U.S. Department of the Interior
U.S. Geological Survey

In cooperation with the
Louisville and Jefferson County
Metropolitan Sewer District

Processes Affecting Dissolved-Oxygen Concentrations in the Lower Reaches of Middle Fork and South Fork Beargrass Creek, Jefferson County, Kentucky

Water-Resources Investigations Report 98–4218

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By KEVIN J. RUHL, Kentucky Natural Resources and Environmental Protection Cabinet–Division of Water, and G. LYNN JARRETT, University of Louisville

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Louisville, Kentucky
1999

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS, VERTICAL DATUM, AND WATER-QUALITY UNITS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per second (ft/s)	0.3048	meter per second
grams of oxygen per square foot per day [g O_2/(ft/d)]	0.09290	grams of oxygen per square meter per day
mile (mi)	1.609	kilometer
milligrams per square foot per day [mg/(ft^2/d)]	0.09290	milligrams per square meter per day
square foot per day (ft^2/d)	0.09290	square meter per day
square foot per second (ft^2/s)	0.09290	square meter per second

Temperatures in degrees Fahrenheit (°F) can be converted to degrees Celsius (° C) and vice versa as follows:

$$^{o}C = (^{o}F - 32)/1.8, \text{ and}$$
$$^{o}F = (^{o}C + 32)1.8.$$

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.

Concentration: Concentrations are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). For concentrations reported here, milligrams per liter are equivalent to parts per million, and micrograms per liter are equivalent to parts per billion.

Processes Affecting Dissolved-Oxygen Concentrations in the Lower Reaches of Middle Fork and South Fork Beargrass Creek, Jefferson County, Kentucky

By Kevin J. Ruhl, Kentucky Natural Resources and Environmental Protection Cabinet–Division of Water, *and* G. Lynn Jarrett, University of Louisville

Abstract

This report provides data on dissolved-oxygen (DO) concentrations and identifies the environmental processes that most affect DO concentrations during base-flow periods in the lower reaches of Middle Fork and South Fork Beargrass Creek in Jefferson County, Kentucky. These reaches are affected by inputs from combined-sewer overflows. Sections of the lower reaches of the two streams run through single-family residential areas and public parks that are used extensively by local residents during the summer. Recreational fishing and wading also are common in the Middle Fork reach.

Continuous-record data collected during the summer and early fall (July–September 1996 on the Middle Fork and July–October 1995 on the South Fork) at three monitoring sites along each reach indicate generally decreasing DO concentrations in the downstream direction except for the South Fork Beargrass Creek at Winter Avenue site where channel modifications have resulted in higher velocities along with shallower depths during low-flow conditions. The channel modifications at this site increased the reaeration-rate coefficient (a measure of the capacity of the stream to absorb oxygen through the air-water interface), increased the potential for algae to attach to the rough concrete surface, and increased algal exposure to sunlight.

Synoptic data available for selected constituent concentrations were used to calibrate and verify a computer model (U.S. Environmental Protection Agency QUAL2E model) capable of simulating processes that affect DO concentrations in streams. The results of the study indicate that streamflow, reaeration, and sediment-oxygen demand (SOD) are the factors that most affect net production and depletion of DO in the lower reaches of Middle Fork and South Fork Beargrass Creek. For the QUAL2E model, streamflow is used in the determination of depth, which in turn is used to estimate the consumption of oxygen by SOD. Streamflow also is used in the determination of the reaeration-rate coefficient. From the QUAL2E simulations, DO concentrations (in the mass balance) attributed to reaeration and SOD were at least an order of magnitude greater than any of the other factors that can affect DO concentrations. Large diurnal variability in DO concentrations resulted at the monitoring sites located at upstream and downstream ends of the Middle Fork and South Fork reaches, but as indicated in model simulation, the net effect of photosynthesis and respiration on DO concentration was small. Nitrogen, ammonia, and carbonaceous biochemical-oxygen demand were present at low concentrations in each of the study reaches; the model results indicate these constituents did not have a substantial effect on DO concentrations.

Model simulations indicated that lowering the SOD rate by 50 percent would result in a substan-

tial improvement in DO concentrations in the Middle Fork Beargrass Creek reach for extremely low base-flow conditions but would result in only limited improvement in DO concentrations in the South Fork Beargrass Creek reach. However, no simulations for extremely low base-flow conditions were conducted for the South Fork Beargrass Creek reach. More information on SOD is needed for stream reaches affected by periodic inputs of effluent. In such stream systems, the temporal and spatial variability of SOD needs to be better defined.

INTRODUCTION

Many communities along the Ohio River are near streams that are affected by inputs of combined-sewer overflow (CSO). In some instances the receiving streams flow through residential areas or areas of recreational use (Ormsbee and others, 1995). Such is the case along lower Middle Fork Beargrass Creek and to a lesser extent along lower South Fork Beargrass Creek in Jefferson County, Kentucky.

Dissolved-oxygen (DO) concentration is a general indicator of the overall health (water quality) of a stream system, and adequate DO is necessary for the existence of aquatic organisms in a stream. If DO concentrations become depleted as a result of any number of naturally occurring or outside processes, stream organisms can be adversely affected. Periodic measurements of DO concentrations are made at selected stream sites throughout Jefferson County as part of a stream water-quality monitoring network that was begun in 1988 through a cooperative program between the Louisville and Jefferson County Metropolitan Sewer District (MSD) and the U.S. Geological Survey (USGS). The lower reaches of Middle Fork and South Fork Beargrass Creek each contain two network sites that were used in the study. The measurements at these network sites typically were made during the early daylight hours when DO concentrations generally are low but increasing. Continuous records of DO concentrations and other water-quality constituents provide timely information on the general water-quality condition of these stream reaches. During this study, concurrent data—which include continuous streamflow, water temperature, specific conductance, pH, and DO concentration—were collected at three monitoring sites along each reach. Each monitoring site constituted the upstream or downstream boundary of a subreach having unique hydraulic characteristics. Continuous DO concentration data for October 1990 through September 1992 also were available at the upstream end of each study reach.

Water-resource managers and planners in Jefferson County, Kentucky, are currently (1998) adopting a watershed approach to evaluate processes affecting stream quantity and quality. In Jefferson County, a continuous hydrologic-simulation model has been developed for the Beargrass Creek watershed (Jarrett and others, in press). The model is conceptually designed to simulate continuous streamflow and daily loads of selected constituents. The information from this study will be available to complement that modeling effort.

Purpose and Scope

The purpose of this report is to describe and determine processes affecting DO concentrations in the lower reaches of Middle Fork and South Fork Beargrass Creek in Jefferson County, Kentucky. This description and determination are based on continuous DO concentration data and data on processes affecting DO concentrations collected during low-flow periods in the summer at selected locations along reaches affected by CSO to Middle Fork and South Fork Beargrass Creeks. The continuous DO concentration data and related information were used to calibrate a steady-state, one-dimensional water-quality model (QUAL2E) to simulate DO concentrations in the lower reaches of Middle Fork and South Fork Beargrass Creek. The data collection and modeling provide information that defines the major processes affecting DO concentration in the respective stream reaches. Because these reaches are affected by CSO, the identification of the major processes affecting DO concentration in these stream reaches may be used to make an assessment of whether eliminating CSO inputs would have the potential to appreciably improve stream-water quality in these reaches with respect to DO.

Acknowledgments

The authors wish to acknowledge the contributions of Charles S. Melching, USGS, to the report. The suggestions provided by Mr. Melching have made the report more readable and have resulted in additional

insight into the processes affecting DO concentrations in the study reaches.

Description of Study Area and Data-Collection Sites

The study area consists of a reach on each of Middle Fork and South Fork Beargrass Creeks in north-central Jefferson County, Kentucky (fig. 1). Land use adjacent to these reaches includes single-family residential, light industrial, commercial, parks, and cemeteries. Land use adjacent to the upstream part of the Middle Fork study reach includes high-usage park and single-family residential areas. Land use adjacent to the downstream part of the Middle Fork study reach includes limited-use park, recreational, and commercial areas. A biking and walking path on Middle Fork Beargrass Creek, beginning just upstream from its confluence with South Fork Beargrass Creek, extends for much of the reach. Land use adjacent to the upstream part of the South Fork study reach includes

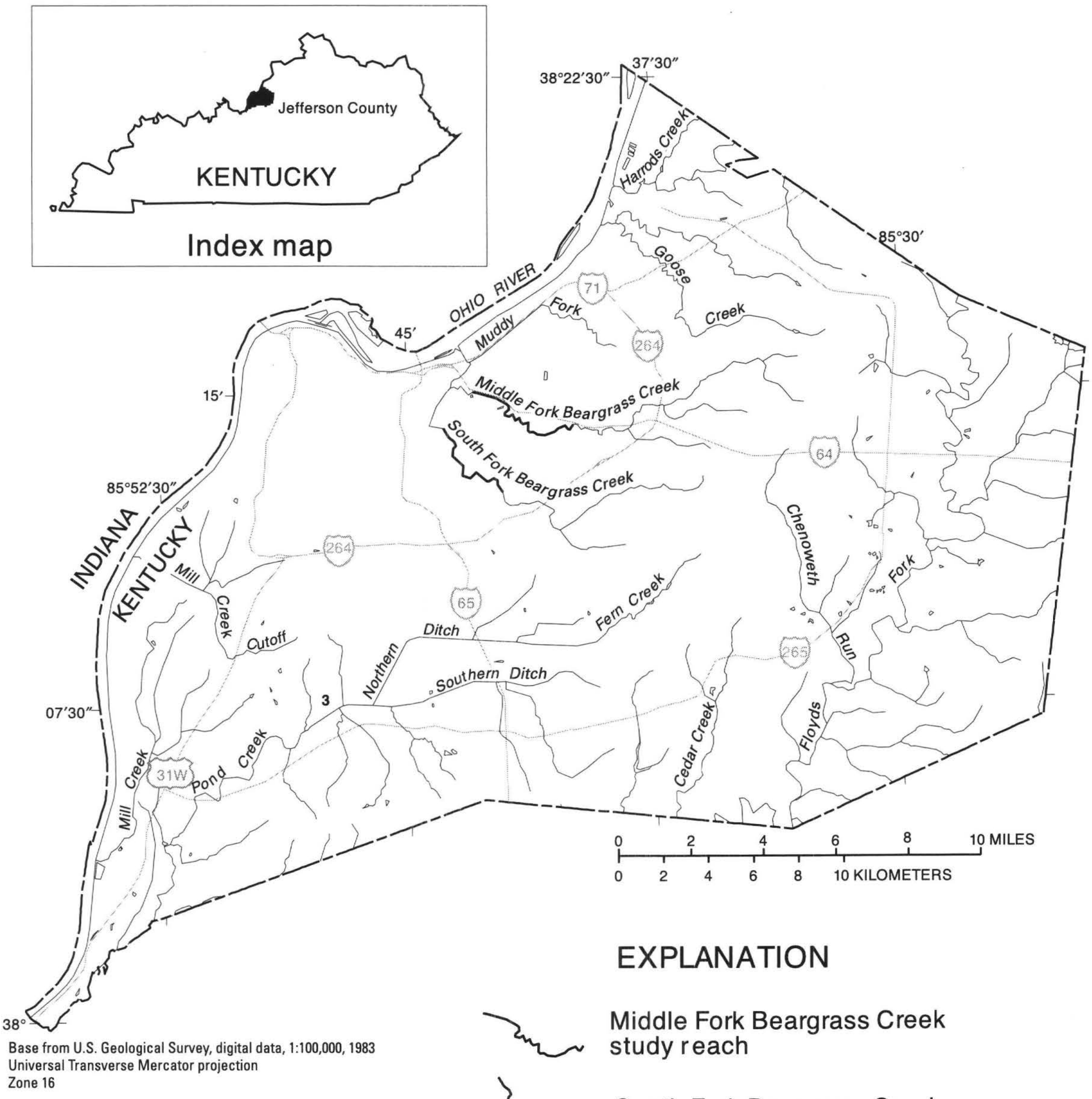


Figure 1. Location of study reaches on Middle Fork and South Fork Beargrass Creeks, Jefferson County, Kentucky.

moderate-use park and recreational areas, open areas, and limited residential and commercial areas. Land use adjacent to the downstream part of the South Fork study reach includes cemeteries, commercial and light-industrial areas, and limited residential areas. The Beargrass Creek Basin is served by sanitary and storm sewers, with CSO's present in the downstream parts of the Middle Fork and South Fork study reaches.

The Middle Fork Beargrass Creek study reach (fig. 2) extends from the bridge on Old Cannons Lane to the bridge on Lexington Road; a continuous-record streamflow-gaging station has been in operation at Old Cannons Lane (03293000) since 1944. A water-quality monitor was installed at the site on June 30, 1996, to collect readings of water temperature, specific conductance, pH, and DO concentration (termed "four-parameter water-quality data" in this report) every 30 minutes (termed "continuous" in this report) during the study period. Temporary continuous-record streamflow-gaging stations and water-quality monitoring sites were established at the bridge on Scenic Loop (03293200, formerly identified as "at Beals Branch Road") and at the bridge on Lexington Road (03293500) on June 30, 1996. A pressure sensor was installed on the same date at each of these sites to collect continuous stream-stage data, and a water-quality monitor was installed at each of these sites to collect four-parameter water-quality data. The gaging stations and monitoring sites were inspected approximately every 2 weeks, and the equipment was recalibrated, if necessary. The stream-stage data, in conjunction with periodic streamflow measurements, were used to provide base-flow information, although mid- and high-flow values of streamflow also were estimated. Miscellaneous water-quantity and water-quality data have been collected at the Old Cannons Lane site and the Scenic Loop site since 1988; therefore, the low-water

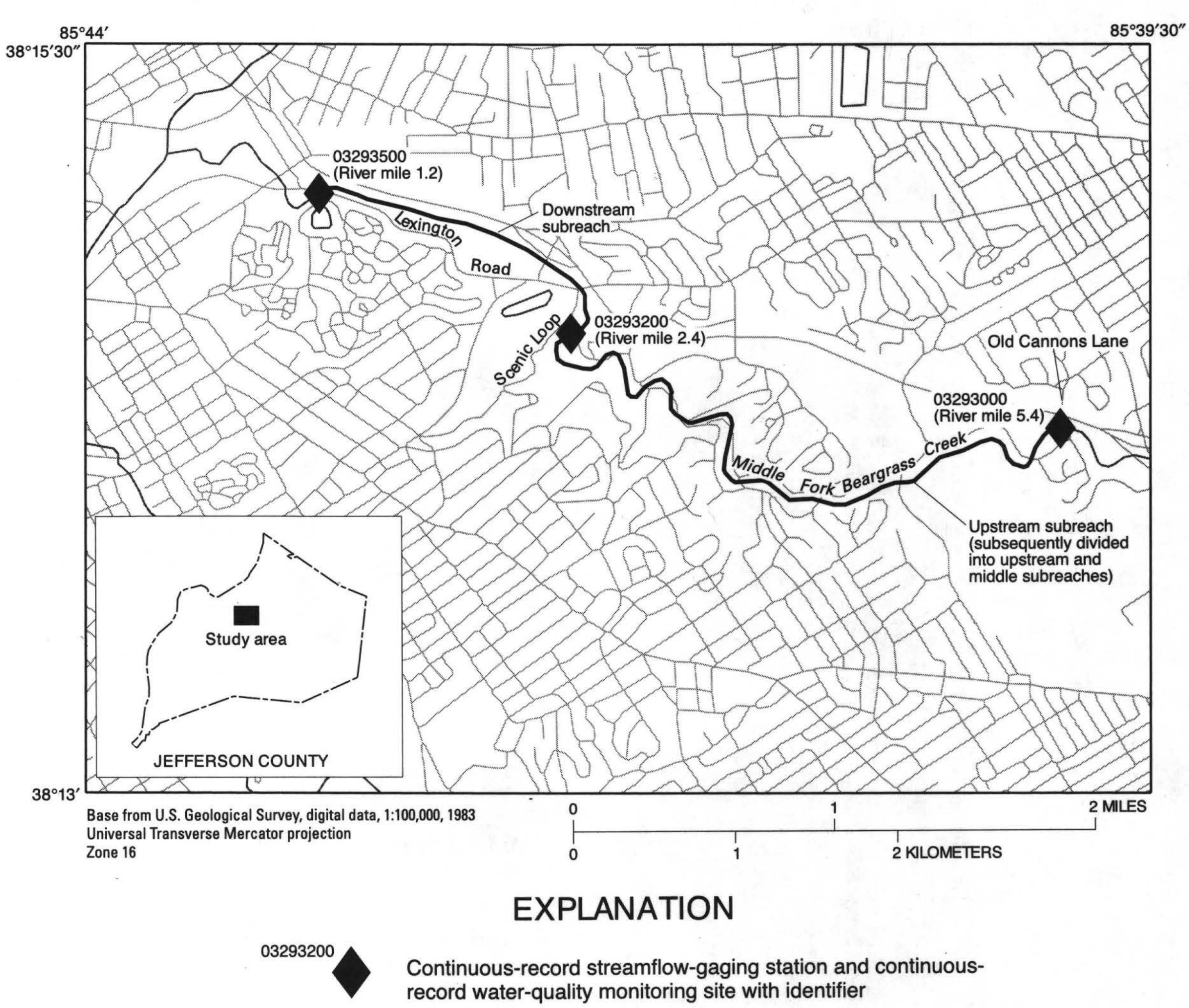


Figure 2. Middle Fork Beargrass Creek study reach, Jefferson County, Kentucky.

streamflow rating at the two monitoring sites is fairly well established, and background water-quality data are available. To maximize the reach length, an additional temporary continuous-record site was established near the bridge on Lexington Road (03293500). No previous water-quality information and only limited water-quantity information were available at this site. As a result, the stage-discharge relation used to determine streamflow from the stage record was not well defined for the Lexington Road site. For the study, stream stage and four-parameter water-quality data were collected at all three monitoring sites for July 1 through September 19, 1996. Because of equipment malfunction at the Lexington Road site, data are not available for July 1–14, 1996.

