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Ohio Water Development Authority
City of Akron
Northeast Ohio Regional Sewer District
Cuyahoga River Community Planning Organization
County of Summit, Ohio

# Effects of Hydrologic, Biological, and Environmental Processes on Sources and Concentrations of Fecal Bacteria in the Cuyahoga River, with Implications for Management of Recreational Waters in Summit and Cuyahoga Counties, Ohio

Water-Resources Investigations Report 98-4089

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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, Acting Director



For additional information write to:

District Chief
U.S. Geological Survey
975 West Third Avenue
Columbus, Ohio 43212-3192

Copies of this report can be purchased from:

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Box 25286, Building 810
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1998

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## CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| pound (lb) | 0.45359 | kilogram |
| mile (mi) | 1.609 | kilometer |
| square foot ($ft^2$) | 0.09290 | square meter |
| square mile ($mi^2$) | 2.590 | square kilometer |
| gallon (gal) | 0.1137 | cubic foot |
| cubic foot ($ft^3$) | 28.32 | liter |
| cubic inch ($in^3$) | 16.39 | milliliter |
| cubic foot per second ($ft^3/s$) | .02832 | cubic meter per second |
| million gallons per day (Mgal/d) | 3,785.4 | cubic meters per day |

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by use of the following equation:

F = 1.8(°C) + 32

Million gallons per day (Mgal/d) can be converted to cubic feet per second by multiplying million gallons per day (Mgal/d) x 1.54723 = cubic foot per second

**Sea level:** In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

**Abbreviated water-quality units used in this report:** Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams and micrograms per liter are units expressing the concentration of chemical constituents in solution as weight (milligrams or micrograms) of solute per unit volume (liter) of water. One-thousandth gram per liter is equivalent to one milligram per liter. One-millionth gram per liter is equivalent to one microgram per liter. For concentrations less than 7,000 mg/L, the numerical value is approximately the same as for concentrations in parts per million. Concentrations of fecal bacteria are given in colonies per 100 milliliters (col/100 mL), which is the same as colony forming units per 100 milliliters (CFU/100 mL).

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

# Effects of Hydrologic, Biological, and Environmental Processes on Sources and Concentrations of Fecal Bacteria in the Cuyahoga River, with Implications for Management of Recreational Waters in Summit and Cuyahoga Counties, Ohio

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## Abstract

Discharges of fecal bacteria (fecal coliform bacteria and *Escherichia coli*) to the middle main stem of the Cuyahoga River from storm water, combined sewers, and incompletely disinfected wastewater have resulted in frequent exceedances of bacteriological water-quality standards in a 23-mile reach of the river that flows through the Cuyahoga Valley National Recreation Area . Contamination of the middle main stem of the Cuyahoga River by bacteria of fecal origin and subsequent transport to downstream areas where water-contact recreation is an important use of the river are a concern because of the potential public-health risk from the presence of enteric pathogens.

Independent field investigations of bacterial decay, dilution, dispersion, transport, and sources, and bacterial contamination of streambed sediments, were completed in 1991-93 during periods of rainfall and runoff. The highest concentration of fecal coliform bacteria observed in the middle main stem during three transport studies exceeded the single-sample fecal coliform standard applicable to primary-contact recreation by a factor of approximately 1,300 and exceeded the *Escherichia coli* standard by a factor of approximately 8,000. The geometric-mean concentrations of fecal bacteria in the middle main stem were 6.7 to 12.3 times higher than geometric-mean concentrations in the monitored tributaries, and 1.8 to 7.0 times larger than the geometric-mean concentrations discharged from the Akron Water Pollution Control Station.

Decay rates of fecal bacteria measured in field studies in 1992 ranged from 0.0018 per hour to 0.0372 per hour for fecal coliform bacteria and from 0.0022 per hour to 0.0407 per hour for *Escherichia coli.* Most of the decay rates measured in June and August were significantly higher than decay rates measured in April and October. Results of field studies demonstrated that concentrations of fecal coliform bacteria were 1.2 to 58 times higher in streambed sediments than in the overlying water. Sediments are likely to be a relatively less important source of fecal bacteria during rainfall and runoff in the middle main stem relative to bacterial loading from point sources.

Numerical streamflow and transport simulation models were calibrated and verified with data collected during field studies. Of the constituents modeled, bacteria exhibited the poorest correspondence between observed and simulated values. The simulation results for a dye tracer indicated that the model reasonably reproduced the timing of dissolved constituents as well as dilution and dispersion effects. Calibrated and verified models for 1991 and 1992 data sets were used to simulate the improvements to bacteriological water quality that might result from reductions in concentrations of fecal bacteria discharged from two major sources.

The model simulation resulting in the greatest improvement in bacteriological water-quality was one in which concentrations of fecal coliform bacteria and *Escherichia coli* were reduced by 90 percent in the Cuyahoga River at the Old Portage gaging station, and to the geometric-mean

bathing-water standards in the effluent of the Akron Water Pollution Control Station (BWS/90 scenario). Compared to the results of the base-simulation, when the BWS/90 scenario was applied in the 1991 model simulation, *Escherichia coli* concentrations were reduced 98.5 percent at Botzum, 97.5 percent at Jaite, and 91.1 percent at Independence. For 1992 model simulations, similar percent reductions in the concentrations of *Escherichia coli* were predicted at the three stream sites when the same reductions were applied to sources. None of the model simulations resulted in attainment of bacteriological water-quality standards.

The potential benefits of source reductions to human health and recreational uses were estimated by comparing the number of illnesses per 1,000 people from concentrations of *Escherichia coli* associated with the BWS/90 simulation, with the base simulation, and with the geometric-mean standard for *Escherichia coli*. The predicted 22 to 26 illnesses per 1,000 people predicted by the *E. coli* concentrations resulting from BWS/90 simulation are 2.8 to 3.3 times higher than the 8 illnesses per 1,000 people associated with the geometric-mean primary-contact water-quality standard for *Escherichia coli*. Risks associated with the base simulation are 4.6 to 4.9 times higher than that associated with the geometric-mean primary-contact water-quality standard for *Escherichia coli*. The illness risks predicted from the BWS/90 scenario, although larger than acceptable, would nevertheless be an improvement over conditions that were encountered during field studies in 1991-93.

## Introduction

The middle main stem of the Cuyahoga River receives discharges containing fecal coliform bacteria and *Escherichia coli* (fecal bacteria) from storm water, partially disinfected domestic sewage, and combined-sewer overflows during periods of rainfall and runoff. These discharges result in elevated concentrations of fecal bacteria that exceed bacteriological standards and limit the recreational uses of the river. Impairments of recreational uses are of greatest concern in a 23-mile reach of the river that flows through the Cuyahoga Valley National Recreation Area (CVNRA) between Akron and Cleveland, Ohio.

Prediction of recreational impairment as a result of bacterial contamination during periods of rainfall and runoff to the river is a complex problem. Past attempts to predict concentrations of fecal bacteria on the basis of simple statistical relations between concentrations of fecal bacteria and streamflow or levels of turbidity have not been sufficiently accurate to provide a reliable basis for the development of canoeing advisories (Gary Rosenlieb and David Ryn, National Park Service, written commun., 1991). Accurate prediction of when and for how long concentrations of fecal bacteria will be elevated above water-quality standards after initial contamination will allow public health officials to better protect public health. Cost effective ways to reduce bacterial contamination and to gain a better understanding of public risk from exposure to fecal-contaminated water are research needs identified in a document published by a community organization responsible for guiding cleanup of the river—the Cuyahoga River Remedial Action Plan (Greg Studen, Cuyahoga River Community Planning Organization, written commun., 1992).

Determining the degree of improvement necessary to achieve bacteriological standards requires an approach that characterizes the relative importance and magnitude of sources that increase fecal bacteria concentrations in the river. In addition, an approach is needed that characterizes hydrologic and biological processes such as decay, dilution, and dispersion, which reduce concentrations of fecal bacteria in the river with time and distance downstream.

To better understand sources of fecal bacteria in the middle main stem of the Cuyahoga River and environmental, hydrologic, and biological processes controlling those sources and their concentrations, the U.S. Geological Survey (USGS) investigated the transport, dilution, dispersion, and decay of fecal bacteria in the river under varying conditions of streamflow, temperature, and season in 1991-93. The Ohio Water Development Authority, City of Akron, Northeast Ohio Regional Sewer District, County of Summit, and Cuyahoga River Community Planning Organization cooperated in these investigations. A one-dimensional transient streamflow and water-quality model was calibrated and verified using data collected during these investigations to (1) evaluate changes in concentrations of fecal bacteria resulting from time-dependent hydrologic and biological processes, (2) evaluate the relative importance of point, nonpoint, and tributary sources of fecal bacteria, and (3) simulate improvements to bacteriological water quality from varying levels of source reductions.

### Purpose and scope

This report describes the results of studies of processes and sources that control the concentrations of fecal bacteria in the Cuyahoga River during periods when the river receives discharges from storm, sanitary, and combined sewers and wastewater treatment plants. Streamflow, bacteriological, and chemical water-quality data were collected at a total of seven sites on the middle main stem, on four tributary streams, at one point source, and at a site on Lake Erie. Data collected in various studies were used to calibrate and verify a numerical streamflow and water-quality model, to estimate bacterial decay rates, and to assess the importance of streambed sediments as a bacterial source and sink. Some sites where bacterial decay data were collected are downstream from the CVNRA. Data used in model simulations were only those collected in the river above the terminus of the park. Most data were collected during the recreational seasons of May 1 through October 15 in 1991-93.

## Description of the study area

The Cuyahoga River drains 813 $mi^2$ in northeastern Ohio (fig. 1). The river is 100 mi long and flows south from the headwaters through Geauga County to Akron, in Summit County, turns and flows north through Cuyahoga County, and discharges to Lake Erie at Cleveland. Land use in the river basin is predominantly urban with two major metropolitan areas: Akron, which straddles the middle main stem, and Cleveland, which straddles the lower main stem. The middle main stem of the Cuyahoga River is defined as the segment between Akron and Cleveland. The lower main stem of the Cuyahoga River is defined as the segment from Cleveland to the mouth at Lake Erie (Ohio Environmental Protection Agency, 1994). The population of the Cuyahoga River basin in 1990 was approximately 880,000, which is slightly more than 1,000 people per square mile (U.S. Department of Commerce, Bureau of the Census, 1990).

At Botzum, Ohio (site 7 on fig. 1), the Cuyahoga River enters the CVNRA, a 50-$mi^2$ area that straddles 23 mi of the middle main stem (fig. 1). The downstream terminus of the CVNRA is at Independence, Ohio (National Park Service, 1989, p. 2.1; site 14 on fig. 1). The National Park Service administers this area and the natural, historical, and recreational features within its boundaries. The National Park Service estimates that more than one-third of the population of Ohio lives within a 1-hour drive of the CVNRA (within a 60-mi radius). The middle main stem of the Cuyahoga River within the CVNRA is the area of primary focus of this report. The middle main stem of the Cuyahoga River is designated a primary-contact recreational water by the Ohio Environmental Protection Agency.

The CVNRA attracts recreational users during all times of the year and especially during the months from May through October. Recreational uses include biking, walking, and hiking on paths that follow the river banks from Akron to Cleveland. Body-contact recreation includes canoeing, fishing, and wading, but these uses are not recommended by the National Park Service (NPS) when fecal coliform concentrations in the river exceed a geometric mean of 1,000 col/100 mL or a single-sample concentration of 2,000 col/100 mL. At these and higher concentrations, the river is contaminated sufficiently to pose a health risk to users (table 1). Canoers frequently use the Cuyahoga River in the State Scenic River section, located in the upper main stem in rural Geauga and Portage Counties, Ohio (fig. 1).

The lower main stem of the Cuyahoga River hosts a range of recreational uses including boating and tourism. Although swimming is not permitted by Cleveland City ordinance, public health must still be protected in the case of accidental immersion. To protect against illness from accidental immersion, the lower main stem is designated a secondary-contact recreational water (Greg Studen, written commun., Sept. 2, 1992) and as such a slightly higher standard for fecal coliform bacteria in a single sample of 5,000 col/100 mL is applied.

The middle main stem of the Cuyahoga River receives discharges of partially treated domestic sewage, intermittent discharges of storm water, combined-sewer overflows (CSOs), and sanitary sewer overflows (SSOs) during wet weather, which are major sources of fecal bacteria, especially in urban watersheds that contain large populations of humans. The middle main stem upstream from the CVNRA also receives treated municipal-wastewater discharges on a continual basis. The river receives approximately 60 Mgal/d of treated municipal and industrial effluents from the Akron Water Pollution Control Station (WPCS). The average daily discharge from the WPCS is equivalent to 93 $ft^3/s$ and as such, the WPCS is one of the largest sources of water to the middle main stem. Wet weather flows ranging from 107-280 Mgal/d (165-433 $ft^3/s$) receive partial treatment at the WPCS. A total of 38 CSOs drain intermittently to the Cuyahoga River from the City of Akron (Dave Crandell, City of Akron, written commun., 1997). All but four SSOs in the Akron sewage-collection and treatment system were eliminated by 1992. Four more SSO pump-station overflows in the Akron system discovered after 1992 also have been eliminated (Dave Crandell, City of Akron, written commun., 1997). The River also receives discharges of treated sewage and intermittent discharges from CSOs, SSOs, and storm water from small communities in Summit County, Ohio. One CSO and 17 SSOs are located in the Cuyahoga Falls collection system that when active discharge to the Cuyahoga River upstream from the CVNRA and upstream from the Little Cuyahoga River. The Summit County sewage collection and treatment system contains 15 SSOs, one of which discharges intermittently to Mud Brook, a major tributary to the middle main stem.

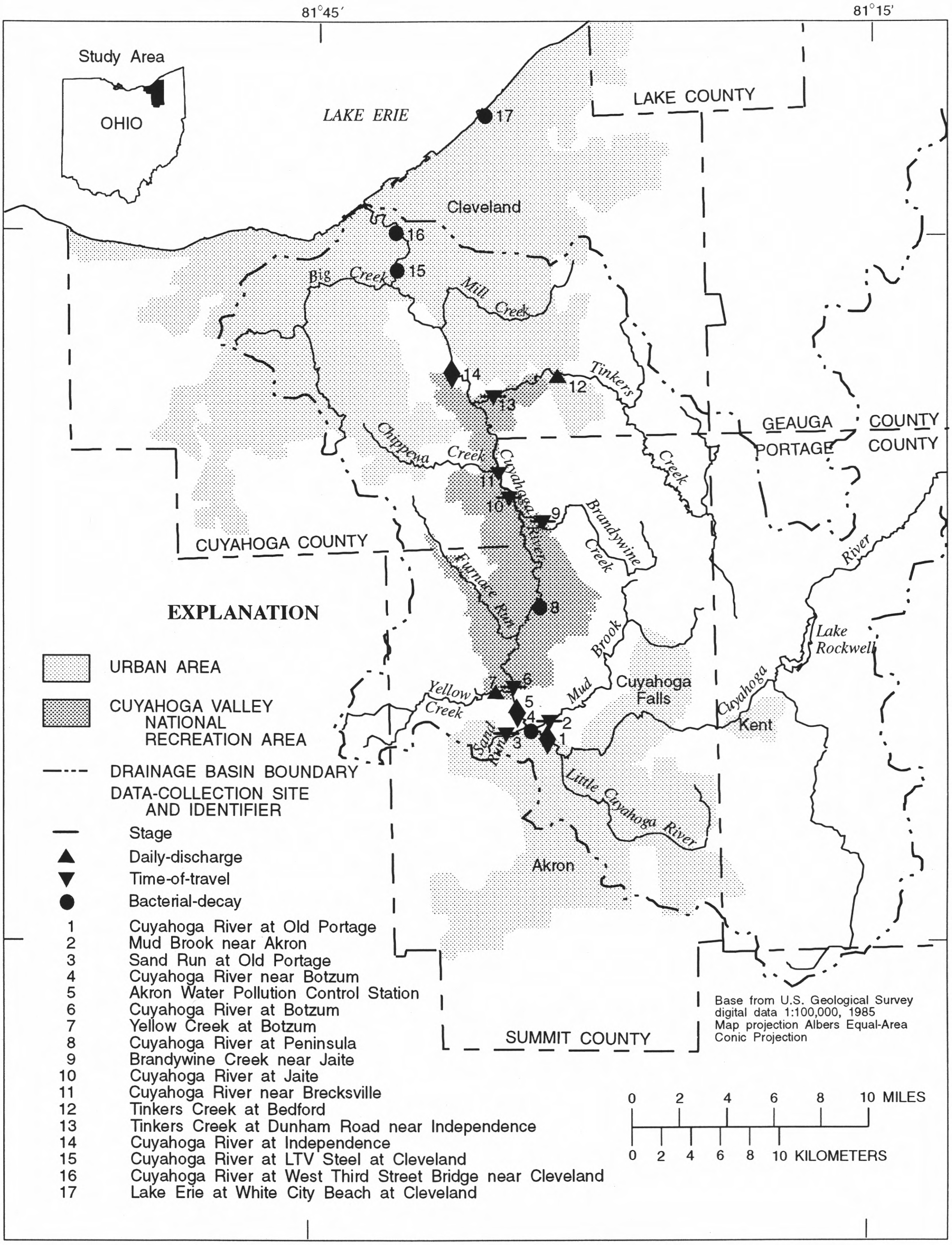


**Figure 1.** Location of the study area, Cuyahoga River Basin, northeastern Ohio.

**Table 1.** Water-quality standards for bacteria in recreational waters in Ohio

[Effective from May 1 through October 15. All values are in colonies per 100 milliliters. na, not applicable. Standards published in Ohio Environmental Protection Agency, 1990]

| Bacteria type | Type of recreational water | | |
|---|---|---|---|
| | Bathing waters[a] | Primary contact[b] | Secondary contact[c] |
| **Fecal coliform:** | | | |
| Geometric mean[d] | 200 | 1,000 | na |
| Single sample[e] | 400 | 2,000 | 5,000 |
| ***Escherichia coli:*** | | | |
| Geometric mean[d] | 126 | 126 | na |
| Single sample[e] | 235 | 298 | 576 |

[a] Bathing waters are suitable for swimming and other full-body-contact exposure where a lifeguard or bathhouse is present.
[b] Primary-contact waters are suitable for full-body contact such as swimming, canoeing, and scuba diving.
[c] Secondary-contact waters are suitable for partial-body contact such as wading.
[d] The geometric mean is based on a minimum of five samples in a 30-day period.
[e] This value cannot be exceeded in more than 10 percent of the samples collected in a 30-day period.

The lower main stem of the Cuyahoga River receives about 80 Mgal/d (about 123 $ft^3/s$) of treated wastewater a few miles upstream from the navigation channel in Cleveland, Ohio, from the Southerly Wastewater Treatment Plant operated by the Northeast Ohio Regional Sewer District (NEORSD). As of 1994, there were 135 CSOs and 167 SSOs intermittently draining to the lower main stem of the Cuyahoga River and its tributaries from the NEORSD system (Cuyahoga River Remedial Action Plan, 1994). The sewage collection and treatment system operated by the NEORSD is mentioned in this report because measurements of bacterial decay were made in the lower main stem of the Cuyahoga River that receives CSO and SSO discharges and at a site on Lake Erie that receives CSO discharges near the Easterly Wastewater Treatment Plant. The primary focus of this report is on the middle main stem of the Cuyahoga River, which for the most part is upstream from the service area of the NEORSD. Discussing the effects of the middle main stem on the bacteriological quality of the lower main stem is beyond the scope of the report.

## Previous investigations

The hydrology, bacteriological, and chemical water quality of the middle and lower main stems of the Cuyahoga River and tributaries have been described in previous reports (Childress 1984, 1985; Ohio Environmental Protection Agency, 1994). Concentrations of fecal bacteria that exceed Ohio's bathing-water, primary-contact, and secondary-contact water-quality standards (table 1) are well documented in the middle and lower main stems of the Cuyahoga River (Shindel and others, 1991, 1992; Shindel and others, 1993; Ohio Environmental Protection Agency, 1994). During dry-weather periods investigated in 1992, the middle and lower main stems typically met geometric mean primary-contact standards for fecal coliform bacteria in recreational waters (Ohio Environmental Protection Agency, 1994). In an earlier study, Childress (1984) documented elevated concentrations of fecal coliform bacteria during a reconnaissance study conducted during summer low-flow conditions in September 1982. Improvements in bacteriological water quality of the middle main stem reported by the Ohio Environmental Protection Agency (1994) are attributed to improved disinfection practices and elimination of CSOs and SSOs that historically discharged to the middle main stem during wet weather.

## Acknowledgments

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Ohio Environmental Protection Agency; and Steve Mack of the Ohio Water Development Authority for their assistance during all data collection and report review phases of the project. The authors also wish to acknowledge Harvey Jobson of the U.S. Geological Survey for assistance with model calibration.

## Methods used in field studies

Most water-quality sampling and analysis methods described in this report are standardized, are widely used, and have been previously published by the USGS or the U.S. Environmental Protection Agency (USEPA). Where applicable, standardized methods are referenced in the report. Methods that were modified to suit the purposes of data collection for this report are described in this section in detail. Modified methods were used to measure the rates of bacterial decay and concentrations of bacteria in streambed sediments.

### Fecal bacteria

Analyses of fecal-coliform bacteria and *E. coli* (*Escherichia coli)* were done by USGS personnel in the laboratories of the Summit County Department of Environmental Services in Munroe Falls, Ohio, and in the USGS Ohio District laboratory in Columbus, Ohio. Fecal bacteria were cultured from stream samples and from streambed sediments using membrane filtration (MF) procedures (Britton and Greeson, 1989; Dufour and others, 1981; U.S. Environmental Protection Agency, 1985). Cellulose-nitrate membrane filters with a pore-size of 0.45 µm (micrometers) were used for MF methods.

