# Calibration of a Continuous Simulation Fecal Coliform Model Based on Historical Data Analysis

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**Abstract:** Since 1984, the major water reclamation plants discharging to the Chicago Waterway System (CWS) have not disinfected their effluents. The possible addition of disinfection at these plants is the subject of an ongoing use attainability analysis (UAA). For the UAA, *Escherichia coli* (*E. coli*) is used as the indicator of bacterial contamination. However, only a few years of *E. coli* data are available for the CWS and the treatment plants discharging to the CWS. Thus, it was decided to develop a model based on fecal coliforms for which more data are available and to develop a relation between fecal coliform and *E. coli* counts for the CWS. A 1:1 relation was found between fecal coliform and *E. coli* counts in the CWS by Limnotech (2004, written communication) as part of the UAA. In order to evaluate the effects of possible disinfection measures on fecal coliform and related *E. coli* counts in the CWS, a simple first-order fecal coliform decay model was added to the continuous-simulation flow-water quality model DUFLOW applied to the CWS system. Due to the limited amount (monthly samples) of measured fecal coliform concentration data for the CWS, a reasonable calibration of the model would have been difficult to achieve based on the traditional trial and error method. In this paper, a new concept of model parameter estimation based on historical data analysis and its application to model calibration is presented. The fecal coliform decay rate $k$ was estimated for every reach of the CWS based on analysis of historical data (1990–2003) between each two consecutive sampling locations and the related travel time between these stations. The fecal coliform decay rate then was determined 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 results obtained indicate that the calibration process was successful, and a good match between measured and simulated fecal coliform concentrations at almost all locations along the CWS is achieved with one model run for several multiple month periods in 1998, 1999, 2001, and 2002.

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## Introduction

In July, 1972, the Metropolitan Water Reclamation District of Greater Chicago (District) began chlorination of the effluent at its Water Reclamation Plants (WRPs) in response to the Illinois Pollution Control Board's implementation of a year round bacterial standard. The District then began a detailed study of the effects of chlorination on the water quality and ecology of the Chicago and Calumet River Systems (Fig. 1). They found that regrowth of bacteria was substantial such that concentrations at the outlet of the Chicago Sanitary and Ship Canal in 1974 after chlorination were similar to those in 1966 before chlorination (Lue-Hing et al. 1976). They also argued that at the state permissible level of 1.0 ppm of residual chlorine more than 4.9 metric tons of chlorine and chlorine compounds were discharged to the Chicago Waterway System (CWS) from the three major WRPs resulting in substantial toxicity (Lue-Hing et al. 1976). They further argued that because of the heavy commercial use of the CWS and the fact that individuals generally only have accidental contact with water in the CWS, the justification for disinfection based on contact was nonexistent (Lue-Hing et al. 1976). In 1984, the Illinois Pollution Control Board accepted the District's argument and reclassified the majority of the CWS as "Secondary Contact and Aquatic Life Waters" allowing the District to discontinue disinfection at the major WRPs. Sedita et al. (1987) showed that after disinfection was stopped, the coliform concentrations at the outlet of CWS were nearly the same as during disinfection, but that the number and variety of fish in the CWS had greatly increased.

In 2003, the Illinois Environmental Protection Agency (IEPA), initiated a use attainability analysis (UAA) for the CWS and neighboring streams to determine if higher water-quality standards and improved uses could be achieved in these waters without creating an undue economic burden [for details on the UAA process, see Novotny et al. (1997)]. In the CWS, the main sources of bacteria during dry weather flow are the Calumet, North Side, and Stickney WRPs (Fig. 2). However, during wet weather flow, bacteria resulting from a large number of combined sewer overflows (CSOs) in the CWS drainage area overshadow the bacteria from the three WRPs. For mitigation of excessive fecal coliform levels in the CWS, the IEPA has requested that the District evaluate disinfection measures at the three major WRPs. Depending on the technology chosen (ultraviolet or ozone disinfection), the cost of installing disinfection at the three plants has been estimated to

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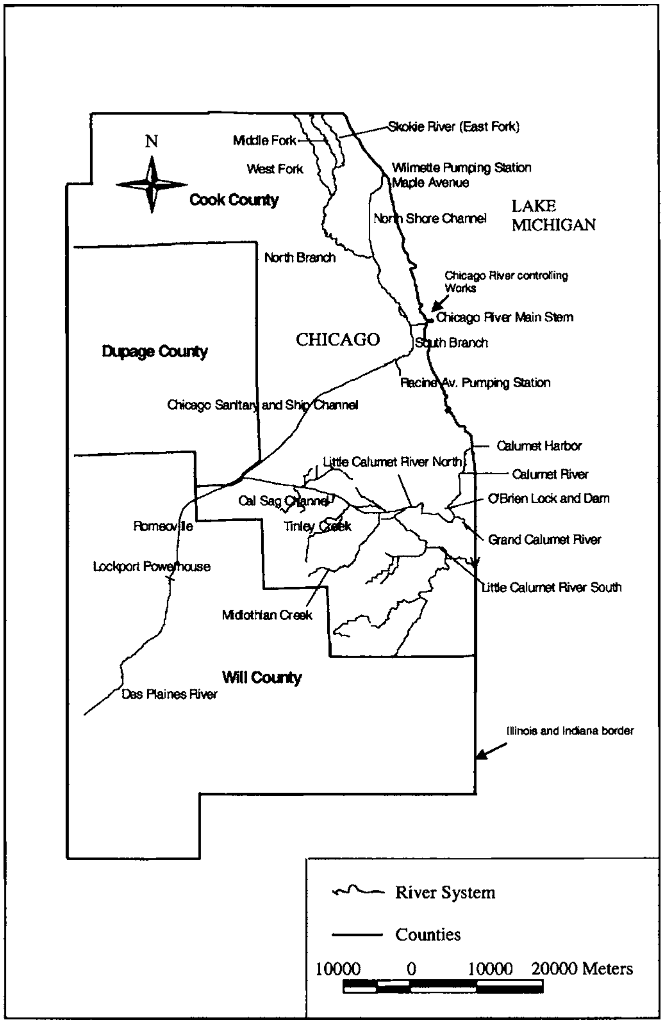

**Fig. 1.** Calumet and Chicago River Systems

be between $1.56 and 1.86 billion (U.S. dollars) with annual operating costs of $30–44 million.