The South Fork Beargrass Creek reach (fig. 3) extends from the bridge on Trevilian Way to a point 200 ft upstream from the bridge on Winter Avenue. A continuous-record streamflow-gaging station was already in operation at Trevilian Way (03292500), and a water-quality monitor was installed at the site to collect continuous four-parameter water-quality data. Temporary continuous-record streamflow-gaging stations and water-quality monitoring sites were established at points where the channel was modified and are located approximately 200 ft upstream from the bridge on Eastern Parkway (03292530) and approximately 200 ft upstream from the bridge on Winter Avenue (03292550). Continuous-stage and four-parameter water-quality data were collected at each of the three monitoring sites from July 7 through October 29, 1995. No data were available from the Trevilian Way site after October 23, 1995, and from the Winter Avenue site after October 19, 1995, because fouling of the monitor probes resulted in erroneous four-parameter water-quality data.

Submersible pressure transducers were installed at all three South Fork Beargrass Creek sites to provide a continuous record of stream stage during the study period. At the Trevilian Way site, the submersible pressure transducer collected stage data concurrent with the stage-sensing equipment already in operation at the site. The stage data collected at the other two sites was supplemented by once-daily observations of stage that were used to make any necessary adjustments to the stage record. These observations of stage were done because the submersible pressure transducers did not meet certain USGS requirements for the collection of continuous-stage data at the time the study was conducted. The pressure transducers were used and the information supplemented by other approved stage-data collection methods because (1) the study focus was on DO concentrations during low-flow conditions, (2) the study was short-term, and (3) the deployment and operation of the equipment was relatively uncomplicated. The concurrent stage data collected at the Trevilian Way site indicated good agreement between the conventional equipment and the submersible pressure transducers used throughout the study period.

A water-quality monitor also was installed at each South Fork Beargrass Creek site to collect continuous four-parameter water-quality data during the study period. These monitors were inspected every 10 to 14 days throughout the study period because of high air (and, therefore, water) temperatures and because of anticipated frequent fouling of the water-quality probes in these reaches, which were substantially affected by CSO outfalls during runoff periods. Miscellaneous water-quantity and water-quality data have been collected at the Trevilian Way site and at the Winter Avenue site since 1988; therefore, the low-water streamflow rating at the two sites is fairly well established, and background water-quality data are available. No previous water-quantity or water-quality information were available for the Eastern Parkway site. A streamflow-gaging station and water-quality monitor were established at this site because of the change in hydraulic characteristics of the stream channel at this location and because the downstream subreach was more affected by inputs from CSO's (fig. 4). The stream-channel cross section in this reach consists of a rectangular concrete section approximately 40 ft wide. A 1-ft deep, 9-ft wide, trapezoidal channel with side slopes of 1 to 1.5 (rise to run) is in the center of the stream channel. During base-flow conditions the flow is entirely contained within the smaller trapezoidal channel.

WATER-QUALITY DATA

The continuous-record, four-parameter water-quality data collected at each of the six monitoring sites are presented in graphs in the following sections. Results of selected statistical analyses of the data also are given. Water-quality data collected during periodic surveys were used as calibration and verification data sets in the QUAL2E model to simulate DO concentrations.

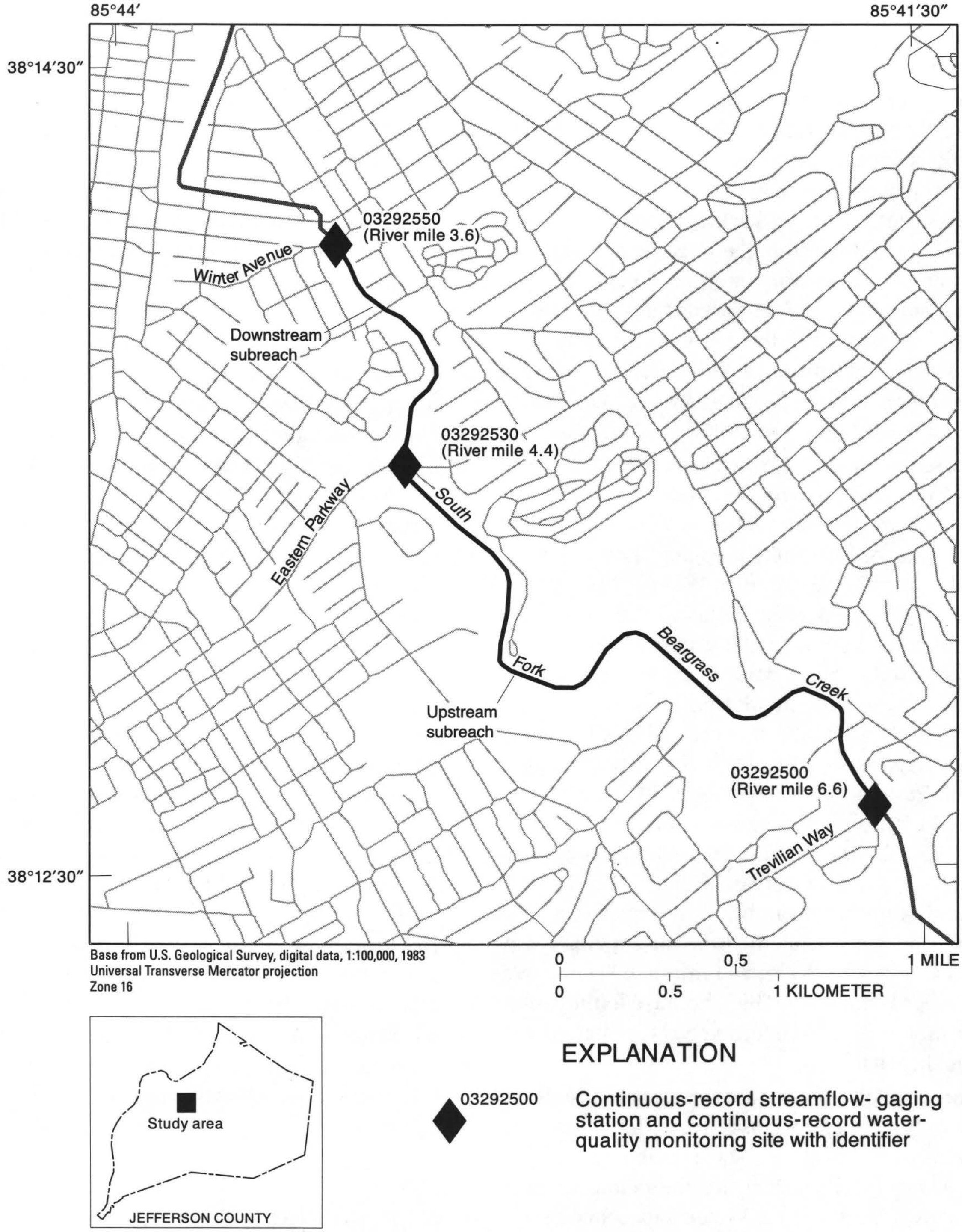
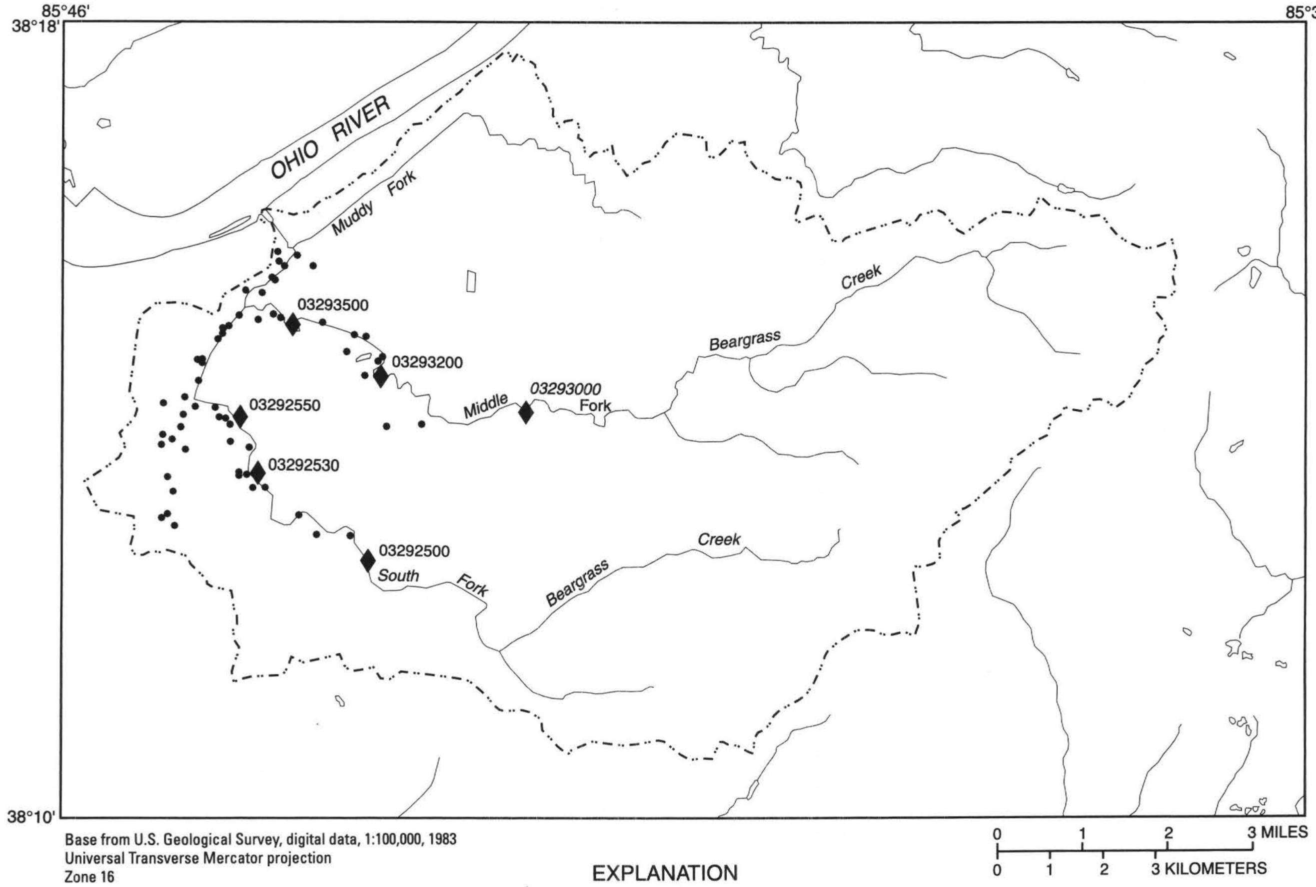


Figure 3. South Fork Beargrass Creek study reach, Jefferson County, Kentucky.



Base from U.S. Geological Survey, digital data, 1:100,000, 1983
Universal Transverse Mercator projection
Zone 16

EXPLANATION

- Boundary of Beargrass Creek watershed
- Combined-sewer overflow outfalls
- 03292500 Continuous-record streamflow-gaging station and continuous-record water-quality monitoring site with identifier

Figure 4. Location of combined-sewer overflow outfalls in Beargrass Creek watershed, Jefferson County, Kentucky.

Continuous-Record Dissolved-Oxygen Data

Concurrent continuous-record streamflow and water-quality data were collected at each site on each of the reaches for periods of 2.5 to 4 months during the summers of 1995 and 1996. Stream-water quality is usually stressed the most during the summer because of low streamflow and high water temperatures. Continuous-record data for the three Middle Fork Beargrass Creek monitoring sites were collected from July 1 through September 19, 1996, and data for the three South Fork Beargrass Creek monitoring sites were collected from July 7 through October 29, 1995. These data were collected at 30-minute intervals.

The summer of 1995, when data were collected from the South Fork reach, was characterized by high air temperatures and correspondingly high water temperatures. Daily high air temperatures of 90°F or greater were recorded for 45 days. Streamflow conditions in early September and mid-October were low, but not exceptionally so, as base-flow conditions throughout the period were augmented by rainfall from periodic storms, including the remnants of Hurricane Erin in early August. This storm was immediately followed (within 1 week) by a major frontal system that kept base flows up. Because of periodic storms throughout the summer, flows did not reach extremely low levels, but did decrease to less than 2.0 ft^3/s at the Trevilian Way site in mid- to late October. Streamflows from July 7 through October 29, 1995, did not approach either the 7-day, 10-year ($7Q_{10}$) low-flow or the 7-day, 2-year ($7Q_2$) low-flow value as reported by Ruhl and Martin (1991). However, as explained later, the published values of the $7Q_2$ and the $7Q_{10}$ low flows may need to be reevaluated. The $7Q_2$ and $7Q_{10}$ low flows are nonexceedance probabilities of the 50 percent and 10 percent chance, respectively, that in any given year that value of streamflow or less will occur at that stream location for a 7-day duration.

During the summer of 1996, when data were collected on the Middle Fork reach, daily maximum air temperatures throughout the period remained in the 80's (°F) except for 12 days when high temperatures were in the 90's (°F). These temperatures are near normal for summer in Jefferson County. Low flows approached the $7Q_{10}$ value in early September but were generally greater than the $7Q_2$ value.

Time-series plots of DO concentrations in water from each of the three Middle Fork monitoring sites are presented in figure 5, in downstream order. Histogram plots of the DO data for the Middle Fork sites are presented in figure 6, and percent DO saturation data are presented in figure 7. Time-series plots of the DO concentrations in water from each of the three South Fork monitoring sites are presented in figure 8, in downstream order. Histogram plots of DO data for the South Fork sites are presented in figure 9, and percent DO saturation data are presented in figure 10. The time-series plots of DO concentrations (figs. 5 and 8) use the same scale for DO concentration (0–15 mg/L) to aid in comparison of data among sites. The plots show the continuous values and the mean DO concentration for each day (daily mean). The plots provide a way to evaluate the variability, or range of values, of DO concentrations in water from the monitoring sites.

Primary water-quality criteria for public health, aquatic life, and recreation are established by Federal government and State agencies. Kentucky's criteria for dissolved oxygen stipulates that the daily mean DO concentration cannot be less than 5.0 mg/L and that the instantaneous DO concentration cannot be less than 4.0 mg/L (Kentucky Natural Resources and Environmental Protection Cabinet, 1991). Figure 5 and 8 show those days when daily mean concentrations of DO were less than 5.0 mg/L and when the lowest instantaneous concentrations of DO were less than 4.0 mg/L.

Middle Fork Beargrass Creek Reach

For the Middle Fork reach, the daily variability in DO concentrations is greatest for water from the Lexington Road monitoring site, although the daily variability in concentrations is similar in magnitude to water from the Old Cannons Lane monitoring site. After a storm late in the day on September 5, this pattern of variability was disrupted because of increased streamflows and decreased stream temperatures after (fig. 5). The data from the Scenic Loop monitoring site indicate much less DO variability than indicated in water from either of the other two sites. This is most likely a result of shading of the stream at the Scenic Loop site and the composition of the stream bottom being less conducive to the growth of attached algae (periphyton).

At the Old Cannons Lane monitoring site, few violations of either of the State's minimum DO concentration criteria occurred during the data-collection period (July 1 through September 19, 1996). The violations that did occur were in early September when streamflow was the lowest observed for that year at that site. At Old Cannons Lane, the observed flow was 0.6 ft^3/s on September 5, 1996. The $7Q_{10}$ low flow at this site is 0.3 ft^3/s, and the $7Q_2$ low flow is 1.6 ft^3/s (Ruhl and Martin, 1991); therefore, the stream was approaching $7Q_{10}$ levels on September 5. This site is not affected by CSO inputs. Bluegill, sunfish, and minnows are routinely observed at this site, and residents routinely fish at a site approximately 0.75 mi farther downstream and have caught both small-mouth and Kentucky bass. Fish habitat generally degrades downstream from this location, although bluegill are observed and caught approximately 0.5 mi upstream from the Scenic Loop site during high base-flow conditions. Carp generally are observed downstream from the Scenic Loop site.

