833.1 MG and 140 MG of river water were diverted into Lake Michigan, respectively.

On August 25, there were two storm events during which the pump stations at 95th Street, 122nd Street, and 125th Street were operated discharging about 66.77 MG, 2.69 MG, and 240.17 MG of CSOs into Howard Slip and the Calumet River, respectively.

On August 30 and 31, there was a rainstorm event during which a river reversal at Wilmette Harbor occurred. 75.3 MG flowed from the North Shore Channel into Lake Michigan. On October 13 and 14, there was a rainstorm event during which the pump stations at 95th Street, 122nd Street, and 125th Street were operated discharging about 62.84 MG, 2.52 MG, and 206.09 MG of CSOs into Howard Slip and the Calumet River, respectively. A river reversal also occurred at Wilmette Harbor during which 90.7 MG of river water were flowed from the North Shore Channel into Lake Michigan.

During and after discharges from the pump stations, samples were collected at the 95th Street Bridge and Ewing Avenue Bridge over the Calumet River at approximately 30-minutes intervals and analyzed for fecal coliforms. Post discharge samples for fecal coliform and E. Coli analysis were also taken at three Chicago area beaches adjacent to the mouth of the Calumet Harbor and at the seven stations around the mouth of the Calumet Harbor. During and after the reversals at CRCW and Wilmette Harbor, samples were taken at 30-minutes intervals at the sluice gate of Chicago Locks and at the gate at the Wilmette Pump Station, respectively. Post-reversal samples were also taken at Chicago Harbor and at the mouth of Wilmette Harbor and adjacent locations. The high flow monitoring results for fecal coliform at the 95th Street Bridge and Ewing Avenue Bridge over the Calumet River, Wilmette Harbor, and at the sluice gate of the Chicago Locks are listed in Table 3.4.

In order to calibrate the fecal coliform model during the high flow periods when reversals to Lake Michigan occurred (i.e. August 2, August 31, and October 13), Duflow model runs were performed for the periods July 25 to August 5, 2001, August 25 to September 3, 2001, and October 12 to October 15, 2001 with a 15-minute calculation time step and 1-hour output time step. For these runs, flow time series at Wilmette and CRCW were considered as the upstream boundary conditions instead of the water levels. Two different values of fecal coliform concentration were considered as input from the three pumping stations and the 28 representative CSO locations. These values represent the median and the 90th percentile of fecal coliform sampling data for Milwaukee (i.e. 170,000 CFU/100 ml and 1,100,000 CFU/100 ml, respectively) as discussed in Section 2.5.2 and shown in Figure 2.2.

The simulation results for the rainstorm of August 2, 2001, at Wilmette Pump Station gate and Chicago Locks sluice gate are illustrated in Figures 3.20 and 3.21, respectively (Logarithmic scale). These results indicate that for the two locations, a good fit between measured and simulated fecal coliform concentrations is obtained when the 90th percentile value of Milwaukee CSOs fecal coliform concentration data is considered as representative of bacterial loads from CSOs.

The normal plots of the simulation results at Wilmette Pump Station gate and Chicago Locks sluice gate during the rainstorm August 2, 2001 (Figures 3.22 and 3.23) show that the peak concentration of fecal coliform is well represented in the DUFLOW model. This match between measured and simulated peak concentration is more visible on Figure 3.22 (Wilmette Pump Station gate) than on Figure 3.23 (Chicago Locks). Taking into account that the interval between the first two measurements at Chicago locks was about 1 hour instead of 30 minutes (see Table 3.4), it is possible that the peak concentration occurred within this interval and the sampling campaign missed that value. It can be, therefore, concluded that the variation of bacterial concentration during rainstorm events can be well represented by the calibrated DUFLOW model.

Table 3.4 High flow monitoring results for fecal coliforms in 2001.