All sampling for fecal bacteria in streamwater, streambed sediments, and effluents was done using sterile equipment and sterile sample bottles. In most cases, streamwater and effluent samples were processed within 6 hours (hr) and streambed samples were processed within 24 hr of collection. The 6-hr holding time was exceeded by up to 3 hr in about 5 percent of the total number of stream samples. Because past analyses showed concentrations of fecal bacteria in the Cuyahoga River to be quite variable, four to nine sample volumes, ranging from 0.001 mL to 30 mL were filtered from individual stream or streambed-sediment samples. Use of a wide range of sample volumes resulted in one or two plates per sample that produced colony counts within the ideal range of 20 to 60 colonies for fecal coliform bacteria and 20 to 80 colonies for *E. coli*.

Approximately 1 kilogram (kg) of sediment was collected from the top 2-3 centimeters (cm) of the streambed using a stainless-steel spoon, and from the deeper areas with a small coring device. The sediment samples were placed in clean, sterile, 1 L polypropylene bottles and chilled to 1-4°C. Analyses were begun in the laboratory within 24 hr of collection.

Laboratory analysis was done by weighing out a wet subsample of 1 gram (g) and diluting the subsample into 99 mL of buffered dilution water. The bottle containing the subsample and buffer mixture was placed on a wrist-action shaker for 45 minutes (min) to remove the bacteria from the sediment particles. Seven dilutions of the original 99 mL sediment samples were made from 0.001 mL to 1.0 mL at half-log steps (0.001, 0.003, 0.01, 0.03, 0.1, 0.3, and 1.0 mL). Samples were subsequently filtered and incubated as prescribed by the MF methods. Data were reported as colonies per gram (col/g) as wet weight. Because 1mL of water weighs approximately 1g, the data from the streambed sediments and overlying water were directly compared.

Investigations were conducted at two sites in the Cuyahoga River to determine concentrations of fecal bacteria in streambed sediments, and thus assess the relative importance of sediments as a bacterial source or sink. The two study sites were in areas of the main stem where dams formed relatively large, quiescent pools in which sediments were deposited. The first site was in the dam pool of the Cuyahoga River at Peninsula, Ohio, and was the same site where bacterial decay was measured. This site is referred to as the "Peninsula dam pool" for purposes of describing bacteria in sediments (site 8). The second site was in the dam pool of the Cuyahoga River near Brecksville, Ohio hereafter referred to as the "Brecksville dam pool" (site 11).

Quality control for bacteria analyses consisted of analyzing several types of samples and conducting certain sampling activities. For example, laboratory equipment blanks were collected and processed by passing 100 mL of sterile, phosphate-buffered water (for fecal coliform analyses) or saline-buffered water (for *E. coli* analyses) through the filtration apparatus. A blank of this type was processed before each sample was filtered. A sample preceded by a blank having colony growth was considered suspect and those data were not used in this report.

All filtration equipment, apparatus, media, buffers, and sample containers were sterilized by autoclaving for 15 min at 121.6°C. Batches of materials and solutions were tested with autoclave tape to assure adequate sterilization. All culture plates were autoclaved for 30 min at 121.6°C prior to disposal. Laboratory practices for microbiological work followed guidelines set forth in Bordner and Winter (1978), Britton and Greeson (1989), and American Public Health Association and others (1992).

At a minimum of once each year, method bias was assessed by use of a check sample that was a lyophilized pure culture of *E. coli* obtained from the USEPA in Cincinnati, Ohio. The check sample contained a known number of cells. When processed and analyzed correctly, an acceptable result should fall within the prescribed confidence limits. All samples of *E. coli* and fecal coliform bacteria analyzed from lyophilized pure cultures were recovered within the acceptable confidence limits.

## Selected physical characteristics and chemical constituents

Streamwater and air temperatures were measured to the nearest 0.5°C. Specific conductance was measured to the nearest 1 microseimens per centimeter (µS/cm) and compensated to 25.0°C by use of Hydrolab[1] 4000 or 4021 meters. Two-point calibrations of specific conductance were made prior to each use according to manufacturer's instructions. Checks on the thermistors of each instrument were made by use of a thermometer traceable to a thermometer certified by the National Institute of Standards and Technology.

Water samples collected to determine concentrations of chloride and total nonfilterable residue were analyzed at the Heidelberg College Water-Quality Laboratory in Tiffin, Ohio. Chloride concentration was determined colorimetrically by use of the automated ferricyanide method (U.S. Environmental Protection Agency, 1979, Method 352.2). Total nonfilterable residue concentration was determined by use of a gravimetric method at 103-105°C (Guy and Norman, 1970; U.S.Environmental Protection Agency, 1979, Method 160.2).

The Heidelberg Water Quality Laboratory participated in the USGS Standard Reference Water Sample Program and has been approved by the USGS's Branch of Technical Development and Quality Systems to perform the water-quality analyses described in this report. The quality-assurance program and quality-control practices of the laboratory are described in Baker and Kramer (1990). Checks of laboratory performance for samples analyzed as part of this report were made independently by use of quality-control samples obtained from the USEPA in Cincinnati, Ohio. Quality-control samples of two different concentrations of chloride and total nonfilterable residue that bracketed expected sample concentrations were prepared in the USGS's Ohio District laboratory and submitted to the Heidelberg College Water-Quality Laboratory or the USGS's Ohio District laboratory along with each set of water samples. Results reported for these check samples for three studies in three separate years were within the acceptable range.

Concentrations of total residual chlorine were measured in the field by use of an Orion Research halide-sensing platinum electrode and a Beckman 21 pH-mV (millivolt) meter. The platinum electrode method for total residual-chlorine measurement is approved for testing wastewater and streamwater samples by the USEPA (Federal Register, 1984). The pH-mV meter was calibrated for use with the chlorine electrode by preparation of a standard curve from five potassium iodate standards and a deionized water blank that bracketed a concentration range between 0 and 1.0 milligram per liter (mg/L) of total residual chlorine. A sample of 5 percent Clorox solution diluted to a concentration of 1 mg/L was used to verify the potassium iodate standard curve. A practical detection limit for this method is approximately 0.3 mg/L. Standardizations were made according to manufacturer's instructions (Orion Research, 1977) with each use of the chlorine measurement system. Samples containing residual chlorine as a disinfectant were neutralized by adding 0.1 mL per 100 mL of a 10-percent solution of sodium thiosulfate.

Concentrations of rhodamine WT dye were measured by use of a Turner model 11 fluorometer according to USGS methods (Wilson and others, 1986). Concentrations were read directly from the instrument after calibration by use of standards at concentrations of 1, 2, 5, 10, 25, and 100 micrograms per liter (µg/L). Standards were prepared by serial dilution of a 20-percent solution of liquid rhodamine WT dye. An instrument reading of zero concentration was set by use of a sample of deionized water. Calibrations were checked after every 10 samples by use of the full-scale calibration standard and the deionized water blank. Recalibrations were made if a reading of the full scale standard was off by more than 5 percent. A streamwater blank was collected at each site to correct for the effect of background fluorescence. The fluorescence of the streamwater blanks ranged between 0.0 and 0.2 µg/L as measured by the instrument after calibration with rhodamine WT standards. The streamwater blank correction varied little from one collection site to another. Site-specific values for streamwater blanks were subtracted from each sample concentration prior to final reporting. Dye concentrations in samples were temperature corrected by analysis in the USGS's Ohio District laboratory at a constant temperature of 21.0°C several days after collection. All rhodamine WT concentrations were temperature corrected prior to use.

## Process studies

Special studies were done to measure processes that can cause changes in bacteria concentrations with time and distance downstream. The first type of study was done to estimate decay rates of fecal bacteria; the second type of study was done to estimate the dispersion, dilution, and transport and the relative importance and magnitude of certain sources, or source areas, of fecal bacteria. These studies were initiated during the first stages of rainfall and runoff and lasted from 24 to 72 hr.

**Fecal-bacteria decay.** Bacterial decay from death and injury is a natural process that reduces bacterial concentrations in streams, lakes, and aquifers (McFeters and Stuart, 1972; Bowie and others, 1985, p. 424-425; Auer and Niehaus, 1993). Fecal bacteria decay when cells that normally inhabit the gastrointestinal tract of warm-blooded animals and humans are exposed to the relatively cold and dilute environment of streams, lakes, or aquifers (Roszak and Colwell,

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[1]The use of trade names is for identification purposes and does not constitute an endorsement by the USGS.

1987). Under these severe conditions, fecal bacteria are thought to survive from a few hours to a few days in streams and lakes, and a few weeks to a few months in streambed sediments and ground water (Roszak and Colwell, 1987; Doyle and others, 1992, Pommepuy and others, 1992). Decay frequently results from cell starvation, although other factors also can reduce concentrations. These factors include predation by natural populations of stream protozoans, destruction by ultraviolet sunlight, and destruction by other physicochemical processes such as chlorination (U.S. Environmental Protection Agency, 1985; Roszak and Colwell, 1987).

Four studies of fecal bacteria decay were done in 1992: on April 20-23, on June 1-4, on August 8-11, and on October 9-12. The influence of seasonal factors such as water temperature, day length, and sunlight intensity were factored into the study design by stratifying the study periods into two categories: the April and October studies represent "spring and fall" conditions that are characterized by cooler temperatures and shorter daylight periods, whereas the June and August studies represent "summer conditions" that are characterized by warmer temperatures with longer daylight periods.

Decay of bacteria was investigated at five sites (sites shown by name and number on fig. 1): the Cuyahoga River near Botzum (site 4), at Peninsula (site 8), at LTV Steel at Cleveland, Ohio (site 15), and at West Third St. Bridge in Cleveland (site 16); and Lake Erie at White City Beach near Cleveland (site 17). The study sites were located in shallow pools, in slow-moving areas of the river, and in a shallow beach area of the lake. The Cuyahoga River site near Botzum and at Peninsula are the only sites in the middle main stem and are within the transport study area. The Cuyahoga River sites at West Third St. Bridge and at LTV Steel at Cleveland are in the lower main stem, downstream from the transport study area in a highly industrialized section of the navigation channel. The beach location along Lake Erie is adjacent to an open lake area that receives discharges of disinfected wastewater from the NEORSD's Easterly Wastewater Treatment Plant and intermittent discharges of untreated combined-sewer effluents. The beach has been permanently closed to swimmers because of a history of elevated concentrations of fecal bacteria during wet weather.

The bacterial-decay process in the Cuyahoga River was measured by use of autoclavable-polycarbonate cylinders of 600-mL capacity that were constructed and fitted with 0.45-µm pore-size membrane filters at the two open ends to form incubation chambers (fig. 2). Samples of streamwater and treated sewage diluted with streamwater were used to fill the chambers. Similar incubation chambers and their use have been described by McFeters and Stuart (1972), Hazen and Esch (1983), and Carillo and others (1985). The membrane filters were held in place and protected from puncture by screened plates placed on the ends of the chambers and secured with stainless-steel hardware. Solid plexiglass outer plates were screwed onto the screened plates to prevent leaking of chamber water through the membrane filters during transport and filling. These solid plates were removed when the chambers were submerged in the river or lake. The design of the chambers, in combination with the 0.45-µm pore size of the membrane filters, provided retention of fecal bacteria inside the chamber while allowing diffusion of water and dissolved substances through the membrane filters. Exposure of bacteria to ambient light was

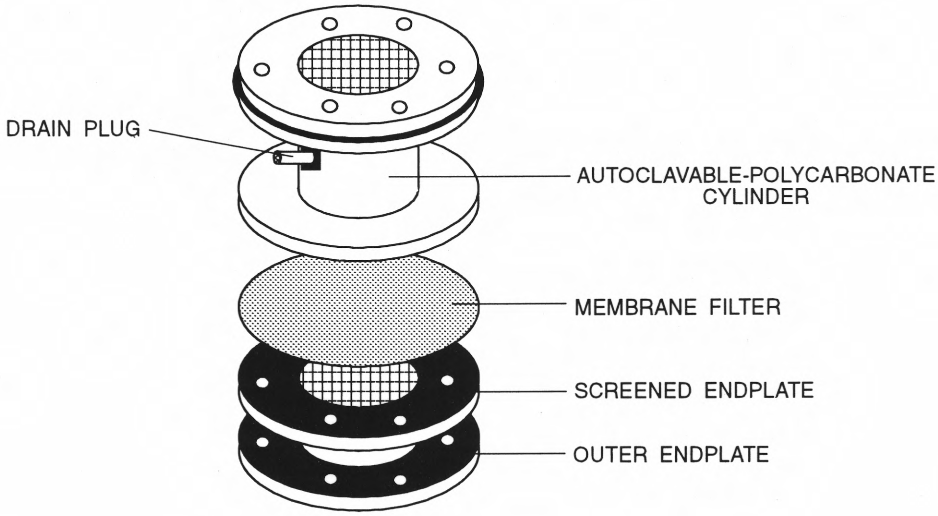


**Figure 2.** Diagram of membrane-filter chamber used in studies of bacterial decay.

maximized by use of the polycarbonate material, which according to the manufacturer, transmits up to 90 percent of ambient ultraviolet light.

Prior to decay studies, laboratory and field studies were done to determine the diffusion properties of the membrane filters for dissolved ions and to assess durability for field use during periods of rainfall and runoff. Several brands of membrane filters were investigated to determine the type of filter exhibiting superior properties of diffusion and durability. Versapor, Supor (Gelman Sciences, Ann Arbor, Michigan), and cellulose nitrate (Micro Filtration Systems, Dublin, California) membrane filters were tested. Supor membrane filters were selected for use in the decay studies because they had equally good diffusion properties compared to other filter types, were autoclavable, and in field tests were less likely to tear than the other filters.

For decay-rate studies, chambers were filled at each site by collecting about 15 L of streamwater directly into a plastic container (churn splitter) that had been disinfected with a chlorine solution and rinsed with autoclaved deionized water to remove residual chlorine. The churn splitter provided a homogenous water sample from which all chambers could be filled. After filling, the chambers were submerged about 18 in. below the water surface in plastic crates suspended by floats and anchored by cement blocks.

Samples fortified with unchlorinated wastewater effluent were used for decay studies when bacterial concentrations were expected to be low in the lower main stem of the Cuyahoga River or Lake Erie. Fortified samples were made by combining equal volumes of unchlorinated treated effluent and stream or lake water. Sewage was obtained from the NEORSD's Easterly Wastewater Treatment Plant. Fortified samples were used in all decay studies conducted at the Lake Erie beach site and for the October 1992 studies at LTV Steel and at West Third St. Bridge sites at Cleveland.

Measurements of bacterial decay were made by periodic collection and analysis of *E. coli* and fecal-coliform bacteria in subsamples withdrawn from incubation chambers. At four of the five sites, a single chamber was collected at each of seven predetermined time steps representing initial conditions and elapsed times of 8, 16, 24, 36, 48, and 72 hr. At one site during each study, duplicate sets of chambers were set and collected at each time step to assess reproducibility of results.The chambers were placed on ice immediately after collection and transported to the laboratory for MF analysis.

**Bacterial sources, transport, dilution, and dispersion.** Transport, dilution, dispersion, and concentrations of fecal coliform bacteria, *E. coli*, and other water-quality constituents are strongly influenced by the timing, areal distribution, and amount of rainfall, runoff, and streamflow. During rainfall and runoff, fecal bacteria and other contaminants are carried downstream away from sources. Concentrations of fecal bacteria have been shown in other studies to depend on streamflow and whether streamflow is rising or falling (Elder, 1987; Hunter and others, 1992). The magnitude of bacterial contamination depends on the number and size of sources of bacteria. Sources investigated for this report are point sources (i.e., the WPCS, CSOs and SSOs) and nonpoint sources, such as urban runoff and streambed sediments.

Three transport studies were done: on September 4-5, 1991, on July 13-14, 1992, and on September 2-3, 1993. All studies were done during periods of rainfall and runoff. An average of 1.0 in. of rain fell on the Akron area during the 1991 study, an average of 3.0 in. of rain fell during the 1992 study, and an average of 1.7 in. of rain fell during the 1993 study.

Transport studies were done by making measurements of streamflow and analyzing stream samples for concentrations of fecal coliform bacteria and *E. coli,* total nonfilterable residue, chloride, and rhodamine WT dye. Dye studies were used to determine time-of-travel and dispersion characteristics (Hubbard and others, 1982). Samples were collected and streamflow measurements were made at four sites in the middle main stem (sites 1, 4, 10 and 14 on fig. 1), at the WPCS (site 5 on fig. 1), at the Ohio Canal outflow near Brecksville, Ohio (near site 11 on fig. 1), and at six sites on five tributary streams (sites 2, 3, 7, 9, 12, and 13 on fig. 1). The middle main stem sites, in downstream order, are at the Old Portage gaging station, at Botzum, at Jaite, and at Independence. The four main stem sites were selected to bracket the segment of the Cuyahoga River within the CVNRA. The five tributaries that were sampled are, in downstream order, Mud Brook near Akron, Ohio; Sand Run at Old Portage in Akron, Ohio; Yellow Creek at Botzum, Ohio; Brandywine Creek near Jaite, Ohio; and two sites on Tinkers Creek, at Bedford and at Dunham Road near Independence, Ohio. These selected tributaries either were large enough to contribute more than 3 percent annually to the total flow of the Cuyahoga River or were thought to receive discharges from important sources or source areas.

Samples analyzed for concentrations of fecal bacteria, total nonfilterable residue, and chloride were collected by use of the equal-width increment (EWI) method (Edwards and Glysson, 1988). Depth-integrated samples were collected at a minimum of four equally spaced locations in the cross sections at each middle main stem site and at most of the tributary sites. EWI sampling could not be done at Sand Run, because of its small cross sectional size. Consequently, samples were obtained at a single location at the center of flow and were depth-integrated using a weighted bottle. All streamwater samples were collected into sterile polypropylene 1-gal or 1-qt containers. A Wheaton sewage sampler with a sterile glass bottle was used to collect effluent samples from the WPCS. Effluent samples were collected and analyzed for fecal bacteria and total nonfilterable residue by personnel at the WPCS and the USGS. Wastewater-effluent samples from the WPCS and samples collected just downstream from the effluent discharge at the Cuyahoga River at Botzum were tested for residual chlorine concentrations during each study. Sodium thiosulfate was added to neutralize the residual chlorine when chlorine was detected.

Periodic observations or automatic recordings of stage and (or) discharge; and samples for analysis of concentrations of fecal bacteria, total nonfilterable residue, chloride, and rhodamine WT dye; and field measurements of air temperature, water temperature, and specific conductance were collected or made at all main stem sites. Except for dye, the same set of measurements or samples was collected from tributaries and the WPCS. Streamflow data were collected at 15-min intervals at recording gaging stations on the Cuyahoga River at Old Portage and at Independence, on Yellow Creek at Botzum, and on Tinkers Creek at Bedford. Where a recording stream gaging station was not present, streamflow was determined from periodic stage observations, obtained either at staff gages or from tape-down measurements taken at reference points on bridges. Stage-discharge ratings were previously developed for each ungaged site from instantaneous measurements of stage and streamflow.

Records of effluent discharge from the WPCS were provided by the City of Akron. Wastewater discharge was measured at a broad-crested weir near the point of discharge by means of a previously developed stage-discharge relation for the weir. Data on the water levels in the weir pool were recorded by means of an acoustic sensor and data-storage unit.

Transport studies were done for purposes of calibration and verification of the one-dimensional Diffusion Analogy FLOW model (DAFLOW) (Jobson, 1989) and the Branched Lagrangian Transport Model (BLTM) (Jobson and Schoellhamer, 1987). The unsteady-flow and transport models selected for use in this report, DAFLOW and BLTM, have been used previously to estimate streamflow and transport for a variety of chemical contaminants and biological constituents (Bulak and others, 1993; Wiley, 1993).

## Hydrologic, biological, and environmental processes affecting concentrations of fecal bacteria

Decay, dilution, dispersion, transport, and concentrations of fecal bacteria in streamwater and effluents and concentrations of fecal bacteria in streambed sediments were characterized in the middle main stem of the Cuyahoga River. These data were collected to estimate how concentrations of fecal bacteria change with time and distance downstream from sources. Sources such as the WPCS, the middle main stem at the Old Portage gaging station upstream from the WPCS and the CVNRA, and four tributaries were sampled and characterized. The results of these studies are reported in the sections that follow.

### Bacterial decay

Decay rates were computed by simple linear regression of the base-10 logarithms of fecal bacteria concentrations in colonies per 100 milliliters (col/100 mL) with elapsed time, in hours. Bacterial concentrations typically decreased 50 to 90 percent from initial concentrations in a 72-hr period (fig. 3). Decay rates ranged from 0.0018 per hour ($hr^{-1}$) to 0.0372 $hr^{-1}$ for fecal coliform bacteria and from 0.0022 $hr^{-1}$ to 0.0407 $hr^{-1}$ for *E. coli* (table 2). Neither the minimum decay rate for fecal coliforms nor the minimum decay rate for *E. coli* were statistically different from zero. Decay rates reported in table 2 fall in the lower range of what are termed disappearance rates for fecal bacteria reported by Bowie and others (1985). Selected summary statistics of the decay rates of both fecal-bacteria types are reported in table 3. Disappearance rates described in Bowie and others (1985) range from 0.005 to 1.1 $hr^{-1}$. A disappearance rate is a measure of the difference in concentration of bacteria between two locations on a stream and represents all factors that contribute to the reduction in bacterial concentrations (including factors mentioned previously as well as dilution, dispersion, adsorption on particulate matter and subsequent deposition, and the effects of other physicochemical factors). In contrast, a decay rate is a measure of the die-off of bacteria in a stream as a result of ultraviolet light and temperature stress, cell starvation, predation by other bacteria and protozoans, and removal by filter feeders (McCambridge and McMeckin, 1980; Korhonen and Martikainen, 1991; Iriberri and others, 1994). Lantrip (1983) used membrane-filter chambers of a type similar to the ones described in this report in a study of bacterial decay in the Potomac River. Decay rates of fecal coliform bacteria reported by Lantrip (1983) were similar to those shown in this report and ranged from 0.0057 to 0.0305 $hr^{-1}$

Light penetration is likely to be an important factor in determining decay rates of bacteria in the Cuyahoga River and Lake Erie. Light penetration is reduced by water turbidity. Concentrations of total nonfilterable residue measured in the range of 38-848 mg/L for the middle main stem of the Cuyahoga River during periods of rainfall and runoff indicate very turbid conditions (Shindel and others, 1991, 1992; Shindel and others, 1993). In Lake Erie, light penetration, and hence decay rates of fecal bacteria, are often higher because there is relatively greater water clarity compared to the Cuyahoga River.