The time-series data from the Scenic Loop site indicated low DO concentrations throughout much of the summer. This site is downstream from several CSO outfalls (fig. 4). When streamflow decreased to less than about 2.0 ft^3/s, the mean DO concentrations for the day decreased to less than 5.0 mg/L. The storm on September 5 resulted in increased base flows and decreased water temperatures, and the daily mean DO concentration decreased to less than 5 mg/L on only 1 day from September 5 through September 19, 1996.

DO concentrations in water from the Lexington Road site (fig. 5) were less than at least one State

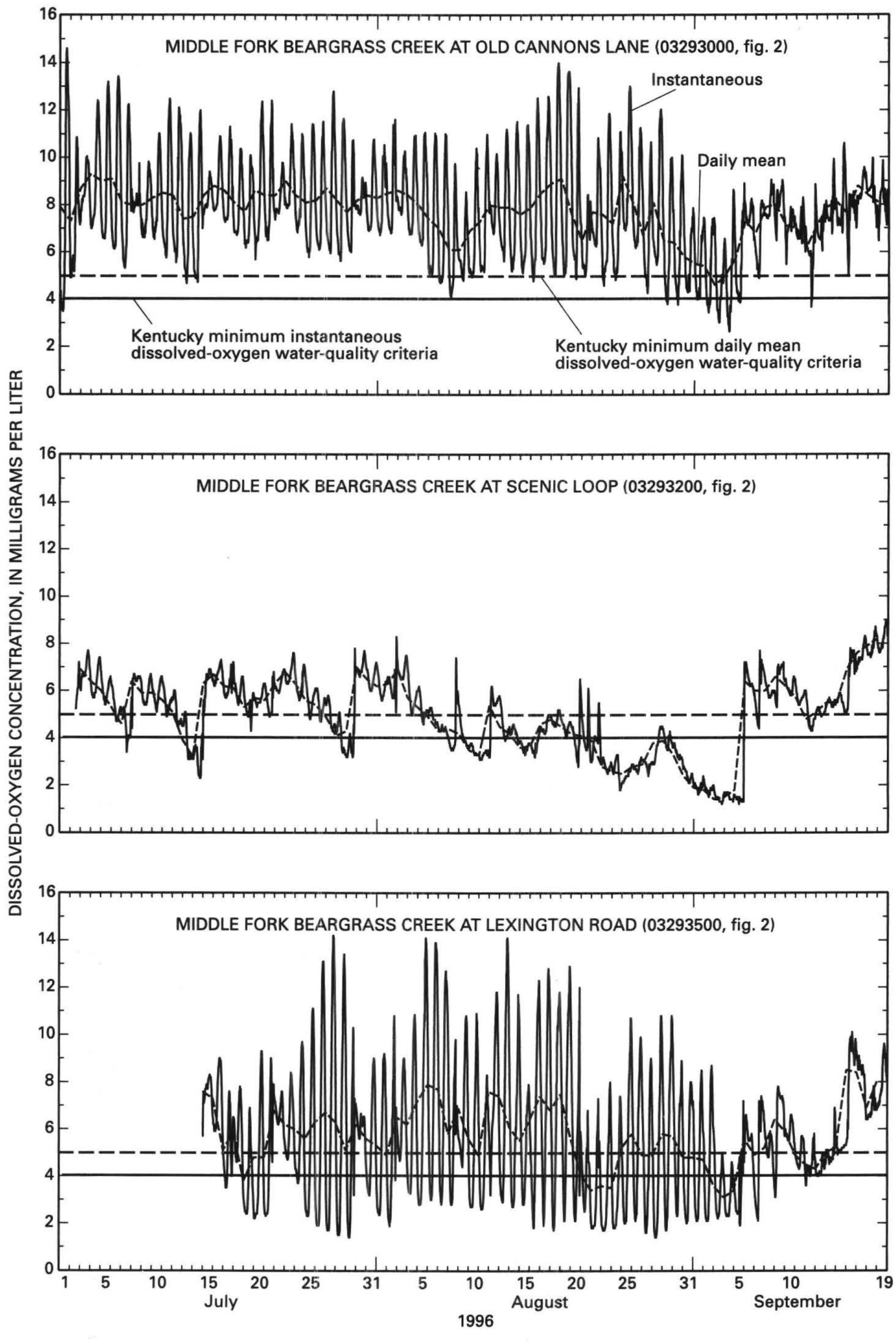


Figure 5. Continuous and daily mean dissolved-oxygen concentrations for July 1 through September 19, 1996, in water from Middle Fork Beargrass Creek monitoring sites, Jefferson County, Kentucky. (Water-quality criteria established by Kentucky Natural Resources and Environmental Protection Cabinet, 1991.)

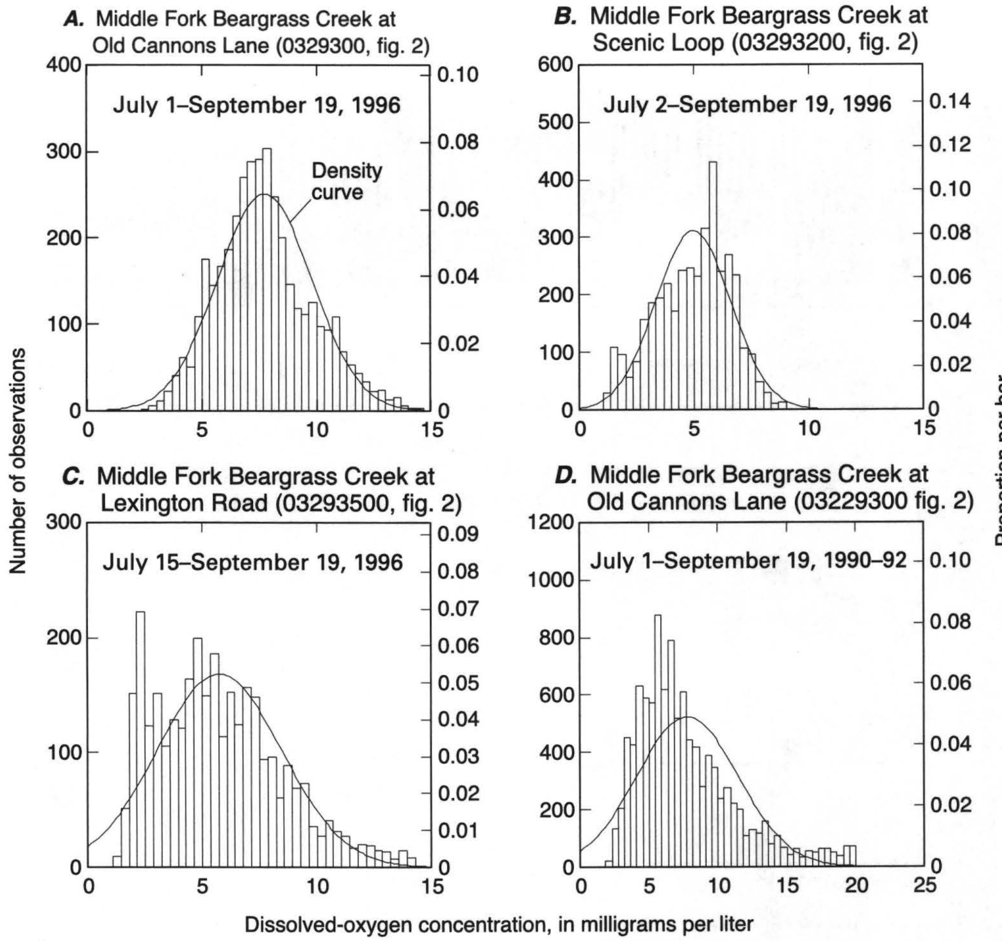


Figure 6. Distribution of instantaneous dissolved-oxygen concentrations in water from Middle Fork Beargrass Creek monitoring sites, Jefferson County, Kentucky, for selected periods.

criteria throughout most of the data-collection period. Daily mean DO concentrations were less than 5.0 mg/L for much of the data-collection period, particularly on days with streamflow values less than about 3.0 ft^3/s. Even after the streamflow increase on September 5, the DO concentration recovered only slightly and then declined sharply. Water temperature was not appreciably reduced during the period. The downstream half of the Middle Fork reach is oriented from southeast to northwest and has few trees along the southwest bank; therefore, this section of the reach is open to direct sunlight for much of the daylight hours, and stream water temperatures are moderated.

During extremely low base-flow periods, the subreach from Old Cannons Lane to Scenic Loop was a losing stream (flow was from the stream downward to ground water). Streamflow in the subreach downstream from the Scenic Loop site was generally constant during low base-flow periods. The tributaries to the Middle Fork reach do not flow in low base-flow periods in the summer. No seepage surveys were done along the Middle Fork reach during the study period, and gains or losses were assumed to be uniform throughout the entire length of the reach.

Histogram plots of the DO concentration data from the three Middle Fork monitoring sites for the July 1 through September 19, 1996, study period are presented in figure 8. A histogram plot of the DO concentration data for July 1 through September 19, 1990–92, for water from the Old Cannons Lane monitoring site also is shown in figure 8. At the Old Cannons Lane site, the mode, mean, and median are all about 7.5 mg/L for the 1996 data (fig. 6 and table 1). The mode, which is the most frequently occurring value in the data set, is represented by the highest bar of the histogram plot. The mean value—the average of all of the values in the data set—is represented by the highest point of the density curve. The median and the standard deviation were obtained through analysis of the data and are not

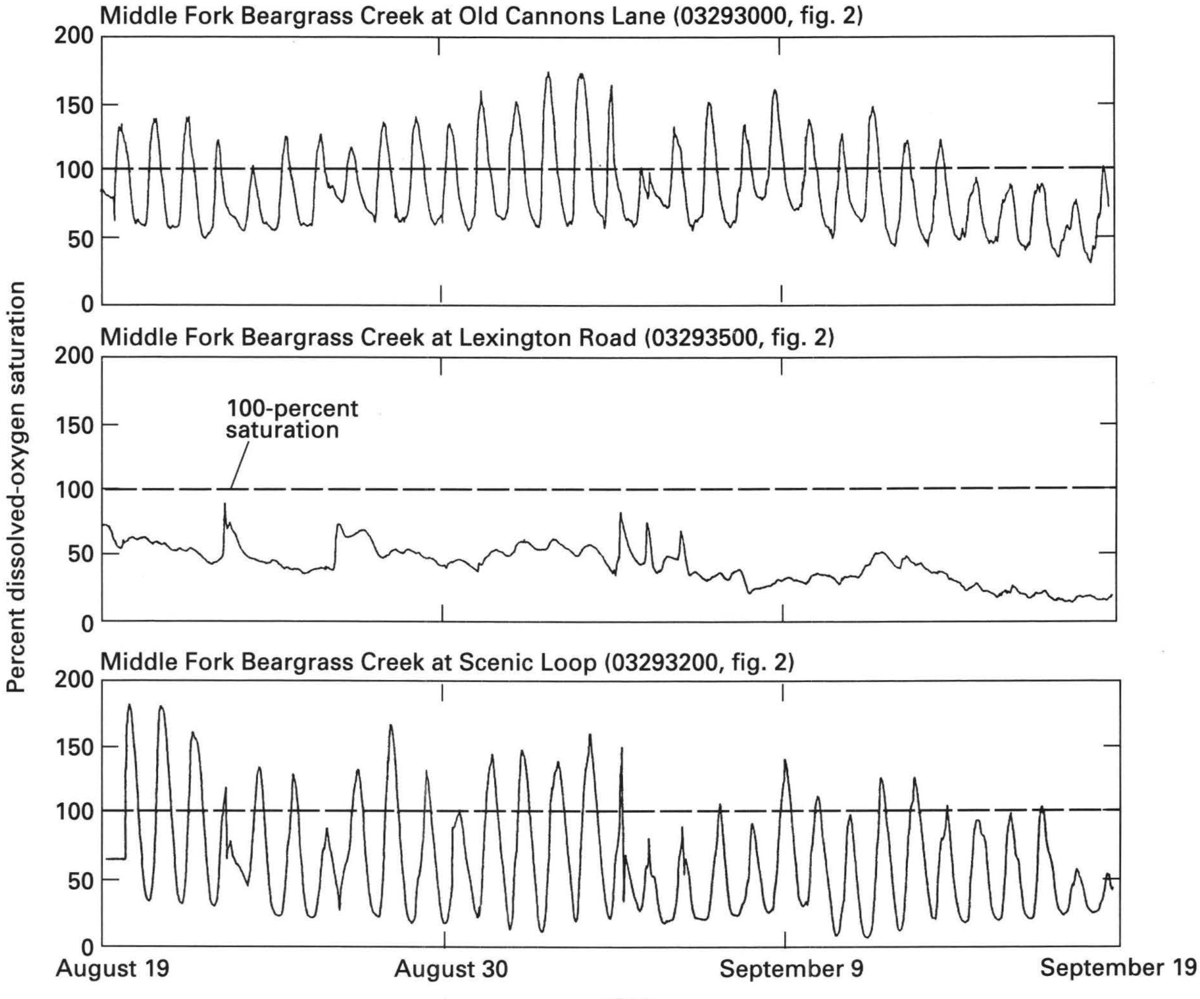


Figure 7. Continuous values of percent dissolved-oxygen saturation for 30-day period, August 19 through September 19, 1996, in water from Middle Fork Beargrass Creek monitoring sites, Jefferson County, Kentucky.

shown graphically but are listed in table 1. The median is the middle concentration if all concentrations in the data set are ordered from lowest to highest. The standard deviation is a measure of the spread of the concentrations about the mean concentration of the data set. The maximum, minimum, and range in DO concentration also are shown in table 1. At the Scenic Loop monitoring site, the mode, mean, median are 6.0, 5.0, and 5.2 mg/L, respectively. The range in values is much less than for the Old Cannons Lane site, as is the standard deviation. The median and the mean of the data from the Lexington Road site are 5.7 and 5.4 mg/L, respectively; however, the mode is 2.0 mg/L. There is greater variability in these DO concentration values (the standard deviation is 2.7 mg/L) than in values from the other two sites. Even though the most frequently observed DO concentration was 2.0 mg/L at the Lexington Road site, this concentration did not represent a large percentage of the observations as can be seen from the histogram plot in figure 6. A number of the histogram bars indicate observations in excess of 100 for selected DO concentrations. These statistics indicate that DO concentrations decrease substantially from the Old Cannons Lane site to the Scenic Loop site and then remain about the same for the subreach from the Scenic Loop site to the Lexington Road site. Water at the Old Cannons Lane and Lexington Road monitoring sites (fig. 5) reflects greater diurnal DO variability because the bottom materials at these sites are more conducive to the growth of attached algae (periphyton). The stream bottom at the Scenic Loop site consists mostly of clay, whereas the stream bottom at the other two sites consists of rocks or slab rock.