Rainstorm event	CALHBR1 Ewing Bridge		CALHBR2 95th St. Bridge		CHGHBR1 Chicago Locks sluice gate		WILHBR1 Wilmette Pump Station gate	
	Sample time	Fecal coliform (CFU/ 100 ml)	Sample time	Fecal coliform (CFU/ 100 ml)	Sample time	Fecal coliform (CFU/ 100 ml)	Sample time	Fecal coliform (CFU/ 100 ml)
07/25/01	11:10	140	11:25	230				
07/25/01	11:40	90	12:05	210				
07/25/01	12:15	50	12:35	130				
07/25/01	12:40	9	13:05	150				
07/25/01	13:10	40	13:35	140				
07/25/01	13:40	<10	14:05	30				
07/25/01	14:10	60	14:35	140				
07/25/01	14:45	40						
08/02/01	11:00	<10	11:00	90	12:00	56000	12:00	52000
08/02/01	11:30	9	11:30	120	13:00	62000	12:30	76000
08/02/01	12:00	<10	12:00	<10	13:30	59000	13:00	97000
08/02/01	12:30	30	12:30	9	14:00	50000	13:30	150000
08/02/01	13:00	40	13:00	<10	14:30	32000	14:00	170000
08/02/01	13:30	20	13:30	<10	15:00	26000	14:30	240000
08/02/01	14:00	20	14:00	600			15:00	130000
08/02/01	14:30	<10	14:30	9			15:30	150000
08/02/01	15:00	<10	15:00	<10			16:00	120000
08/02/01	15:30	<10	15:30	<10			16:30	130000
08/02/01	16:00	<10	16:00	<10			17:00	140000
							17:30	120000
08/25/01	14:15	99	14:00	40				
08/25/01	14:45	320	14:30	240				
08/25/01	15:15	300	15:00	200				
08/25/01	15:45	210	15:30	210				
08/25/01	16:15	200	16:00	140				
08/25/01	16:45	260	16:30	220				
08/25/01	17:15	30	17:00	9				
08/25/01	17:45	140	17:30	50				
08/31/01							1:00	26000
08/31/01							1:30	13000
08/31/01							2:00	220000
08/31/01							2:30	330000
08/31/01							3:00	230000
08/31/01							3:30	150000
08/31/01							4:00	140000
10/13/01	21:00	4400	21:00	<10			19:05	95000
10/13/01	21:30	580	21:30	<10			19:35	42000
10/13/01	22:00	740	22:00	<10			20:05	150000
10/13/01	22:30	30	22:30	<10			20:35	57000
10/13/01	23:00	<10	23:00	<10			21:05	142000
10/13/01	23:30	200	23:30	<10			21:35	135000
10/14/01	0:00	130	0:00	<10			22:05	122000
10/14/01	0:30	<10	0:30	<10			22:21	260000
10/14/01	1:00	<10	1:00	<10				
10/14/01	1:30	<10	1:30	<10				
10/14/01	2:00	<10	2:00	<10				
10/14/01	2:30	<10	2:30	<10				
10/14/01	3:00	<10	3:00	<10				
10/14/01	3:30	<10						

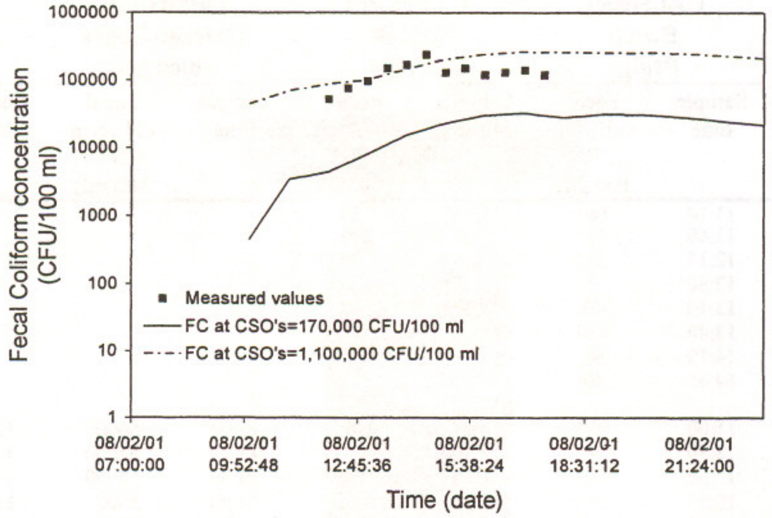

Figure 3.20 Simulated and measured fecal coliform concentrations at the Wilmette Pump Station gate for the storm of August 2, 2001 (Logarithmic scale).

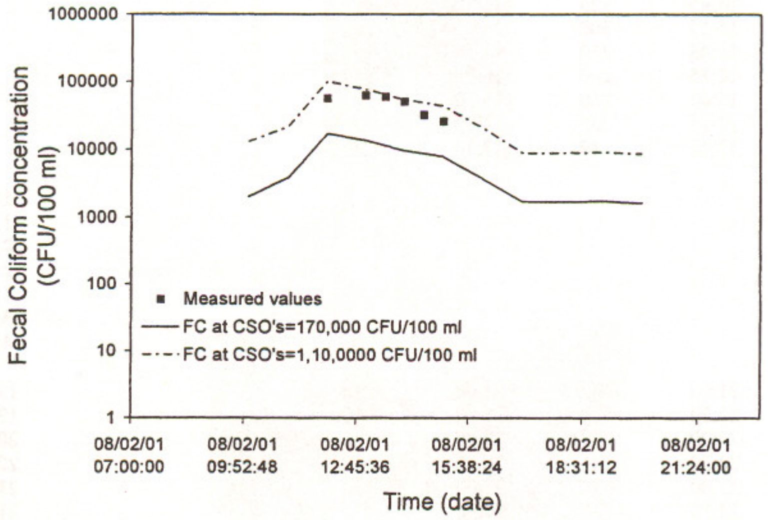

Figure 3.21 Simulated and measured fecal coliform concentrations at the Chicago Locks sluice gate for the storm of August 2, 2001 (Logarithmic scale).