Decay of fecal bacteria also is affected by temperature and, therefore, has a seasonal component in temperate latitudes (Phelps, 1944; Velz, 1970; Bowie and others, 1985; Terzieva and McFeters, 1991). Median temperatures for April and October studies ranged from 10.7 to 18.8°C (table 2). Median temperatures for June and August studies ranged from 16.5 to 25.2°C (table 2).

Water temperatures at two downstream sites in the Cuyahoga River, at LTV Steel and at West Third Street Bridge, did not consistently fit the anticipated seasonal

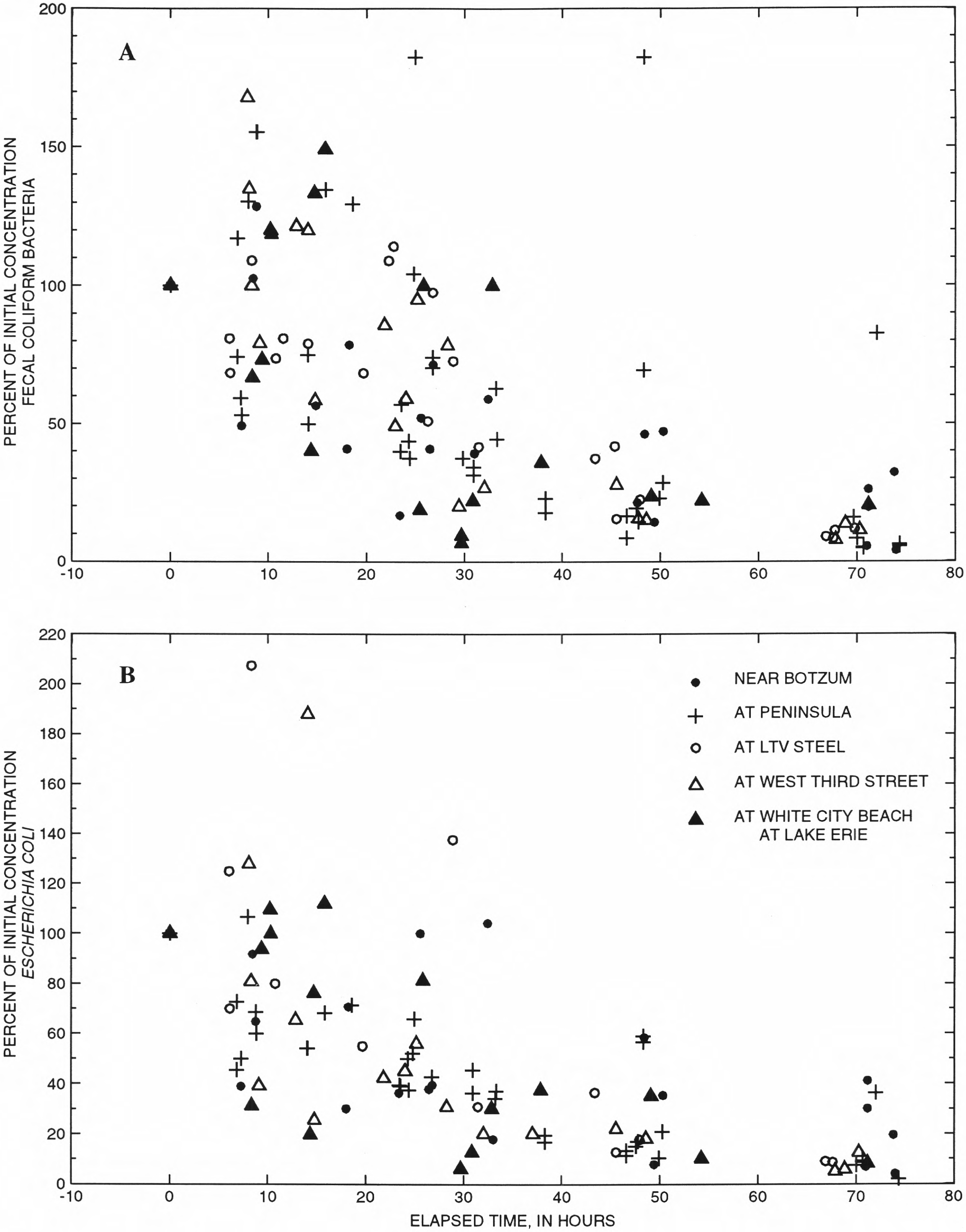


**Figure 3.** Percentage of initial concentration of (A) fecal coliform bacteria and (B) *Escherichia coli* remaining after elapsed time during bacterial decay studies, April, June, August, and October 1992.

**Table 2.** Results of bacterial-decay studies at four sites in the Cuyahoga River and one site in Lake Erie

[Decay studies were completed April 20-23, June 1-4, August 8-11, and October 9-12, 1992; (k) in $hr^{-1}$, hourly rate of bacterial decay; *n*, sample size; *p*-value, probability that decay rate is equal to zero at $\alpha$=0.05]

| Date 1992 | Median temperature, degrees Celsius | Fecal coliform (k), in $hr^{-1}$ (*n*) | Fecal coliform *p*-value | Escherichia coli (k), in $hr^{-1}$ (*n*) | Escherichia coli *p*-value |
|---|---|---|---|---|---|
| **Cuyahoga River near Botzum, Ohio** | | | | | |
| April | 14.6 | 0.0087 (7) | 0.0026 | 0.0100 (3) | 0.1624 |
| June | 17.5 | .0176 (6) | .0005 | .0180 (6) | .0017 |
| August | 21.4 | .0152 (6) | .0576 | .0140 (6) | .0598 |
| October | 14.7 | .0076 (6) | .0021 | .0089 (6) | .0023 |
| **Cuyahoga River at Peninsula, Ohio** | | | | | |
| April | 14.6 | .0132 (13) | .0000 | .0155 (10) | .0000 |
| June | 17.6 | .0182 (13) | .0000 | .0204 (11) | .0000 |
| August | 21.8 | .0195 (13) | .0000 | .0148 (13) | .0000 |
| October | 15.3 | .0018 ( 8) | .4813 | .0056 ( 8) | .0033 |
| **Cuyahoga River at LTV Steel in Cleveland, Ohio** | | | | | |
| April | 17.1 | .0155 (7) | .0094 | .0216 (3) | .1340 |
| June | 18.4 | .0135 (7) | .0023 | .0022 (3) | .8659 |
| August | 23.7 | .0157 (4) | .0115 | .0156 (4) | .0002 |
| October | 16.6 | .0142 (7) | .0008 | .0143 (6) | .0017 |
| **Cuyahoga River at West Third Street Bridge near Cleveland, Ohio** | | | | | |
| April | 16.4 | .0172 (7) | .0076 | .0153 (5) | .0264 |
| June | 19.1 | .0141 (4) | .0141 | .0407 (3) | .0494 |
| August | 25.2 | .0193 (6) | .0021 | .0186 (6) | .0009 |
| October | 18.8 | .0142 (7) | .0010 | .0176 (7) | .0000 |
| **Lake Erie at White City Beach near Cleveland, Ohio** | | | | | |
| April | 10.7 | .0372 (5) | .0067 | .0400 (4) | .0124 |
| June | 16.5 | .0122 (5) | .0960 | .0186 (4) | .1358 |
| August | 24.3 | .0122 (7) | .0299 | .0157 (7) | .0101 |
| October | 16.1 | .0365 (4) | .1829 | .0060 (3) | .6280 |

**Table 3.** Statistical summary of fecal bacteria decay rates at four sites in the Cuyahoga River and one site in Lake Erie

[Studies done in April, June, August, and October 1992; id, insufficient data; S.D., standard deviation; k, in $hr^{-1}$, Decay rate]

| Decay rate, k, in $hr^{-1}$ | Cuyahoga River near Botzum, Ohio | Cuyahoga River at Peninsula, Ohio | Cuyahoga River at LTV Steel at Cleveland, Ohio | Cuyahoga River at West Third in Cleveland, Ohio | Lake Erie at White City Beach near Cleveland. Ohio |
|---|---|---|---|---|---|
| **Median** | 0.0120 | 0.0182 | 0.0149 | 0.0157 | 0.0244 |
| **Mean** | .0123 | .0170 | .0147 | .0162 | .0245 |
| **One S.D.** | +/- .0049 | +/- .0033 | +/- .0011 | +/- .0025 | id |

pattern compared to the two upstream sites, near Old Portage and at Peninsula. For the Cuyahoga River at LTV Steel, thermally heated discharges from industrial sources resulted in relatively warmer spring and fall temperatures during the decay-rate studies. At the Cuyahoga River at West Third St., the depth of the channel, 28 ft, reduced the extremes of seasonal temperatures. At these two sites, median temperatures during all four bacterial decay-rate studies were warmer than at the two upstream sites and at Lake Erie (table 2).

Temperature differences were typically less than 5.0°C between successive studies and less than 10.0°C between the warmest and coolest studies. Also, the effects of water turbidity are not accounted for. As determined by previous investigators, this factor plays an important role in decay. The day length and hence duration of exposure to light would be the greatest for June studies, even though August temperatures were the warmest. On the basis of the data presented in this report, it is difficult to predict whether June and August would be similar or different with regard to decay rates as shown in figure 4 for Peninsula.

Analysis of covariance (ANCOVA) was used to identify significant seasonal differences in rates of bacterial decay at each of the five study sites. Only those decay rates (table 2) that were determined to have a slope significantly different from zero ($\alpha$=0.05) and are based on six or more observations per study were tested for seasonal differences in the ANCOVA. During two studies, some of the incubation chambers were lost because of river flooding. Wave action in the lake also resulted in loss of samples. For these studies, sample sizes were less than 6 over the 72-hr period.

For each site, the results of ANCOVA for seasonal differences in decay rates are expressed as a *t*-value and an associated the *p*-value (table 4). The sign of the *t*-value denotes whether the decay rate tested (denoted by month of study) was larger or smaller than the rate computed for the preceding study. For example, at any site, if a decay rate for an April study is smaller than a decay rate for a June study, the sign of the *t*-value is negative; conversely, if the decay rate from the April study is higher than the rate in the June study, the sign of the *t*-value is positive. A total of 13 ANCOVA tests were done to compare seasonal values of decay rates at the four Cuyahoga River sites (table 4). Of the 13 ANCOVA tests, 9 tests showed that either June or August decay rates were significantly higher than April or October decay rates ($p< 0.05$; table 4). Three of the four other ANCOVA tests showed June or August decay rates to be higher than those in October, but *p*-values associated with those comparisons were slightly higher than 0.05 (table 4).

## Accumulation of fecal bacteria in sediment

In two studies, one in March and the other in June 1993, concentrations of fecal bacteria in the overlying water column were compared to concentrations in streambed sediments. The purpose of these studies was to determine, at least qualitatively, the potential importance of sediments as a source or sink of fecal bacteria to the water column.

Concentrations of fecal bacteria in the streambed sediments were from 1.2 to 58 times more concentrated per unit wet weight than in the overlying water (table 5). This result indicates that fecal bacteria are present in sediments at similar or higher concentrations than in overlying water and consequently could be available for resuspension during storm runoff given adequate shear stress on the streambed. Sediments are likely to be a relatively less important source of fecal bacteria during rainfall and runoff periods in the CVNRA than discharges of fecal bacteria to the river because few large and bacterially contaminated areas of deposited sediment are present within the middle main stem and because of the relatively large bacterial loading from point sources. Lower bacterial concentrations were found in sediments in the dam pool at Peninsula, where sediments are sandy, compared to bacterial concentrations in samples from the dam pool near Brecksville, where sediments are silty.

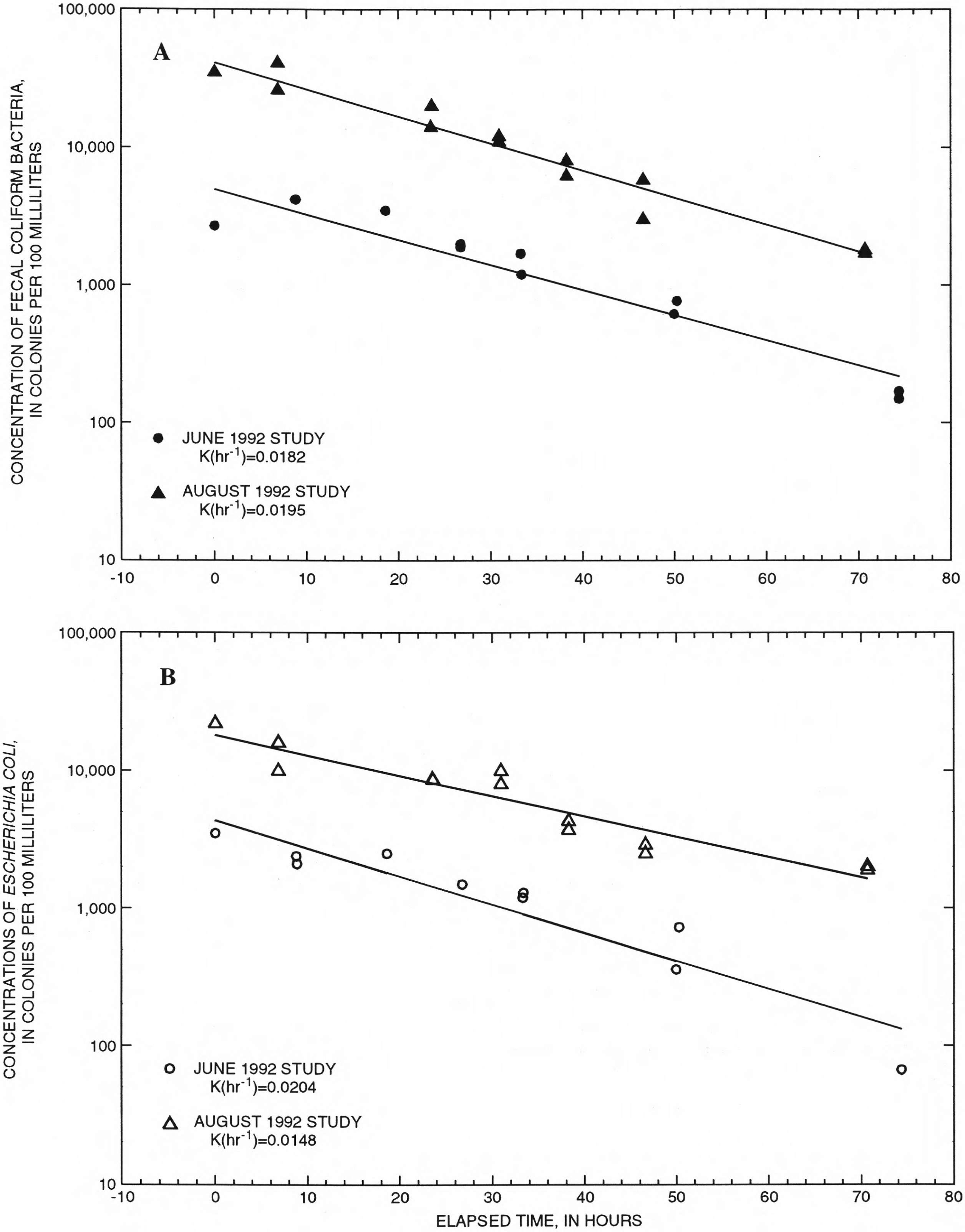


**Figure 4.** Decay rates of fecal bacteria at Peninsula, Ohio, June and August, 1992: (A) fecal coliform bacteria and (B) *Escherichia coli*.

**Table 4.** Results of *t*-tests comparing rates of decay of fecal coliform bacteria and *Escherichia coli* at four sites in the Cuyahoga River

[*t*-value; t-test computed value, *p*-value, value equal to or less than the probability that the seasonal decay rates are not significantly different; nt, not tested; *n*, sample size]

| | April compared to | | | June compared to | | August compared to |
|---|---|---|---|---|---|---|
| **Cuyahoga River** | **June** | **August** | **October** | **August** | **October** | **October** |
| **near Botzum** | | | **Fecal coliform bacteria ($n$=19)[1]** | | | |
| *t*-value | -95.1 | nt | 10.7 | nt | 2.09 | nt |
| *p*-value | <0.0000 | nt | <0.0000 | nt | 0.0569 | nt |
| | | | ***Escherichia* coli (n=19)[1,2]** | | | |
| *t*-value | nt | nt | nt | 19.0 | 2.01 | 1.76 |
| *p*-value | nt | nt | nt | <0.0000 | 0.0653 | 0.1013 |
| **at Peninsula** | | | **Fecal coliform bacteria ($n$=40)[3]** | | | |
| *t*-value | -25.4 | -15.4 | nt | -11.7 | nt | nt |
| *p*-value | <0.0000 | <0.0000 | nt | <0.0000 | nt | nt |
| | | | ***Escherichia coli* (n=40)** | | | |
| *t*-value | -27.1 | 10.2 | nt | 6.92 | nt | nt |
| *p*-value | <0.0000 | <0.0000 | nt | <0.0000 | nt | nt |
| **at LTV Steel** | | | **Fecal coliform bacteria ($n$=16)** | | | |
| *t*-value | nt | nt | 12.2 | nt | nt | nt |
| *p*-value | nt | nt | <0.0000 | nt | nt | nt |
| | | | ***Escherichia coli* (n=16)[2,4]** | | | |
| *t*-value | nt | nt | nt | nt | nt | 7.40 |
| *p*-value | nt | nt | nt | nt | nt | <0.001 |
| **at West Third Street** | | | **Fecal coliform bacteria ($n$=21)** | | | |
| *t*-value | nt | -30.0 | 11.0 | nt | nt | 5.36 |
| *p*-value | nt | <0.0000 | <0.0000 | nt | nt | <0.0000 |
| | | | ***Escherichia coli* (n=21)** | | | |
| *t*-value | nt | -48.3 | -17.6 | nt | nt | 9.27 |
| *p*-value | nt | <0.0000 | <0.0000 | nt | nt | <0.0000 |

[1] Decay rate for August study not significantly different from 0.0.
[2] Decay rate for April study not significantly different from 0.0.
[3] Decay rate for October study not significantly different from 0.0.
[4] Decay rate for June study not significantly different from 0.0.

**Table 5.** Summary of concentrations of fecal coliform bacteria and *Escherichia coli* in streambed sediment and overlying water in the dam pools of the Cuyahoga River near Brecksville and at Peninsula, Ohio

[*E. coli, Escherichia coli*]

| Source | Geometric mean or single-sample concentration, in colonies per gram wet weight (sample size) | | | |
|---|---|---|---|---|
| | Cuyahoga River near Brecksville, Ohio March 17, 1993 "Brecksville dam pool" | | Cuyahoga River at Peninsula, Ohio June 16, 1993 "Peninsula dam pool" | |
| | Fecal coliform bacteria | *E. coli* | Fecal coliform bacteria | *E. coli* |
| **Stream** | 360 (5) | 330 (1) | 3 (2) | 5 (2) |
| **Sediment** | 21,000 (2) | 3,700 (1) | 11 (4) | 6 (4) |
| **Average ratio of water to sediment concentration** | 58.3 | 11.2 | 3.7 | 1.2 |

## Dilution, dispersion, and transport of fecal bacteria and other constituents

The following description of the bacteriological and chemical water quality of the middle main stem of the Cuyahoga River during the transport studies serves two purposes. The first purpose is to describe the effects of rainfall and runoff on recreational uses. This information applies only to the segment of the middle main stem from the Old Portage gaging station to the Independence gaging station (sites 1 and 14, respectively). The second purpose is to provide a conceptual model of changes in the bacteriological quality of the river with time and distance downstream as a prelude to the modeling discussion in this report. Data on concentrations of fecal bacteria, chloride, total nonfilterable residue, and values of water temperature, specific conductance, and streamflow from these studies are published elsewhere (Shindel and others, 1991, 1992; Shindel and others, 1993).

Concentrations of fecal coliform bacteria and *E. coli* in the Cuyahoga River in the segment from Old Portage to Independence were highly variable and positively correlated with each other during the three transport studies in 1991-93 (Francy and others, 1993). Concentrations of fecal coliform bacteria and *E. coli* have been shown to be positively correlated in other Ohio streams (Francy and others, 1993).

During the transport studies, the geometric-mean concentrations of fecal coliform bacteria in the middle main stem were from 8.4 to 12.3 times higher and geometric-mean concentrations of *E. coli* were from 6.7 to 11.6 times higher than those observed in the monitored tributaries (table 6). During the transport studies, the median and geometric-mean concentrations of fecal bacteria measured in the monitored tributaries also were lower than that discharged from the WPCS (table 6).

The range of geometric-mean concentrations of fecal coliform bacteria at four sites on the middle main stem were from 1.8 to 7.0 times higher than those observed in the discharge from the WPCS. Likewise, the range of geometric mean *E. coli* concentrations were roughly 2.1 to 5.9 times higher at sites on the middle main stem than those observed in the discharge from the WPCS (table 6). One very low set of concentrations for fecal coliform bacteria and *E. coli* in the discharge from the WPCS contributed to the overall lower geometric mean compared to the geometric mean at Botzum. The maximum concentration of fecal coliform bacteria, 1,500,000 col/100 mL, and the maximum concentration of *E. coli*, 620,000 col/100 mL, in the effluent from the WPCS were similar in range to the maximum concentrations of fecal bacteria in the middle main stem at the Old Portage gaging station, at Botzum, at Jaite, and at Independence (table 6, fig. 5).