Given that such large expenditures may be needed, the District wished to analyze the fecal coliform concentrations in the CWS using a model that was capable of simulating the effects of the substantial CSO loads to the CWS. The DUFLOW (2002) model developed in The Netherlands by the combined efforts of the Rijkswaterstaat (National Water Authority), International Institute for Hydraulic and Environmental Engineering of the Delft University of Technology, STOWA (Foundation for Applied Water Management Research), and the Agricultural University of Wageningen had already been applied for simulation of water quality in the CWS during unsteady flow conditions by Marquette University (Shrestha and Melching 2003; Alp and Melching 2004). A fecal coliform simulation routine was added to the DUFLOW water-quality model of the CWS so that disinfection or other fecal coliform reduction alternatives could be evaluated.

Monthly grab samples were available to calibrate the model at several locations along the CWS and its tributaries. A new concept of model parameter estimation was developed in this study and applied in the model calibration process. This paper presents a procedure for the estimation of the fecal coliform decay rate for each of the river sections based on historical data analysis and the application of the estimated parameters in model calibration and verification.

## Fecal Coliform Modeling

After discharge to a water body, fecal coliform decay/loss is dominated by several factors such as sunlight, temperature, salinity, sedimentation, resuspension, predation, aftergrowth, etc. A broad review of these factors can be found in Bowie et al. (1985) and Crane and Moore (1986). Wilkinson et al. (1995) demonstrated that bed sediments also may be a significant source of fecal coliforms during storm periods.

Crane and Moore (1986) reviewed several models that had been proposed to simulate fecal coliform concentrations in stream flow. They noted that Mancini (1978) made an interesting effort to integrate the data found in other studies into a model that directly accounted for the effects of temperature, solar radiation, and salinity. Mancini's (1978) model generally is considered the most complete model of the fecal coliform decay/loss process (Thomann and Mueller 1987, p. 237), and it is given as follows:

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

where $P_{\mathrm{SW}}$=percent seawater (%); $T$=temperature (°C); $\alpha$=proportionality constant; $I_0(t)$=surface solar radiation (cal/cm$^2$ h); $H$=water depth (m); $K_e$=vertical light extinction coefficient (1/m), $F_p$=fraction of the bacteria attached to particles; and $v_s$=settling velocity of particulate bacterial forms (m/day). When detailed data are available to parametrize this model and to define the fecal coliform loads to the water body, this model may be used very effectively as shown by Connolly et al. (1999) in the simulation of pathogens in Mamala Bay, Hawaii.

In many modeling cases, the use of a 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 is impractical. Generally, a simple first-order kinetics decay model is used to characterize the change of the coliform population in rivers or streams (Chick 1908)

$$C_t=C_0e^{-kt} \tag{2}$$

where $C_t$=concentration of fecal coliforms at time $t$ (CFU/100 ml); $C_0$=initial concentration of fecal coliforms at the outfall (CFU/100 ml); $k$=decay rate (die-off) coefficient (1/day); and $t$=exposure time (day). In this simple model, the overall net loss rate $k$ is used as a measure of bacterial kinetics. Some researchers (e.g., Auer and Niehaus 1993) have divided $k$ into component parts of the death rate in the dark (which includes the effects of temperature, salinity, and predation), death rate due to solar radiation, and loss rate due to sedimentation. Because these factors may change with time use of a constant $k$ in continuous modeling may result in problems. However, Elshorbagy and Ormsbee (2006) successfully simulated fecal coliform concentrations in streams draining rural watersheds in southeastern Kentucky using a constant $k$ value throughout the simulation period.

For a variety of situations, the simple exponential decay of fecal coliforms (i.e., the first-order model) is a good representation of real data. Crane and Moore (1986) stated that the first-order model is appropriate for an environment that is totally unsuited to the indicator bacteria and decay is constant with time. On the basis of their literature review, they noted that the first-order model appears to accurately describe the decay of bacteria under all conditions; however, the decay rate coefficient is a highly variable parameter spanning several orders of magnitude for any given bacterial type. This highlights the need to use site-