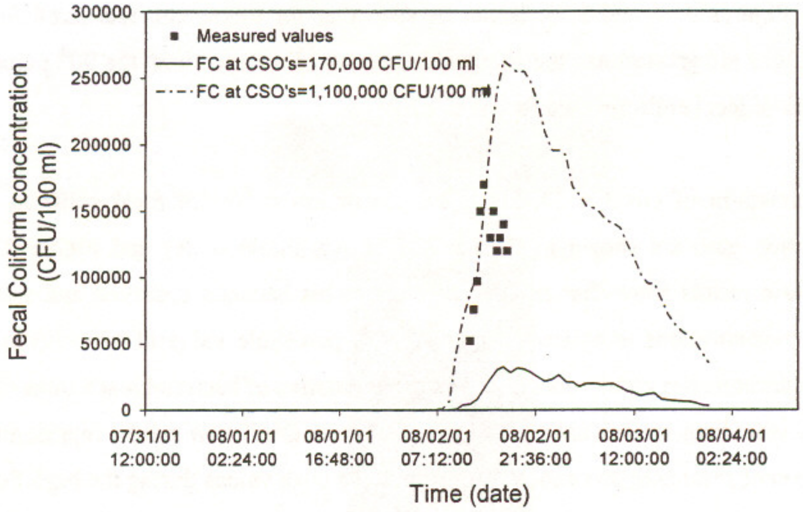

Figure 3.22 Simulated and measured fecal coliform concentrations at the Wilmette Pump Station gate for the storm of August 2, 2001 (Normal scale).

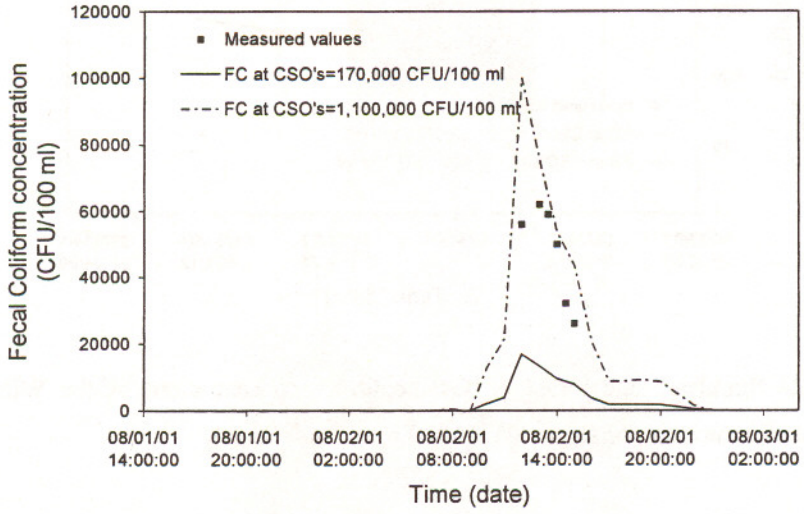

Figure 3.23 Simulated and measured fecal coliform concentrations at the Chicago Locks sluice gate for the storm of August 2, 2001 (Normal scale).

The simulation results for the rainstorm of August 31, 2001 at Wilmette Pump Station gate are shown in Figures 3.24 and 3.25. It can be seen that for this event, measured fecal coliform concentrations are greater than the simulated concentrations even with the 90th percentile values of Milwaukee fecal coliform data for the CSOs.

For the rainstorm of October 13, 2001, the simulation results of fecal coliform at Wilmette Pump Station gate are shown in Figure 3.26 (Logarithmic scale) and Figure 3.27 (Normal scale). These results show that an adequate agreement between observed and simulated fecal coliform concentrations is obtained when the 90th percentile value of Milwaukee CSOs fecal coliform concentration data is considered as representative of bacterial loads from CSOs. As can be clearly seen from the normal plot (Figure 3.27), the DUFLOW model represents adequately the variation of fecal coliform concentrations and the peak values during the high flow periods.

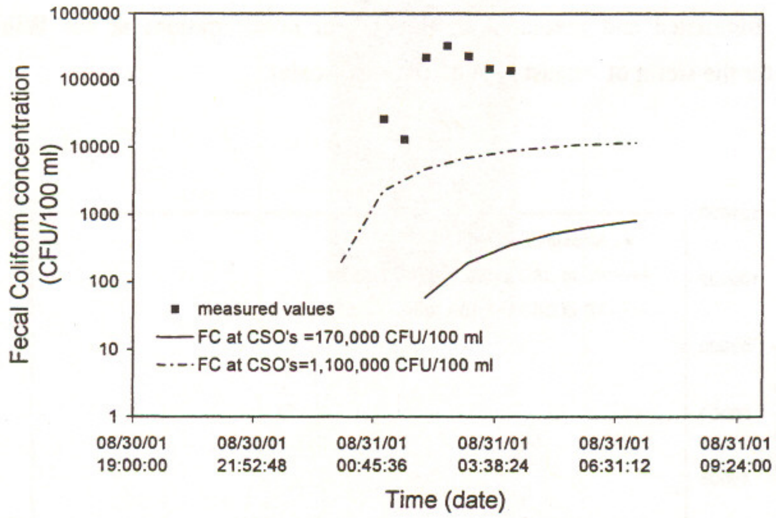

Figure 3.24 Simulated and measured fecal coliform concentrations at the Wilmette Pump Station gate for the storm of August 31, 2001(Logarithmic scale).