Data for July 1 through September 19, 1990–92, from the Old Cannons Lane site (fig. 6*D*) were used to

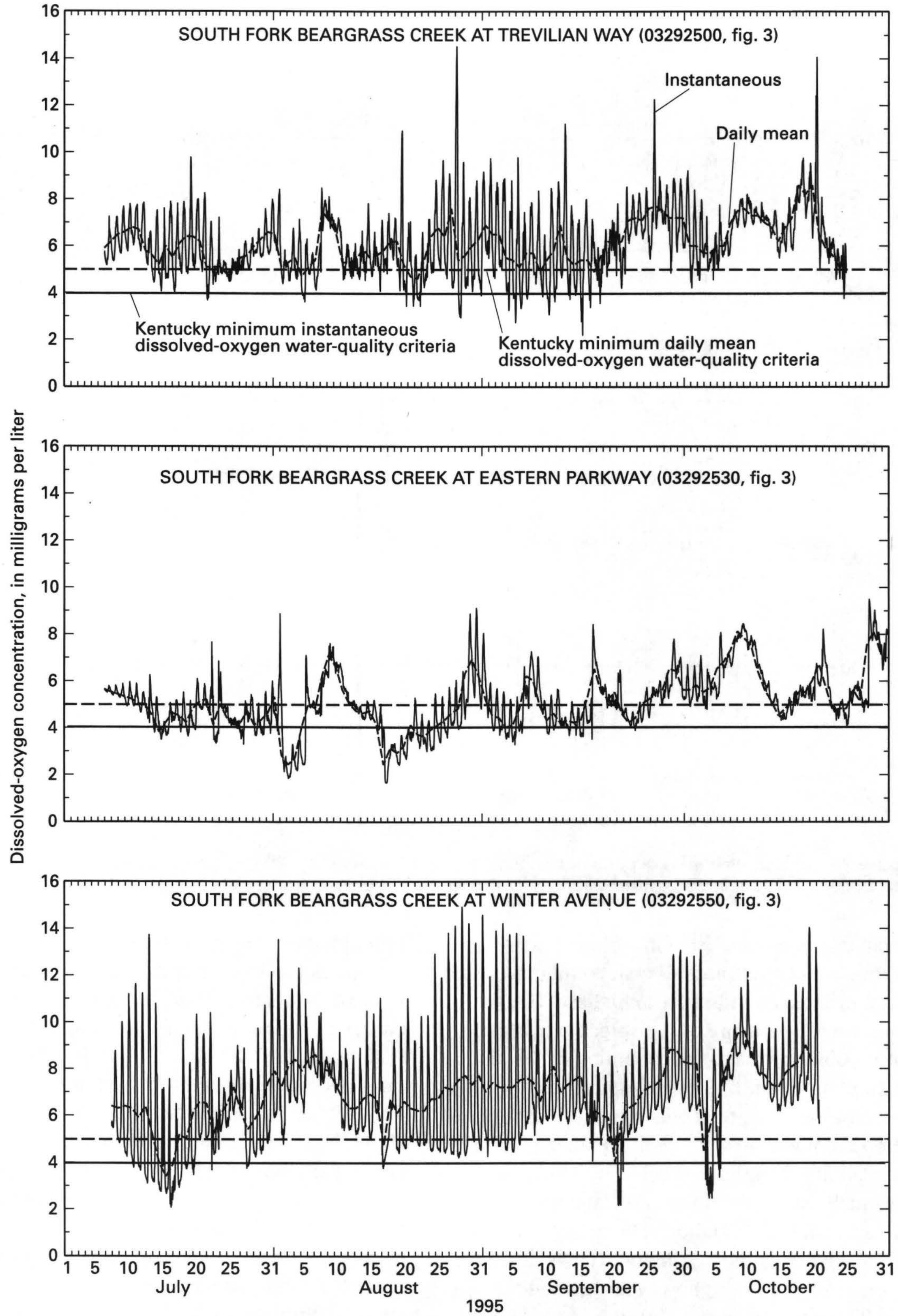


Figure 8. Continuous and daily mean dissolved-oxygen concentrations for July 7 through October 29, 1995, in water from South Fork Beargrass Creek monitoring sites, Jefferson County, Kentucky. (Water-quality criteria established by Kentucky Natural Resources and Environmental Protection Cabinet, 1991.)

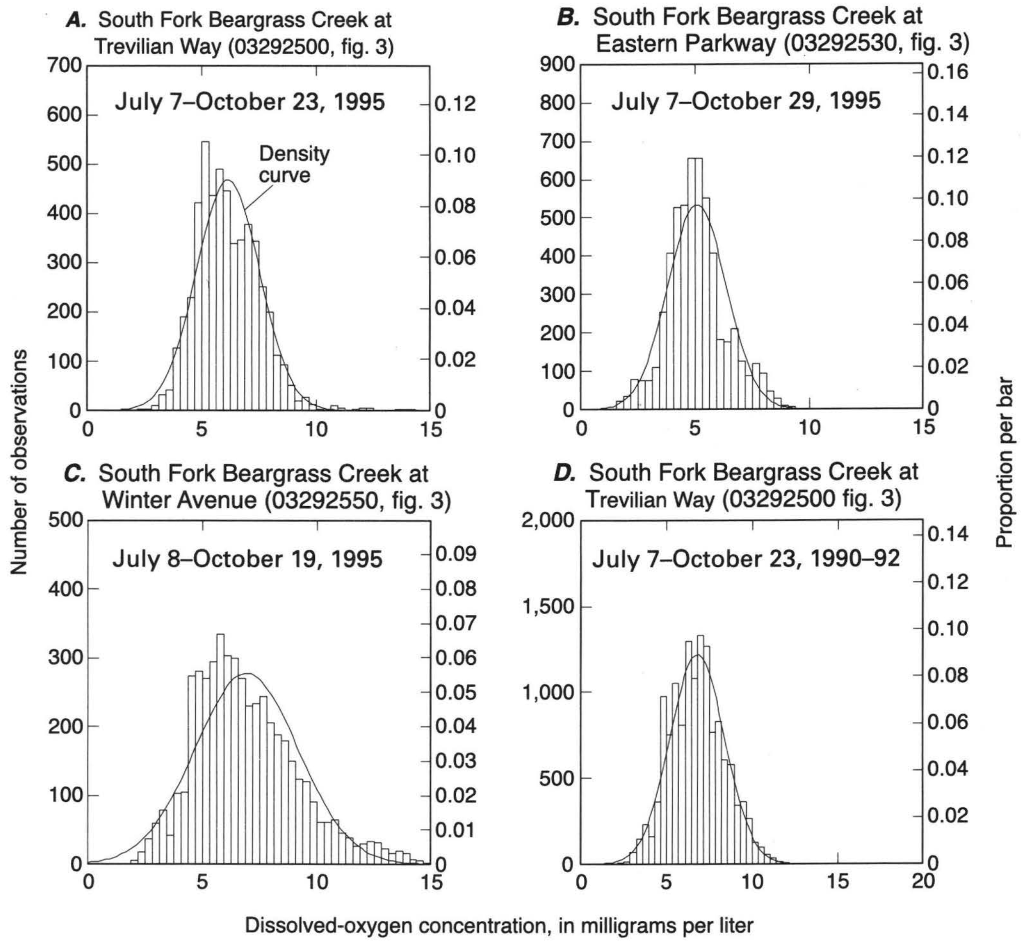


Figure 9. Distribution of instantaneous dissolved-oxygen concentrations in water from South Fork Beargrass monitoring sites, Jefferson County, Kentucky, for selected periods.

compare the available historical data to the data collected during the study period (fig. 6*A*). The plots in figure 6 indicate that the two data sets are similar. Mode, mean, and median values for the historical data are 5.5, 7.8, and 6.8 mg/L, respectively (table 1). A slightly greater variability is indicated in the historical data (standard deviation of 3.7 mg/L and maximum DO concentration of 20 mg/L) as compared with the data collected during the study period (standard deviation of 2.1 mg/L and maximum concentration of 14.6 mg/L). Overall, it appears that the DO data from the study period are fairly similar in magnitude and variability compared with that collected during the historical period; therefore, the data collected at the Scenic Loop and Lexington Road monitoring sites during the study period should be fairly representative of DO concentrations from historical periods.

The percent saturation data for the Middle Fork monitoring sites (fig. 7) indicate that biological processes (primary production by algae in particular) have a substantial effect on DO concentrations in water from the Old Cannons Lane and Lexington Road sites because the DO concentrations exceeded 100 percent during the daylight hours on most days; however, this was not the case for the Scenic Loop site. As seen in figure 7, the processes affecting DO at the three sites are appreciably different; these differences probably occur throughout the Middle Fork study reach.

South Fork Beargrass Creek Reach

Time-series plots of DO concentrations in water from each of the three South Fork Beargrass Creek monitoring sites are presented in figure 8. For the South Fork Beargrass Creek reach, the greatest variability in DO concentrations throughout the day occurred in water from the Winter Avenue monitoring site (the most downstream site). The subreach from Eastern Parkway to Winter Avenue is affected sub-

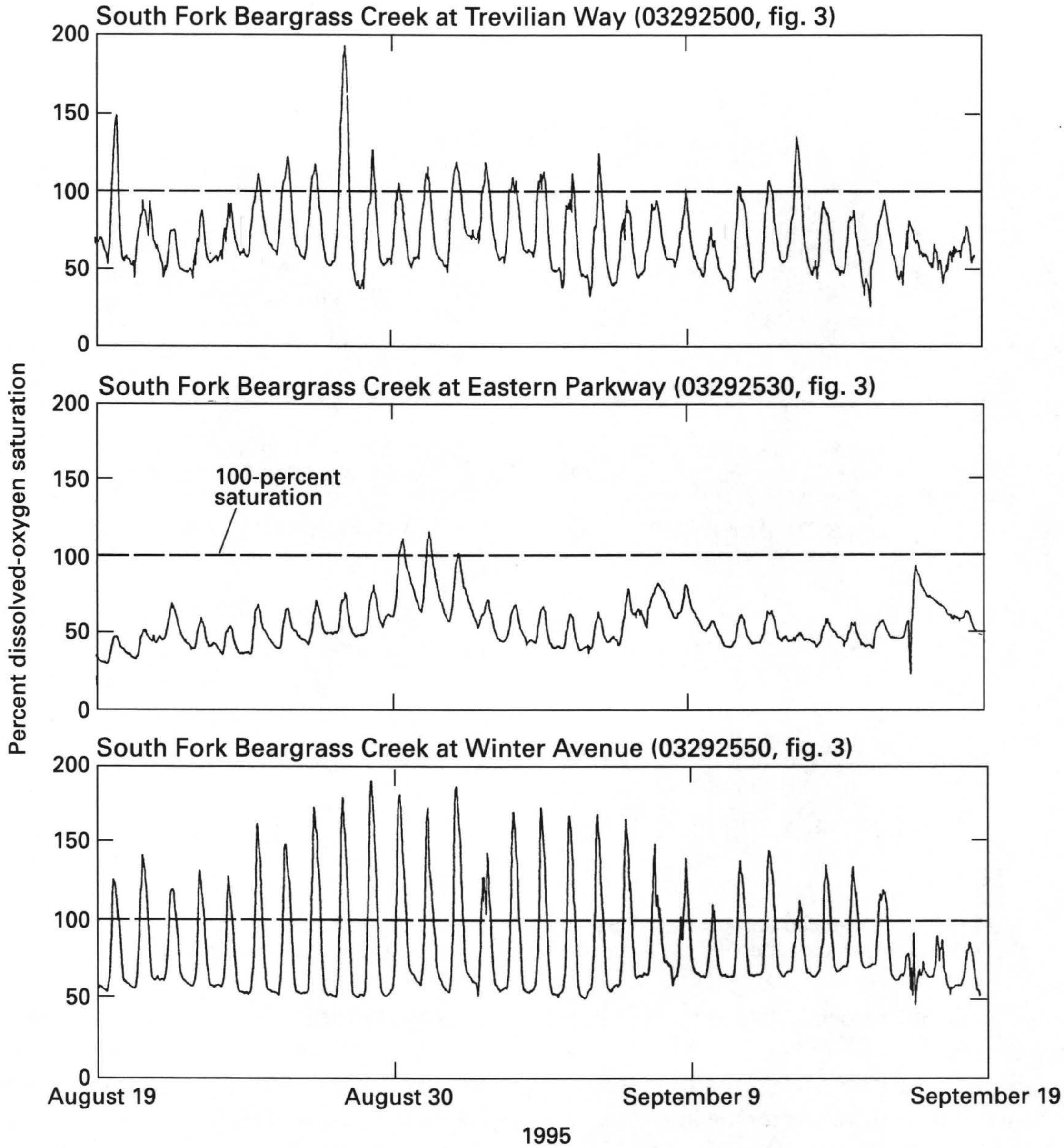


Figure 10. Continuous values of percent dissolved-oxygen saturation for 30-day period, August 19 through September 19, 1995, in water from South Fork Beargrass Creek monitoring sites, Jefferson County, Kentucky.

stantially by CSO inputs during most rainfall periods, and the trapezoidal concrete channel at times exhibits substantial attached-algae (periphyton) growth; much of this subreach is shaded. DO concentrations vary less in water from the Trevilian Way site (the most upstream site). Upstream and immediately downstream from the Trevilian Way site, vegetation is limited along either bank, allowing for exposure to direct sunlight. DO concentrations vary less throughout the day in water from the Eastern Parkway site than in water from the other two South Fork sites. As with the Scenic Loop site on Middle Fork Beargrass Creek, the reach upstream from the Eastern Parkway site is shaded. The channel also is relatively deep at this site (upstream from the concrete section), and the water often was very turbid when observed during site visits throughout the study period. Minnows were commonly observed at the Trevilian Way site as were fishing activities upstream from the site. At the Eastern Parkway and Winter Avenue monitoring sites, shad were observed on a number of occasions feeding on the algae growing on the sides of the trapezoidal channel.

Table 1. Statistical summary for continuous-record dissolved-oxygen data from Middle Fork and South Fork Beargrass Creek monitoring sites, Jefferson County, Kentucky, for selected time periods

Site identifier (figs. 2 and 3)	Site	Time period (month/day/year)	Dissolved-oxygen concentration, in milligrams per liter						
			Mode	Mean	Median	Standard deviation	Maximum	Minimum	Range
			Middle Fork Beargrass Creek						
03929300	Middle Fork Beargrass Creek at Old Cannons Lane	7/1/96–9/19/96	7.5	7.7	7.5	2.1	14.6	2.6	12
		7/7/90–10/23/90 7/7/91–10/23/91 7/7/92–9/30/92	5.5	7.8	6.8	3.7	20.0	2.0	18.0
03293200	Middle Fork Beargrass Creek at Scenic Loop	7/2/96–9/19/96	6.0	5.0	5.2	1.6	9.0	1.2	7.8
03293500	Middle Fork Beargrass Creek at Lexington Road	7/15/96–9/19/96	2.0	5.7	5.4	2.7	14.2	1.4	12.8
			South Fork Beargrass Creek						
03292500	South Fork Beargrass Creek at Trevilian Way	7/7/95–10/23/95	5.0	6.1	6.0	1.4	14.5	2.2	12.3
		7/7/90–10/23/90 7/7/91–10/23/91 7/7/92–9/30/92	6.8	6.8	6.7	1.6	18.7	2.1	16.6
03292530	South Fork Beargrass Creek at Eastern Parkway	7/7/95–10/29/95	5.0	5.1	5.0	1.4	9.5	1.6	7.9
03292550	South Fork Beargrass Creek at Winter Avenue	7/8/95–10/19/95	6.0	6.9	6.6	2.3	14.9	2.1	12.8

Only sporadic exceedances of the DO-concentration criteria occurred at the Trevilian Way monitoring site during the study period of July 7 through October 23, 1995. These exceedances occurred throughout the data-collection period and were associated in particular with periods when the water temperature was high. An unusually large number of days occurred during the summer when the maximum air temperature was greater than 90 °F. These days also were characterized by extended periods of low base flow; however, the lowest computed daily flow was 0.43 ft^3/s. The lowest measured streamflow was 1.7 ft^3/s. The $7Q_{10}$ low flow at the Trevilian Way site is 0 ft^3/s, and the $7Q_2$ low flow is 0.43 ft^3/s (Ruhl and Martin, 1991). The $7Q_{10}$ low flow of ft^3/s is based largely on the observed zero flows in 1940, 1949, 1951–53, 1955, and 1960–61. Only peak-flow data were collected from 1962 to 1970, and since 1970 zero flow has not been observed at this site. Even during the drought of 1988 (late June and early July), streamflow at the site was greater than 1.5 ft^3/s, whereas streamflow at the Old Cannons Lane site decreased to less than the $7Q_{10}$ low flow of 0.30 ft^3/s (0.26 ft^3/s on July 4, 1988). After 1970, the lowest daily mean flow value at the Trevilian Way site was 0.26 ft^3/s. Because of the extended period of base flow (that is, a period of no runoff) and warm temperatures in late September and early October 1997, a water-quality sample was collected and streamflow measurements were made at all of the six monitoring sites (both reaches) on October 12, 1997. At the Old Cannons Lane site, streamflow was measured as 0.30 ft^3/s, whereas flow at the Trevilian Way site was measured as 2.4 ft^3/s. These discrepancies indicate that streamflow during extreme base-flow conditions at the two sites is not well correlated; however, it does appear that the $7Q_{10}$ low flow at the Trevilian Way site is not 0 ft^3/s.

Instantaneous concentrations of DO in water from the Eastern Parkway site for any particular day indicated far less variability than that observed in water from the Trevilian Way site. The lack of variability in the range of instantaneous values is consistent with the channel geometry and related physical characteristics of the stream channel at the Eastern Parkway site, which include long pools and turbid stream conditions. There also is at least partial shading of the stream channel upstream from the site. Sporadic occurrences of instantaneous DO concentrations less than 4.0 mg/L were observed in July, and DO decreased substantially during the first part of August until the remnants of Hurricane Erin substantially increased streamflows on August 5. A frontal system produced more rain on August 7–9, and the daily mean DO concentration remained greater than 5.0 mg/L until August 13. After a slight increase on August 21, water temperatures decreased, the minimum daily DO concentrations generally remained greater than 4.0 mg/L, and daily mean DO concentrations ranged between 4.0 and 6.0 mg/L. After the streamflow increase on September 15, minimum DO concentrations remained greater than 4.0 mg/L, and daily mean DO concentrations only sporadically decreased to less than 5.0 mg/L.