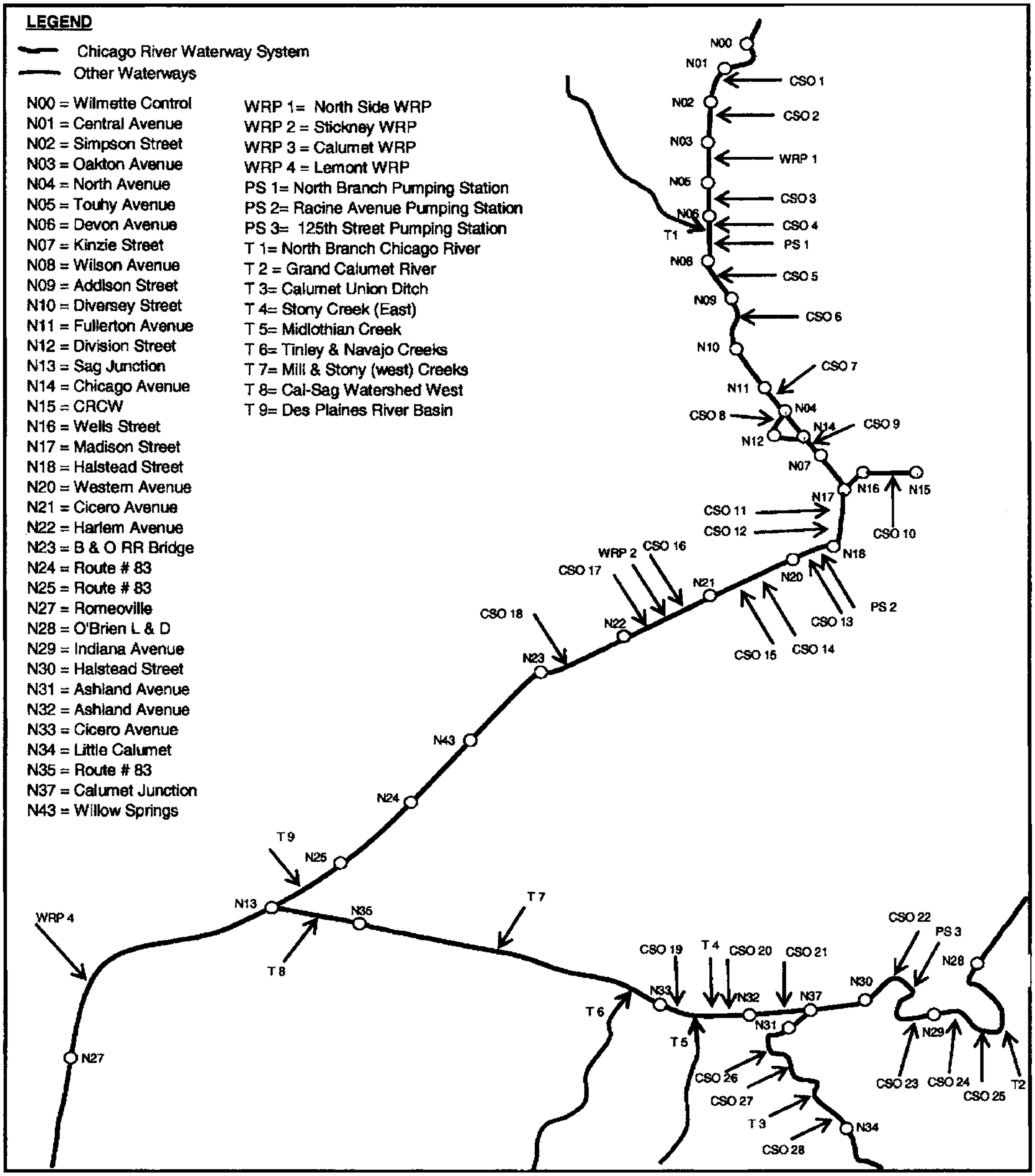

**Fig. 2.** Schematic of the DUFLOW model network of the Chicago Waterway System and model input from different sources of fecal coliform: WRP=water reclamation plant; CSO=representative combined sewer overflow location; PS=CSO pumping station; T=tributaries; and N=model nodes

specific data to estimate the decay rate *k*. Finally, Crane and Moore (1986) noted that in many of the investigations reviewed, bacterial decay was not complete and residual populations at low levels were observed for time periods much longer than would be determined by use of a first-order model. Thus, the first-order model may only be appropriate for shorter travel times (residence times), and computational models applying the first-order approach should include several reaches so that the decrease in *k* farther downstream from point loads (Thomann and Mueller 1987, p. 239–241) can be properly accounted for.

### Implementation of Fecal Coliform Process Simulation in the DUFLOW Model

In the computation of flow hydraulics, the DUFLOW (2002) model solves the full de Saint Venant equations of motion for unsteady flow (see, e.g., Sturm 2001, p. 269–274). This hydraulic model can be directly coupled with one of two predefined water-quality models: EUTROF1 and EUTROF2. EUTROF1 is 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. In EUTROF2 three algal species are included and interactions between the sediment and the overlying water column are taken into consideration while other water-quality kinetics are simulated in a similar way as in EUTROF1. Because the hydraulic and water-quality models are directly coupled DUFLOW offers computational advantages over the versions of WASP available when this project started in 2000. DUFLOW has been applied with great success to several European river systems (e.g., Manache and Melching 2004). In the study of Manache and Melching (2004), DUFLOW was found to be computationally robust with few computational failures encountered over thousands of runs. DUFLOW is compatible with geographical information systems, which facilitate representation and display of the river system. It is compatible with Microsoft Windows and data can be imported easily from and output can be exported easily to Microsoft Excel, and it also has a versatile graphical user interface for displaying output and processing input. Finally, it has a relatively low license cost. Given these capabilities and advantages, DUFLOW was selected for modeling the CWS.

The EUTROF2 was selected for water-quality simulation in the CWS, but it does not include a fecal coliform decay process. However, taking into account that DUFLOW has an open model structure that allows modelers to include any water-process description, it was feasible to add a fecal coliform routine to EUTROF2. The first-order decay model expressed by Eq. (2) is used to describe the die-off of fecal coliforms in the CWS. As noted previously, regrowth of fecal coliforms was found to be a problem in the CWS during the period when the WRP effluents were chlorinated (Lue-Hing et al. 1976). However, regrowth was not considered in the simulation of fecal coliform concentrations for future proposed disinfection scenarios in order to isolate the effect of CSO discharges on the ability to meet enhanced use standards in the CWS. Historical data on regrowth in the CWS could be evaluated, and a regrowth function added to DUFLOW if desired by the District, IEPA, or the Stakeholder Advisory Committee for the UAA.

In this project, DUFLOW was run with the following computational setup:

- Hydraulic calculation time step: 15 min;
- Fecal coliform calculation time step: 15 min; and
- Model output (i.e., fecal coliform concentration): 1/day.

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

## Calibration of Process-Based Fecal Coliform Models

Use of process-based, continuous-simulation models is highly data intensive requiring continuous time series of flows or stages and water-quality constituent concentrations at the boundaries and for all tributaries (streams, CSOs, etc.) and diffuse lateral loads. Preparation of these data including compilation, quality assurance, filling in missing records, and estimation of ungauged flows is very time consuming. Thus, it is common practice to select a reference period of a typical year for model application, see, for example, Melching and Bauwens (2001) and Manache and Melching (2004) for applications of such models to simulation of dissolved oxygen in streams and Connolly et al. (1999) for an application of coupled hydrodynamic and fecal coliform models for simulation of coastal waters. In the example reported here, five 2–4 month periods concentrated in the recreational season (April to early November) were considered.

During a typical year, only nine or ten monthly fecal coliform samples may have been collected and analyzed because samples are not collected in winter months. Thus, traditional calibration wherein $k$ is adjusted for each reach to obtain a good match between the simulated and measured concentration values would be based on a very small set of measurements, and, thus, be a poor basis on which to make multimillion dollar decisions. Thus, an alternative approach for calibration, i.e., determination of $k$, is needed. One alternative approach is to measure $k$ in the laboratory using mixtures of water and wastewater from the area of interest (e.g., Auer and Niehaus 1993). This approach yielded good results in the simulation of fecal coliform concentrations in Onondaga Lake near Syracuse, N.Y. (Canale et al. 1993). However, the laboratory analysis associated with this approach can be costly and time consuming, and the accuracy of this approach is limited by how well the laboratory conditions reflect actual field conditions in the water body of interest.

The new concept of calibration proposed here determines the fecal coliform decay rate on the basis of many years of historical monthly fecal coliform samples rather than the limited number of monthly samples collected in the typical calibration period to which process-based, continuous-simulation models are commonly applied. The application of this approach relies on careful evaluation of the historical data for representative flow and loading conditions as described in the case study. This approach also relies on detailed simulation of travel times in the study water courses.