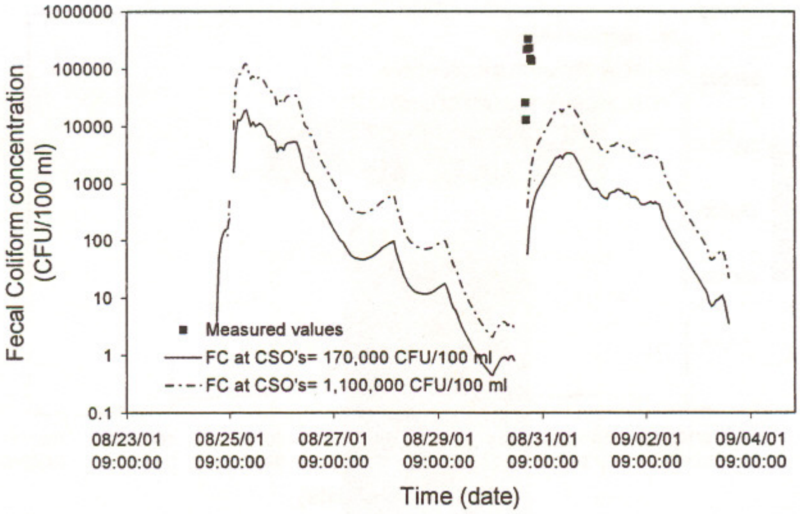

Figure 3.25 Simulated and measured fecal coliform concentrations at the Wilmette gate Pump Station gate for the storm of August 31, 2001(Logarithmic scale).

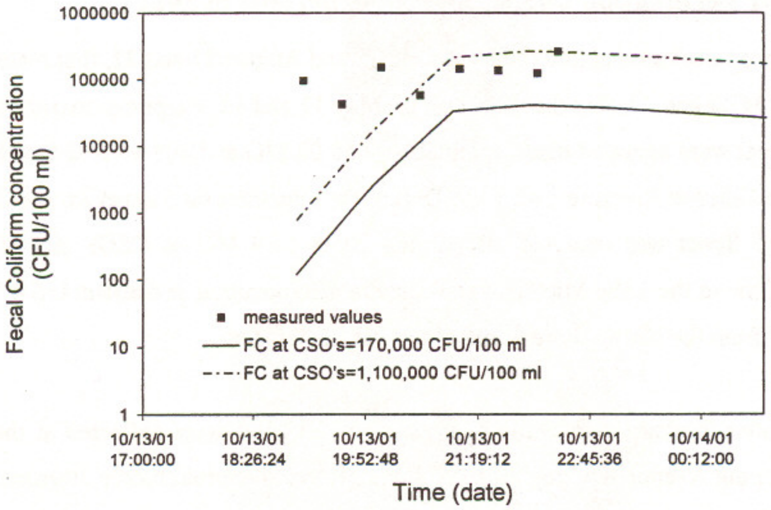

Figure 3.26 Simulated and measured fecal coliform concentrations at the Wilmette Pump Station gate for the storm of October 13, 2001(Logarithmic scale).

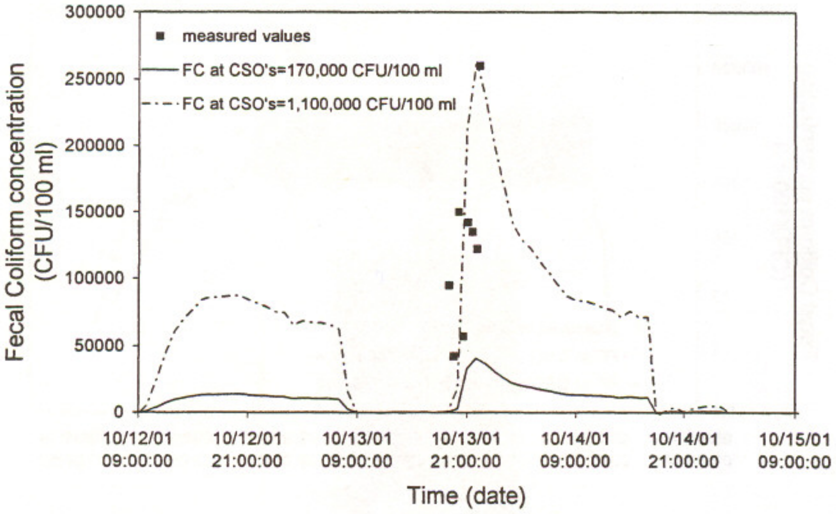

Figure 3.27 Simulated and measured fecal coliform concentrations at the Wilmette Pump Station gate for the storm of October 13, 2001 (Normal scale).

3.11 Model Verification during high flow periods in 2002

There were two rainstorms in 2002, May 11 and 12 and August 21 and 22, that resulted in flows toward Lake Michigan. During the rainstorm on May 11 and 12, the pump stations at 95th Street and 125th Street were operated discharging about 650.08 MG and 303.61 MG into Howard Slip and the Little Calumet River, respectively. During the rainstorm on August 21 and 22, the pump station at 95th Street was operated discharging about 55.9 MG of CSOs into Howard Slip. Reversal of flow to the Lake Michigan at Wilmette also occurred and about 455.4 MG of river water flowed from the North Shore Channel into lake Michigan.

During and after discharges from the pump stations, samples were collected at the 95th Street Bridge and Ewing Avenue Bridge over the Calumet River at approximately 30-minutes intervals and analyzed for fecal coliforms. Post discharge samples for fecal coliform and E. Coli analysis were also taken at three Chicago area beaches adjacent to the mouth of the Calumet Harbor.