The greatest variability in DO concentrations throughout the day was measured at the Winter Avenue site. Algae in the channel was probably the factor most affecting high maximum concentrations, which generally occurred during mid-afternoon. The periods when DO concentration was highest indicate a significant reduction during periods of runoff, which could be the result of (1) the DO probe temporarily fouling as a result of solids covering the membrane, (2) the depleted DO in the stream because of the presence of the solids washed off in runoff, or (3) a combination of the two. Whichever is the case, DO concentrations recovered within a matter of days, which indicates that if fouling of the probe was occurring, it was only temporary.

The rapid recovery of DO concentrations and the lack of extremely low DO concentrations at the Winter Avenue site probably result, in large part, from the high reaeration-rate coefficient in the downstream subreach. The reaeration-rate coefficient, which is discussed in greater detail later in the report, is a measure of the capacity of the stream to absorb oxygen from the atmosphere. This capacity generally is considered to be a function of flow velocity, stream slope, and channel depth. The reaeration-rate coefficient measured for the downstream subreach, which is channelized, was an order of magnitude greater than that measured in the upstream (natural channel) subreach of South Fork Beargrass Creek. The higher reaeration-rate coefficient kept minimum DO concentrations from decreasing to extremely low levels during nighttime periods, even though dense algae mats often were present in the subreach channel from July 8 through October 19, 1995.

Histogram plots of DO concentrations measured at the three South Fork monitoring sites from July 7 through October 29, 1995, study period are shown in figure 9. A histogram plot of DO concentrations for July 7 through October 23, 1990–92, for the Trevilian Way site also is shown in figure 9. A statistical summary of the data is given in table 1. At the Trevilian Way site for 1995, the mode, mean, and median DO concentrations are 5.0, 6.1, and 6.0 mg/L, respectively. The mode, mean, and median DO concentrations from the Eastern Parkway site are all about 5.0 mg/L, and the range in values is much smaller than at the Trevilian Way site; however, the standard deviation of the data at both sites is 1.4 mg/L. The mode, mean, and median DO concentrations at the Winter Avenue site are 6.0, 6.9, and 6.6 mg/L, respectively, and are higher than those determined at the other two sites. There also is much greater variability in the Winter Avenue data (the standard deviation is 2.3 mg/L) than for the data at the other two sites as noted earlier in describing the time-series data shown in figure 8.

Data for July 7 through October 23, 1990–92, from the Trevilian Way site were used to construct a histogram (fig. 9*D*) to compare the available historical data to the data collected during the study period at that site (fig. 9*A*). The data collected during the study period are similar to data from the historical period, but the mode, mean, and median DO concentrations are all lower (table 1) and are possibly the result of high air temperatures observed during the summer of 1995. However, mean and median water temperatures at the Trevilian Way site 73 and 75 °F, respectively, for both the study and historical periods. For the historical data, mode, mean, and median DO concentrations are 6.8, 6.8, and 6.7 mg/L, respectively. These values are all higher than the respective DO concentrations of 5.0, 6.1, and 6.0 mg/L determined for data collected during the study period. The variability in DO concentrations from the two data sets is similar. The standard deviations of the historical data and study-period data are 1.6 and 1.4 mg/L, respectively. Overall, it appears that the DO data from the study period are similar in variability with that collected during the historical period but are lower in magnitude by about 10 percent. Therefore, the DO concentration data collected at the Eastern Parkway and Winter Avenue sites during the study period can be considered representative of data collected during historical periods with respect to variability but may be lower in magnitude by about 10 percent.

The percent saturation data for the South Fork monitoring sites (fig. 10) indicate that biological processes (primary production by algae in particular) have a substantial effect on DO concentrations at the Winter Avenue site and to a lesser extent at the Trevilian Way site. DO concentrations exceed 100-percent saturation during the daylight hours on most days at these two sites; however, this is not the case at the Eastern Parkway site. Figure 10 shows that the processes affecting DO at the three sites are different and that this variability probably extends throughout the South Fork study reach.

Periodic Water-Quality Data

Periodic determinations of selected water-quality constituents that affect DO concentrations also were made during the study period. The data are shown in tables 2 and 3 for the Middle Fork and South Fork sites, respectively. The data collected during 1997 when streamflows were at a minimum for that summer and fall also are included in the tables. Concentrations of nitrogen and phosphorus species were available for only the August and October 1997 samples at all of the monitoring sites. For other selected periodic samples, these data were available only for the two network monitoring sites in each reach. The network monitoring sites were Old Cannons Lane and Scenic Loop (formerly identified as "at Beals Branch Road") on the Middle Fork Beargrass Creek, and Trevilian Way and Winter Avenue on the South Fork. All data marked with an asterisk in tables 2 and 3 are estimated on the basis of (1) data values from the closest sample in time collected at that site, (2) interpolation or extrapolation of values from the site immediately upstream or downstream, and (or) (3) data from the August and October 1997 periodic samples. Because there was a substantial percentage increase in the concentration of ammonia (NH_3) in water from the downstream monitoring sites on the Middle Fork reach for the August and October 1997 samples, it would have been too subjective to estimate values of NH_3 at the Lexington Road site for the surveys made in 1996.

Field determinations shown in the tables 2 and 3 were made by USGS personnel or jointly by USGS and MSD personnel. Laboratory analyses for biochemical-oxygen demand (BOD), chemical-oxygen demand (COD), and organic nitrogen, ammonia (NH_3), nitrite (NO_2), nitrate (NO_3), organic phosphorus, and dissolved phosphorus concentrations were done by the MSD laboratory. Values in the tables, with respect to significance, are as reported by the MSD laboratory.

Table 2. Selected field and laboratory determinations from periodic samples used as calibration and verification data sets in QUAL2E model, Middle Fork Beargrass Creek reach, Jefferson County, Kentucky

[Q, discharge; WT, water temperature; AT, air temperature; BP, barometric pressure; HRS, hours of daylight; SOLAR, daily solar radiation; SP CD, specific conductance; DO, dissolved oxygen; %SAT, percent saturation of dissolved oxygen; BOD, carbonaceous biochemical-oxygen demand; COD, chemical oxygen demand; ORG N, organic nitrogen; NH_3, ammonia; NO_2, nitrite; NO_3, nitrate; ORTHO P, orthophosphorus; TOTAL P, total phosphorus; ft^3/s, cubic foot per second; °F, degrees Fahrenheit; mmHg, millimeters of mercury; BTUs ft^2/d, British thermal units per square foot per day; $\mu S/cm^2$, microsiemens per square centimeter; mg/L, milligrams per liter; (<2), less than detection limit of 2 mg/L; ND, not detected; --, not determined]

Date (month/ day/year)	Q (ft^3/s)	WT (°F)	AT (°F)	BP (mmHg)	HRS (hours)	SOLAR (BTUs ft^2/d)	pH (standard units)	SP CD ($\mu S/cm^2$)	DO (mg/L)	%SAT	BOD (mg/L)	COD (mg/L)	ORG N (mg/L)	NH_3 (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	ORTHO P (mg/L)	TOTAL P (mg/L)
Middle Fork Beargrass Creek at Old Cannons Lane (03293000, fig. 2)																		
07/24/96	6.5	71	77	760	14.4	2,520	8.0	592	7.7	86	(<2) 0.4	7	0.25	0.07	0.01	1.3	0.05	0.07
08/05/96	3.9	74	85	753	14.0	2,180	7.8	546	7.7	92	(<2) .7	6	*.24	*.07	*.01	*1.4	*.05	*.07
08/15/96	1.5	73	78	753	13.6	2,410	7.7	539	5.2	61	(<2) .7	8	*.23	*.07	*.01	*1.5	*.05	*.07
08/26/96	.90	75	81	753	13.2	2,160	7.9	563	8.0	96	(<2) .8	11	*.21	*.07	*.01	*1.6	*.05	*.06
09/05/96	.60	72	76	750	12.8	2,020	7.3	627	3.9	46	(<2) .8	20	*.19	*.08	*.01	*1.8	*.05	*.06
09/19/96	10.1	62	57	754	12.3	2,130	7.6	634	8.8	91	(<2) .4	12	.17	.08	.01	1.9	.05	.06
08/18/97	4.9	77	83	755	13.6	1,040	8.2	608	9.9	120	(<2) .4	6	.30	.09	.01	1.2	.05	.06
10/12/97	.30	67	83	752	11.4	1,770	7.5	659	7.3	80	(<2) ND	9	.12	.04	.01	.8	.03	.06
Middle Fork Beargrass Creek at Scenic Loop (03293200, fig. 2)																		
07/24/96	7.6	72	85	762	14.4	2,520	8.0	555	6.3	72	(<2) .3	10	.26	.06	.01	1.2	.08	.14
08/05/96	4.3	75	90	754	14.0	2,180	7.6	447	4.6	55	(<2) .5	6	*.25	*.06	*.01	*1.3	*.08	*.13
08/15/96	1.7	72	79	754	13.6	2,410	7.5	479	3.5	40	(<2) .8	12	*.24	*.07	*.01	*1.4	*.08	*.12
08/26/96	1.2	71	81	753	13.2	2,160	7.3	471	2.5	28	(<2) 1.0	20	*.21	*.07	*.02	*1.5	*.07	*.11
09/05/96	.19	71	76	750	12.8	2,020	7.1	609	1.3	15	(<2) .8	16	*.18	*.08	*.03	*1.7	*.06	*.09
09/19/96	12.4	62	63	756	12.3	2,130	7.7	619	7.9	82	(<2) .5	6	.15	.09	.03	1.8	.06	.07
08/18/97	5.4	76	82	756	13.6	1,040	7.7	579	4.0	48	(<2) .7	8	.33	.15	.03	1.2	.10	.12
10/12/97	.07	66	83	754	11.4	1,770	7.3	631	3.3	36	(<2) ND	12	.12	.08	.01	.5	.13	.16
Middle Fork Beargrass Creek at Lexington Road (03293500, fig. 2)																		
07/24/96	9.1	73	89	750	14.4	2,520	7.5	537	4.2	50	(<2) 1.0	16	*0.27	--	*0.02	*1.2	*0.10	*0.16
08/05/96	3.8	77	92	754	14.0	2,180	7.5	412	6.6	82	(<2) .7	11	*.28	--	*.02	*1.3	*.10	*.15
08/15/96	1.8	75	81	754	13.6	2,410	7.4	450	2.9	13	(<2) 1.0	11	*.29	--	*.02	*1.4	*.09	*.14
08/26/96	1.7	75	73	752	13.2	2,160	7.4	423	2.3	17	(<2) 2.0	24	*.30	--	*.04	*1.5	*.09	*.13
09/05/96	.19	74	76	750	12.8	2,020	7.1	499	2.6	31	(<2) 1.3	28	*.32	--	*.04	*1.7	*.08	*.11
09/19/96	11.6	64	72	756	12.3	2,130	7.6	603	7.6	81	(<2) .5	9	*.28	--	*.06	*1.8	*.07	*.08
08/18/97	5.7	75	80	756	13.6	1,040	7.4	572	2.5	29	(<2) 1.1	7	.34	0.46	.07	.83	.13	.15
10/12/97	.10	66	85	754	11.4	1,770	7.2	604	1.9	21	(<2) ND	15	.13	.20	.02	1.1	.12	.17

*, estimated value.

Table 3. Selected field and laboratory determinations from periodic samples used as calibration and verification data sets in QUAL2E model, South Fork Beargrass Creek reach, Jefferson County, Kentucky

[Q, discharge; WT, water temperature; AT, air temperature; BP, barometric pressure; HRS, hours of daylight; SOLAR, daily solar radiation; SP CD, specific conductance; DO, dissolved oxygen; %SAT, percent saturation of dissolved oxygen; BOD, carbonaceous biochemical-oxygen demand; COD, chemical oxygen demand; ORG N, organic nitrogen; NH_3, ammonia; NO_2, nitrite; NO_3, nitrate; ORTHO P, orthophosphorus; TOTAL P, total phosphorus; ft^3/s, cubic foot per second; °F, degrees Fahrenheit; mmHg, millimeters of mercury; BTUs ft^2/d, British thermal units per square foot per day; $\mu S/cm^2$, microsiemens per square centimeter; mg/L, milligrams per liter; (<2), less than detection limit of 2 mg/L]

Date	Q (ft^3/s)	WT (°F)	AT (°F)	BP (mmHg)	HRS (hours)	SOLAR (BTUs ft^2/d)	pH (standard units)	SP CD ($\mu S/cm^2$)	DO (mg/L)	% SAT	BOD (mg/L)	COD (mg/L)	ORG N (mg/L)	NH_3 (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	ORTHO P (mg/L)	TOTAL P (mg/L)
South Fork Beargrass Creek at Trevilian Way (03292500, fig. 3)																		
09/21/95	4.0	70	72	750	12.2	1,810	7.2	467	5.9	66	2.0	20	0.67	0.39	0.08	1.3	0.11	0.46
10/19/95	1.7	62	72	753	11.1	1,380	7.7	853	7.7	80	(<2) .6	4	.60	.34	.07	1.2	.06	.09
08/19/97	4.3	76	76	755	13.5	730	7.7	1,060	6.6	79	2.0	13	.46	.50	.06	1.6	.11	.16
10/12/97	2.4	65	69	754	11.4	1,770	7.3	1,770	7.0	75	2.0	13	.04	.44	.09	2.2	.08	.15
South Fork Beargrass Creek at Eastern Parkway (03292530, fig. 3)																		
09/21/95	5.0	67	62	751	12.2	1,810	7.5	511	4.5	50	2.0	21	*.66	*.20	*.07	*1.2	*.08	*.45
10/19/95	1.9	55	49	752	11.1	1,380	7.7	688	5.7	55	(<2) 1.0	7.8	*.50	*.17	*.06	*1.3	*.06	*.09
08/19/97	4.9	76	73	756	13.5	730	7.4	578	3.4	41	(<2) 1.2	9	.45	.19	.08	.75	.07	.11
10/12/97	1.9	65	77	754	11.4	1,770	7.2	860	4.2	45	(<2) .8	8	.11	.18	.05	.67	.08	.12
South Fork Beargrass Creek at Winter Avenue (03292550, fig. 3)																		
09/21/95	4.7	67	71	750	12.2	1,810	7.3	573	6.2	69	2.0	14	.65	.12	.06	1.2	.08	.43
10/19/95	2.3	56	57	753	11.1	1,380	7.3	570	9.2	90	(<2) .8	5	.45	.07	.05	1.4	.07	.09
08/19/97	5.1	75	70	756	13.5	730	7.4	583	5.6	67	(<2) 1.1	12	.44	.17	.08	.87	.08	.10
10/12/97	1.8	69	82	754	11.4	1,770	7.7	854	13.5	152	(<2) .8	12	.12	.08	.03	.76	.06	.09

*, estimated value.

All of the laboratory analyses for this study were done by the MSD laboratory. The MSD laboratory is approved by the U.S. Environmental Protection Agency (USEPA) to do routine wastewater analyses such as BOD and COD. The MSD laboratory is an approved laboratory by the USGS from the standpoint that data for selected constituents are usable in interpretive studies conducted by the USGS. This includes the analysis of the nitrogen and phosphorus species shown in tables 2 and 3. The MSD laboratory also undergoes other reviews conducted by outside parties (Patti Grace-Jarrett, MSD, oral commun., 1998).

The MSD laboratory also participates in the USGS Standard Reference Sample Program, which includes approximately 150 laboratories. Samples are sent to these laboratories for analysis, and from the results a most probable value of the sample concentration is determined. A review of the nitrogen and phosphorus concentrations determined by the MSD laboratory indicate that the laboratory did well on the determination of the phosphorus species and ammonia as nitrogen, but that the determinations of nitrite and nitrate as nitrogen may not be accurate. The concentrations of nitrogen species for the Middle Fork and South Fork sites were present at low levels and, as will be indicated in the DO simulations discussed later, had only a minor effect on DO concentrations.

SIMULATION OF PROCESSES AFFECTING DISSOLVED OXYGEN

An attempt was made to identify the major processes affecting DO concentrations in the study reaches of Middle Fork and South Fork Beargrass Creeks. The QUAL2E model (Brown and Barnwell, 1987) was chosen to simulate DO concentrations on the basis of data collected during the selected time periods. The following sections provide information about the QUAL2E model, the water-quality constituents simulated, and the calibration and verification of the model through the adjustment of the various rate coefficients.

Description of Dissolved-Oxygen Model

The QUAL2E model (Brown and Barnwell, 1987) was chosen to simulate DO concentrations for the lower reaches of Middle Fork and South Fork Beargrass Creek. QUAL2E is a one-dimensional, steady-state stream water-quality model typically used for waste-allocation analysis and water-quality investigations (Kentucky Natural Resources and Environmental Protection Cabinet, 1990).