### 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 reaches of a river system. If the in-stream samples were taken on the same day at sites located on a particular reach of the river system (as is common field practice), the variation in fecal coliform concentration between two successive locations should reasonably follow the first-order decay model expressed by Eq. (2) (i.e., $C_t = C_0 e^{-kt}$). In this equation, $C_t$ and $C_0$ represent the concentration of fecal coliforms at the downstream and upstream locations, respectively.

Frequency analysis of the historical fecal coliform data then may be done for each pair of successive sampling sites on the study river. A graphical representation of this analysis is shown in Fig. 3 for some of the sampling sites included in the case study. As can be seen from Fig. 3, a nearly constant decrease in fecal coliform concentration indicated by the nearly parallel frequency curves between upstream and downstream sampling locations is apparent from Touhy Avenue to Wilson Avenue to Diversey Avenue to Madison Street (Fig. 3).

In order to derive $k$ between two successive locations from Eq. (1), the travel time should first be identified. This may be done with a hydraulic model such as DUFLOW. A slight modification of the DUFLOW code was made to compute travel time and include it as an explicit model output. DUFLOW computes the flow discharge, water–surface elevation, and velocity for each computational node (spaced no more than 500 m apart in the case study) for each computational time (15 min in the case study) on the basis of boundary conditions and tributary inflows using the full de Saint Venant equations. The travel time for each computational element is then estimated as the distance between two computational nodes divided by the mean of the velocities at these nodes. The travel time between every two consecutive lo-

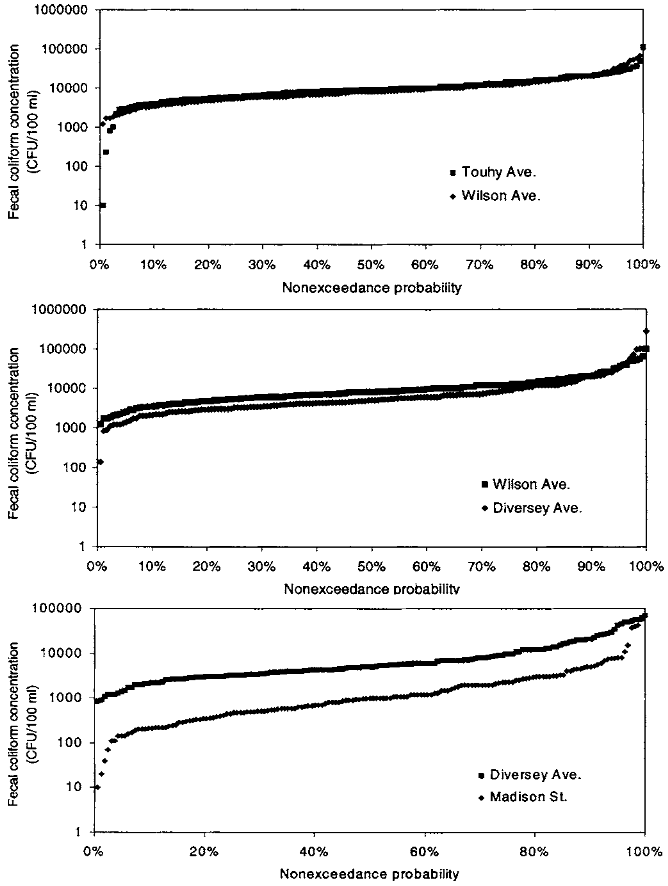

**Fig. 3.** Nonexceedence probability distribution of fecal coliform concentrations at Touhy Avenue, Wilson Avenue, Diversey Avenue, Madison Street on the North Shore Channel, North Branch Chicago River, and South Branch Chicago River for 1990–2003

cations is summed from intervening computational elements. In the case study, the mean travel time was computed based on the model run for the period July 12 to September 15, 2001. A mean and median value of the fecal coliform decay rate *k* was computed for every section by reorganizing Eq. (2) as follows:

$$k = \frac{\ln\left(\dfrac{C_0}{C_t}\right)}{t} \tag{3}$$

where $C_t$ and $C_0$=fecal coliform concentrations having the same probability of exceedance (quantile) at the downstream and upstream locations (CFU/100 ml); and $t$=mean travel time between upstream and downstream locations (day). This is done for many selected quantiles, and the computed mean and median decay rate values are found. In the case study, similar mean decay rate values were obtained when Eq. (3) was applied on the paired data of fecal coliform concentrations collected at two successive samplings on the same date.

## Case Study

### Description of the Chicago Waterway System

The CWS consists of 123 km of canals and rivers where 62% of the total length are man-made canals. The Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag (Cal-Sag) Channel, North Shore Channel, North Branch Chicago River downstream from the North Shore Channel, South Branch Chicago River, Chicago River Main Stem, and Little Calumet River (north and south) are constituent parts of the CWS (Fig. 1). The upper reaches of the CWS are generally much narrower and shallower than the lower reaches. Much of the CWS from the North Shore Channel in Wilmette to Lockport and eastward through the Cal-Sag Channel to the Calumet Harbor has been dredged and is maintained for commercial navigation and urban drainage. Treated municipal and industrial wastewater, stormwater, diverted Lake Michigan water, and CSOs are conveyed by the CWS.

In the CWS, the major sources of fecal coliform during dry weather are the Calumet, North Side, and Stickney WRPs. However, during wet weather, the CWS receives substantial fecal coliform loads from three CSO pumping stations—Racine Avenue, North Branch, and 125th Street—in addition to the loads from nearly 200 CSO outfalls from the CWS drainage area (see Fig. 2).

### Application of the DUFLOW Model to the CWS

The DUFLOW model (DUFLOW, 2002) was used to represent flow and water quality in the CWS. 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 tributaries, four WRPs, pumping stations, and CSOs, are given at the model nodes and schematization points. In the DUFLOW model, the nearly 200 CSO outfalls were represented by 28 discharge points (Alp and Melching 2004) as shown in Fig. 2.

The fecal coliform concentration in the WRP effluents was available for a single sample on a weekly basis (i.e., about four or five measurements a month). Linear interpolation in time between these measurements was applied in the DUFLOW model to estimate coliform concentrations from the WRPs for each 15 min computational time point. The 15 min time step is necessary to simulate unsteady flow in the CWS and is supported by 15 min flow and/or stage values at the boundaries and tributaries and hourly flows at the WRPs and CSO pumping stations.