During the reversal at Wilmette Harbor, samples were taken at 30-minutes intervals at Wilmette Pump Station gate. Post-reversal samples were also taken at adjacent locations in Wilmette Harbor. The high flow monitoring results for fecal coliform at the 95th Street Bridge and Ewing Avenue Bridge over the Calumet River, and at Wilmette Harbor are listed in Table 3.5.

The DUFLOW fecal coliform model was verified during the high flow period when reversal to Lake Michigan occurred at the Wilmette gate on August 22, 2002. Duflow model runs were performed for the period August 17 to August 25, 2002 with a 15-minute calculation time step and 1-hour output time step. As discussed in Section 3.10, two values of fecal coliform concentration were considered as input from the CSOs and pump stations (i.e. 170,000 CFU/100 ml and 1,100,000 CFU/100 ml).

The simulation results of fecal coliform concentrations at Wilmette Pump Station gate for the rainstorm of August 22, 2002 are illustrated in Figure 3.28 (Logarithmic scale) and Figure 3.29 (Normal scale). It can be noticed that the variations given by the measurements data are well expressed by the model for the assumption of CSOs concentrations during the event equal to 1,100,000 CFU/100 ml. After model calibration and verification for the large rainstorms in 2001 and 2002, it can be concluded that bacterial concentration of about 1,100,000 CFU/100 ml (i.e. the 90th percentile of Milwaukee CSOs data) is a good estimation of the bacterial contamination resulting from the CSOs in the CWS area.

Table 3.5 High flow monitoring results for fecal coliforms in 2002.

Rainstorm event	CALHBR1 Ewing Bridge		CALHBR2 95th St. Bridge		WILHBR1 Wilmette Pump Station gate	
	Sample time	Fecal coliform (CFU/ 100 ml)	Sample time	Fecal coliform (CFU/ 100 ml)	Sample time	Fecal coliform (CFU/ 100 ml)
05/12/02	2:45	20	2:45	2900		
05/12/02	3:15	40	3:15	3700		
05/12/02	3:45	50	3:45	4500		
05/12/02	4:15	30	4:15	5000		
05/12/02	4:45	20	4:45	30000		
05/12/02	5:15	<10	5:15	14000		
05/12/02	5:45	310	5:45	21000		
05/12/02	6:15	160	6:15	11000		
05/12/02	6:45	1300	6:45	6900		
05/12/02	7:15	2900	7:15	1700		
05/12/02	7:45	3500	7:45	3100		
05/12/02	8:15	4600	8:15	3300		
08/22/02	8:30	220	8:45	6600	6:30	29000
08/22/02	9:00	17000	9:15	30000	7:00	35000
08/22/02	9:15	17000	9:45	300	7:30	80000
08/22/02	10:00	38000	10:15	2400	8:00	78000
08/22/02	10:30	23000	10:45	4500	8:30	120000
08/22/02	11:00	42000	11:15	34000	9:00	75000
08/22/02	11:30	15000	11:45	39000	9:30	100000
08/22/02	12:00	4000			10:00	84000
08/22/02					10:30	89000
08/22/02					11:00	79000
08/22/02					11:30	84000
08/22/02					12:00	95000

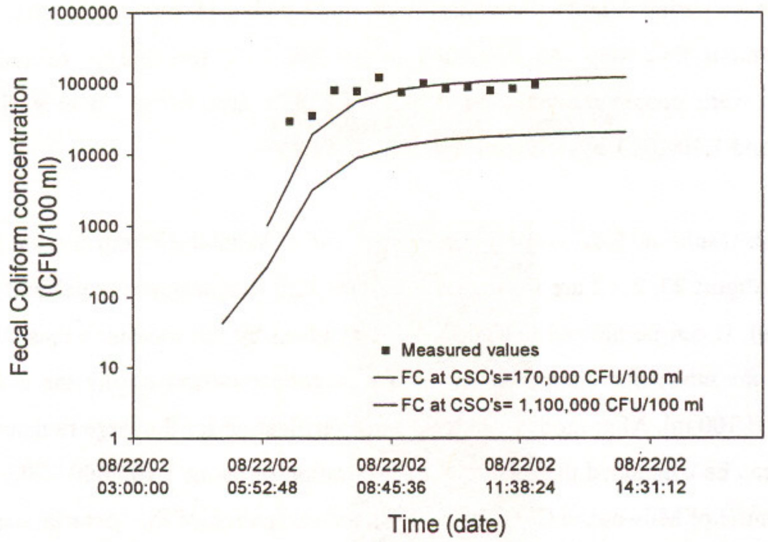

Figure 3.28 Simulated and measured fecal coliform concentrations at the Wilmette Pump Station gate for the storm of August 22, 2002 (Logarithmic scale).