A stream reach is simulated in the QUAL2E model as a series of completely mixed reactors of identical stream length that are sequentially linked by transport and dispersion mechanisms. Subreaches are defined as sequential groups of these reactors with identical hydrogeometric properties, such as stream slope and dispersion coefficient, and identical biological rate constants, such as carbonaceous biochemical-oxygen demand (BOD) decay rate and benthic source rates. As many as 15 water-quality constituents and properties can be simulated with QUAL2E. A complete description of the QUAL2E model and the various rate coefficients used in the model are provided by Brown and Barnwell (1987).

For this study, the emphasis was on the simulation of DO concentration and the interaction of the constituents and coefficients affecting DO concentration. These constituents and coefficients include water temperature, BOD, nitrogen species, algae (dependent on nitrogen and phosphorus), reaeration, and SOD. A number of hydraulic properties also affect DO concentration and are simulated in QUAL2E. Reaeration-rate coefficients, SOD rates, and various hydraulic properties were determined by field measurement. Rate constants for BOD, nitrogen, and phosphorus were determined through calibration (and confirmed through verification) of the model using data collected during the periodic surveys. A number of biological processes that can have a substantial effect on DO concentration, including the growth of zooplankton, periphyton, and rooted aquatic plants, are not simulated in QUAL2E.

The first step in simulating DO concentrations in the two study reaches was to divide each reach into subreaches that have uniform hydraulic and biochemical characteristics. Each reach was initially divided into two subreaches, which were assigned unique hydraulic and reaeration characteristics. These subreaches are defined as the stream sections between the streamflow-gaging stations shown in figures 2 and 3.

The Middle Fork Beargrass Creek reach had fairly uniform hydraulic characteristics throughout its entire length, but it was divided into separate subreaches to reflect the channel gradient and extended pools present in the downstream part of the reach. The model essentially prorates the reaeration characteristics between subreaches at the point where the subreaches meet. For the simulation of DO concentrations in the Middle Fork study reach, this would have resulted in an unrealistic increase in DO concentration at the junction of the subreaches. In an attempt to correct this condition, the initial upstream Middle Fork subreach was divided at its midpoint to allow for a more gradual transition in the reaeration-rate coefficients (K_2) between the original upstream and downstream subreaches. Reaeration and hydraulic characteristics were redefined for the new middle and upstream subreaches.

The South Fork Beargrass Creek reach consisted of a natural section and a channelized (concrete) section. Because the hydraulic properties of each section were different, the reach was divided at the Eastern Parkway site, where the channelized section began. An increase in the simulated DO concentration resulted at the junction of these two subreaches, but this was mostly the result of the large increase in K_2 to a constant value of 14.4 $days^{-1}$ for the channelized, concrete section. The proration of the reaeration characteristics between the two subreaches actually resulted in a DO concentration lower than expected at the first element of the downstream subreach.

Each subreach for both the Middle Fork and South Fork reaches then was divided into computational elements that were 0.2 mi in length. No point sources of inflow are present within either of the reaches during base-flow conditions; therefore, only the streamflow-gaging station locations were defined as nodes.

The water-quality constituents and coefficients simulated using the QUAL2E model for the Middle Fork and South Fork reaches include concentrations of DO, BOD, organic nitrogen as nitrogen, ammonia (NH_3) as nitrogen, nitrite (NO_2) as nitrogen, nitrate (NO_3) as nitrogen, organic phosphorus, and dissolved phosphorus. Algae as chlorophyll *a* was not simulated directly, but diurnal variations in DO concentrations were used to provide an estimate of the net DO concentration from photosynthesis and respiration. Typical values for chlorophyll *a* and associated rate coefficients were used in the model to simulate net DO production resulting from photosynthesis and respiration.

Model Parameter Determination from Field Measurements

A description of the use of field measurements to determine model-parameter values for the lower reaches of Middle Fork and South Fork Beargrass Creek is presented in the following sections. These sections describe the delineation of hydraulic and biochemical characteristics of each of the subreaches for the Middle Fork and South Fork reaches, including geometry and flow resistance, longitudinal dispersion, reaeration-rate coefficient, and SOD rates.

Hydraulic Characteristics

Hydraulic characteristics for the lower reaches of Middle Fork and South Fork Beargrass Creek were determined from time-of-travel studies and channel-geometry surveys conducted on parts of each reach during different streamflow conditions. Time-of-travel data were available for the Middle Fork Beargrass Creek reach (Smoot, 1988). Time-of-travel data were collected on the South Fork reach during this study. Rhodamine WT dye was used as the conservative tracer in the time-of-travel measurements, and discrete samples were analyzed using a fluorometer. Techniques for calibration of fluorometers and dye tracing are described by Hubbard and others (1982).

To simulate stream hydraulics, QUAL2E can use relations of the form:

$$v = aQ^b \quad \text{and} \quad d = xQ^y, \qquad (1)$$

where

v is velocity, in feet per second;
Q is streamflow, in cubic feet per second;
d is depth, in feet; and
a, b, x, and y are empirical constants.

The dye-tracer information from Smoot (1988) was used to develop the relations for the Middle Fork Beargrass Creek reach. The relations of mean velocity and depth to streamflow for the middle subreach of the Middle Fork reach are shown in figure 11. An additional observation from a part of this reach was used to extend the relation down to a streamflow of 0.51 ft^3/s.

Only a limited amount of dye-tracer information was available for the South Fork reach; however, the upstream South Fork subreach is very similar to the downstream Middle Fork subreach. The information from the dye-trace study by Smoot (1988) and the channel-geometry survey of the upstream South Fork subreach was used in conjunction with the reaeration-rate coefficients assigned to the downstream Middle Fork subreach to define reaeration-rate coefficients for

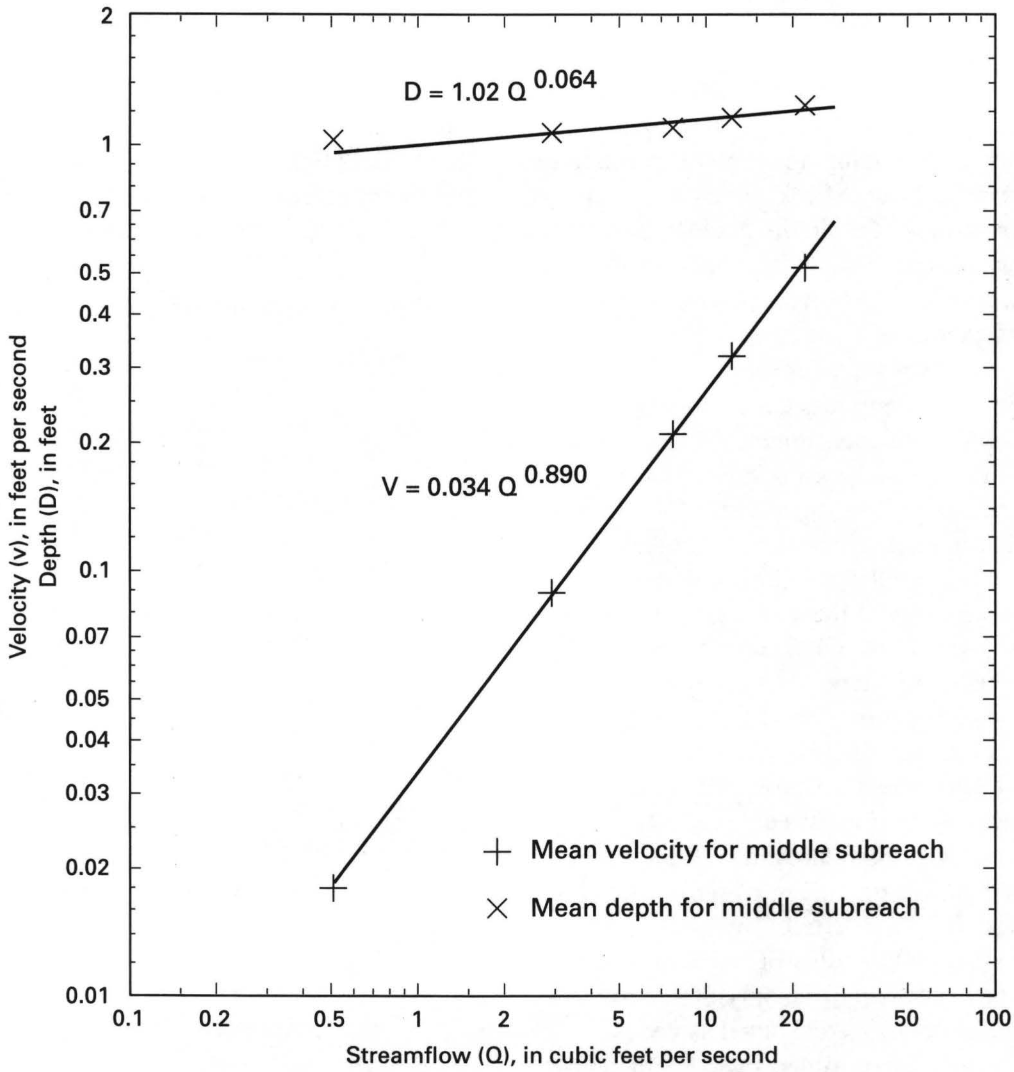


Figure 11. Relations of mean velocity and depth to streamflow as used in QUAL2E model for middle subreach of Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

the upstream South Fork subreach. Because the trapezoidal channel is uniform throughout the downstream South Fork subreach, streamflow measurements at various stages were used in conjunction with the dye-tracer information to define the hydraulic-geometry coefficient and exponent for the velocity and depth relations for the lower South Fork subreach. The hydraulic-geometry coefficients and exponents are listed in table 4.

Longitudinal Dispersion

Longitudinal dispersion was determined from the dye-tracer information available for the lower reaches of Middle Fork and South Fork Beargrass Creek. Longitudinal dispersion is defined by Fisher (1968) as the rate of change in variance of travel-time of a conservative tracer and can be calculated by:

$$D = \frac{1}{2}V^2\frac{\sigma_{t_d}^2 - \sigma_{t_u}^2}{\bar{t}_d - \bar{t}_u} , \qquad (2)$$

where

D is the longitudinal dispersion coefficient, in square feet per second;

V is the mean reach velocity, in feet per second;

σ_t^2 is the variance of the concentration-time curve, in seconds squared; and

$\bar{t}$ is the centroidal traveltime, in seconds.

The subscripts d and u denote the downstream and upstream ends of the reach, respectively. The variance

Table 4. Hydraulic-geometry coefficients and exponents used in QUAL2E model to simulate hydraulic characteristics of Middle Fork and South Fork Beargrass Creek reaches, Jefferson County, Kentucky

[ft/s, foot per second; ft, foot]

Model reach (figs. 2 and 3)	Hydraulic-geometry coefficient for Velocity (ft/s)	Hydraulic-geometry coefficient for Depth (ft)	Hydraulic-geometry exponent for Velocity (ft/s)	Hydraulic-geometry exponent for Depth (ft)
Middle Fork Beargrass Creek (upper)	0.041	0.70	0.892	0.067
Middle Fork Beargrass Creek (middle)	.034	1.02	.890	.064
Middle Fork Beargrass Creek (lower)	.038	1.14	.857	.092
South Fork Beargrass Creek (upper)	.027	1.50	.836	.142
South Fork Beargrass Creek (lower)	.700	.23	.477	.513

of the concentration-time curve is determined by the method of moments and is expressed by:

$$\sigma_t^2 = \frac{\Sigma t^2 C}{\Sigma C} - (\bar{t})^2 , \qquad (3)$$

where

C is the dye concentration, in micrograms per liter; and

t is the time from the start of injection for a specified dye concentration, in seconds.

Values of longitudinal dispersion were calculated using equation 2 after adjustments for dye loss were made. The lowest value of longitudinal dispersion measured for the reaches was used in the model.

The value of the dispersion constant (K) was determined from:

$$D = Kdu_* , \qquad (4)$$

where

K is the dispersion constant, dimensionless;

d is the mean depth in the reach, in feet; and

u_* is the shear velocity, in feet per second.

Values of shear velocity were determined from:

$$u_* = (gRS)^{0.5} , \qquad (5)$$

where

g is the acceleration of gravity, in square feet per second;

R is the hydraulic radius, in feet; and

S is the slope of the energy gradient, in feet per feet.

The roughness coefficient was determined from Manning's equation:

$$v = 1.486/n\,(R)^{0.67}\,(S)^{0.5} , \qquad (6)$$

where

v is the mean stream velocity, in feet per second; and

n is the Manning's roughness coefficient, dimensionless.

The values of the longitudinal dispersion coefficient, dispersion constant, shear velocity, and Manning's n are listed in table 5. The Manning's roughness coefficients computed using equation 6 are unreasonably high compared to those values found in hydraulics text (Chow, 1959, p. 101–123) and the publication on roughness values by Barnes (1967). Power functions using streamflow were used in the model to estimate velocity and the reaeration-rate coefficient instead of the unreasonably high roughness coefficients shown in table 5.

Reaeration-Rate Coefficient

The reaeration-rate coefficients for this study were determined on the basis of the hydrocarbon gas-tracer technique described by Rathbun and Grant (1978), Yotsukura and others (1983), and Kilpatrick and others (1989). This technique was adapted from the method described by Tsivoglou and Neal (1976). The hydrocarbon gas-tracer technique is based on the assumption that a constant relation is present between the absorption coefficient for oxygen and the desorption coefficient for a selected hydrocarbon gas, which was propane for these measurements.

A constant-rate injection method was used in the determination of the desorption coefficient for a hydrocarbon gas (propane) in the South Fork Beargrass Creek subreaches. A one-dimensional dispersion rate in the lateral direction and the principle of superposition are assumed in the application of the method (Kilpatrick and others, 1989). If a constant rate of injection is made for the gas tracer and if the streamflow is constant throughout the measurement period, then a plateau concentration will be reached at downstream locations. If gas injection continues for a sufficiently long period, longitudinal dispersion is no longer a factor in determining gas concentration levels. The amount of gas that was desorbed through the

Table 5. Longitudinal dispersion coefficients, dispersion constants, shear velocities, and Manning's roughness coefficients (*n*) used in QUAL2E model for Middle Fork and South Fork Beargrass Creek reaches, Jefferson County, Kentucky

[ft^2/s, square feet per second; ft/s, foot per second]

Model reach (figs. 2 and 3)	Dispersion coefficient (ft^2/s)	Dispersion constant (dimensionless)	Shear velocity (ft/s)	Manning's *n* (dimensionless)
Middle Fork Beargrass Creek (upper)	25.3	92.7	0.346	0.845
Middle Fork Beargrass Creek (middle)	19.9	68.4	.272	.806
Middle Fork Beargrass Creek (lower)	17.3	85.5	.158	.520
South Fork Beargrass Creek (upper)	15.7	83.3	.103	.360
South Fork Beargrass Creek (lower)	7.5	114	.140	.023

subreach then is determined as the upstream gas concentration minus the downstream gas concentration, adjusted for temperature. The constant-rate injection must be made for a period longer than the duration of the response curve at the most downstream site that would result from an instantaneous slug injection. To make sure that this criterion is met, an instantaneous slug injection of dye is made when the gas tracer is injected, and the dye concentrations are determined throughout the measurement.

The approximate solution for the gas-desorption coefficient (K_t) is:

$$K_t = \frac{1}{t_c} \ln \frac{(C_g Q)_u}{(C_g Q)_d} , \qquad (7)$$

where

Q_u and Q_d are streamflow at the upstream and downstream measuring sections, respectively;

C_{gu} and C_{gd} are the weighted average plateau concentrations of the gas at the upstream and downstream measuring sections, respectively; and

t_c is the time of travel of the centroid of the dye-tracer response curves between the upstream and downstream measuring sections.

The data needed to determine t_c were acquired by an instantaneous slug injection of a dye tracer made at the same location as that of the continuous gas-tracer injection.

The gas-desorption coefficient is related to reaeration-rate coefficient by the relation:

$$K_2 = rK_t , \qquad (8)$$

where

K_2 is the reaeration-rate coefficient; and

r is the coefficient ratio for oxygen and a tracer gas, which is 1.39 for propane.

Because the reaeration-rate coefficient changes proportionally with temperature, the value is adjusted to 20 °C using the equation

$$K_2 \; @20\,°C \; = K_2(1.0241)^{20-T} , \qquad (9)$$

where

T is the water temperature at which the measurement was made, in degrees Celsius.

The data from Smoot (1988) were used to construct a plot of streamflow with the reaeration-rate coefficient for the Middle Fork subreaches. For this study, a power function was developed for estimating K_2 as a function of streamflow for the Middle Fork and upstream South Fork subreaches. The relation for the downstream subreach of the Middle Fork reach is shown in figure 12. The hydraulics of the upstream South Fork Beargrass Creek subreach are similar to that of the downstream Middle Fork subreach. Because of the similarity and reaeration-rate coefficient field determinations made on the upstream South Fork subreach, a reaeration-rate coefficient relation was developed for the upstream South Fork subreach. The coefficients and exponents for the power functions to estimate the reaeration-rate coefficient for the subreaches are listed in table 6, and the equation has the form $K_2 = aQ^b$ (equation 1), where K_2 is the reaeration-rate coefficient, Q is the streamflow, and a and b are empirical constants. The a represents the coefficient of flow for K_2, and b represents the exponent of flow for K_2.