Since no bacteriological data on discharges from CSOs were available for the study area, fecal coliform input concentrations to the DUFLOW model were estimated. The median value of the sampling data available for CSOs in Milwaukee for the period of 2001–2004 is considered as representative of fecal coliform concentrations at the pumping stations and CSOs because both Milwaukee and Chicago have deep tunnel systems to intercept and treat the first flush of storm runoff pollutants from combined sewers. 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.

Unlike other studies where relations between flow and coliform loads have been found for some rivers (e.g., Elshorbagy et al. 2005), no relations between flow and coliform concentrations were found for the tributaries to the CWS. Thus, for the gauged tributaries—North Branch Chicago River, Little Calumet River, and Grand Calumet River—historical monthly fecal coliform concentrations were used as input with 15 min values linearly interpolated in time between the adjacent monthly mea-

**Table 1.** 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 and North Branch Chicago River | Diversey Parkway | Touhy Avenue | 98 |
| | | Central Avenue | 84 |
| | | Oakton Street | 100 |
| | | Wilson Avenue | 99 |
| South Branch and Chicago Sanitary and Ship Canal | Cicero Avenue | Madison Street | 100 |
| | | Western Avenue | 100 |
| | | Harlem Avenue | 100 |
| | | Route 83 | 100 |
| Little Calumet River and Cal-Sag Channel | Cicero Avenue | Halsted Street | 99 |
| | | Ashland Avenue (Calumet) | 100 |
| | | Indiana Avenue | 100 |
| | | Route 83 | 100 |
| | | Ashland Avenue (Cal-Sag) | 99 |

surements. For ungauged tributaries, fecal coliform concentration data were estimated based on data analysis of Chicago area streams that are not affected by WRPs or CSOs. Monthly median values of fecal coliform concentration for one representative stream (Thorn Creek, which is a tributary to the Little Calumet River) were applied to each 15 min value for all ungauged tributaries. A schematic representation of the DUFLOW model network of the CWS and model input from different sources is shown in Fig. 2.

On the basis of the foregoing assumptions, for the period of July 18–September 18, 2001, the WRPs contributed about 34% of the fecal coliform loads, the CSOs (including the pump stations) contributed about 65%, and the other tributaries contributed about 1%. This was a relatively wet period. So, it is expected that the CSOs contribute up to twice as much fecal coliforms as do the WRPs.

## Calibration and Verification of the Fecal Coliform Model

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 of 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 of July 12–November 10, 2001 and May 5–September 29, 2002. After model calibration to the available bacterial data for the period of July 12–September 15, 2001, the model is verified for the periods of September 11–December 30, 1998; February 5 to May 24, 1999; September 2–November 10, 2001; and May 5–September 29, 2002.

### *Available Fecal Coliform Data for Model Calibration*

Monthly fecal coliform data for the CWS and other rivers in the region are available for the period of 1990–2003, which is representative of current and future loading to the CWS. These data were provided by the District for 16 sites within the CWS that were used 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 in Fig. 2), and for the major tributaries to the CWS.

The measurements at the 16 sampling sites included in the DUFLOW model were used for model calibration and verification. 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 CSSC, 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 CWS section is listed in Table 1. 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 as those taken at Diversey Avenue. Similar results can be seen in Table 1 for the other CWS sections.

### *Flow Data Analysis*

A suitable representation of the river daily 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 Powerhouse Forebay where weekly data were available, it was necessary to examine whether the flows during the days of fecal coliform bacteria sampling are representative of the flow regime of the CWS.

Based on the historical daily flows available for the North Branch Chicago River at Albany Avenue, 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., Albany Avenue, Wentworth Avenue, and Lockport Powerhouse Forebay, respectively). An example of the flow–duration curves derived is shown for the North Branch Chicago River at Albany Avenue in Fig. 4. A good match is obtained between the flow–duration curves representing all

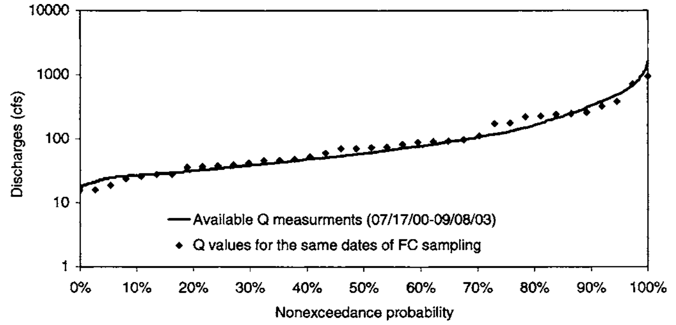

**Fig. 4.** Flow duration curve for the North Branch Chicago River at Albany Avenue [All daily flows versus daily flows measured on the dates of fecal coliform (FC) sampling]

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 sampling.

### 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 of July 12–September 15, 2001. In this study, the determination of the best $k$ values for practical modeling (model calibration) was done in three steps. In the first step, a model run was done with a typical bacteria decay rate of $k=0.8$ as reported in the literature (Thomann and Mueller 1987, p. 235). This value was considered for all the river sections. In the second step, model runs were performed with the mean and median computed decay rates for each river section (i.e., Columns 5 and 6 of Table 2). These simulations detected several reaches where the $k$ value determined on the basis of the historical data did not work well. The third step involved estimating reasonable $k$ values for the reaches where the $k$ value determined from historic data did not work well. The reasons why the historic data did not work well and the rationale for the estimated values are given as follows.