The highest concentration of fecal coliform bacteria was detected in the middle main stem at Botzum just downstream from the WPCS (fig. 5). At 2,600,000 col/100 mL, this sample exceeded Ohio's single-sample primary-contact recreational standard (2,000 col/100 mL) by a factor of 1,300. The highest observed concentration of *E. coli* also was detected at Botzum, and at 2,400,000 col/100 mL, this sample exceeded the single-sample primary-contact recreational standard for *E. coli* (298 col/100 mL) by a factor of 8,054. The maximum concentrations of fecal bacteria detected during the transport studies in the middle main stem and in the WPCS effluent are characteristic of contamination by unchlorinated sewage and (or) raw sewage (Bordner and Winter, 1978, p. 127; Myers and Sylvester, 1997).

**Table 6.** Geometric mean, median, range, and sample size for concentrations of fecal coliform bacteria, *Escherichia coli*, and total nonfilterable residue collected at selected sites in the Cuyahoga River, Mud Brook, Brandywine Creek, Tinkers Creek, and the Water Pollution Control Station

[Samples collected September 4-5, 1991, July 13, 1992, and September 2-3, 1993; mg/L, milligrams per liter; col/100 mL, colonies per 100 milliliters; *n*, sample size]

| Station name | Mean, median, range, and sample size | Fecal coliform bacteria (col/100 mL) | *Escherichia coli* (col/100 mL) | Total nonfilterable residue[a] (mg/L) |
|---|---|---|---|---|
| **Cuyahoga River at Old Portage** | Geometric mean | 41,000 | 35,000 | 164 |
| | Median | 19,000 | 22,000 | 124 |
| | Range | 11,000-1,000,000 | 7,700-620,000 | 40-584 |
| | *n* | 16 | 16 | 16 |
| **Mud Brook near Akron** | Geometric mean | 13,000 | 8,600 | 644 |
| | Median | 13,000 | 7,700 | 192 |
| | Range | 6,900-25,000 | 2,400-27,000 | 74-3,540 |
| | *n* | 7 | 8 | 9 |
| **Water Pollution Control Station** | Geometric mean | 23,000 | 17,000 | 26.7 |
| | Median | 18,000 | 13,000 | 19.0 |
| | Range | 66-1,500,000 | 59-620,000 | 6.0-58.0 |
| | *n* | 20 | 18 | 16 |
| **Cuyahoga River at Botzum** | Geometric mean | 160,000 | 100,000 | 313 |
| | Median | 180,000 | 100,000 | 240 |
| | Range | 19,000-2,600,000 | 8,000-2,400,000 | 62.0-848 |
| | *n* | 23 | 22 | 21 |
| **Brandywine Creek near Jaite** | Geometric mean | 15,000 | 15,000 | 158 |
| | Median | 8,700 | 9,500 | 123 |
| | Range | 2,100-700,000 | 3,900-300,000 | 101-475 |
| | *n* | 11 | 10 | 11 |
| **Cuyahoga River at Jaite** | Geometric mean | 130,000 | 96,000 | 316 |
| | Median | 170,000 | 100,000 | 252 |
| | Range | 20,000-1,000,000 | 14,000-570,000 | 84.0-808 |
| | n | 20 | 20 | 22 |
| **Tinkers Creek near Independence** | Geometric mean | 19,000 | 13,000 | 142 |
| | Median | 21,000 | 14,000 | 107 |
| | Range | 2,800-97,000 | 2,700-73,000 | 61-398 |
| | *n* | 17 | 14 | 17 |
| **Cuyahoga R. at Independence** | Geometric mean | 76,000 | 36,000 | 259 |
| | Median | 92,000 | 30,000 | 288 |
| | Range | 8,300-530,000 | 2,400-150,000 | 38-542 |
| | *n* | 17 | 17 | 18 |

[a]Arithmetic mean.

Longitudinal changes in concentrations of fecal bacteria and other water-quality constituents in the middle main stem were tracked by sampling from a discrete volume of the stream demarcated with rhodamine WT dye. Samples were obtained from the volume of water demarcated with dye as it moved downstream from the initial dye injection point. In downstream order, geometric-mean concentrations in the middle main stem increased by a factor of 3.9 for fecal coliform bacteria and by a factor of 2.9 for *E. coli* from the Old Portage gaging station to Botzum; geometric-mean concentrations then decreased by a factor of 2.1 for fecal coliform bacteria and by 2.8 for *E. coli* in a downstream direction from Botzum to Independence.

Concentrations of fecal bacteria were highly variable over relatively short periods of time as well as over relatively short distances. Results of the 1993 study (fig. 6) show that concentrations of fecal bacteria can vary by factors of 2 to 3 over 2 to 3 hr during the initial periods of rainfall and runoff, and can vary by a factor of 10 over a period of 10 to 12 hr. Figure 6 also shows the smoother and more predictable changes in rhodamine WT dye concentration with time and distance downstream compared to the fluctuating

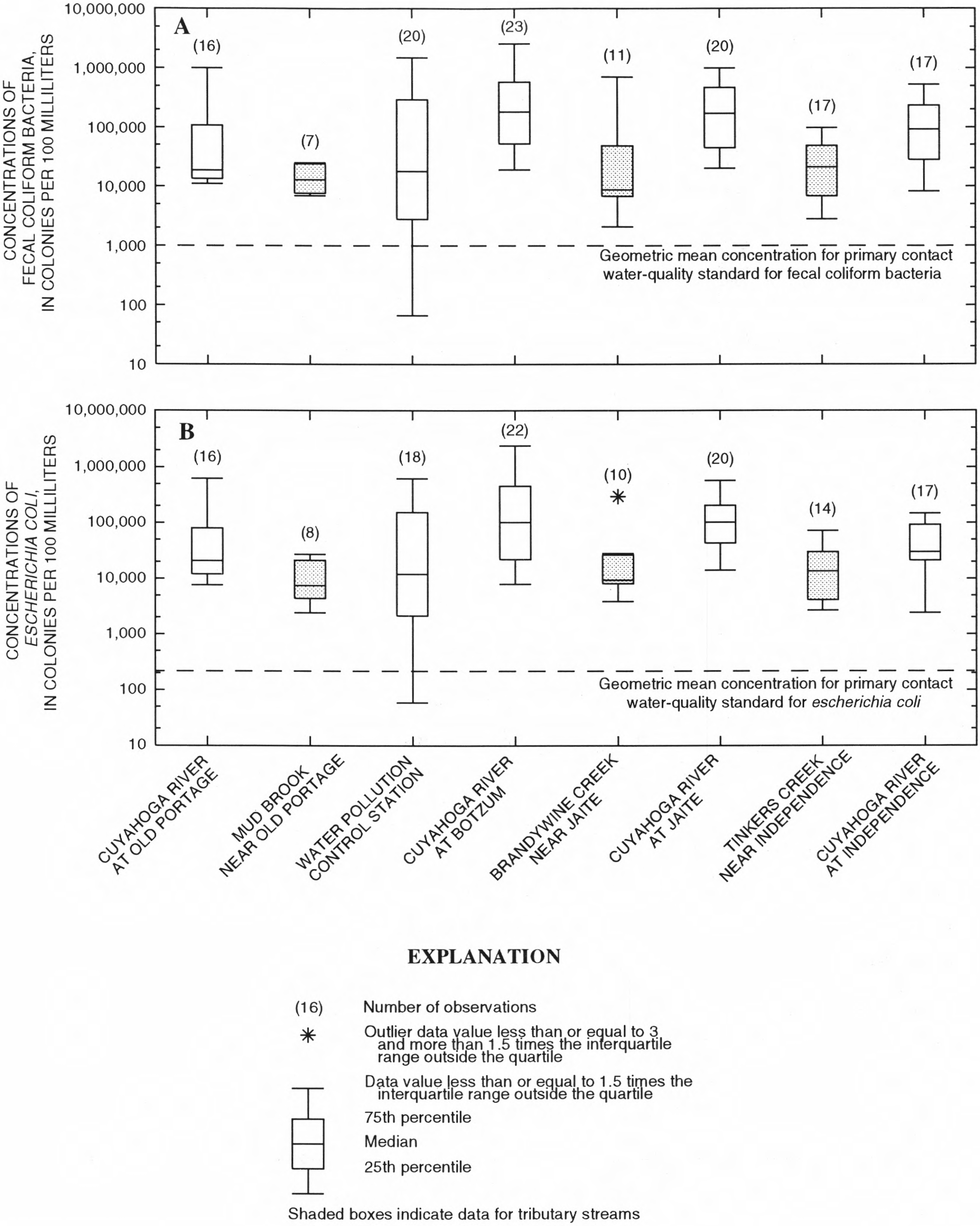


**Figure 5.** The relation of the concentration of fecal bacteria to bacteriological standards at selected sites in the Cuyahoga River, tributary streams, and the Water Pollution Control Station: (A) fecal-coliform bacteria and (B) *Escherichia coli*.

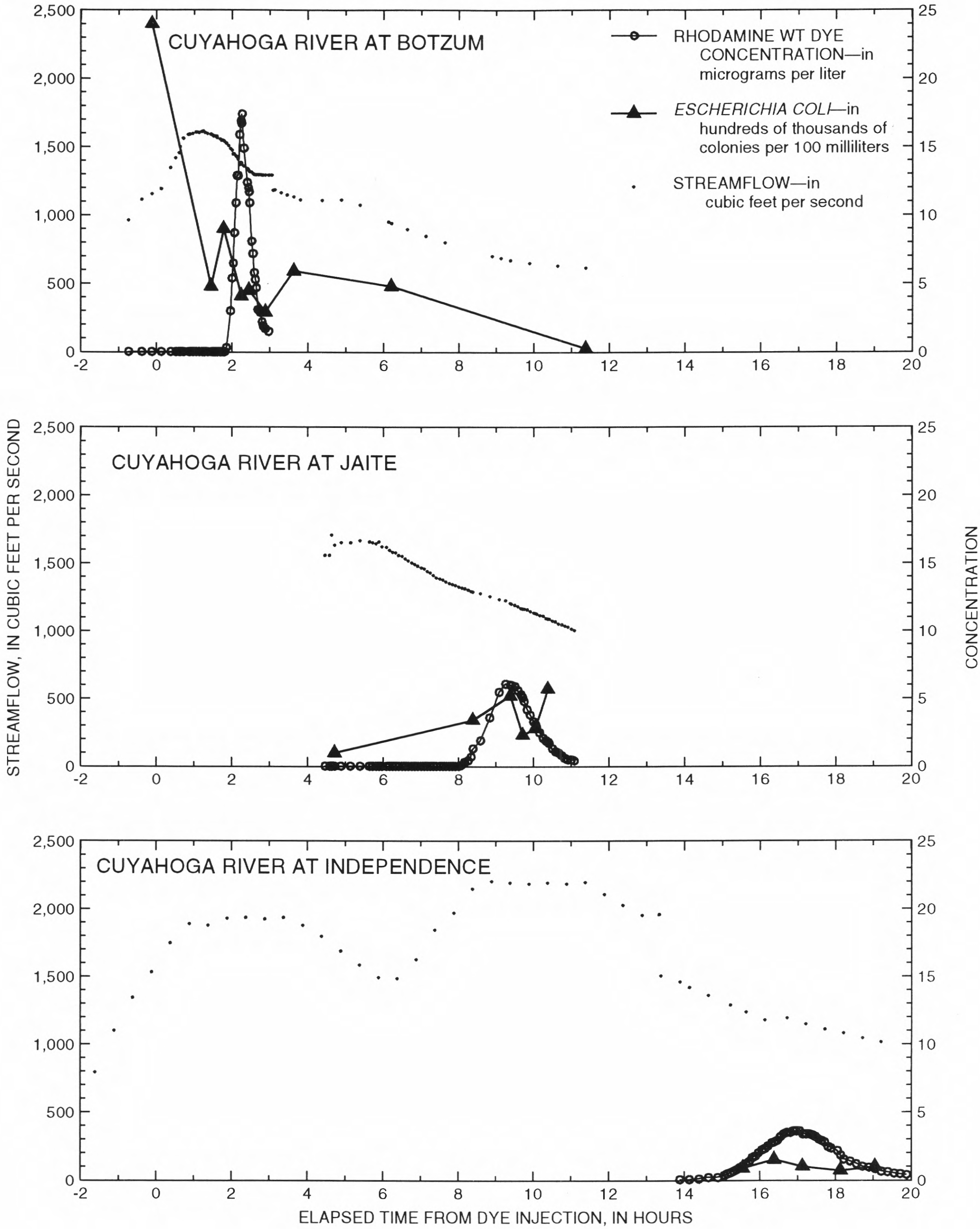


**Figure 6.** Changes in concentrations of rhodamine WT dye, *Escherichia coli*, and changes in streamflow with time and distance downstream from Botzum to Independence during transport studies, September 2-3, 1993.

**Table 7.** Summary of regression statistics for relations between concentrations of fecal bacteria and concentrations of total nonfilterable residue and streamflow for the Cuyahoga River at four sites, for all stream sites, and for the Water Pollution Control Station

[Data collected during transport studies in 1991-93; $R^2$, coefficient of determination; *b*, coefficient of slope; *a*, y-intercept; *p*-value, probability that the coefficient of slope is equal to zero; *p*-values in **bold** are significantly different than zero at or less than a probability of a=0.05; *n*, sample size; WPCS, Akron Water Pollution Contol Station]

| | Regression statistics describing the relation between the base-10 logarithms of concentrations of fecal bacteria and streamflow | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fecal coliform bacteria | | | | | *Escherichia coli* | | | | |
| Station name | $R^2$ | b | a | *p*-value | n | $R^2$ | b | a | *p*-value | n |
| Cuyahoga River at Old Portage gage | 0.014 | 0.578 | 2.890 | 0.664 | 16 | 0.026 | 0.757 | 2.297 | 0.553 | 18 |
| Cuyahoga River at Botzum | .133 | 1.162 | 1.734 | .087 | 23 | .232 | 1.827 | -0.447 | **.023** | 22 |
| Cuyahoga River at Jaite | .001 | .127 | 4.799 | .880 | 18 | .000 | -.024 | 5.085 | .976 | 18 |
| Cuyahoga River at Independence | .181 | 1.067 | 1.735 | .086 | 17 | .281 | 1.202 | 1.039 | **.029** | 17 |
| All stream sites | .319 | .704 | 2.883 | **<.000** | 105 | .288 | .676 | 2.773 | **<.000** | 102 |
| WPCS | .584 | 4.061 | -4.362 | **<.000** | 20 | .583 | 3.907 | -4.140 | **<.000** | 18 |

| | Regression statistics describing the relation between the base-10 logarithms of concentrations of fecal bacteria and concentrations of total nonfilterable residue | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fecal coliform bacteria | | | | | *Escherichia coli* | | | | |
| Location | $R^2$ | b | a | *p*-value | n | $R^2$ | b | a | *p*-value | n |
| Cuyahoga River at Old Portage gage | 0.358 | 1.211 | 2.076 | **0.024** | 14 | 0.553 | 1.660 | 1.028 | **0.002** | 14 |
| Cuyahoga River at Botzum | .441 | 1.285 | 2.160 | **.001** | 21 | .461 | 1.457 | 1.593 | **.001** | 20 |
| Cuyahoga River at Jaite | .114 | 0.656 | 3.527 | .146 | 20 | .118 | 0.607 | 3.498 | .139 | 20 |
| Cuyahoga River at Independence | .402 | .954 | 2.661 | **.006** | 17 | .586 | 1.064 | 2.120 | **.003** | 17 |
| All stream sites | .275 | 1.050 | 2.351 | **<.000** | 106 | .318 | 1.125 | 2.018 | **<.000** | 102 |
| WPCS | .171 | 1.026 | 3.417 | .112 | 16 | .186 | 1.085 | 3.126 | .109 | 15 |

concentrations of fecal bacteria at the same three sites and times. The smoother changes in dye concentration are the result of a single slug injection of dye at a single site, whereas the erratic changes in fecal bacteria concentrations are the result of the pulsed inputs from many sources throughout the watershed above and within the transport study area.

Fecal bacteria were observed to be either positively associated or not associated with streamflow at individual sites in the middle main stem (table 7) ($p<0.05$). The coefficients of determination ($R^2$-values) from regressions of base-10 logarithms of streamflow and fecal bacteria concentration ranged from 0.000 to 0.281 for four middle main stem sampling sites (table 7 and figs. 7 and 8). When streamflow data and concentrations of fecal bacteria were examined in aggregate for all stream sites, statistically significant relations were detected. The $R^2$-values from simple linear regressions of aggregated base-10 logarithms of concentration and streamflow data were 0.319 for fecal coliform bacteria and 0.288 for *E. coli,* (table 7 and fig. 7). The weak relation between concentrations of fecal bacteria and streamflow at individual sites is likely the result of small sample sizes and pulsed inputs of bacteria from sources such as combined sewers and wastewater effluents.

Stronger associations, as indicated by $R^2$-values of approximately 0.583 and 0.584, were found for the relation between base-10 logarithms of concentrations of fecal coliform bacteria and *E. coli* respectively, and discharges from the WPCS (table 7, fig. 8). In addition, the unit loading of bacteria from the WPCS was greater (as indicated by the higher $R^2$ values) than the unit loading for all stream sites computed for the river and tributaries in aggregate (table 7, figs. 7 and 8). In other words, a unit increase in the discharge from the WPCS resulted in a greater unit increase in the concentration of fecal bacteria than did an equivalent unit increase in streamflow at any of the middle main stem or tributary sites. The higher unit loading of fecal bacteria from the WPCS compared to the middle main stem is a key factor in determining the magnitude and importance of the WPCS as a major source.

The base-10 logarithms of fecal bacteria concentrations were shown to be positively related to the base-10 logarithms of flow from the WPCS. This association was used to estimate concentrations of fecal bacteria in discharges from the WPCS for which no samples were collected. These data were subsequently used to establish boundary conditions for the WPCS in the model. Data used to develop these regressions were obtained at the WPCS sampling site during the three transport studies. As shown in figures 7 and 8, a threshold of about 90 $ft^3/s$ appeared to be the flow above which bacterial concentrations in the effluent from the WPCS appears to sharply increase.

Fecal bacteria are known to be associated with suspended sediments (Sherer and others, 1992) and other particles that are transported by streamflow. The association between the concentration of particles in suspension, measured as total nonfilterable residue, and concentrations of fecal bacteria were examined for data collected on the middle main stem, tributaries, and at the WPCS during the transport studies in 1991-93.

Simple linear regression analyses were done to assess the relation between the base-10 logarithms of streamflow and the base-10 logarithms of total nonfilterable residue concentrations. The results of those analyses (table 7, fig. 7) indicate the existence of statistically significant associations between total nonfilterable residue concentrations and streamflow at three of four stream sites and when data for all stream sites were analyzed in aggregate. No significant association was detected between base-10 logarithms of total nonfilterable residue concentrations and flows from the WPCS.

Because the primary sources of total nonfilterable residue and fecal bacteria are different, increases in one do not necessarily cause increases in the other. Humans and other warm-blooded animals are the sources of fecal bacteria, whereas particulates from sewage and suspended sediment are the predominant sources of total nonfilterable residue in the middle main stem. As water moved downstream from Botzum to Independence, concentrations of fecal bacteria consistently decreased. This pattern is consistent with the identification of major sources of bacteria upstream from the CVNRA. Unlike bacteria, as water moved downstream from Old Portage to Independence, concentrations of total nonfilterable residue varied up and down. This pattern is consistent with major inputs of suspended sediment from tributaries along the middle main stem.

Concentrations of fecal bacteria detected in discharges from the WPCS were not statistically associated with concentrations of total nonfilterable residue (table 7, fig. 7), even though the WPCS is a major source of bacteria. Further, WPCS discharges appear to contribute a relatively small part of the total nonfilterable residue load to the river during rainfall and runoff. This is evidenced in part by the relatively low concentrations of total nonfilterable residue in the effluent compared to the concentrations in the river (table 6). The results of regressions (table 7) only indicate that fluvial transport characteristics of concentrations of total nonfilterable residue and fecal bacteria are similar even though the sources of the two types of constituents are very different.

## Simulation of streamflows and constituent transport and decay

Three field-based time-of-travel and transport studies of less than 48 hr duration were conducted in 1991-93. Streamflow and transport simulation models were prepared to correspond to each year's field study and are subsequently referred to in this report by model year. For example, the streamflow simulation corresponding to the field study conducted in 1991 is referred to as the 1991 model simulation for streamflow.

**Unsteady-flow model.** The unsteady-flow model DAFLOW (Jobson, 1989) was used to numerically simulate streamflow characteristics. The DAFLOW model computes one-dimensional, unsteady flow characteristics by applying the continuity equation and a simplified form of the diffusion wave equation.