The reaeration-rate coefficient measured for the upstream South Fork subreach was 1.47 $days^{-1}$ at a streamflow of 3.7 ft^3/s. There was no wind during the measurement, which was made on August 28, 1996. Several equations presented in the QUAL2E manual were tested to estimate the reaeration-rate coefficient

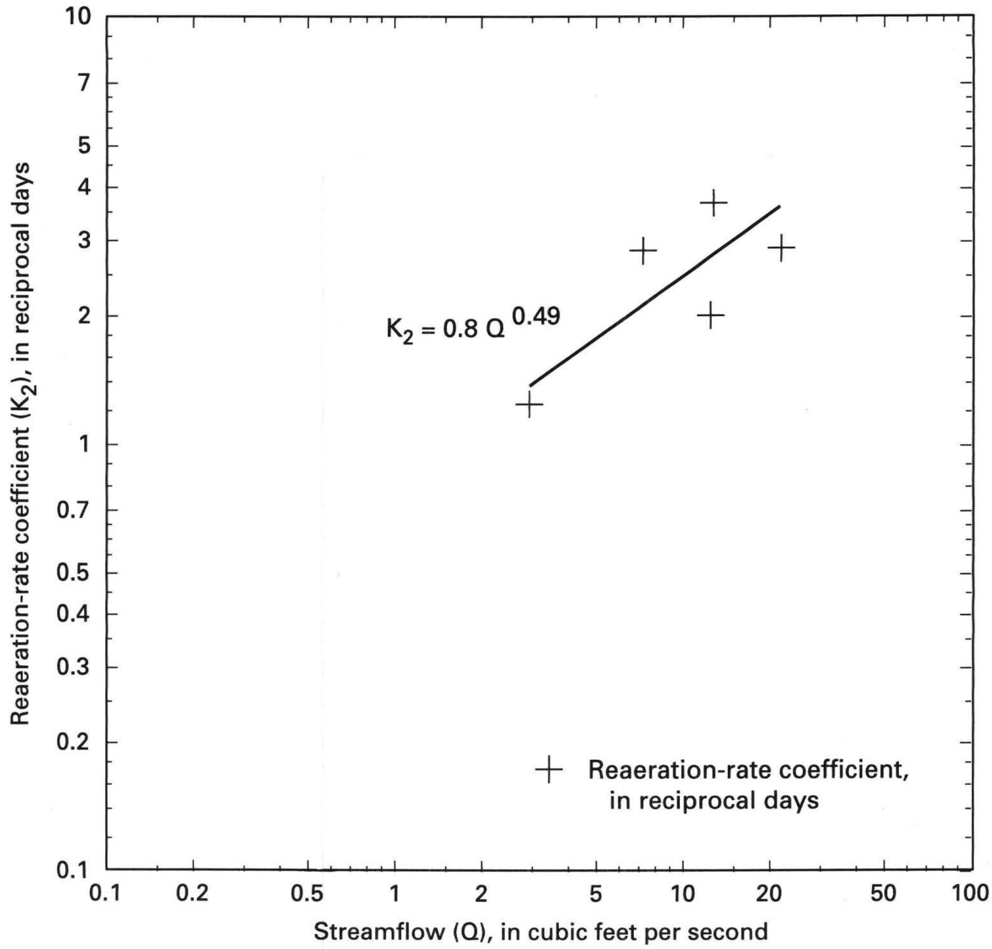


Figure 12. Relation of mean reaeration-rate coefficients to concurrent streamflow used in QUAL2E model for lower subreach of Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

on the basis of conditions present during the measurement. The O'Connor and Dobbins (1958) equation yields an estimate of 1.48 $days^{-1}$. Smoot (1988) found that this equation also provided estimates with consistently small errors when compared to measured values. The Tsivoglou and Wallace (1972) equation yields an estimate of 0.14 $days^{-1}$, approximately an order of magnitude less than the measured value (1.47 $days^{-1}$).

The measured reaeration-rate coefficient for the downstream South Fork Beargrass Creek subreach was 14.4 $days^{-1}$ at a streamflow of 4.4 ft^3/s. This measurement was made on August 27, 1996. Several different equations were tested to investigate the changes of this coefficient with respect to (1) depth and (2) depth and velocity. Estimates of 17.3 $days^{-1}$ and 21.7 $days^{-1}$ were determined by applying the Tsivoglou and Wallace (1972) and Smoot (1988) equations, respectively. An estimate of 48 $days^{-1}$ was determined with the O'Connor and Dobbins (1958) equation. Using the curves developed previously for depth and velocity for this reach (figs. 11 and 12), the estimated reaeration-rate coefficient actually increased slightly with decreasing streamflow; therefore, the value of 14.4 $days^{-1}$ was applied as a constant for all values of streamflow used in the model. This appears to be an appropriate assumption given that the DO concentration at the Winter Avenue site did not reach extremely low levels during the nighttime period as might result in a pool-and-riffle stream affected by effluent discharged to the stream.

Sediment-Oxygen Demand

Periodic field determinations of sediment-oxygen-demand (SOD) rates were made at selected locations, and these values were used as reach averages. Cham-

Table 6. Coefficients and exponents of flow used in QUAL2E model to simulate reaeration-rate coefficients *(K_2)* for Middle Fork and South Fork Beargrass Creek reaches, Jefferson County, Kentucky

Model reach (figs. 2 and 3)	Coefficient of flow for K_2	Exponent of flow for K_2
Middle Fork Beargrass Creek (upper)	3.0	0.51
Middle Fork Beargrass Creek (middle)	1.5	.48
Middle Fork Beargrass Creek (lower)	.8	.49
South Fork Beargrass Creek (upper)	.8	.37

bers to measure SOD were constructed out of darkened Plexiglas, and the measurements were made using procedures as recommended by Hatcher (1986). The curve used to define the SOD rate on September 23, 1996, at the Trevilian Way monitoring site is shown in figure 13. Although generally preferred over laboratory methods (Hatcher, 1986), field determinations of SOD represent the value at only one location within the stream reach. Values collected during the study period ranged from 0.10 to 0.18 g O_2 (ft^2/d). These values compare favorably with values obtained by U.S. Environmental Protection Agency personnel during a field survey of two Kentucky streams in 1988 (David M. Leist, Kentucky Division of Water, written commun., 1988). The two streams were Town Branch and South Elkhorn Creek, which are both affected by waste-effluent discharges from sewage-treatment plants near Lexington, Kentucky. At four of the six stream monitoring sites near Lexington, the SOD rates ranged from 0.095 to 0.18 g O_2 (ft^2/d). At the other two sites, the rates were 0.32 and 0.37 g O_2 (ft^2/d). No explanation was included as to why these two values were so much higher than those obtained at the other four sites, but these results indicate that SOD rates can vary substantially along a stream reach.

Field determinations of SOD rates made for the downstream reaches of Middle Fork and South Fork Beargrass Creeks during the study period are shown in table 7. No SOD-rate measurements were made at the Old Cannons Lane monitoring site because the streambed is mostly rock slab and the Plexiglas chamber would not work under those conditions because a good seal between the bottom of the chamber and the streambed was not possible. No SOD-rate measurements were made at the Eastern Parkway site. It was assumed that the Trevilian Way measurement would represent the upstream subreach, and the Winter Avenue measurement would represent the downstream subreach of the South Fork Beargrass Creek reach (fig. 3). The SOD rates measured during the study are consistent with values presented by Thomann and Mueller (1987, p. 292) for what is classified as municipal sewage sludge that is "aged" (some distance downstream from the outfall, but not directly at the outfall).

Model Calibration and Verification

For the Middle Fork reach, the July 24 and September 19, 1996, periodic water-quality samples were used as calibration data sets and were supplemented by information obtained from the other periodic samples shown in table 2 for 1996. The August 18 and October 12, 1997, samples were used as verification data sets. Unfortunately, nitrogen and phosphorus data were not available at the Lexington Road site for the July 24 and September 19, 1996, data sets, but continuous-record DO concentrations were available for all three monitoring sites in the Middle Fork reach on these dates. Therefore, concentrations of selected nitrogen and phosphorus species were estimated for the calibration data set. However, the depletion of DO with respect to nitrogen was small for all of the Middle Fork simulations as is indicated later in the report. Phosphorus concentrations also are low for the data sets considered.

For the South Fork reach, the September 21 and October 19, 1995, periodic samples were used as calibration data sets, and the August 19 and October 12, 1997, samples were used as verification data sets (table 3). Unfortunately, nitrogen and phosphorus concentrations were not available for the Eastern Parkway site for the September 21 and October 19, 1995, data sets, but the continuous record of DO concentrations was available for all three monitoring sites on these dates; therefore, concentrations of selected nitrogen and phosphorus species were estimated for the September 21 and October 19, 1995, data sets. Fortunately, data were available for each end of the South Fork reach, and as is indicated later in the report, the depletion of DO with respect to nitrogen was small for all of the South Fork simulations. Phosphorus concentrations also were low for the data sets considered.

The calibration and verification results are presented jointly for the Middle Fork and South Fork

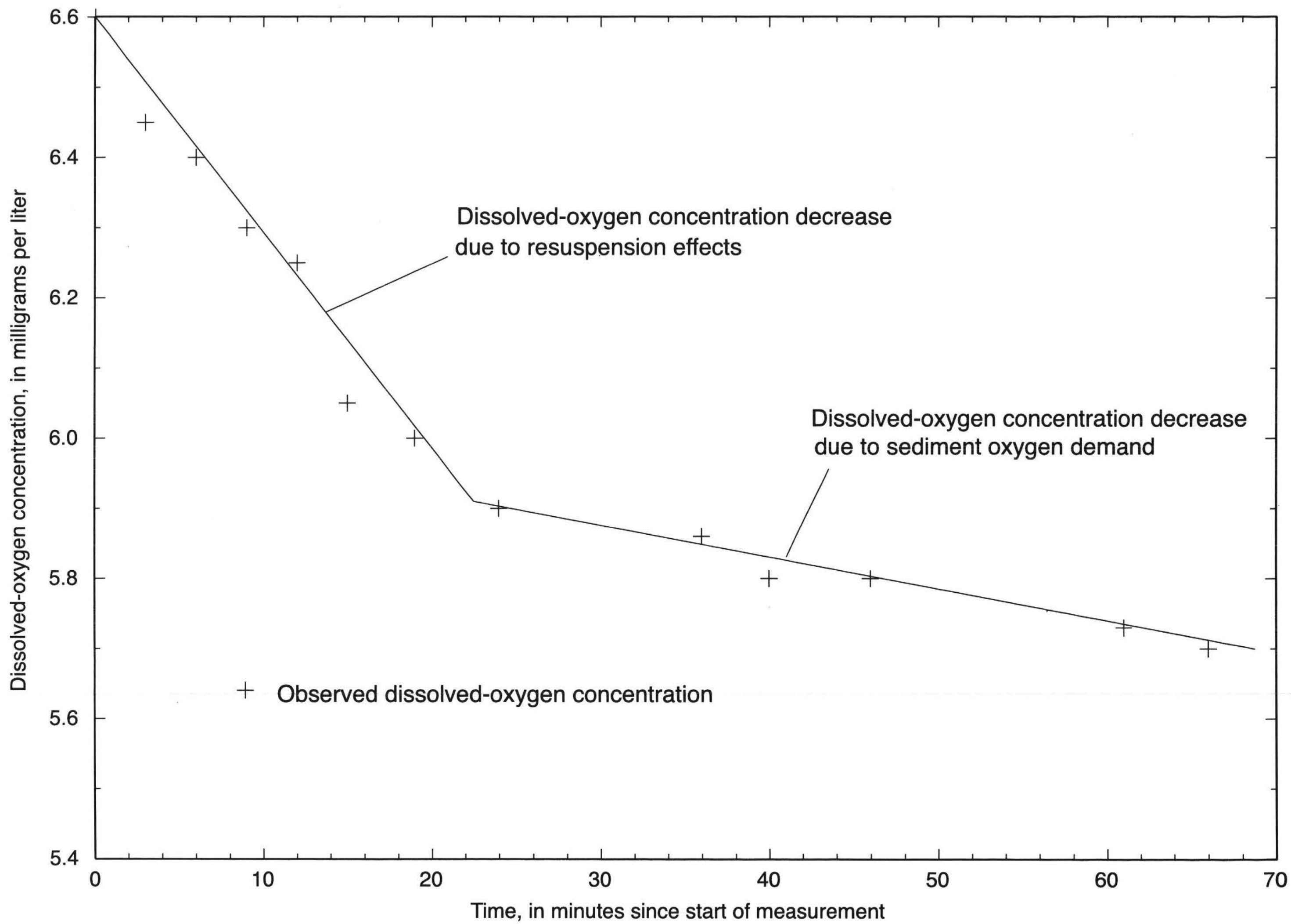


Figure 13. Curve used to define sediment-oxygen-demand rate on basis of dissolved-oxygen concentrations at South Fork Beargrass Creek at Trevilian Way monitoring site, Jefferson County, Kentucky, September 23, 1996.

Table 7. Sediment-oxygen-demand rates determined for selected Middle Fork and South Fork Beargrass Creek monitoring sites, Jefferson County, Kentucky

[SOD, sediment oxygen demand; g $O_2(ft^2/d)$, grams of oxygen per square foot per day]

Date of collection (month/day/year)	Monitoring site (figs. 2 and 3)	SOD rate [g $O_2(ft^2/d)$]
	Middle Fork Beargrass Creek	
08/15/96	Scenic Loop	0.13
	Lexington Road	*
08/26/96	Scenic Loop	.10
	Lexington Road	*.02
10/27/97	Scenic Loop	*
	South Fork Beargrass Creek	
09/23/96	Trevilian Way	.10
	Winter Avenue	.10
10/11/97	Trevilian Way	**.18
	Winter Avenue	***

*Initial dissolved-oxygen concentration was very low at the site; therefore, measurement was deemed unusable.

**Effluent mat observed approximately 1,200 feet upstream from the SOD measurement location; coliform counts were very high.

***Water depth was too shallow to do the measurement using the available Plexiglas chamber.

reaches. The rate coefficients that compose the calibration and verification analyses are presented in the following sections.

Streamflow

Streamflow was measured at each site during each periodic sample. The streamflow value at the upstream end of each reach was input to the model as an initial condition. Measured streamflow at the downstream sites was simulated in the model by inputting the appropriate incremental inflow into the model. Because periodic samples were made during base-flow conditions, no tributary inflow was present along either reach; therefore, any increase or decrease in inflow from one monitoring site to the next was treated as occurring uniformly throughout the given subreach.

It is evident that streamflow did decrease in the subreach from Old Cannons Lane to Scenic Loop during extremely low base-flow conditions (tables 2 and 3). The October 12, 1997, sampling on the South Fork reach also indicated that streamflow was decreasing in the downstream direction; however, the measuring conditions at the Eastern Parkway and Winter Avenue sites were extremely poor because of the larger amount of attached algae present in the trapezoidal concrete channel than that at the Trevilian Way site.

Stream Temperature

Stream temperature was not simulated in QUAL2E. Average values of stream temperature based on the observations made at the ends of each subreach at the time of the sampling were input as initial conditions to the model. This was done so that the proper saturation DO concentration and temperature-adjusted rate constants were utilized.

Ultimate Carbonaceous Biochemical-Oxygen Demand

Determinations of the 5-day carbonaceous biochemical-oxygen demand (BOD_5) were made from periodic samples collected during the study period (tables 2 and 3). BOD_5 is determined by monitoring the oxygen consumption of the samples over a 5-day period. Within the QUAL2E model, the BOD_5 value is converted to the ultimate BOD value (BOD_u) through the equation:

$$BOD_u = BOD_5 / [1 - exp(-5 K_1)] , \qquad (10)$$

where

BOD_u is the ultimate concentration of BOD;
BOD_5 is the 5-day concentration of BOD; and
K_1 is the BOD decay-rate coefficient.

No laboratory determinations of BOD_u were made; therefore, the program-default value of 0.23 $days^{-1}$ was used initially for K_1 (Brown and Barnwell, 1987) for both the Middle Fork and South Fork reaches.

The concentration of BOD_5 was undersimulated for both reaches using a K_1 of 0.23 day^{-1}. There are no known sources of BOD along the reaches during base-flow conditions. A leaking CSO during low-flow periods would produce elevated concentrations of BOD, and DO concentrations would decrease substantially; however, the increases determined at the downstream monitoring sites were small, and no leaking CSO's were observed during the study period.