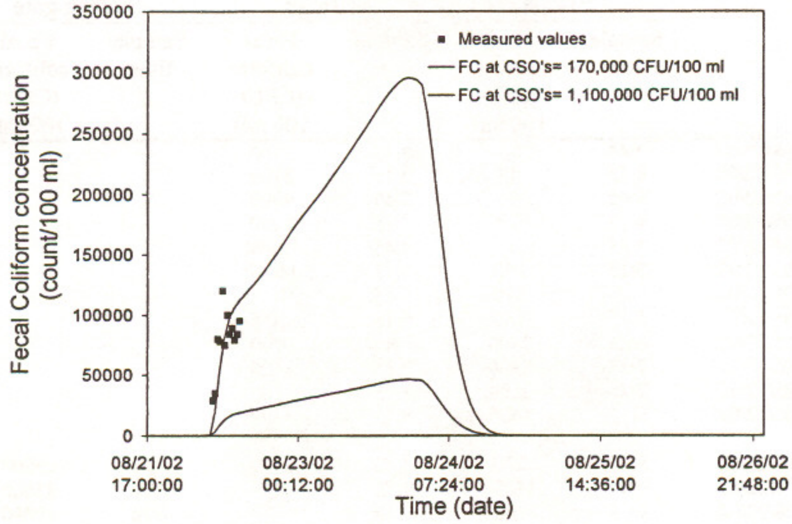

Figure 3.29 Simulated and measured fecal coliform concentrations at the Wilmette Pump Station gate for the storm of August 22, 2002 (Normal scale).

3.12 Application of the calibrated fecal coliform model for evaluating disinfection alternatives

The main goal of developing and calibrating the fecal coliform model for the CWS is its application as a useful tool to evaluate potential disinfection measures to be applied at the WRPs and/or CSOs. The development and evaluation of possible disinfection technologies is carried out by CTE/EACOM in cooperation with Limno-Tech, Inc. (CTE team). After the reasonable calibration and verification of the fecal coliform model, it was used as a tool to assess the impact of the WRPs, CSOs and other pollutant sources, and, to compare management options and/or disinfection measures. Multiple simulation runs were done based on the disinfection scenarios that the CTE team required for evaluating CSOs treatment and WRPs disinfection strategies.

The bacterial removal scenarios that have been suggested by the CTE team and the description of treatment/disinfection measures for each scenario are summarized in Table 3.6. In total, 25 remediation scenarios were considered. For each scenario, the DUFLOW model was run for the six calibration and verification periods mentioned in Section 3.1 (i.e. July 12 to September 15, 2001, September 2 to November 10, 2001, May 5 to September 29, 2002 , September 11 to December 30, 1998, and February 5 to May 24, 1999). An hourly fecal coliform concentration was computed for all the scenarios. In total, about 180 model runs were performed and the fecal coliform simulation results were transmitted to the CTE team for scenario analysis and evaluation.

Table 3.6 Suggested disinfection scenarios and the assumptions made by the CTE team.

Scenario	Disinfection measures at WRPs	Disinfection measures at CSOs
Scenario 1a (baseline a)	No FC removal is considered for the WRPs	CSO FC concentration at 170,000 CFU/100 ml
Scenario 1b (baseline b)	No FC removal is considered for the WRPs	CSO FC concentration at 1,100,000 CFU/100 ml
Scenario 2a	100% FC removal from all WRPs	CSO FC concentration at 170,000 CFU/100 ml
Scenario 2b	100% FC removal from all WRPs	CSO FC concentration at 1,100,000 CFU/100 ml
Scenario 3	100% FC removal from all WRPs	100% FC removal from all CSOs
Scenario 4a	100% FC removal from the NSWRP No FC removal from the other WRPs	CSO FC concentration at 170,000 CFU/100 ml
Scenario 4b	100% FC removal from the NSWRP No FC removal from the other WRPs	CSO FC concentration at 1,100,000 CFU/100 ml
Scenario 5a	100% FC removal from the Stickney WRP No FC removal from the other WRPs	CSO FC concentration at 170,000 CFU/100 ml
Scenario 5b	100% removal of FC from the Stickney WRP No FC removal from the other WRPs	CSO FC concentration at 1,100,000 CFU/100 ml
Scenario 6a	100% FC removal from the Calumet WRP No FC removal from the other WRPs	CSO FC concentration at 170,000 CFU/100 ml
Scenario 6b	100% FC removal from the Calumet WRP No FC removal from the other WRPs	CSO FC concentration at 1,100,000 CFU/100 ml
Scenario 7	No FC removal is considered for the WRPs	100% FC removal from all CSOs
Scenario 8	No FC removal is considered for the WRPs	1-log FC removal from all CSOs
Scenario 9	No FC removal is considered for the WRPs	CSO FC concentration at 1,030 CFU/100 ml
Scenario 10	1.1-log FC removal from the NSWRP and Stickney WRP 1-log FC removal from the Calumet WRP	CSO FC concentration at 170,000 CFU/100 ml
Scenario 11	1.53-log FC removal from the NSWRP and Stickney WRP 1.42-log FC removal from the Calumet WRP	CSO FC concentration at 170,000 CFU/100 ml
Scenario 12	NSWRP and Calumet WRP= 1030 CFU/100 ml; Stickney WRP= 2740 CFU/100 ml	CSO FC concentration at 170,000 CFU/100 ml