**Selection of initial parameter values.** Model parameters include $A_0$, the average cross-section area at zero flow; $A_1$ and $A_2$, the hydraulic geometry coefficient and exponent for cross-section area, respectively; $W_1$ and $W_2$, the hydraulic geometry coefficient and exponent for

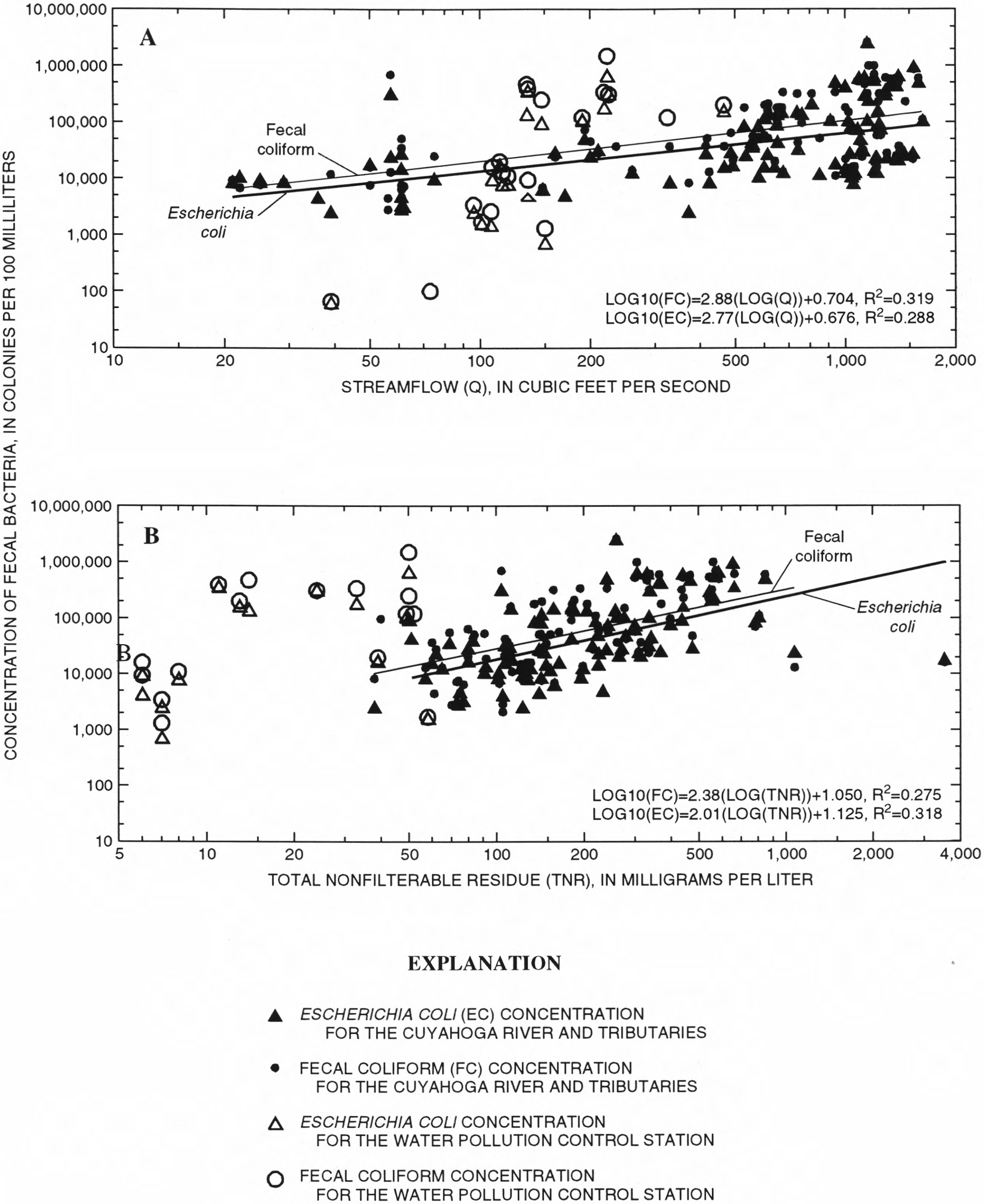


**Figure 7.** Relation between (A) streamflow and concentration of fecal bacteria, and (B) concentration of total nonfilterable residue and concentration of fecal bacteria for all sites in the Cuyahoga River and selected tributaries, and for the Water Pollution Control Station, 1991-93.

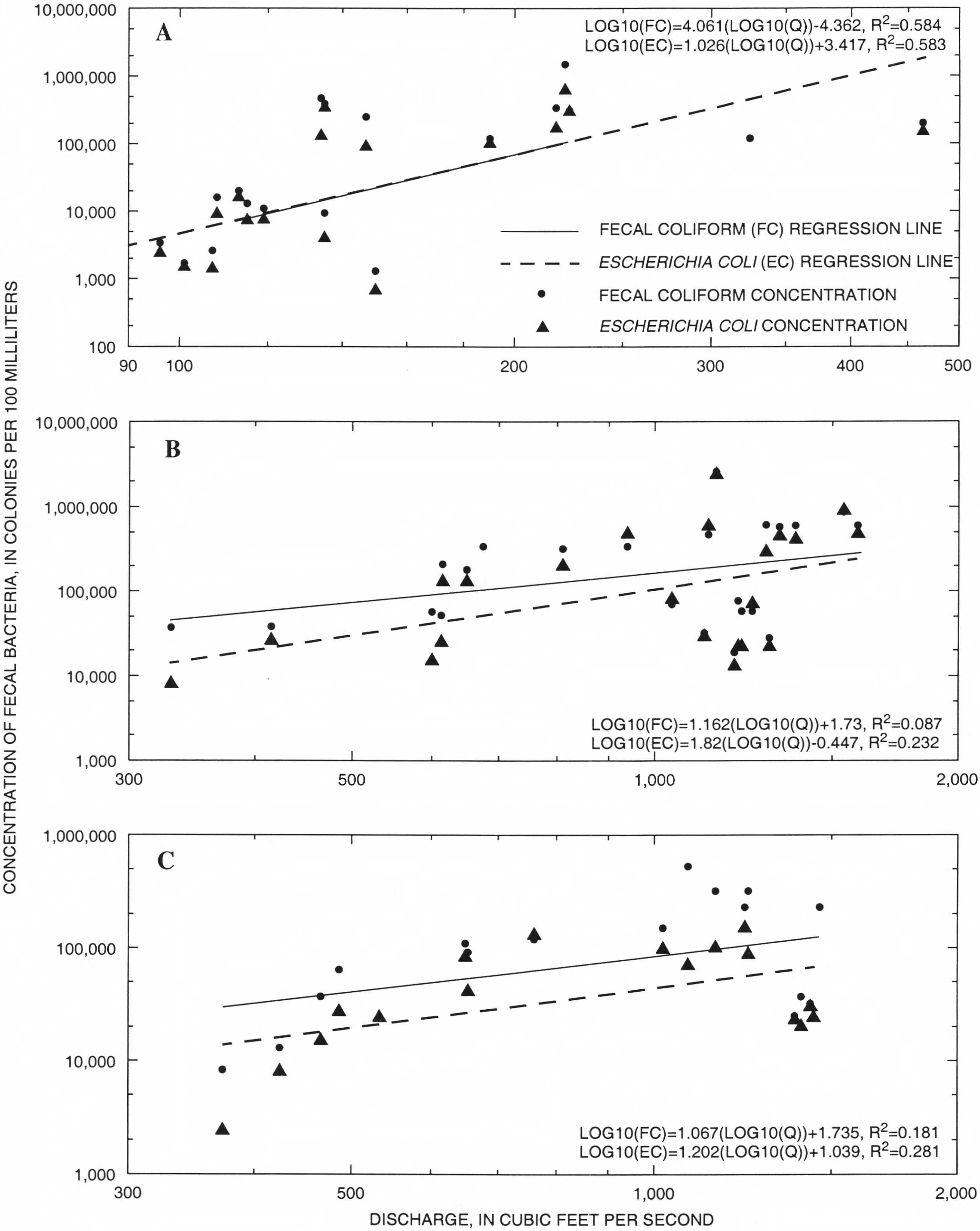


**Figure 8.** Relation between concentration of fecal coliform bacteria and *Escherichia coli* and discharge of (A) the Water Pollution Control Station, and the Cuyahoga River at (B) Botzum, Ohio, and (C) Independence, Ohio. (Abbreviations in the equations are defined in fig. 7, on facing page.)

cross-section width, respectively; and $D_f$, the wave dispersion coefficient. Only the parameters $A_1$, $A_2$, and $D_f$ affect the computed streamflow.

An equation of the form

$$A = A_1(Q_s)^{A_2} + A_0$$

is used in DAFLOW to relate the cross-sectional area (A) to the normal streamflow ($Q_S$). Initial values for model parameters $A_1$ and $A_2$ were determined by assuming $A_0 = 0$ and regressing the logarithm of cross-sectional area on the logarithm of streamflow. The area and corresponding streamflow information were compiled from notes summarizing streamflow measurements obtained to develop stage-discharge ratings at selected sites on the Cuyahoga River and its tributaries.

Although the parameters $W_1$ and $W_2$ do not directly affect the computation of streamflow, initial values of $W_1$ and $W_2$ were estimated to facilitate the estimation of initial values of the wave-dispersion coefficients. An equation of the form

$$W = W_1(Q_s)^{W_2},$$

is used in DAFLOW to relate the channel width (W) to the normal streamflow. In a manner analogous to the area coefficients, the width coefficients were determined by regressing the logarithm of channel width on the logarithm of streamflow. Data necessary to perform the regressions were again compiled from notes summarizing streamflow measurements obtained to develop stage-discharge ratings at selected sites on the Cuyahoga River and its tributaries.

Initial values of the wave-dispersion coefficient ($D_f$) were estimated using the following equation

$$D_f = \frac{Q^{(1-W_2)}}{2S_oW_1},$$

where Q equals the streamflow and $S_o$ equals the bed slope. Bed slope data were obtained from stream profiles presented in published flood-plain information studies (U.S. Army Corps of Engineers, 1968 and 1969).

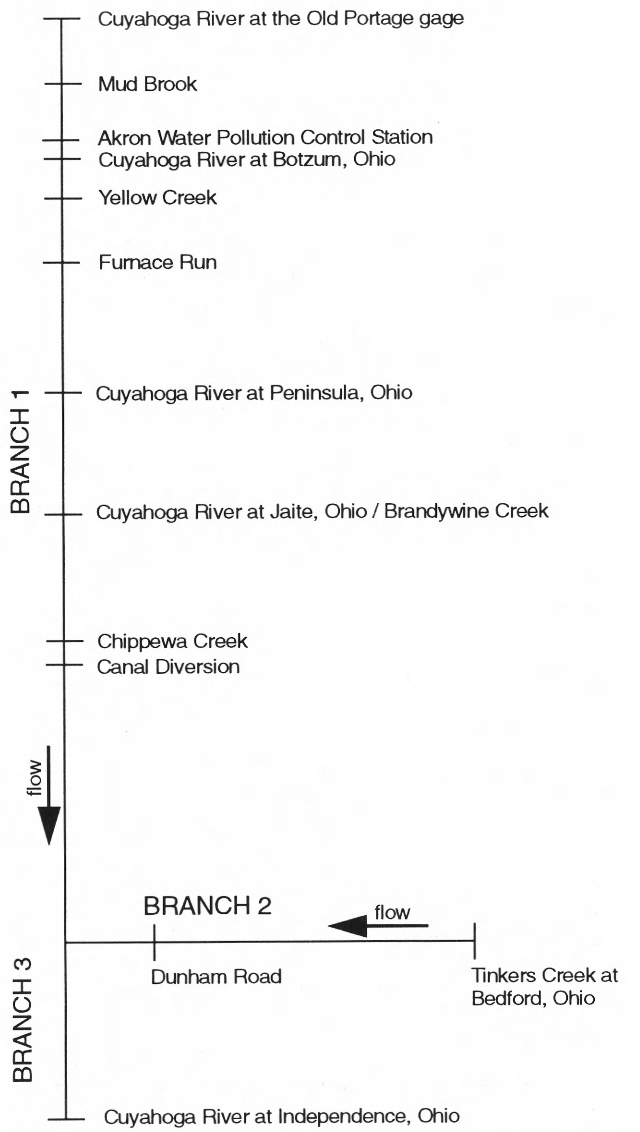


**Figure 9.** Schematization of the Cuyahoga River and Tinkers Creek used for modeling streamflow and constituent transport.

**Model definition.** The study reach was schematized into three branches (fig. 9). The first and third branch represent the middle main stem of the Cuyahoga River within the study area. The second branch represents Tinkers Creek. The first branch extends approximately 23.5 mi from the streamflow-gaging station on the Cuyahoga River known as the Old Portage gaging station to the confluence with Tinkers Creek. The second branch extends approximately 6.5 mi from the streamflow-gaging station on Tinkers Creek at Bedford to its mouth. The third branch extends approximately 3.6 mi from the confluence of Tinkers Creek and the Cuyahoga River to the streamflow-gaging station on the Cuyahoga River at Independence.

Streamflow data from gaging stations on the Cuyahoga River at Old Portage and Tinkers Creek at Bedford were used as boundary conditions for the model. Exceptions were made for the 1992 simulation, when streamflow data obtained at Dunham Road (near Independence, Ohio) were used as the upstream boundary condition for Tinkers Creek, and for the 1993 simulation, when streamflow data obtained at Botzum were used as the upstream boundary condition for the Cuyahoga River. Both exceptions were necessary because data for the respective streamflow-gaging stations and simulation periods were missing or determined to be inaccurate.

In addition to Tinkers Creek, inflows from Mud Brook, the WPCS, Yellow Creek, Furnace Run, Brandywine Creek, and Chippewa Creek were accounted for in the simulations. Inflow information was derived from several sources. Hourly effluent discharge information for the WPCS was provided by the City of Akron's Department of Public Service, Public Utilities Bureau. Streamflow information collected at 15-min intervals at the streamflow-gaging station on Yellow Creek at Botzum, Ohio (approximately 0.8 mi upstream from the confluence with the Cuyahoga River) was used as the Yellow Creek inflow to the Cuyahoga River. The Furnace Run inflow was assumed to be equal to the Yellow Creek inflow multiplied by 0.66, the ratio of the drainage areas of Furnace Run to Yellow Creek. Inflow information for Mud Brook and Brandywine Creek generally was determined on the basis of periodic stage and discharge measurements made during the simulation periods at sites on the respective streams. The stage measurements were used along with stage-discharge ratings developed for this report to supplement the discharge information. Inflow from Chippewa Creek was assumed to be equal to the inflow from Brandywine Creek multiplied by 0.23. The factor 0.23 was determined as the drainage-area ratio of Chippewa Creek to Brandywine Creek, further modified so that the discharge computed for Chippewa Creek from the Brandywine Creek data equaled the discharge measured on Chippewa Creek at a single point in time during the 1993 field exercise.

When applicable, outflow to a canal diversion located on the Cuyahoga River approximately 0.2 mi downstream of the confluence with Chippewa Creek was also accounted for in the simulations. Outflow to the canal diversion only occurred during the 1993 simulation period and was assumed to be a constant 80 $ft^3/s$, based on a single discharge measurement made during the simulation period.

**Flow model calibration and verification.** The DAFLOW model was calibrated by adjusting the hydraulic geometry coefficients and exponents for cross-section area ($A_1$ and $A_2$) so that the timing of observed and simulated streamflow peaks was coincident, and then adjusting the wave dispersion coefficients ($D_f$) so that the peak flow attenuations were accurately reflected. The model, which was run with a 0.1-hr time step, was calibrated on the 1991 and 1993 data sets and verified on the 1992 data set. Because it was impossible to select a single set of model parameters that provided perfect calibration for the 1991 and 1993 simulations, model parameters were chosen to provide the best general fit. Plots showing the observed and simulated streamflows at selected stream locations are shown in figure 10. The most obvious discrepancies between the observed and the simulated streamflows in the calibration simulations occurred at the downstream end of the study reach. Differences between the timing of the observed and simulated peak streamflows were generally small; however, the magnitude of simulated peak streamflows underestimated the observed peaks by an average of 12 percent.

The DAFLOW model was verified by simulating streamflow for the 1992 data set using the model parameters determined by means of the calibration steps just described (fig. 10). The root-mean-square (RMS) errors for the streamflow simulations expressed as a percentage of the mean observed streamflows are shown in table 8.

**Transport model.** The Branched Lagrangian Transport Model (BLTM) (Jobson and Schoellhamer, 1987) was used to numerically simulate constituent transport and decay. BLTM is a one-dimensional water-quality model based on a Lagrangian frame of reference (one in which the computational nodes move with the flow). BLTM solves the one-dimensional convective-dispersion equation for up to 10 constituents moving in as many as 30 branches connected at junctions. Reaction kinetics can be supplied for those constituents that are decayed, produced, and (or) transformed.

The following data are required to run a BLTM simulation: stream cross-section areas, top widths, and velocities at each model grid point for each time step; information on dispersion and minimum dispersive velocities; concentrations of each constituent at each grid point at time zero (initial conditions); and concentrations of each constituent at upstream junctions and in each tributary during each time step (boundary conditions). In this study, the previously described DAFLOW model was used to supply the unsteady flow hydraulics to BLTM; and consequently, the model time step and schematization used for BLTM was identical to that used for the DAFLOW model.

**Transport model calibration.** All model parameters were calibrated against data collected during field studies in one or more calendar years from 1991-93 and verified against data collected in the remaining year or years. The year(s) of field-study data used to calibrate a particular model parameter varied by parameter and were those judged to have the most complete and accurate data. Ultimately, a single set of model parameters (with the exception of decay parameters, which varied as a function of constituent) was used for all constituents to prepare simulations for all three models. Consequently, changes in the simulation results from year to year reflect only those changes due to differences in hydraulics and boundary conditions.

The best calibration was determined by combining visual goodness-of-fit and RMS errors determined by comparing observed concentrations to simulated concentrations. For conservative constituents that do not undergo transformations or decay, calibration of the transport model was accomplished by adjustments to the $A_0$ parameter (the average cross-sectional area at zero flow) in the unsteady flow model and the DQQ parameter (the dimensionless dispersion coefficient) in the transport model. The $A_0$ parameter does not affect the simulated streamflow values, but it does affect

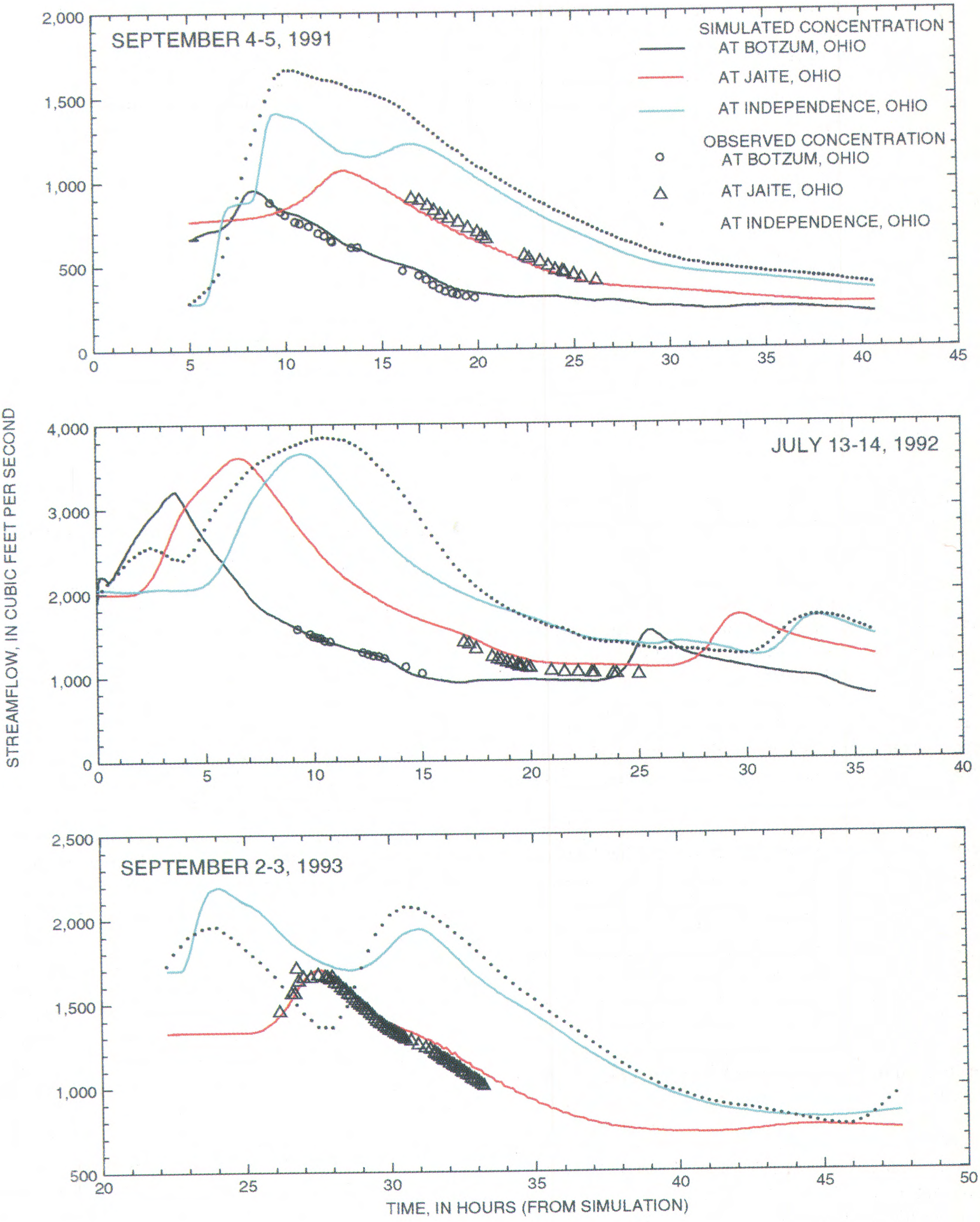


**Figure 10.** Simulated and observed streamflows for the 1991-93 model-year simulations.

**Table 8.** Simulation errors for streamflow and dye concentrations for the model grid points at Botzum, Jaite, and Independence, model years 1991-93

[n/a, not applicable]

| Year | Streamflow or dye concentration | Root-mean-square errors expressed as a percentage of the mean observed streamflow or concentration at indicated grid point | | |
|---|---|---|---|---|
| | | Botzum | Jaite | Independence |
| 1991 | Streamflow | 6.09 | 5.87 | 18.83 |
| | Dye | n/a | 19.72 | 30.11 |
| 1992 | Streamflow | 1.6 | 9.4 | 15.66 |
| | Dye | 31.99 | 14.14 | 5.93 |
| 1993 | Streamflow | n/a | 4.09 | 11.34 |
| | Dye | n/a | 19.28 | 13.36 |

the timing of constituents in transport. The $A_0$ parameter was calibrated by iterative trial and error so that the timing of the observed and simulated dye chemographs was approximately synchronized.