1. The flow in the reach upstream of the North Side WRP (Central Avenue to Oakton Street) is generally very small ($\approx 0.6\ \mathrm{m}^3/\mathrm{s}$) and the water–surface slope throughout the system is very low, thus, flow from the North Side WRP frequently backs up into the upper North Shore Channel causing the nominal definitions of upstream and downstream and the mean travel time to be meaningless in this reach. Thus, the computed decay rate values were replaced by the literature value ($k=0.8$) for this reach.
2. The reaches between Indiana Avenue and Halsted Street on the Little Calumet River, Oakton Street and Touhy Avenue on the North Shore Channel, and Cicero Avenue and Harlem Avenue on the CSSC receive effluent from the Calumet, North Side, and Stickney WRPs, respectively. Thus, the change in fecal coliform concentrations from the upstream to the downstream stations is dominated by the effluent not the decay process. The first two reaches also were affected by the same boundary effect as the Central Avenue to Oakton Street reach, and, thus, the computed decay rate values were replaced by the literature value ($k=0.8$) for these reaches. The value determined for the preceding reach was selected for the Cicero Avenue–Harlem Avenue reach (i.e., $k=0.2$).
3. Sampling only took place at Western Avenue from 2001 to 2002 and at Oakton Avenue from 2001 to 2003. Thus, at these sites only 22 and 35 historical fecal coliform samples were available, whereas at all other sites listed in Table 2 136–172 historical samples were available. Thus, it comes as no surprise that the computed $k$ value worked poorly in the reaches between Madison Street and Western Avenue and Western Avenue and Cicero Avenue. For the reach between Madison Street and Western Avenue, the $k$ value from the upstream reach (=1.6) was used rather than the computed mean of 0.98. 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. This illustrates the potential problems in the conventional calibration approach of fitting the model to the monthly measurements available in only one or two "typical" years.

For all other reaches, the estimated value was the rounded off value of the computed mean $k$. For six of the seven reaches where

**Table 2.** Estimated Decay Rate for Fecal Coliforms Based on Historical Data Analysis

| | | | | Computed decay rate | | |
|---|---|---|---|---|---|---|
| Sampling site (upstream) | Sampling site (downstream) | Waterway | Travel time | 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 Parkway | North Branch | 0.25 | 1.60 | 1.60 | 1.6 |
| Diversey Parkway | 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 Avenue | 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 Calumet | 1.46 | −2.50 | −2.60 | 0.8 |
| Halsted Street | Ashland Avenue | Cal-Sag | 1.72 | 0.10 | 0.06 | 0.1 |
| Ashland Avenue | 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 |

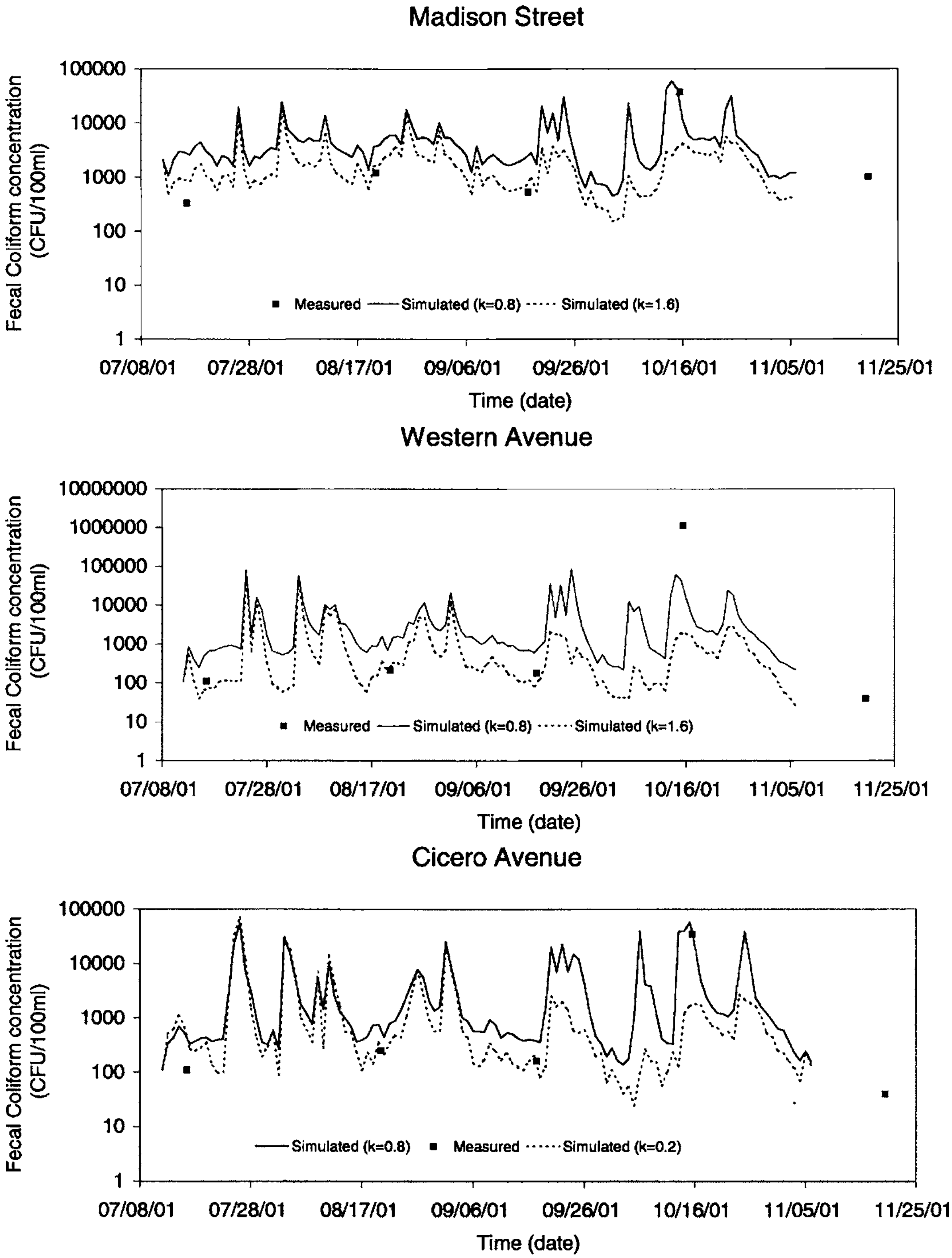

**Fig. 5.** Simulated and measured fecal coliform concentrations for the period July 12 to November 10, 2001, for three locations along the South Branch Chicago River and Chicago Sanitary and Ship Canal: Madison Street, Western Avenue, and Cicero Avenue (note: simulated curves have been extended beyond the end of the calibration period, i.e., September 15, 2001, to facilitate comparison of the simulated and measured values)

the rounded value of the computed mean *k* value was used in the final model, the difference between the mean and median *k* value is small, indicating that the statistical bias in the proposed approach was small.