Scenario	Disinfection measures at WRPs	Disinfection measures at CSOs
Scenario 13	2-log FC removal from all WRPs	CSO FC concentration at 170,000 CFU/100 ml
Scenario 14	1.1-log FC removal from the NSWRP and Stickney WRP 1-log FC removal from the Calumet WRP	CSO FC concentration at 17,000 CFU/100 ml
Scenario 15	1.53-log FC removal from the NSWRP and Stickney WRP 1.42-log FC removal from the Calumet WRP	CSO FC concentration at 17,000 CFU/100 ml
Scenario 16	NSWRP and Calumet WRP= 1030 CFU/100 ml; Stickney WRP= 2740 CFU/100 ml	CSO FC concentration at 17,000 CFU/100 ml
Scenario 17	2-log FC removal from all WRPs	CSO FC concentration at 17,000 CFU/100 ml
Scenario 18	1.1-log FC removal from the NSWRP and Stickney WRP 1-log FC removal from the Calumet WRP	CSO FC concentration at 1,700 CFU/100 ml
Scenario 19	1.53-log FC removal from the NSWRP and Stickney WRP. 1.42-log FC removal from the Calumet WRP	CSO FC concentration at 1,700 CFU/100 ml
Scenario 20	NSWRP and Calumet WRP= 1030 CFU/100 ml; Stickney WRP= 2740 CFU/100 ml	CSO FC concentration at 1,700 CFU/100 ml
Scenario 21	2-log FC removal from all WRPs	CSO FC concentration at 1,700 CFU/100 ml
Scenario 22	1.1-log FC removal from the NSWRP and Stickney WRP 1-log FC removal from the Calumet WRP	CSO FC concentration at 1,030 CFU/100 ml
Scenario 23	1.53-log FC removal from the NSWRP and Stickney WRP 1.42-log FC removal from the Calumet WRP	CSO FC concentration at 1,030 CFU/100 ml
Scenario 24	NSWRP and Calumet WRP= 1030 FC/100ml; Stickney WRP= 2740 CFU/100 ml;	CSO FC concentration at 1,030 CFU/100 ml
Scenario 25	2-log FC removal from all WRPs	CSO FC concentration at 1,030 CFU/100 ml

Note: WRP = Water Reclamation Plant, CSO = combined sewer overflow, NS = north Side, FC = fecal coliform)

3.13 Model limitations

The DUFLOW model computes a fecal coliform concentration at each of the model nodes, schematization points, and computational points (interpolated cross sections spaced at approximately 500 m (1640 ft) intervals between nodes that were added to improve the numerical solution of the governing flow and water-quality equations) every 15 minutes. However, because of the limitations of the input data and assumptions regarding CSOs, the model cannot reliably estimate the complete trajectory of coliform concentrations throughout the CWS for each time step. If such a trajectory were sought, one would be trying to get higher precision out of the model than is possible given the current configuration of the inputs. In the true CWS there are nearly 200 active CSO locations. In the DUFLOW model these are aggregated into 28 representative locations. The reason for aggregating is to keep the number of inputs manageable (and also to keep from implying higher precision than is possible with the crude estimation of CSO flows and loads used in the model). The governing concept/assumption is that as long as an approximately correct volume of flow and load into the CWS are applied at approximately the right locations and right time the mixing and travel time in the CWS will allow acceptable results to be obtained at downstream monitoring locations. This is an extrapolation of a principle stated by Novotny and Olem (1994, p. 484) "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."

This input precision problem is especially acute in the upper NSC because during storms, the CSOs are the main flow components in the upper NSC. Further downstream the local CSOs are not the dominant flow component and computational instabilities (discussed in detail later) and errors in the location CSO inputs do not have as large an effect on model results. Upstream of the NSWRP, DUFLOW has two CSO inflow points. These represent 21 Tunnel and Reservoir Plan (TARP) drop shaft overflow locations (further there may be more than one CSO per drop shaft drainage area). Therefore, the areal distribution of coliform concentrations upstream of the NSWRP during storms only is a crude approximation as at least 21 overflow points have been aggregated into 2. Thus, in the reach above the NSWRP concentrations at Central Avenue, Oakton Avenue, and Maple Avenue/Wilmette Pump Station boundary are the most reliable. Similar problems can result on the Chicago River main stem where inflows from Lake Michigan are stopped during rainfall events and a single CSO location represents 8 TARP drop shaft overflow locations.

Computational instabilities result because of rapid changes in fecal coliform concentrations resulting from CSOs and the WRPs (particularly the NSWRP). For example, the fecal coliform concentration on the upper NSC upstream of the NSWRP typically are less than or equal to 1,000 CFU/100 ml (see values for Oakton Avenue in Figures 3.6, 3.12, and 3.14) whereas the fecal coliform concentration in the NSWRP effluent is frequently greater than 10,000 CFU/100 ml. This order of magnitude change in concentration from one side to the other of the NSWRP results in computational instabilities and even frequent negative concentrations. Similarly, when CSOs discharge into the upper NSC and the Chicago River main stem more than an order of magnitude change in fecal coliform concentrations can result and cause computational instabilities and negative concentrations such as the blank periods in simulated fecal coliform concentrations at Oakton avenue (Figures 3.6, 3.12, and 3.14) and at Wells Street (Figure 3.11). CSOs elsewhere in the system can result in brief instabilities, but the larger upstream flow tends to dilute the fecal coliform concentrations, and, thus, the change in concentration is not great enough to result in serious computational problems. Many of the negative concentrations were eliminated by switching to a 250 m computational step in a trial run. However, large fluctuations still resulted because of rapid changes in concentration in space. Further, the 250 m computational step resulted in some computational problems at certain times and at certain locations. Thus, reducing the computational space step could not completely eliminate numerical oscillations in the results because of the large, real changes in concentration that take place over short distances in the CWS particularly when CSOs are occurring. Thus, the computational space increment of 500 m was retained in the DUFLOW model.