Dispersion is one process by which pollutants are mixed throughout a stream. With respect to dissolved pollutants in a stream system, vertical dispersion is a relatively rapid process, lateral dispersion is much slower, and longitudinal dispersion continues indefinitely (Jobson, 1996). The effect of dispersion on a slug of pollutant is to reduce the peak concentration and lengthen the amount of time it takes for the pollutant plume to pass a given stream cross section.

Results of the dye-tracer studies were used to calibrate and verify DQQ. The calibration was accomplished by means of iterative trial and error methods. The rhodamine WT dye used in this study is not completely conservative. Rhodamine WT dye can undergo changes in mass or concentration due to chemical, biological and (or) physical factors. In particular, small amounts of dye have, in the past, been observed to be lost due to adhesion on sediments, photochemical decay, and, occasionally, chemical degradation (Scott and others, 1969; Tai and Rathbun, 1988; Hetling and O'Connell, 1996). Prior to calibrating DQQ, the measured dye concentrations were adjusted to account for dye losses by application of a tracer-recovery ratio computed as

$$R = \frac{M_r}{M_i} ,$$

where

R is the tracer recovery ratio,
$M_r$ is the mass of tracer recovered, and
$M_i$ is the mass of tracer injected.

Nonconservative constituents are those that decay (undergo changes in mass or concentration) due to chemical, biological, and (or) physical factors. In this study, fecal bacteria were treated as nonconservative constituents and assumed to decay according to a first-order reaction (that is, the rate of loss of fecal bacteria is proportional to the concentration at that point in time) based on rates determined from the decay-rate studies (described in the section titled "Bacterial Decay"). The decay rates shown in table 9 were used for all base simulations[2].

For constituents other than dye, simulation of transport of constituents posed added challenges. Unlike dye, which had a single controlled source, the other constituents had multiple sources with time-varying concentrations that generally could not be measured near ideal frequencies because of physical and monetary constraints. As a result, simplifying assumptions were made to supply boundary condition data at the time step required for the model (0.1 hr). These assumptions generally took one of the following three forms: (1) the concentration at a constituent source was assumed to remain constant over the duration of the simulation, (2) the concentration at a constituent source was assumed to vary as a function of streamflow, or (3) the concentration at a constituent source was assumed to have a chemograph identical to that of another source. Assumptions of form 1 were used when the concentration at a source (as determined from field-based measurements) was relatively invariant and (or) when the available data did not support assumptions of forms 2 or 3. Constant concentrations, when

[2] The term "base simulation" refers to simulations performed when all hydraulic and boundary conditions are set to represent the best estimates of conditions that were prevalent during the time period being simulated.

**Table 9.** Low, high, and base-simulation bacterial decay rates used for sensitivity analysis in transport models

[k in $hr^{-1}$, bacterial decay rates]

| Stream reach | Bacterial decay rates (k), in $hr^{-1}$ | | | | | |
|---|---|---|---|---|---|---|
| | Fecal coliform bacteria | | | Escherichia coli | | |
| | Low rate[1] | Rate used for base simulation | High rate[1] | Low rate[1] | Rate used for base simulation | High rate[1] |
| Old Portage gage to Botzum | 0.0076 | 0.0164 | 0.0176 | 0.0089 | 0.0160 | 0.0180 |
| Botzum to Independence | .0132 | .0186 | .0195 | .0148 | .0176 | .0204 |

[1]Low and high decay rates were selected based on results of decay-rate studies conducted in 1992.

used, were generally determined by taking the arithmetic or geometric mean of concentrations measured from samples collected at the site over 1 or more years. Assumptions of form 2 were used when it was judged that the constituent concentration did vary as a function of discharge, and one or more suitable regression relationships could be developed from the available data. Assumptions of form 3 were used when insufficient data were available to develop a suitable regression relation, and there was reason to believe that the constituent chemograph at one location would be reasonably similar to the chemograph at a second location.

With the exception of the bacterial transport simulations, initial stream concentrations were inferred from first available stream observations. Initial stream concentrations of fecal bacteria were assumed to be zero everywhere due to the paucity of measured initial-condition data and the relatively large variability of bacterial concentrations. Because of uncertainty about initial conditions (for all constituents except dye), the simulation results for the early part of simulation periods are likely to be less accurate than the latter part of the simulation periods (by which time the supplied boundary-condition data would have propagated through the model reach).

**Transport model verification.** Plots of the simulated and observed dye concentrations at selected locations on the Cuyahoga River for all three models are shown in figure 11. The timing of the peak concentrations and the overall shape of the simulated and observed concentration chemographs (graphs of concentration as a function of time) track reasonably well for all three models. The most apparent differences occur in the magnitudes of the observed and simulated peak concentrations; however, there appears to be no tendency to consistently overestimate or underestimate the peak concentrations for all models. RMS errors for the plots range from 0.3 to 9.6 µg/L with all but one of the RMS errors being less than or equal to about 3.7 µg/L. Table 8 shows the RMS errors for the dye simulations expressed as a percentage of the mean observed dye concentrations.

Plots of the simulated and observed chloride concentrations are shown in figure 12. The ragged character of some of the simulated chemographs does not reflect instability in the model, but instead is an artifact of the Lagrangian model algorithm (that can occur at or near input sources). The true concentration curve, just downstream from the grid location, is a smooth curve passing along the maximum points on the ragged curve. Simulation results for chloride were of mixed quality. RMS errors tended to be smallest for the 1992 simulation (3.1 to 6.4 mg/L) and largest for the 1993 simulation (4.9 to 16.7 mg/L). The RMS error of 16.7 mg/L was associated with the simulation for the Cuyahoga River at Jaite in 1993. The relatively large magnitude of this error was the result of one highly influential observation.

Plots of simulated and observed fecal coliform and *E. coli* concentrations are shown in figures 13 and 14. Of the constituents modeled, fecal bacteria exhibited the poorest correspondence between observed and simulated values. This result is not surprising given the relatively large variability in bacterial concentrations and the fairly simple assumptions adopted to supply boundary conditions for bacterial concentration at the frequency required by the model. Rather than discuss chemograph timing issues or RMS errors for the bacterial simulations (which are difficult to interpret in light of the uncertainty about the boundary conditions), it is probably more instructive to view the simulation results in relative terms. The simulation results for dye indicated that the model did a reasonably good job of simulating the timing of dissolved constituents as well as simulating dilution and dispersion effects. Based on these results, the model would also be expected to do a reasonably good job of simulating the transport of fecal bacteria given accurate information on bacterial loadings (boundary conditions) and decay. The effects of uncertainty about bacterial decay rates can be (and were) assessed by means of sensitivity analyses.

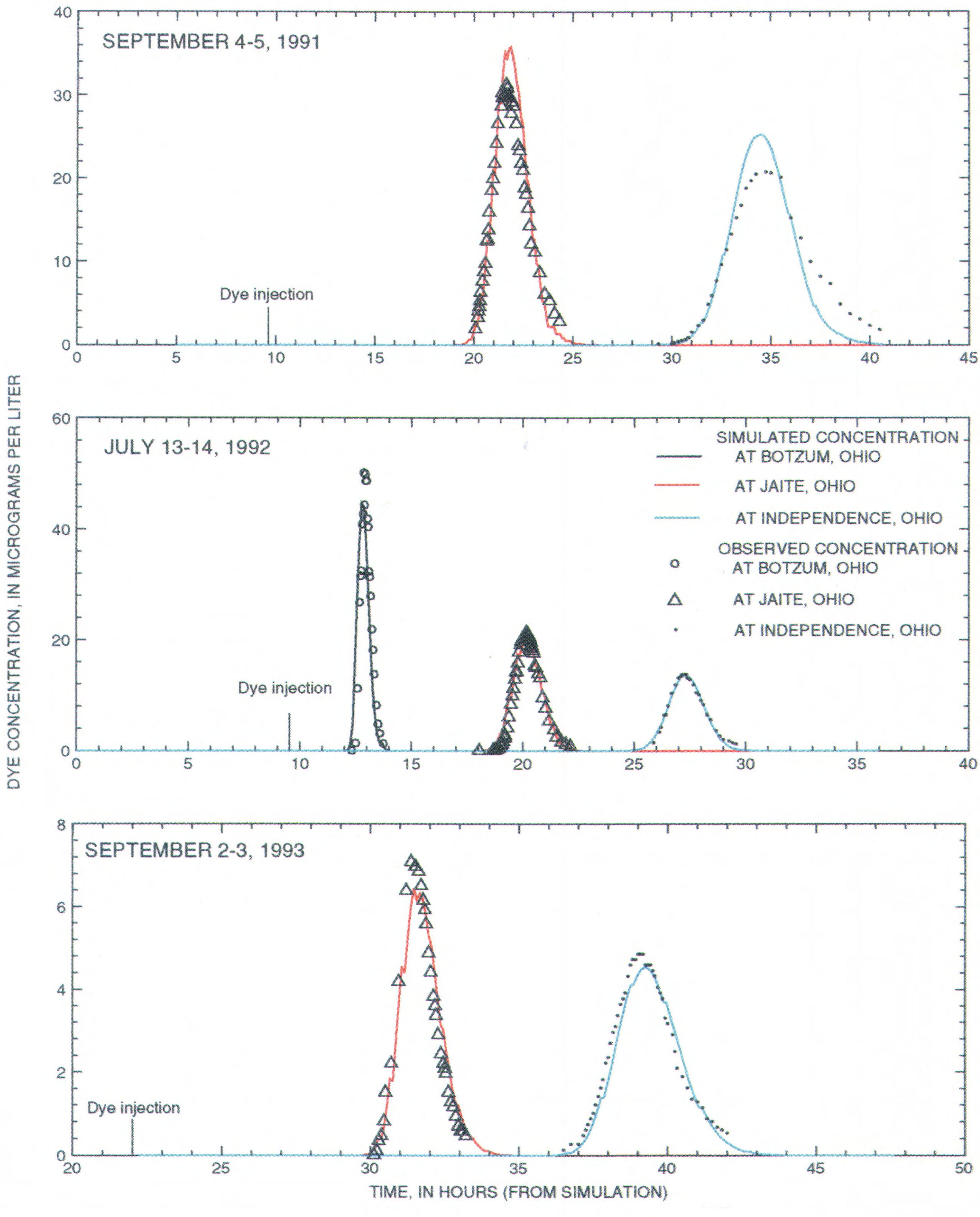


**Figure 11.** Simulated and observed dye concentrations for the 1991-93 model-year simulations.

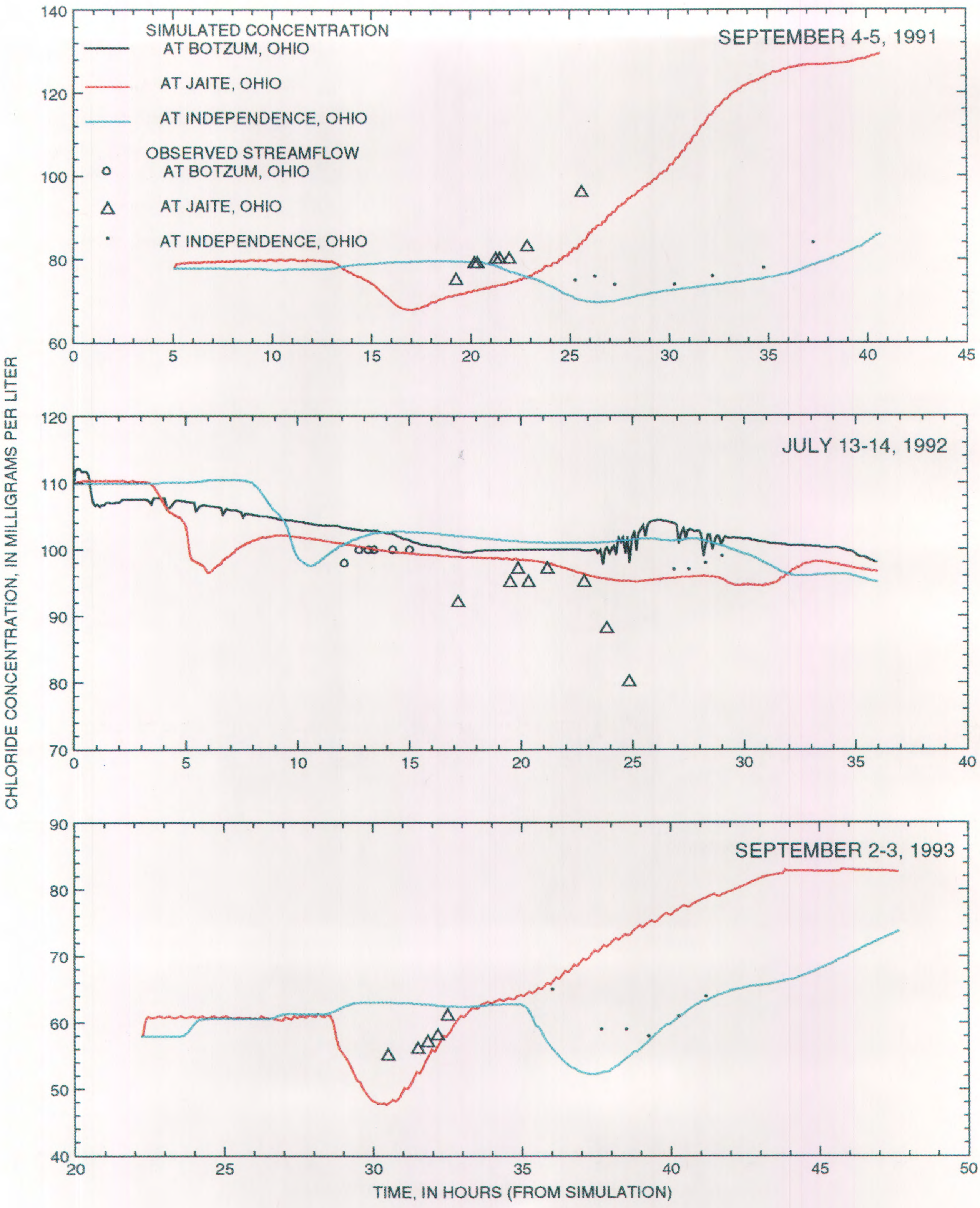


**Figure 12.** Simulated and observed chloride concentrations for the 1991-93 model-year simulations.

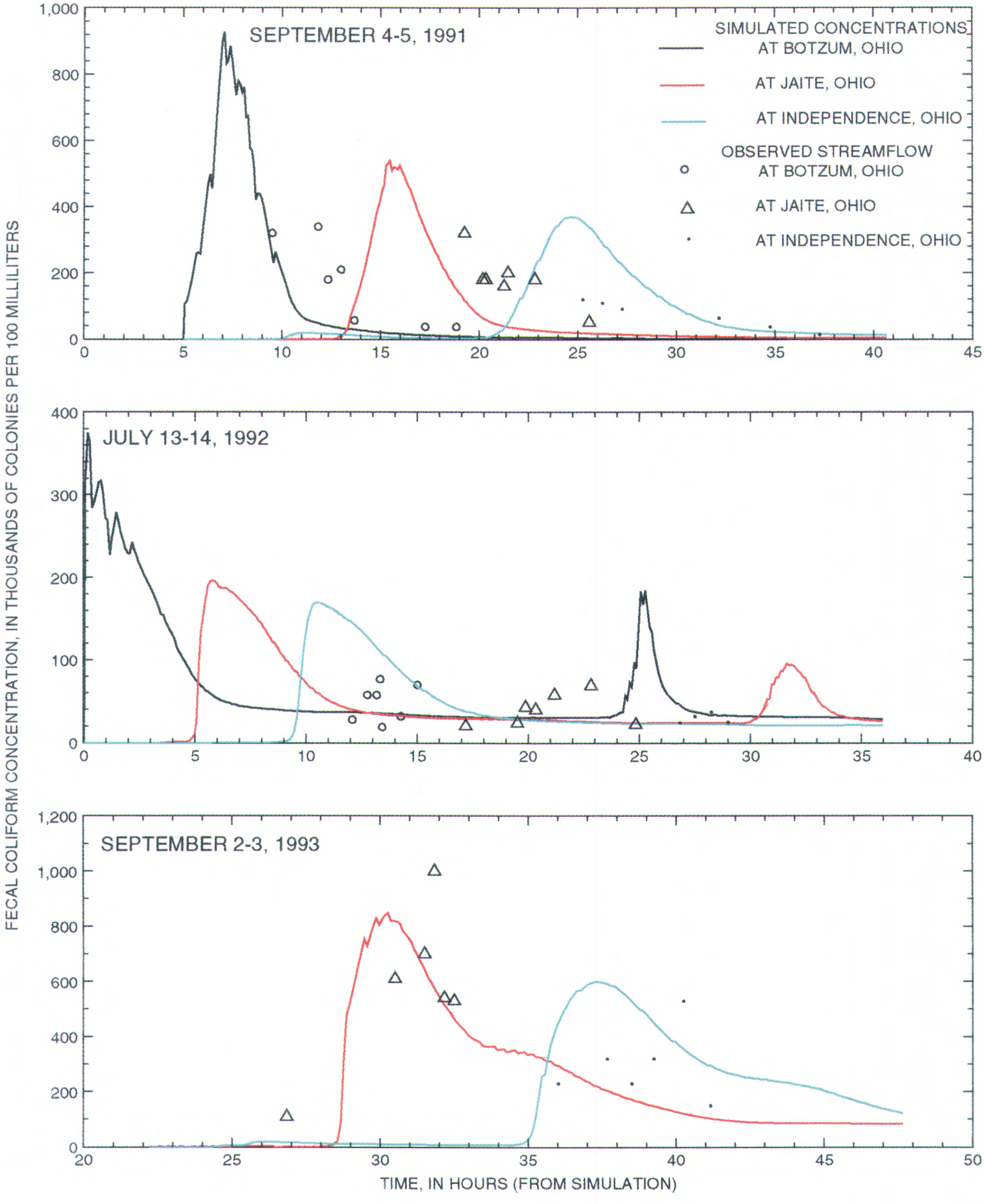


**Figure 13.** Simulated and observed fecal coliform bacteria concentrations for the 1991-93 model-year simulations.

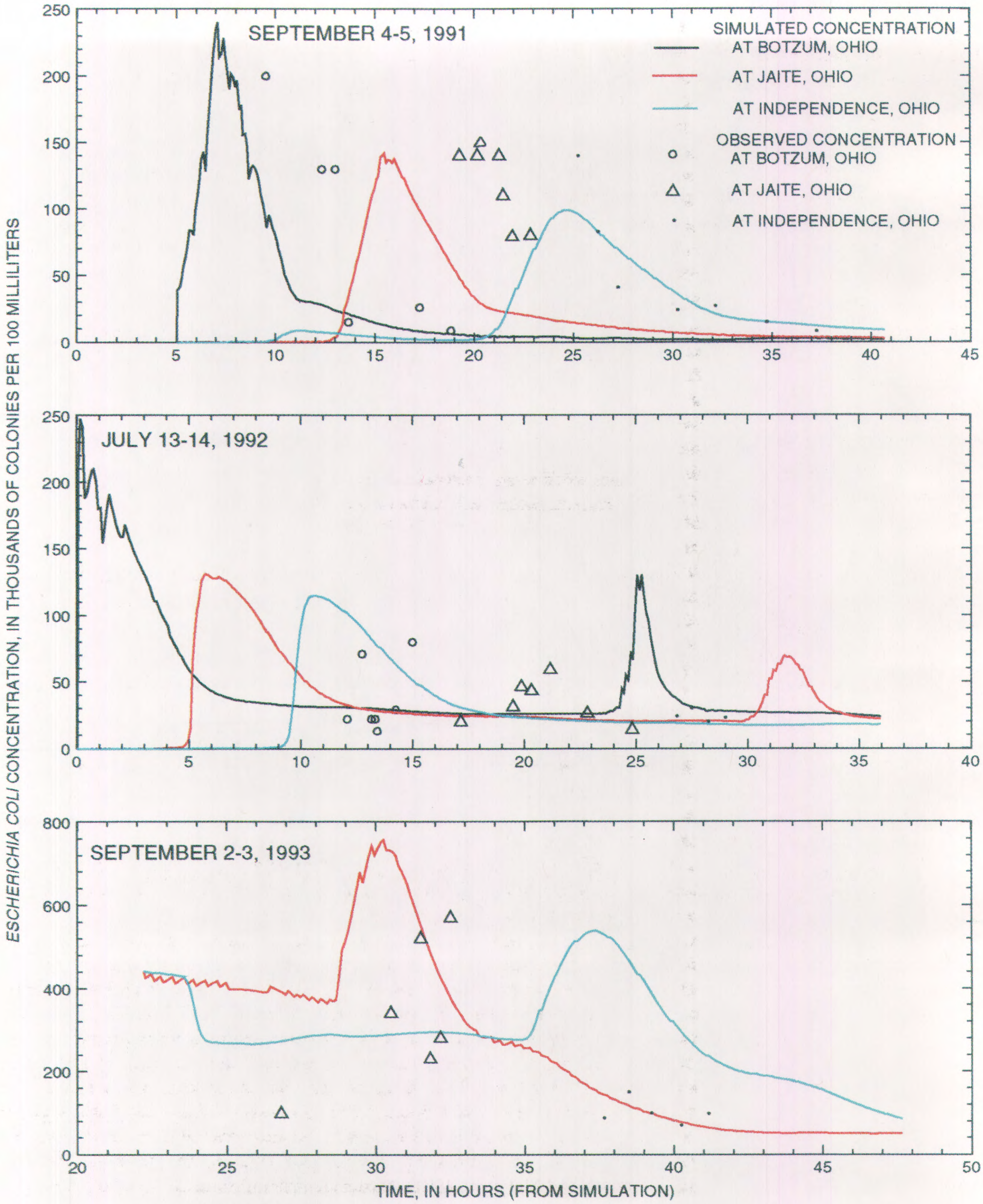


**Figure 14.** Simulated and observed *Escherichia coli* concentrations for the 1991-93 model-year simulations.

If the simulation results are relatively insensitive to the range of expected uncertainty in the decay rates, most of the inaccuracy in the simulated bacterial concentrations should be attributable to uncertainty (or inaccuracy) in the bacterial concentration boundary conditions.