Fig. 5 represents the calibration results obtained from the first and final model runs at three locations on the CWS: Madison Street, Western Avenue, and Cicero Avenue (CSSC). As can be seen from Fig. 5, the use of the estimated decay rate values based on historical data analysis allows a good match between measured and simulated fecal coliform concentrations to be obtained. Similar results were obtained for the remaining 13 locations with one model run as detailed in Manache and Melching (2005). It should be noted that the selection of the *k* value had little effect on the peak fecal coliform concentrations simulated throughout the CWS in response to CSO events as shown for all locations in Fig. 5. Thus, it is clear that storm loads overwhelm the effects of bacterial decay immediately after CSO events.

A statistical analysis of the comparison between simulated and measured concentrations is not presented because even compiling the six periods run in the model calibration and verification com-

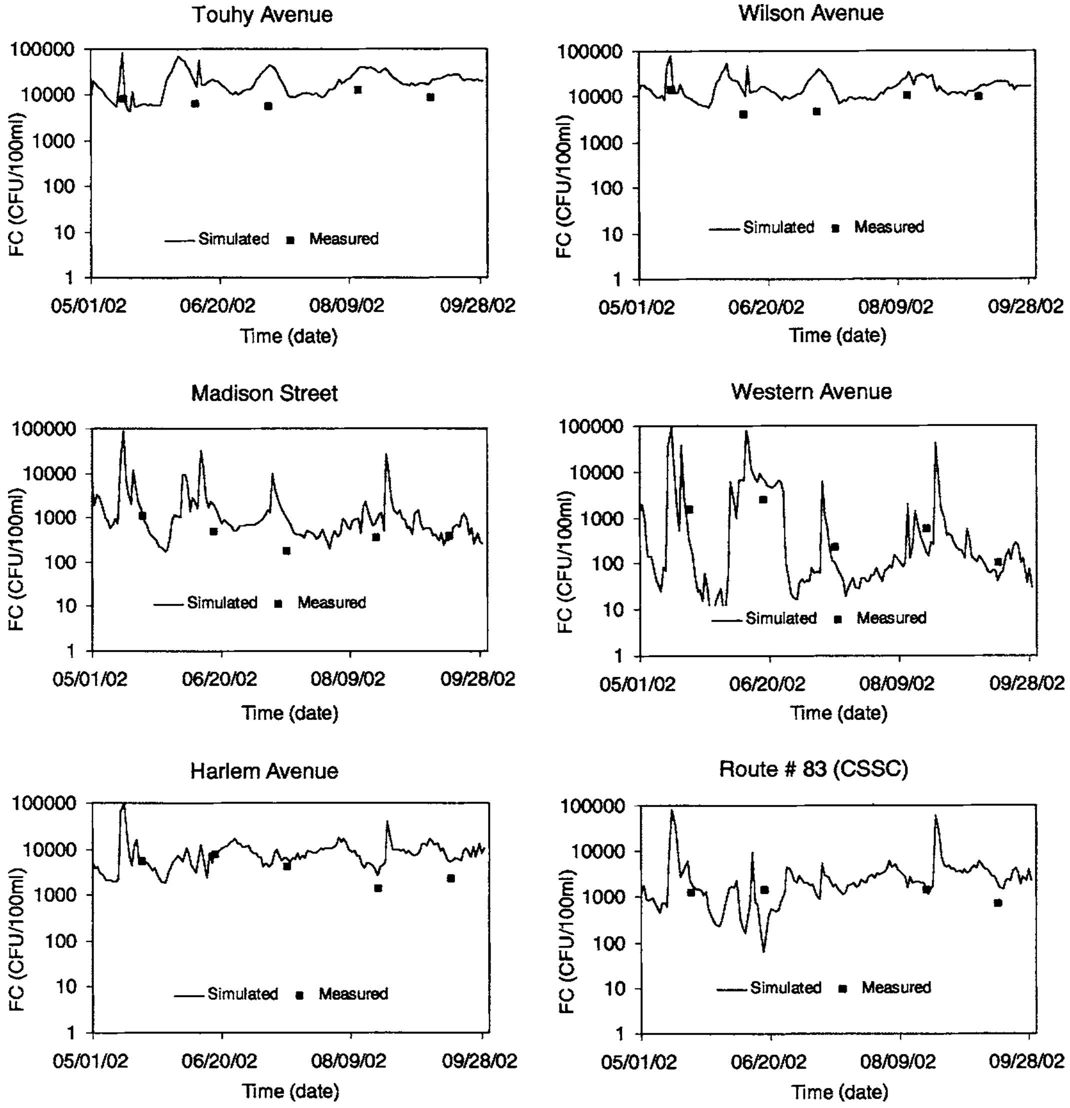

**Fig. 6.** Simulated and measured fecal coliform concentrations for the period May 1 to September 29, 2002, for various locations along the North Shore Channel, North Branch Chicago River, South Branch Chicago River, and Chicago Sanitary and Ship Canal (CSSC) (note: FC=fecal coliform concentration)

parison of measured and simulated concentrations can only be done for at most 16 dates. With such a small sample size, it is difficult to compute meaningful statistics because even one day of poor agreement between measured and simulated values can distort an overall fit statistic, such as the coefficient of model-fit efficiency (Nash and Sutcliffe 1970). For example, the model achieved model-fit efficiencies near 95% at Route 83 on the CSSC and Madison Street on the South Branch Chicago River, indicating excellent performance by the model, but at other locations the model had large negative efficiencies primarily resulting from one or two bad days whose influence could not be negated because of the small sample size. Poor model performance on a few days may be a function of the use of weekly measurements of fecal coliform concentrations in the WRP effluent. Thus, with such a small sample for consideration visual comparison of simulated and measured concentrations is the only reliable way to evaluate the model. Canale et al. (1993) also used only visual comparisons to evaluate the quality of their fecal coliform model of Onondaga Lake. They noted that a statistical approach to evaluating the goodness of model fit serves poorly in their study because of the inherent uncertainty in the measurement of fecal coliform concentrations.

### Verification of the Fecal Coliform Model

After model calibration to the available bacterial data for the period of July 12–September 15, 2001, the model was verified for the periods of September 11–December 30, 1998; February 5–May 24, 1999; September 2–November 11, 2001; and May 5–September 29, 2002. Model verification results for the May 5–September 29, 2002, period at various locations along the North Shore Channel, North Branch Chicago River, South Branch Chicago River, and CSSC are illustrated in Fig. 6. Fig. 6 clearly demonstrates that a good match between simulated and measured fecal coliform concentrations is present at almost all sites. Similar results were obtained for the remaining sampling sites included in the DUFLOW model and the other verification periods (Manache and Melching 2005), but are not included here due to space limitations.