Finally, it should be clearly stated that the results of this model are most reliable at the points where measured coliform concentrations are available and, thus, at which the model has been thoroughly tested. Other computed concentrations are less reliable particularly in the immediate vicinity of CSOs in portions of the CWS where CSOs compose a large portion of the flow.

The final limitation of the DUFLOW model is with respect to the time step of the output. Concentrations are calculated every 15 minutes and output on a one-hour time step as per the request of the CTE team, however, the hourly results imply greater precision than is possible with the current DUFLOW model input. That is, the coliform input to the model is weekly concentrations (i.e. about four or five measurements a month) at the WRPs, monthly concentrations for tributaries, and assumed average concentrations for the CSOs the timing of which is based on the operational times of the pump stations as opposed to the actual opening times for the CSOs, and, thus, it is not appropriate to worry about the difference between the daily mean concentration (computed from hourly data) and the concentration at a representative time of day (as shown in the figures in this report).

Chapter 4

CONCLUSIONS

Summary and Conclusions

The Use Attainability Analysis (UAA) for the Chicago Area Waterways carried out in 2003 by Camp, Dresser and McKee (CDM) has shown that fecal coliforms and dissolved oxygen problems are concerns at several locations along the Chicago Waterway System (CWS). In order to provide modeling support to the District to evaluate the effect of potential disinfection measures at WRPs and/or CSOs on fecal coliform counts in the CWS, Marquette University suggested including a fecal coliform simulation routine to the DUFLOW water-quality model developed for the CWS.

Since DUFLOW has an open model structure, it was feasible to include a fecal coliform decay process in the EUTROF2 water-quality code of DUFLOW. A simple first-order kinetics decay model that characterizes the dynamics of fecal coliform bacteria in rivers or streams was then successfully implemented in the EUTORF2 code. Due to the limited amount of observed fecal coliform concentration data for the CWS, a reasonable calibration would have been difficult to achieve based on the traditional trial and error method. Therefore, a new concept of parameter estimation was developed in this study and applied in model calibration. With this concept, the fecal coliform decay rate k was estimated for every section of the CWS based on analysis of historical data (1990-2003) between every two consecutive locations and the related travel time between these locations. This new concept parameterizes the fecal coliform decay rate on the basis of many years (14 years in this case) of monthly fecal coliform samples rather than the few monthly samples taken in a typical calibration period.

The fecal coliform model was calibrated to the available measurements at 16 locations along the CWS for the period July 12 to September 15, 2001. The results showed that a successful calibration is achieved with the parameters estimated from historical data. One model run was enough to get a good match between measured and simulated fecal coliform concentrations at almost all locations. Following the calibration process, the model was verified for the periods September 2 to November 10, 2001; May 5 to September 29, 2002; September 11 to December 30, 1998; and February 5 to May 24, 1999. The verification results demonstrated clearly that the model represents quite well the fecal coliform dynamics in the CWS.

During wet weather flow, combined sewer overflows (CSOs) contribute high bacterial loads to the CWS and their impacts are more significant than the impact of bacterial loads coming from the water reclamation plants (WRPs). Since no bacteriological data from the CSOs were available in the study area, fecal coliform input concentrations to the DUFLOW model were estimated based on the analysis of the available data from the Milwaukee Metropolitan Sewerage District (MMSD). The median (170,000 CFU/100 ml) and the 90th percentile (1,100,000 CFU/100 ml) values of the sampling data were considered in this study as representative of fecal coliform concentrations from the pumping stations and CSOs.

In order to check and validate the order of magnitude of bacterial loads during large rainstorms, the fecal coliform model for the CWS was further calibrated and verified during high flow periods when flow reversals to the Lake Michigan occurred. The calibration and verification results demonstrated that the 90th percentile value of Milwaukee CSO fecal coliform concentrations is more appropriate to represent bacterial loads during high flow periods. Moreover, the results obtained confirmed that the variation of fecal coliform concentrations and the peak values during rainstorm events can be well represented by the calibrated DUFLOW model.

The major findings and conclusions of this study can be summarized as follows:

1. A first-order decay model describing the variation of fecal coliform concentrations in rivers was easily implemented in the existing DUFLOW model of the CWS.
2. The calibration of the model to the available observed data was successful at almost all the locations along the CWS.
3. The model verification conducted for different periods confirmed that the model reproduces quite well the fecal coliform bacteria dynamics in the CWS throughout the year.
4. The concept of fecal coliform decay rate estimation from historical data developed in this study appears to be an efficient approach to calibrate the continuous simulation fecal coliform model of the CWS. The calibration concept developed here may be useful for application to other river systems for which continuous-simulation unsteady-flow models are proposed.
5. The 90th percentile value of Milwaukee CSO fecal coliform concentration data can be considered representative to bacterial loads from combined sewer overflows during large rainstorm events.

6. Based on the model calibration and verification results, the fecal coliform model implemented in DUFLOW should be a useful support to the District for evaluating potential disinfection scenarios.

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