**Model sensitivity to decay rate.** Sensitivity of bacterial simulation results to uncertainty in decay rates was assessed by performing additional simulations where decay rates were set to lower and higher rates than the decay rates used for the base simulations (table 10). The low and high decay rates used for the sensitivity analysis, shown in table 9, were based on results of decay-rate studies conducted in 1992. The peak concentrations simulated for three stream sites (model grid points) in the base simulations were compared to the newly simulated peak concentrations, and the results of those comparisons are summarized in table 10.

Sensitivity to changes in decay rate is greatest at Independence (table 10). This is because Independence is furthest from some of the largest sources of bacterial loading in the model reach and represents the simulation grid point at which bacterial inputs had the greatest opportunity to decay. The largest change in simulated maximum bacterial concentration (9.88 percent) resulted from reductions in reach-based decay rates that ranged from about 29 to 54 percent of base-simulation decay rates. The variations in decay rates did not produce large changes in simulated concentrations; therefore, most of the variability in the model predictions can be attributed to the uncertainty in concentrations of fecal bacteria.

## Simulated reductions in concentrations of fecal bacteria

Simulations of bacterial transport and decay under base-simulation conditions indicate that, for all models, the maximum instream bacterial concentrations at Botzum, Jaite, and Independence far exceeded Ohio's single-sample primary- and secondary-contact water-quality standards for fecal coliform bacteria and *E. coli*. Two important sources of bacterial loading to the model reach are the WPCS and sources, such as CSOs, which intermittently discharge bacteria and flow to the middle main stem of the Cuyahoga River as it enters the model reach at the Old Portage gaging station. Several scenarios involving reductions in bacterial concentrations were simulated to assess the relative effects of the WPCS and Old Portage boundary conditions on bacterial concentrations at Botzum, Jaite, and Independence. The scenarios, which were simulated for 1991-92 models, involved separate or concurrent reductions in bacterial boundary-condition concentrations at the Old Portage gaging station and the WPCS. All flows and other boundary conditions were left unchanged from base-simulation levels.

Scenarios involving 50- and 90-percent reductions in the base-simulation concentrations were tested for the Old Portage and WPCS boundary conditions. In addition, simulations where the WPCS boundary conditions were set to Ohio's geometric mean bathing-water standards of 200 col/100 mL for fecal coliform bacteria and 126 col/100 mL for *E. coli* were also tested.

**Table 10.** Percent change in predicted bacterial concentrations at Botzum, Jaite, and Independence resulting from the use of low and high bacterial decay rates in the base simulation

[nd, not determined]

| Year | Bacteria type | Percent change in peak concentrations in the base simulation resulting from use of low/high decay rates at indicated grid points | | |
|---|---|---|---|---|
| | | Botzum | Jaite | Independence |
| 1991 | Fecal coliform | 0.11/-0.01 | 4.64/-0.76 | 9.88/-1.54 |
| | *Escherichia coli* | 0.08/0.00 | 2.39/-2.32 | 5.03/-4.72 |
| 1992 | Fecal coliform | 0.11/0.00 | 2.94/-0.51 | 5.51/-0.88 |
| | *Escherichia coli* | 0.08/-0.04 | 1.52/-1.52 | 2.78/-2.69 |
| 1993 | Fecal coliform | nd | 4.41/0.0 | 7.85/-1.17 |
| | *Escherichia coli* | nd | 2.85/-0.94 | 3.87/-3.89 |

The geometric mean bathing-water standards were used instead of the less stringent primary-contact standard of 1,000 col/100 mL for fecal coliform bacteria, which is currently specified in the discharge permit of the Akron WPCS, to assess the effect of a "best case" scenario. In this instance, the "best case" refers to a condition in which fecal-bacteria concentrations in the WPCS effluent do not exceed the geometric-mean concentrations established for bathing waters. Concurrent boundary-condition-reduction scenarios were limited to combinations in which the WPCS boundary conditions were reduced to 200 col/100 mL for fecal coliform bacteria and 126 col/100 mL for *E. coli* and the Old Portage boundary conditions were reduced 50 and 90 percent from base-simulation levels. For the purposes of further discussion, the most stringent source control scenarios (where the WPCS boundary conditions was reduced to the geometric-mean Bathing Water Standard, 200 col/100 mL for fecal coliforms and 126 col/100 mL for *E. coli*, and the Old Portage boundary conditions were reduced 90 percent from base-simulation levels) will hereafter be referred to as the BWS/90 scenarios.

As shown in tables 11 and 12, reducing base-simulation concentrations by 50 and 90 percent at the Old Portage gaging station resulted in little or no reduction in peak simulated bacterial concentrations at Botzum, Jaite, and Independence. In contrast, reductions in boundary conditions at the WPCS resulted in appreciable reductions in peak simulated bacterial concentrations at Botzum, Jaite, and Independence (tables 13 and 14). These results indicated that, for conditions simulated, the WPCS is by far the larger, and consequently the more important of the two sources of bacterial loading to the middle main stem of the Cuyahoga River within the CVNRA. It is worth noting that all of the reduction scenarios considered so far resulted in peak simulated bacterial concentrations at the Botzum, Jaite, and Independence that exceeded Ohio's geometric mean and single-sample numerical standards for primary- and secondary-contact recreation waters.

Results of simulations where boundary conditions at the WPCS were set to 200 col/100 mL for fecal coliforms and 126 col/100 mL for *E. coli* and boundary conditions at the Old Portage gaging station were reduced by 50 and 90 percent over base-simulation conditions are shown in tables 15 and 16. Simulation results indicate that even under these fairly stringent reduction scenarios, peak concentrations of fecal bacteria at Botzum, Jaite, and Independence still exceed Ohio's single-sample and geometric mean numerical standards for primary- and secondary-contact recreation waters. This result is not entirely unexpected since peak bacterial boundary-condition concentrations at the Old Portage gaging station ranged from 41,000 to 59,000 col/100 mL for fecal coliform bacteria and from 35,000 to 48,000 col/100 mL for *E. coli* in the 1991-92 base simulations. Consequently, a 90-percent reduction in base-simulation concentrations at the Old Portage gaging station results in peak bacterial concentrations that are an order of magnitude greater than the single-sample primary-contact recreation standards for *E. coli* and several factors higher than a the 2,000 col/100 mL similar standard for fecal coliform bacteria. It is also important to note that bacteria sources in the model reach, other than those at the Old Portage gaging station and the WPCS, remained at base-simulation concentration levels and consequently also contributed to the elevated bacterial concentrations. These results suggest that meeting primary-contact recreation standards in the middle main stem of the Cuyahoga River during rainfall and runoff periods will require major reductions in bacterial concentrations from sources upstream of the Old Portage gaging station as well as from the WPCS.

**Table 11.** Predicted peak concentrations of fecal coliform bacteria at Botzum, Jaite, and Independence resulting from simulated reductions in concentrations of fecal coliform bacteria of 50 and 90 percent at the Old Portage gage grid point

[Concentrations reported in thousands of colonies per 100 milliliters]

| | Predicted peak fecal coliform concentrations at indicated model grid points resulting from indicated percent reduction in boundary condition concentrations at the Old Portage gage (percentage reduction) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | at Botzum | | | at Jaite | | | at Independence | | |
| **Year** | **0[1]** | **50** | **90** | **0[1]** | **50** | **90** | **0[1]** | **50** | **90** |
| **1991** | 930 | 930 | 930 | 540 | 540 | 540 | 370 | 370 | 370 |
| **1992** | 360 | 360 | 360 | 200 | 200 | 200 | 170 | 170 | 170 |

[1] Base simulation.

**Table 12.** Predicted peak concentrations of *Escherichia coli* at Botzum, Jaite, and Independence resulting from simulated reductions in concentrations of *Escherichia coli* of 50 and 90 percent at the Old Portage gage grid point

[Concentrations reported in thousands of colonies per 100 milliliters]

| Year | Predicted peak *Escherichia coli* concentrations at indicated grid point resulting from indicated percent reduction to boundary condition concentrations at the Old Portage gage (percentage reduction) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | at Botzum | | | at Jaite | | | at Independence | | |
| | 0[1] | 50 | 90 | 0[1] | 50 | 90 | 0[1] | 50 | 90 |
| **1991** | 240 | 240 | 240 | 140 | 140 | 140 | 100 | 99 | 98 |
| **1992** | 240 | 240 | 240 | 130 | 130 | 130 | 120 | 110 | 110 |

[1] Base simulation.

**Table 13.** Predicted peak concentrations of fecal coliform bacteria at Botzum, Jaite, and Independence resulting from simulated reductions in concentrations of fecal coliform bacteria of 50 and 90 percent and to bathing-water standards for the effluent at the Water Pollution Control Station

[WPCS, Water Pollution Control Station; BWS, geometric-mean bathing-water standard for fecal coliform bacteria of 200 colonies per 100 milliliters; concentrations reported in thousands of colonies per 100 milliliters]

| Year | Predicted peak fecal coliform concentrations at indicated grid point resulting from indicated reduction to boundary condition concentrations at the WPCS (percentage reduction) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | at Botzum | | | | at Jaite | | | | at Independence | | | |
| | 0[1] | 50 | 90 | BWS | 0[1] | 50 | 90 | BWS | 0[1] | 50 | 90 | BWS |
| **1991** | 930 | 470 | 100 | 66 | 540 | 280 | 71 | 45 | 370 | 190 | 52 | 31 |
| **1992** | 360 | 180 | 56 | 37 | 200 | 100 | 41 | 29 | 170 | 92 | 36 | 25 |

[1] Base simulation.

**Table 14.** Predicted peak concentrations of *Escherichia coli* at Botzum, Jaite, and Independence resulting from simulated reductions in concentrations of *Escherichia coli* of 50 and 90 percent and to bathing-water standards for the effluent at the Water Pollution
Control Station

[WPCS, Water Pollution Control Station; BWS, geometric-mean bathing-water standard for *Escherichia coli* concentrations of 126 colonies per 100 milliliters; concentrations reported in thousands of colonies per 100 milliliters]

| Year | Predicted peak *Escherichia coli* concentrations at indicated grid point resulting from indicated reduction to boundary condition concentrations at the WPCS (percentage reduction) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | at Botzum | | | | at Jaite | | | | at Independence | | | |
| | 0[1] | 50 | 90 | BWS | 0[1] | 50 | 90 | BWS | 0[1] | 50 | 90 | BWS |
| **1991** | 240 | 120 | 38 | 32 | 140 | 73 | 27 | 22 | 100 | 52 | 19 | 16 |
| **1992** | 240 | 120 | 43 | 32 | 130 | 74 | 32 | 24 | 120 | 65 | 29 | 21 |

[1] Base simulation.

**Table 15.** Predicted peak concentrations of fecal coliform bacteria at Botzum, Jaite, and Independence, resulting from simulated reductions in concentrations of fecal coliform bacteria of 50 and 90 percent at the Old Portage gage and the Water Pollution Control Station boundary condition set to 200 colonies per 100 milliliters

[WPCS, Water Pollution Control Station; concentrations reported in thousands of colonies per 100 milliliters]

| Year | Predicted peak fecal coliform concentrations at indicated grid point resulting from indicated reduction to boundary condition concentrations at Old Portage and the WPCS boundary condition concentration set to 200 colonies per 100 milliliters<br>Percentage reduction | | | | | |
|---|---|---|---|---|---|---|
| | at Botzum | | at Jaite | | at Independence | |
| | 50 | 90 | 50 | 90 | 50 | 90 |
| 1991 | 46 | 30 | 32 | 22 | 23 | 20 |
| 1992 | 19 | 5.6 | 16 | 5.9 | 14 | 7.7 |

**Table 16.** Predicted peak concentrations of *Escherichia coli* at Botzum, Jaite, and Independence resulting from simulated reductions in concentrations of *Escherichia coli* of 50 and 90 percent at the Old Portage gage and the Water Pollution Control Station boundary condition set to 126 colonies per 100 milliliters

[WPCS, Water Pollution Control Station; concentrations reported in thousands of colonies per 100 milliliters]

| Year | Predicted peak *Escherichia coli* concentrations at indicated grid point resulting from indicated reduction to boundary condition concentrations at Old Portage and the WPCS effluent concentration set to 126 colonies per 100 milliliters<br>Percentage reduction | | | | | |
|---|---|---|---|---|---|---|
| | at Botzum | | at Jaite | | at Independence | |
| | 50 | 90 | 50 | 90 | 50 | 90 |
| 1991 | 16 | 3.6 | 12 | 3.4 | 8.9 | 8.9 |
| 1992 | 16 | 4.2 | 13 | 4.4 | 12 | 5.1 |

## Implications for management of recreational waters

The results of simulations of bacterial transport for rainfall and runoff periods in 1991 and 1992 indicate that the Akron WPCS was the largest single source of fecal bacteria to the middle main stem of the Cuyahoga River in the CVNRA. Results of source-reduction simulations indicated that during rainfall and runoff, minimal improvement in bacteriological water quality would result from management of sources in the watershed upstream from the Old Portage gaging station unless the effluent from the WPCS receives almost complete disinfection. Results of source-reduction simulations further suggest that even when discharges from the WPCS meet Ohio's geometric-mean bathing-water standards for fecal bacteria, reductions in concentrations of fecal bacteria from sources in the upper watershed of greater than 90 percent also may be needed to meet standards for primary-contact recreation in the CVNRA.

Of the source-reduction scenarios simulated, the greatest improvement to bacteriological water quality in the middle main stem was achieved when concentrations of fecal bacteria at the Old Portage gaging station were reduced by 90 percent and the discharges from the WPCS were reduced to a constant 200 col/100 mL for fecal coliform bacteria and 126 col/100 mL for *E. coli*. This simulation came the closest to resulting in bacteriological water quality that meets the standards for primary-contact recreation. The results of this simulation will be the focus of the remaining discussion.

Natural processes alone cannot reduce fecal-bacteria concentrations by the amount needed to achieve standards for primary-contact recreation in the CVNRA. Base simulations for the 1991 and 1992 models showed that natural processes can reduce peak concentrations of fecal coliform bacteria by 52.8 to 60.2 percent and peak concentrations of *E. coli* by 50.0 to 58.3 percent (figs. 15 and 16, tables 11 and 12) during the 35- to 40-hr traveltimes in the middle main stem from the Old Portage gaging station to the

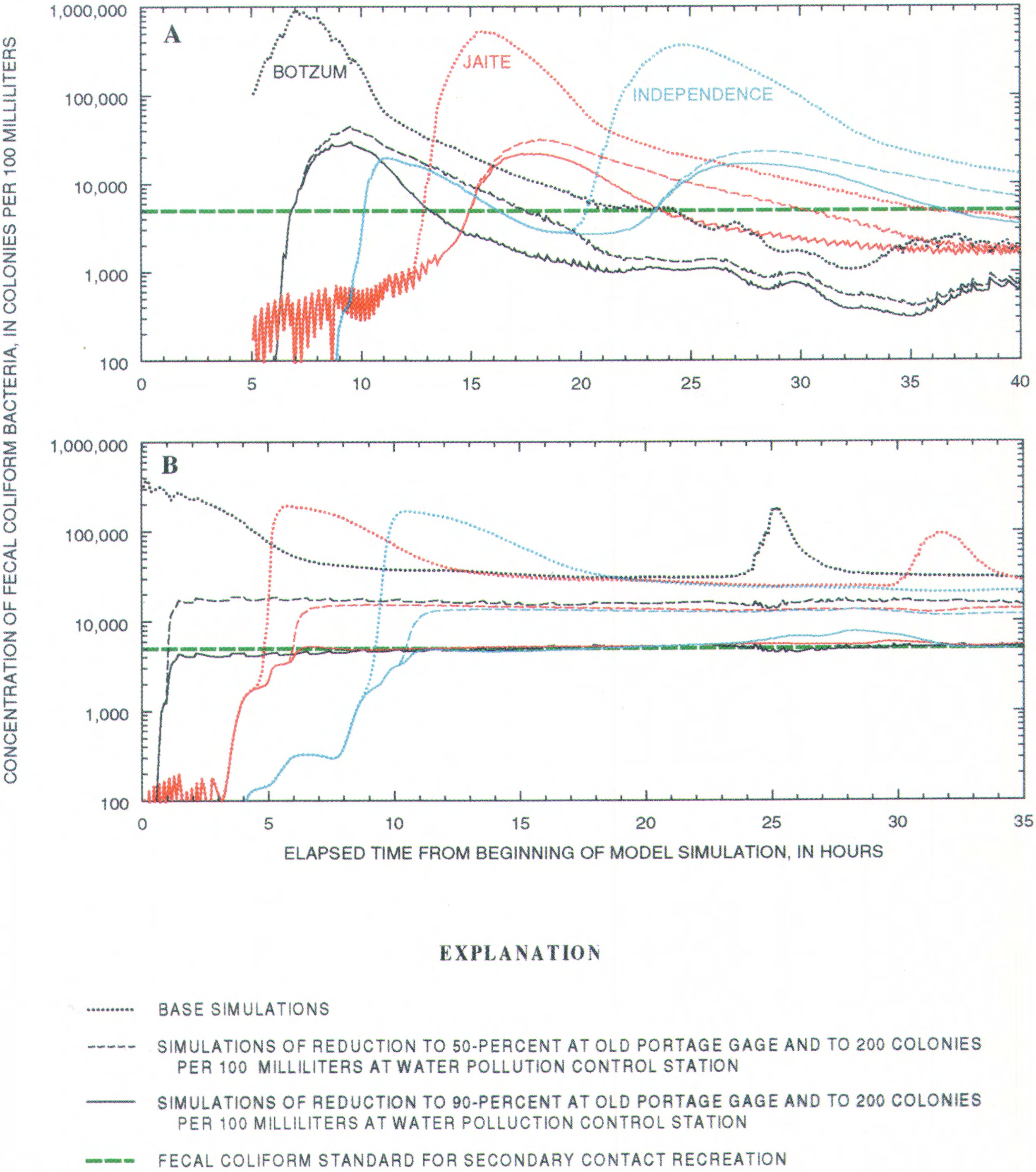


**Figure 15.** Simulations of reductions in concentrations of fecal coliform bacteria in the Cuyahoga River at Botzum, Jaite, and Independence, Ohio, in model years (A) 1991 and (B) 1992.

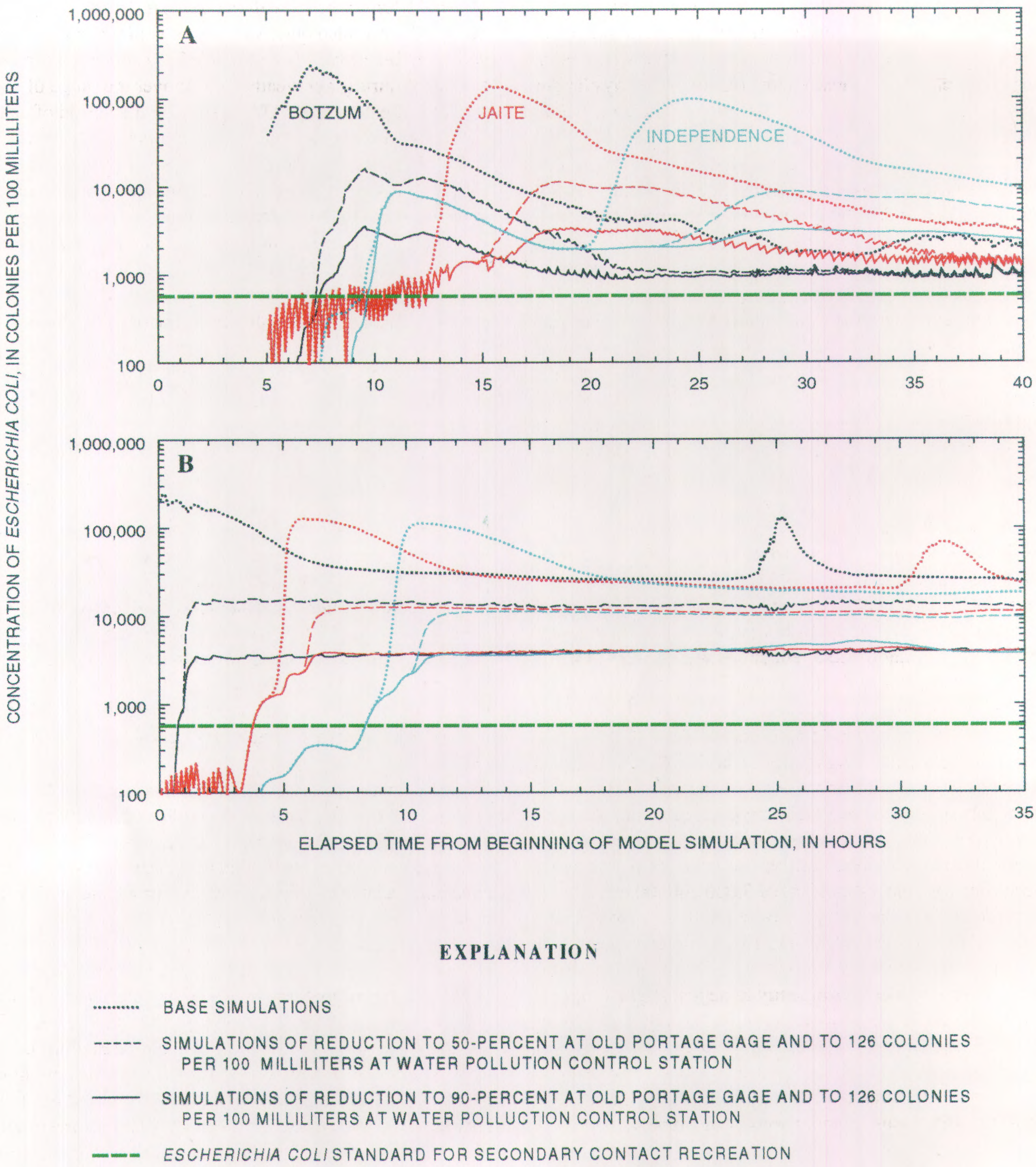


**Figure 16.** Simulations of reductions in concentrations of *Escherichia coli* in the Cuyahoga River at Botzum, Jaite, and Independence, Ohio, in model years (A) 1991 and (B) 1992.