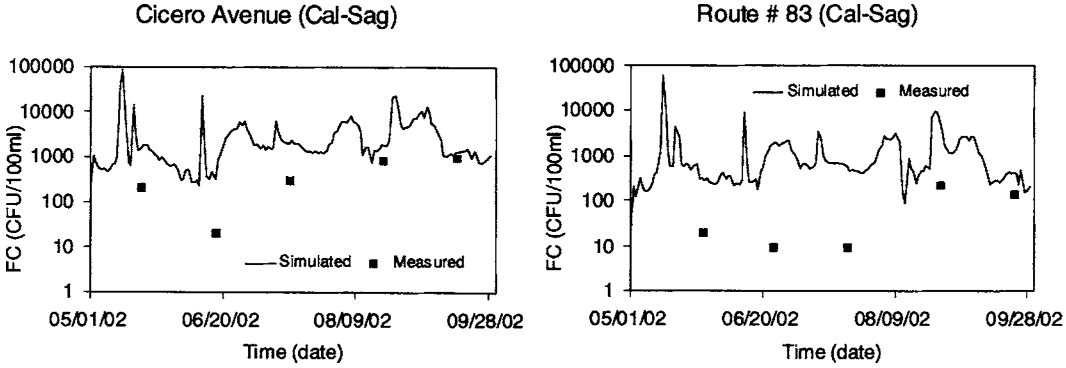

**Fig. 7.** Simulated and measured fecal coliform concentrations for the period May 1 to September 29, 2002, for Cicero Avenue and Route 83 on the Calumet-Sag Channel

## Limitations of the Proposed Approach

Whereas the proposed approach of using long-term historic data to parametrize a process-based, continuous-simulation model worked in this case, a number of potential limitations in the approach were encountered that may require further study in other cases. These limitations are discussed in this section.

The first limitation of any modeling approach is that the data selected for the calibration and verification of a water-quality model must be representative of the flows, loads, and other conditions likely to occur in the future periods of interest in the modeling. This is especially important for the approach proposed here because long-term water-quality data are used to determine *k*. In the case study, data from 1990 onward were selected because by this time the Chicago Deep Tunnel system intercepting CSOs to the CWS was basically complete (the full deep tunnel system was completed in 2006, but the tunnels completed between 1990 and 2006 primarily were outside of the model domain).

In this case, use of a single *k* value for each reach resulted in adequate results for all time periods. As noted earlier, this is not unique, as Elshorbagy and Ormsbee (2006) also found the use of a single *k* value gave adequate results for streams in southeastern Kentucky. However, the decay rate is a function of temperature and solar radiation, which vary throughout the year. Thus, one might expect a seasonal *k* value to yield better results. Conversely, in their laboratory experiments to estimate the total decay rate as the sum of the dark decay rate (including the effects of temperature, salinity, and predation), solar radiation decay rate, and loss due to settling, Auer and Niehaus (1993) could not find a consistent relation between the dark decay rate and temperature. They reviewed the literature on temperature effects and concluded: “it is difficult to justify the application of a temperature adjustment function.” In summary, it is suggested that the use of a single decay rate be attempted, and if this is not adequate, the historic data should be subdivided into seasons and the proposed approach can be applied to determine seasonal *k* values.

Because the estimated *k* value used in the modeling is focused on the central tendency of the computed *k* values, the model will not perform well for extreme conditions. This is illustrated for the simulation of the fecal coliform concentrations at downstream locations on the Calumet-Sag Channel (i.e., Cicero Avenue and Route 83) in the summer of 2002 shown in Fig. 7. In the summer of 2002, extraordinarily low values of 20, 9, and 9 CFU/100 mL were recorded for May, June, and July, respectively, at Route 83, whereas for these same months the median concentrations for 1990–2003 were 360, 195, and 110 CFU/100 mL, respectively. The summer of 2002 was extraordinarily dry and hot and it is speculated that high temperatures and improved water clarity (due to the absence of storm loads) resulted in unusually high die-off of fecal coliforms. A model calibrated for “mean” conditions cannot simulate such behavior. If such behavior were common for all summers, seasonally derived *k* values should be developed and applied. However, since 2002 was an unusual summer the inability to match the measured concentrations in the lower Calumet-Sag Channel for this year does not detract from the use of this model for evaluation of fecal coliform management strategies because the District cannot rely on unusually high die-off to eliminate bacteria problems in the CWS.

Another limitation of the proposed approach as applied in the case study is that the verification periods were included in the period of historic data used to derive the *k* values. Therefore, the verification is not fully independent of the derivation of the *k* values used. However, it should be noted that fecal coliform measurements were available on only 16 dates during the calibration and verification periods, whereas most of the *k* values were derived on the basis of 136–172 fecal coliform measurements. Thus, the bias in the verification should be fairly small. If possible, modelers should try to avoid such biases, but given that the available representative data generally are sparse similar approaches may be necessary in other cases.

## Conclusions

Since 1984 the major water reclamation plants discharging to the Chicago Waterway System have not disinfected their effluents. The possible addition of disinfection at these plants is the subject of an on-going use attainability analysis. A simple first-order kinetics decay model that characterizes the dynamics of fecal coliform bacteria in rivers was implemented in the DUFLOW model applied to the CWS to support the use attainability analysis. Due to the limited amount (monthly values) of measured fecal coliform concentration data for the CWS, a reasonable calibration would have been difficult to achieve based on the traditional trial and error method for the typical, short calibration and verification periods (1–2 years). Therefore, the fecal coliform decay rate *k* was estimated for every section of the CWS based on historical data (1990–2003) analysis between every two consecutive sampling locations and the related travel time between these stations. This new concept parametrizes 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 major findings and conclusions of this study can be summarized as follows:

1. The calibration of the model to the available measured data was satisfactory at almost all the locations along the river system.
2. The model verification conducted for different periods confirmed that the model reasonably reproduces the fecal coliform bacteria dynamics in the CWS throughout the year. Although at some times and locations, order of magnitude differences between simulated and measured fecal coliform concentrations were obtained.
3. 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 applied here may be useful for application to other river systems for which continuous-simulation unsteady-flow models are proposed. Although for other cases, it may be necessary to develop a seasonal approach to the analysis of the historical data.
4. Based on the model calibration and verification results, the fecal coliform model implemented in DUFLOW should be a useful support tool for the District for evaluating potential disinfection scenarios.

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