Independence gaging station. However, the magnitude of reduction in concentrations resulting from natural processes of bacterial decay, dilution, dispersion, and transport could vary to the extent that those factors are controlled by climate, hydrology, and meteorological conditions, which can vary from storm to storm.

Simulated reductions associated with the BWS/90 scenarios (simulations for which the boundary-condition-concentrations at the Old Portage gaging station were reduced by 90 percent and the boundary condition concentrations at the WPCS were reduced to 200 col/100 mL for fecal coliform bacteria and 126 col/100 mL for *E. coli*) did not reduce concentrations sufficiently to achieve either geometric mean or single-sample primary-contact standards in the middle main stem of the Cuyahoga River for the storms modeled in 1991 and 1992. Simulated reductions associated with the BWS/90 scenarios for the 1991 model studies showed that concentrations of fecal coliform bacteria can be reduced by a total of 96.7 percent at Botzum, by a total of 95.9 percent at Jaite, and by a total of 94.6 percent at Independence (tables 15 and 16). Likewise, the BWS/90 scenarios for the 1991 model showed that concentrations of *E. coli* can be reduced by a total of 98.5 percent at Botzum, by a total of 97.5 percent at Jaite, and by a total of 91.1 percent at Independence compared to base simulation scenarios (tables 15 and 16). Similar percent reductions were observed with the BWS/90 scenarios for the 1992 models (tables 15 and 16).

Even though secondary-contact standards are not applicable to the Cuyahoga River in the CVNRA, it is useful to compare simulations to these standards as an indicator of the degree of improvement that might be achieved through source reductions. In the 1991 simulation, the maximum length of time when fecal coliform concentrations exceeded the secondary-contact standard of 5,000 col/100 mL decreased from 17 hr to 8 hr at Botzum, from 23 to 8 hr at Jaite, and from more than 20 hr to 13 hr at Independence (fig. 15). In the 1992 simulation, concentrations of fecal coliform bacteria were reduced sufficiently to be just slightly higher than the secondary-contact standard for the entire period of the simulation (fig. 15). None of the simulations done for this report resulted in attainment of primary-contact standards or secondary-contact standards for *E. coli* in the middle main stem (fig. 16). Again, comparisons of this type help to answer the question of "how long after rainfall and runoff will water-quality standards be exceeded in the Cuyahoga River?"

The dynamic nature of urban rainfall and runoff and fecal contamination in the middle main stem creates a challenge for water-quality managers in terms of controlling sources. During the field studies, the flow and bacteriological quality of the river changed by factors of 2 to 3 in as many hours and changed by a factor of 10 in 10 to 12 hr. Streamflows and rainfall amounts measured during rainfall and runoff studies were typical of conditions that are commonly observed during the recreational season. The discharge from the WPCS was also quite variable in volume and quality. In addition, the effluent from the WPCS received only partial treatment during wet weather flows over the range of 107-280 Mgal/d (166-433 $ft^3/s$) during the period of data collection (Dave Crandell, written commun., October, 1997). The discharge from the WPCS varied from 45-317 Mgal/d (70-490 $ft^3/s$), which in some cases was above the range of what could be adequately disinfected. If a reduction in bacterial concentrations (and consequently, the disease-producing potential) of storm-generated flows is desired, then highly variable amounts and qualities of sewage would need to be disinfected. Typically, reductions of that nature are accomplished by use of high-rate disinfection practices and disinfection facilities that are adaptable to intermittent use and varying dosage requirements (O'Shea and Field, 1991).

During the period of the study, the WPCS underwent improvements in treatment. As a result of construction activities associated with improvements at the WPCS, the plant was operating at about 83 percent of full capacity and the disinfection system was not operating properly (Dave Crandell, written commun., October, 1997). A change in the disinfectant and certain other adjustments in the disinfection system were made at the WPCS after this study was completed. There may still be secondary bypasses of similar quality to those monitored for this report when the effluent discharge rises above 107 Mgal/d, the level above which disinfection is incomplete (Dave Crandell, written commun., October, 1997).

Estimates of the 90 $ft^3/s$ threshold for the 1991-93 studies could be a reflection of a reduced capacity to completely disinfect effluents during those years. The flow of 90 $ft^3/s$, identified as a threshold in the transport studies, may have been related to a flow above which adequate disinfection could not be maintained at the WPCS; however, this is not consistent with what was reported by the City of Akron for that time (Dave Crandell, written commun., October, 1997). Further refinement in identifying the current threshold could be important in terms of predicting and managing effluent quality. If such a threshold could be established and found dependable, then monitoring the discharge might be one way of predicting, at least in part, "when and for how long the river will be contaminated after rainfall and runoff."

The larger implication of this work is that reductions in bacterial contamination in the middle main stem of the Cuyahoga River would likely result in a decrease in the health risk to recreational users regardless of whether or not primary-contact water-quality standards are achieved because the risk of illness from immersion in fecal-contaminated water is directly related to the concentration of *E. coli*. The relation between swimmer illness and sewage contamination was demonstrated in a study that showed a statistically significant relation between the concentrations of *E. coli* and "highly credible" cases of gastroenteritis among swimmers studied at several beaches around the nation (Dufour, 1984). In those studies, fecal coliform concentrations were not shown to be predictive of illness in swimmers.

The public-health benefits of reducing concentrations of fecal bacteria in the Cuyahoga River can be estimated by comparing the risks associated with the BWS/90 scenarios and base simulations. Peak concentrations from the base and BWS/90 scenario simulations were inserted into the risk equation (Dufour, 1984) shown below for the middle main stem sites at Botzum, Jaite, and Independence. Although the risk equation developed by Dufour (1984) requires use of a geometric mean *E. coli* concentration, for purposes of example, the risk estimates in this report were computed by using the maximum simulated (peak) concentration, which may be more comparable to a single-sample concentration than a geometric-mean concentration. The predicted peak *E. coli* concentrations associated with the BWS/90 scenarios for 1991 and 1992 models (table 16) were inserted into the following equation:

$$y=-11.74 + 9.397(\log10(x)),$$

where y = swimming-associated gastrointestinal symptom rate per 1,000 swimmers, and

x = geometric mean *E. coli* concentration, in col/100 mL.

The risks associated with the peak concentrations from the BWS/90 scenarios in 1991 are 22, 21, and 25 illnesses per 1,000 swimmers for the Botzum, Jaite, and Independence, and in 1992 are 22, 22, and 23 respectively (table 17). The risks associated with the predicted peak concentrations in 1991 and 1992 models from the base simulations are 39, 37, and 35 illnesses per 1,000 swimmers.

Compared to the risk of 8 illnesses per 1,000 swimmers when the primary-contact water-quality standard of 126 col/100 mL is attained for *E. coli*, risks associated with the BWS/90 scenarios are higher than acceptable by factors of 2.6 to 3.1. Risks associated with the base simulation are higher than acceptable by a factor of 4.6 to 4.9. Although peak concentrations predicted by the BWS/90 scenarios are higher than *E. coli* standards, the reductions in risk of illness by 28.6 to 43.6 percent are improvements.

The maximum benefit to water quality predicted by model simulations in terms of reduced risk appears to be at Botzum, just below the WPCS. Compared to the health risk from immersion at Botzum, the slightly higher peak concentrations and correspondingly higher risks observed at the two downstream locations, Jaite and Independence (table 17, figs. 15 and 16), are likely the result of tributary contributions. Under the BWS/90 scenario simulations, additional reductions in tributary inputs of fecal bacteria would be needed to gain additional benefits to the recreational quality of the middle main stem within the CVNRA.

**Table 17.** Predicted peak concentrations of *Escherichia coli*, risk rate to swimmers, percent reduction in peak concentrations, and percent reduction in risk associated with concentrations of *Escherichia coli* predicted by the BWS/90 simulation compared to the base simulation for Botzum, Jaite, and Independence in model years 1991-92

[*E. coli*, *Escherichia coli*, all concentrations are in colonies per 100 milliliters; BWS/90, where the Water Pollution Control Station boundary conditions are 126 colonies per 100 milliliters and the boudary conditions at the Old Portage gage are reduced 90 percent from the base simulation]

| Cuyahoga River at | (1) Predicted peak concentration for *E. coli* associated with the base simulation | (2) Predicted peak concentration for *E. coli* associated with the BWS/90 scenario | Risk per 1,000 swimmers associated with peak concentration in (1) | Risk per 1,000 swimmers associated with peak concentration in (2) | Percent reduction in peak concentrations of *E. coli* associated with (2) when compared to the base simulation | Percent reduction in risk associated with (2) when compared to the base simulation |
|---|---|---|---|---|---|---|
| | | | **1991 simulation** | | | |
| **Botzum** | 240,000 | 3,600 | 39 | 22 | 98.5 | 43.6 |
| **Jaite** | 140,000 | 3,400 | 37 | 21 | 97.5 | 43.2 |
| **Independence** | 100,000 | 8,900 | 35 | 25 | 91.1 | 28.6 |
| | | | **1992 simulation** | | | |
| **Botzum** | 240,000 | 4,200 | 39 | 22 | 98.3 | 43.6 |
| **Jaite** | 130,000 | 4,400 | 37 | 22 | 96.6 | 40.5 |
| **Independence** | 120,000 | 5,100 | 35 | 23 | 95.8 | 34.3 |

From a national perspective, recent studies of waterborne diseases associated with recreation (Center for Disease Control, 1991) indicate that during the period 1988-89, 18 states reported 30 outbreaks of illness from exposure to contaminated recreational waters, resulting in 1,062 affected people. A more recent study by Kramer and others (1996) for the period 1993-94 indicated that 9 states reported 14 outbreaks, resulting in 1,437 affected people.

From a regional perspective, Fuller (1996) reported that in 1995, the Ohio Department of Health collected 485 samples from beaches along Lake Erie and reported 67 standards violations, which represent a frequency of about 14 percent. These violations resulted in 10 beach closings (Fuller, 1996). Combined-sewer, sanitary-sewer, and storm-water overflows to beach areas across the nation were cited as the most probable causes of the closings (Fuller, 1996). Although these incidents were not known to be associated with the study area or conditions described in this report, this information underscores the importance of monitoring for concentrations of fecal bacteria in recreational waters and the importance of adequate disinfection for control of waterborne-disease outbreaks.

## Summary

Discharges from storm water, combined sewers, and wastewater-treatment systems to the middle main stem of the Cuyahoga River between Akron and Cleveland, Ohio, result in frequent exceedances of bacteriological water-quality standards for recreation during rainfall and runoff. Contamination of the Cuyahoga River by fecal bacteria and subsequent transport of enteric pathogens and their bacterial indicators downstream impairs recreational use of the river in the Cuyahoga Valley National Recreation Area (CVRNA), a 50-$mi^2$ area that straddles a 23-mi reach of the middle main stem of the Cuyahoga River. Water-contact recreation in the CVNRA includes canoeing and wading, but these uses are not recommended by the National Park Service during periods of rainfall and runoff because of health risks associated with elevated concentrations of fecal bacteria.

Decay, transport, dilution, and dispersion of fecal bacteria were evaluated in the Cuyahoga River in field studies to estimate how concentrations of fecal bacteria change with time and distance downstream from sources. In addition, the contributions from two major sources were measured at the Akron Water Pollution Control Station (WPCS) and at the gaging station at the Cuyahoga River at Old Portage, a site that represents the integration of the watershed draining to a modeled reach of the river.

Decay rates ranged from 0.0018 $hr^{-1}$ to 0.0372 $hr^{-1}$ for fecal coliform bacteria and from 0.0022 $hr^{-1}$ to 0.0407 $hr^{-1}$ for *E. coli.* ANCOVA tests were used to determine significant differences in rates of bacterial decay between seasons at each of five study sites. ANCOVA tests showed that the majority, 9 of 13, decay rates measured in June and August were significantly higher than decay rates measured in April and October. The importance of streambed sediments as a source of bacteria was evaluated by collecting and enumerating fecal bacteria from sediments at two locations in the river. The concentrations of fecal bacteria in sediments from two pools in the middle main stem of the Cuyahoga River were investigated in March and June 1993—one at Peninsula and one near Brecksville. Fecal bacteria in the sediments ranged from 1.2 to 58 times higher per unit wet weight than concentrations of fecal bacteria in the overlying water. This indicates that fecal bacteria are present, viable, and available for resuspension during storm runoff, given adequate shear stress on the streambed. The bed sediments can be a source and sink of fecal bacteria; however, because of the lack of extensive areas of bacteria-laden sediment deposits in the middle main stem, and because of the magnitude of sewage sources, sediments are not likely to be a relatively large source of bacterial loading.

Transport, dilution, and dispersion, and concentrations of fecal bacteria in discharges from major sources were estimated by making measurements of streamflow and analyzing samples for concentrations of fecal coliform bacteria, *E. coli,* total nonfilterable residue, chloride, and rhodamine WT dye. Samples were collected and streamflow measurements were made at four sites in the middle main stem, at five tributary streams, and at the WPCS during three studies in 1991-93. The middle main stem was degraded to a greater degree in relation to bacteriological standards than the monitored tributary streams. Relative to other sources of bacteria to the middle main stem such as combined sewers, storm water, and incompletely disinfected sewage, the contribution from tributaries was likely smaller.

The highest concentration of fecal coliform bacteria was detected in a sample collected from the Cuyahoga River at Botzum, just downstream from the WPCS. At 2,600,000 col/100 mL, this sample exceeded Ohio's single-sample primary-contact standard (2,000 col/100 mL) by a factor of 1,300. The highest observed concentration of *E. coli,* also detected at Botzum; was 2,400,000 col/100 mL. This sample exceeded the single-sample primary-contact standard for *E. coli* (298 col/100 mL) by a factor of 8,054.

A streamflow model, DAFLOW, was calibrated by adjusting the hydraulic geometry coefficients and exponents for cross-section area so that the timing of observed and simulated streamflow peaks was coincident, and then adjusting the wave-dispersion coefficients so that the peak flow attenuations were accurately reflected. Differences between the timing of the observed and simulated peak streamflows were generally small; however, the magnitude of simulated peak streamflows underestimated the observed peaks by an average of 12 percent.

A transport model, BLTM, was used to numerically simulate constituent decay, transport, dilution, and dispersion. The timing of the peak concentrations and the overall shape of the simulated and observed concentration chemographs (graphs of concentration as a function of time) tracked reasonably well for dye for the three models (1991-93). Simulation of transport of other constituents posed added challenges, because unlike dye, which was injected at a single controlled source, other constituents were discharged from multiple sources with time-varying concentrations that could not be as accurately measured. Of the constituents modeled, bacteria exhibited the poorest correspondence between observed and simulated values.

Because the simulation results for dye indicated that the model did a reasonably good job of simulating the timing of dissolved constituents as well as simulating dilution and dispersion effects, the model was also expected to simulate the transport of bacteria reasonable accurately given accurate information on bacterial loadings (boundary conditions) and decay. The effects of uncertainty about bacterial decay rates were assessed by means of sensitivity analyses. The results of the sensitivity analyses showed that the largest change in simulated maximum bacterial concentration, 9.88 percent, resulted from reductions in reach-based decay rates that ranged from about 29 to 46 percent of base-simulation decay rates.

Several scenarios involving 50- and 90-percent reductions in base-simulation concentrations for the Old Portage gaging station and the WPCS boundary conditions were tested, as were simulations in which the WPCS boundary conditions were set to 200 col/100 mL for fecal coliforms and 126 col/100 mL for *E. coli*. Concurrent boundary-condition reduction scenarios were limited to combinations in which the WPCS boundary conditions were reduced to 200 col/100 mL for fecal coliform bacteria and 126 col/100 mL for *E. coli* and boundary conditions at the Old Portage gaging station were reduced 50 and 90 percent from base-simulation levels (BWS/90 scenario). Base simulations for the 1991 and 1992 models indicate that during the 35- to 40-hour traveltimes from the Old Portage gaging station to Independence, concentrations of fecal coliform bacteria were reduced by 52.8 to 60.2 percent and concentrations of *E. coli* were reduced by 50.0 to 58.3 percent as a result of natural processes such as decay, dilution, dispersion, and transport.

Transport and decay are important processes governing the concentrations of fecal bacteria and the length of time recreational water-quality standards are exceeded after rainfall and runoff. These reductions from natural processes alone, however, cannot reduce fecal bacteria by the amount needed to achieve bacteriological standards for recreation. The BWS/90 scenario simulations for 1991 and 1992 models resulted in peak concentrations of *E. coli* that were lower than the base simulation by 98.3 to 98.5 percent at Botzum, by 96.6 to 97.5 percent at Jaite, and by 91.1 to 95.8 percent at Independence, respectively. Similar results were computed for fecal coliform concentrations in the 1991 and 1992 models.

The results of model simulations show that the single largest source of fecal bacteria to the middle main stem of the Cuyahoga River during these studies was the WPCS. Simulated reductions of fecal bacteria in this source show that the greatest single improvement to bacteriological water quality was predicted through nearly complete disinfection of all wet-weather discharges of incompletely treated wastewater. A larger implication of this work is that even though it may be difficult to control and reduce fecal contamination in the middle main stem of the Cuyahoga River, reductions of the magnitude described in this report would likely result in a decrease in the health risk to recreational users regardless of whether or not water-quality standards are fully achieved. Because the risk of illness from immersion in fecal-contaminated water is directly related to the concentration of *E. coli*, any improvement in bacteriological quality will reduce the risk of illness to swimmers.

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**Appendix 1.** DAFLOW and BLTM modelling coefficients for the Cuyahoga River and Tinkers Creek

[$A_1$, hydraulic geometry coefficient for area; $A_2$, hydraulic geometry exponent for area; $A_0$, average cross section area at zero flow; $D_f$, wave dispersion coefficient; $W_1$, hydraulic geometry coefficient for width; $W_2$, hydraulic geometry exponent for width; DQQ, dimensionless dispersion coefficient; na, not applicable]

| Branch | Grid point | Grid point description | Mile | $A_1$ | $A_2$ | $A_0$ | $D_f$ | $W_1$ | $W_2$ | DQQ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Old Portage gage | 0.00 | 18.5 | 0.430 | 0.000E+00 | 0.357E+04 | 18.7 | 0.265 | 0.14 |
| 1 | 2 | Confluence Sand Run | 0.44 | 18.5 | 0.430 | 0.000E+00 | 0.357E+04 | 18.7 | 0.265 | 0.14 |
| 1 | 3 | Confluence Mud Brook | 1.10 | 18.5 | 0.430 | 0.000E+00 | 0.357E+04 | 18.7 | 0.265 | 0.14 |
| 1 | 4 | Akron Water Pollution Control Station | 2.89 | 18.5 | 0.430 | 0.000E+00 | 0.357E+04 | 18.7 | 0.265 | 0.14 |
| 1 | 5 | Botzum | 3.00 | 1.87 | 0.748 | 1.050E+02 | 0.676E+04 | 25.0 | 0.228 | 0.14 |
| 1 | 6 | Confluence Yellow Creek | 3.43 | 1.87 | 0.748 | 1.050E+02 | 0.676E+04 | 25.0 | 0.228 | 0.14 |
| 1 | 7 | Confluence Furnace Run | 6.77 | 1.87 | 0.748 | 1.050E+02 | 0.676E+04 | 25.0 | 0.228 | 0.14 |
| 1 | 8 | Peninsula | 10.57 | 1.87 | 0.748 | 1.050E+02 | 0.676E+04 | 25.0 | 0.228 | 0.14 |
| 1 | 9 | Confluence Brandywine Creek | 15.62 | 1.30 | 0.783 | 1.800E+02 | 0.500E+04 | 49.1 | 0.105 | 0.09 |
| 1 | 10 | Confluence Chippewa Creek | 18.94 | 1.30 | 0.783 | 1.800E+02 | 0.500E+04 | 49.1 | 0.105 | 0.09 |
| 1 | 11 | Canal diversion | 19.10 | 1.30 | 0.783 | 1.800E+02 | 0.500E+04 | 49.1 | 0.105 | 0.09 |
| 1 | 12 | Confluence Tinkers Creek | 23.47 | na | na | na | na | na | na | na |
| 2 | 1 | Tinkers Creek gage | 0.00 | 5.80 | 0.477 | 0.000E+00 | 0.284E+04 | 19.0 | 0.229 | 0.00 |
| 2 | 2 | Dunham Road | 4.23 | 5.80 | 0.477 | 0.000E+00 | 0.284E+04 | 19.0 | 0.229 | 0.00 |
| 2 | 3 | Confluence Cuyahoga River | 6.48 | na | na | na | na | na | na | na |
| 3 | 1 | Confluence Tinkers Creek | 0.00 | 1.30 | 0.783 | 1.800E+02 | 0.500E+04 | 32.3 | 0.194 | 0.09 |
| 3 | 2 | Independence gage | 3.60 | na | na | na | na | na | na | na |

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