The increase in BOD could be the result of leaking sewer lines located along the creek. Material from leaking sewer lines could leach out into the soil and be delivered to the stream even during base-flow conditions. This condition was observed at the Trevilian

Way site during the October 12, 1997, sampling. There had been no appreciable rainfall for several weeks prior to the sampling. A mat of sewage material was present in the stream along the right bank approximately 1,200 ft upstream from the monitoring site at Trevilian Way. For the October 12, 1997, sampling, the BOD at the Trevilian Way site was reported as 2.0 mg/L, and the BOD at both downstream sites was reported as 0.8 mg/L (table 3). The fecal-coliform count at the Trevilian Way site was reported as 4,200 colonies per 100 milliliters of sample, whereas the counts at the two downstream sites were 200 and 110 colonies per milliliter of sample, respectively. During the evening of October 12, rainfall increased the streamflow, and base-flow conditions did not reach the October 12, 1997, levels for the remainder of 1997. MSD personnel were notified of the condition, but the mat had been washed away, and MSD personnel could not locate any leaks in the sewer line in that area.

Other researchers (Melching and Chang, 1996) have observed similar increases in BOD as previously discussed without being able to identify an associated known point source of BOD. Melching and Chang (1996) also cited a study done by the New Jersey Department for Environmental Protection (1987), which indicated similar results. It was stated in the New Jersey report that algal respiration within the BOD sample results in elevated concentrations of BOD. In the New Jersey study, adequate information on algal production and respiration was available to develop a relation to adjust the value of BOD; however, for this study the type of data needed to produce such a relation was not available.

To account for the increased BOD, the value of K_1 (the BOD decay rate) for the Middle Fork simulations was not reduced but was kept at 0.23 $days^{-1}$. This value is the default in Brown and Barnwell (1987). The model would not accept a negative BOD settling rate (K_3); therefore, K_3 was set to 0 $days^{-1}$, and an incremental inflow of BOD was used to account for the increase in BOD at the downstream sites. Incremental inflow concentrations of BOD of 2.0, 2.0, and 4.0 mg/L, respectively, were used for the upstream, middle, and downstream subreaches of the Middle Fork reach. The resulting simulations are shown in figure 14 for the Middle Fork calibration and verification data sets and indicate generally good agreement with measured BOD concentrations. Concentrations of BOD from the October 12, 1997, sampling were reported only as less than (<) 2 mg/L (table 2); therefore, a BOD simulation for that date was not done. The resulting decrease in the simulated DO concentration by using the incremental inflow of BOD was quite small and ranged from 0 to 0.05 mg/L.

For the South Fork reach, the concentrations of BOD remained fairly constant or indicated a slight decrease in the downstream direction (table 3). Simulated and measured BOD concentrations for the South Fork calibration and verification data sets are shown in figure 15. The graphs show generally poor agreement between the BOD calibration and verification data sets; however, the concentrations for some samples were reported to the nearest integer, whereas others were reported to the nearest hundredth. Because of this reporting to different significance levels, a rigorous attempt to match the measured concentrations of BOD was not done, and the calibration and verification data sets were evaluated jointly to make a determination of the most appropriate values for K_1 and K_3 and were set to 0.23 $days^{-1}$ and 0 $days^{-1}$, respectively, as was done for the Middle Fork subreaches. Also, no incremental inflow of BOD was added to either of the two subreaches as was done for the Middle Fork modeling of BOD. As with the Middle Fork analysis, the effect of BOD on DO concentration for the South Fork reach is relatively small compared to the deficit resulting from other factors, in particular SOD.

Organic Nitrogen

For the study period, organic nitrogen concentrations (tables 2 and 3) were consistently low throughout the two reaches. The QUAL2E model calculates the amount of oxygen consumed on the basis of the following series of reactions. Organic nitrogen present in the stream decomposes to form ammonia (NH_3). The ammonia then is oxidized to nitrite (NO_2), and the nitrite is further oxidized to nitrate (NO_3). This process of oxidation from NH_3 to NO_2 and from NO_2 to NO_3 is termed nitrification. Nitrification consumes oxygen and can result in substantial decreases in DO concentrations.

At the Middle Fork monitoring sites, concentrations of organic nitrogen ranged from 0.12 to 0.34 mg/L, and at the South Fork sites, concentrations ranged from 0.04 to 0.67 mg/L. Because concentrations of organic nitrogen are low and fairly consistent throughout the reach for each sampling period, a value of 0.02 day^{-1} was used as the rate constant for the hydrolysis of organic nitrogen to ammonia (β_3). This

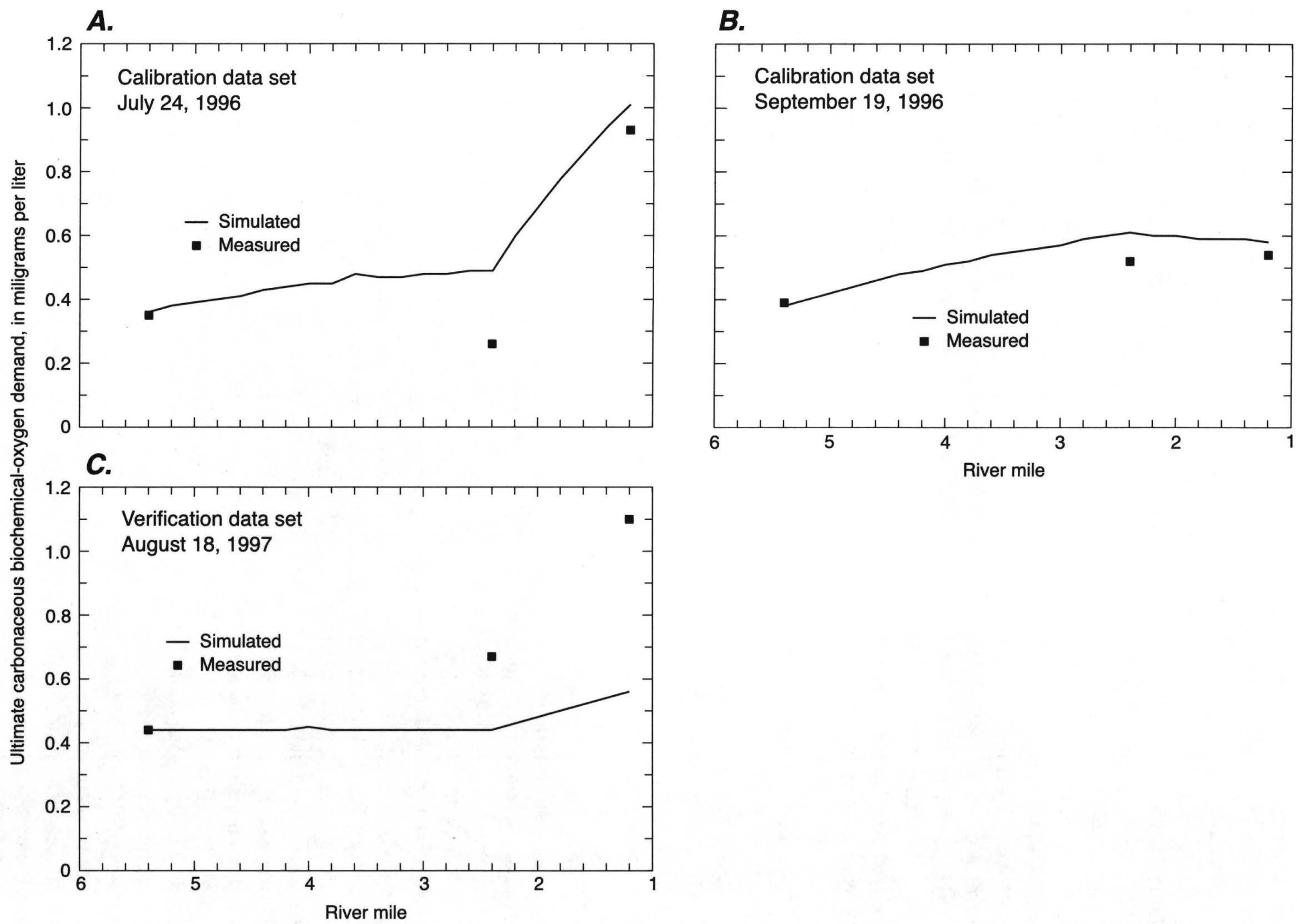


Figure 14. Simulated and measured concentrations of ultimate carbonaceous biochemical-oxygen demand for calibration (July 24 and September 19, 1996) and verification (August 18, 1997) data sets, Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

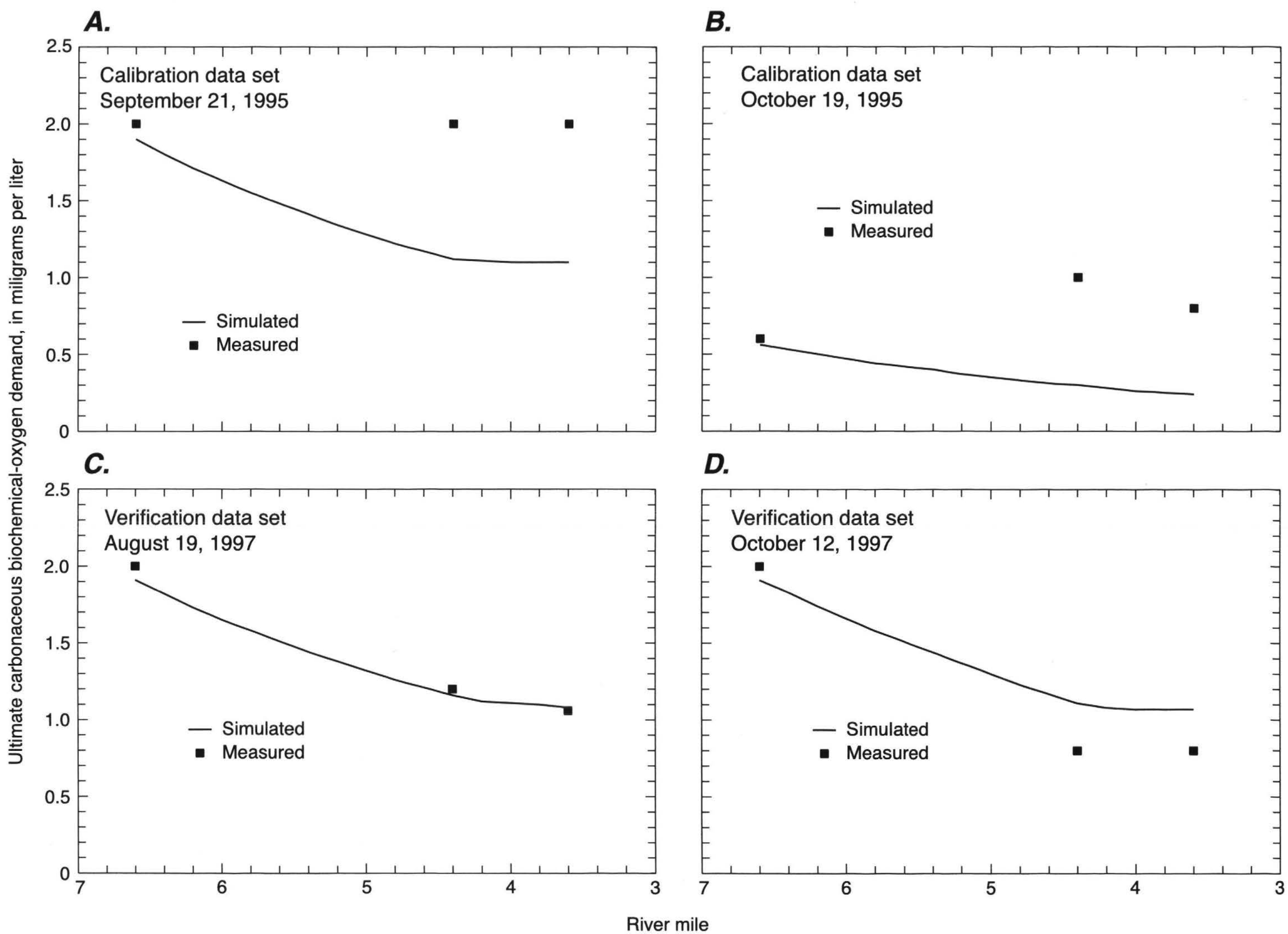


Figure 15. Simulated and measured concentrations of ultimate carbonaceous biochemical-oxygen demand for calibration (September 21 and October 15, 1995) and verification (August 19 and October 12, 1997) data sets, South Fork Beargrass Creek reach, Jefferson County, Kentucky.

value is the lower limit of values recommended by Brown and Barnwell (1987) for β_3. The nitrogen settling rate, σ_4, was set to 0 day^{-1}. To account for the concentration of organic nitrogen remaining fairly constant throughout the Middle Fork reach, an incremental inflow concentration of 0.3 mg/L was applied to all three of the subreaches. Simulated and measured concentrations of organic nitrogegn for the Middle Fork subreaches indicate fairly good agreement (fig. 16).

Simulated and measured concentrations of organic nitrogen for the calibration and verification data sets for the South Fork subreaches are shown in figure 17. A value of 0.02 day^{-1} was used for β_3, and σ_4 was set to 0 day^{-1}. These values are the same as those used for the Middle Fork subreaches. The graphs in figure 17 indicate generally good agreement between the simulated and measured concentrations of organic nitrogen.

Total Ammonia as Nitrogen

As with organic nitrogen, concentrations of total ammonia as nitrogen (NH_3 in tables 2 and 3) were quite low and fairly consistent throughout both the Middle Fork and South Fork reaches for each sampling period. Concentrations of NH_3 increased in the downstream direction on the Middle Fork reach for the August 18 and October 12, 1997, samplings but not to appreciably high concentrations. Conversely, the South Fork reach had elevated (but not high) concentrations at the upstream boundary, and these concentrations decreased substantially at the downstream monitoring sites. Measured concentrations ranged from 0.06 to 0.50 mg/L for both the Middle Fork and South Fork reaches. Because the measured concentrations of NH_3 were quite low (consistent with the measured concentrations of organic nitrogen), a value of 0.20 day^{-1} was used for the rate constant for the biological oxidation of ammonia to nitrite (β_1) for both subreaches. This value is near the lower limit of the values recommended in Brown and Barnwell (1987).

For the Middle Fork reach, values of 0.5, 0.5, and 1.0 mg/(ft^2/d) were used for the benthic source rate for ammonia nitrogen (σ_3) in the upstream, middle, and downstream subreaches, respectively, because of the increase in ammonia concentration throughout the reach (fig. 18). Because ammonia concentrations increased for the August 18 and October 12, 1997, samplings at the Scenic Loop and Lexington Road monitoring sites, it was deemed too subjective to estimate ammonia concentrations at the Lexington Road site for the samplings made during the 1996 data-collection period. Although the increase in ammonia concentration is small through the reach in the downstream direction, no physical evidence is available to explain the increase in ammonia in the Middle Fork reach.

Simulated and measured concentrations of ammonia nitrogen for the Middle Fork reach for the calibration and verification data sets are in close agreement (fig. 18). No measured concentrations at the Lexington Road site are shown except for August 18 and October 12, 1997. Because the measured concentrations of ammonia nitrogen are quite small at each of the monitoring sites, the corresponding decrease in DO that is attributed to ammonia nitrogen is less than or equal to 0.12 mg/L for all of the simulations.

Simulated and measured concentrations of total ammonia as nitrogen for the South Fork subreaches are shown in figure 19. The graphs indicate generally good agreement between the simulated and measured concentrations for both the calibration and verification data sets. Measured concentrations of NH_3 decreased throughout the reach; therefore, a value of 0 mg/(ft^2/d) was used for σ_3 for each subreach. Values of β_1 of 0.20 and 1.00 day^{-1} [1.00 day^{-1} being the upper limit of values recommended by Brown and Barnwell (1987)] were used for the upstream and downstream subreaches, respectively. The high value assigned to the downstream subreach is probably appropriate because periphyton is able to attach more readily to the sides of the concrete channel and, therefore, have better access to available ammonia.

Nitrite and Nitrate as Nitrogen

Concentrations of nitrite (NO_2) and nitrate (NO_3) nitrogen are quite low throughout both reaches but are lowest for the Middle Fork reach (table 2), ranging from 0.01 to 0.07 mg/L for nitrite and 0.5 to 1.9 mg/L for nitrate. The low concentrations of nitrite indicate that the oxidation of nitrite to nitrate occurs rapidly, which is typical of a riverine environment. Concentrations of nitrite and nitrate also are quite low for the South Fork reaches (table 3), ranging from 0.09 to 0.12 mg/L for nitrite and 0.67 to 1.4 mg/L for nitrate. For the QUAL2E simulations, the concentrations of nitrite and nitrate were summed for comparison with measured values.

For the Middle Fork reach, the value of the rate constant for the biological oxidation of nitrite to

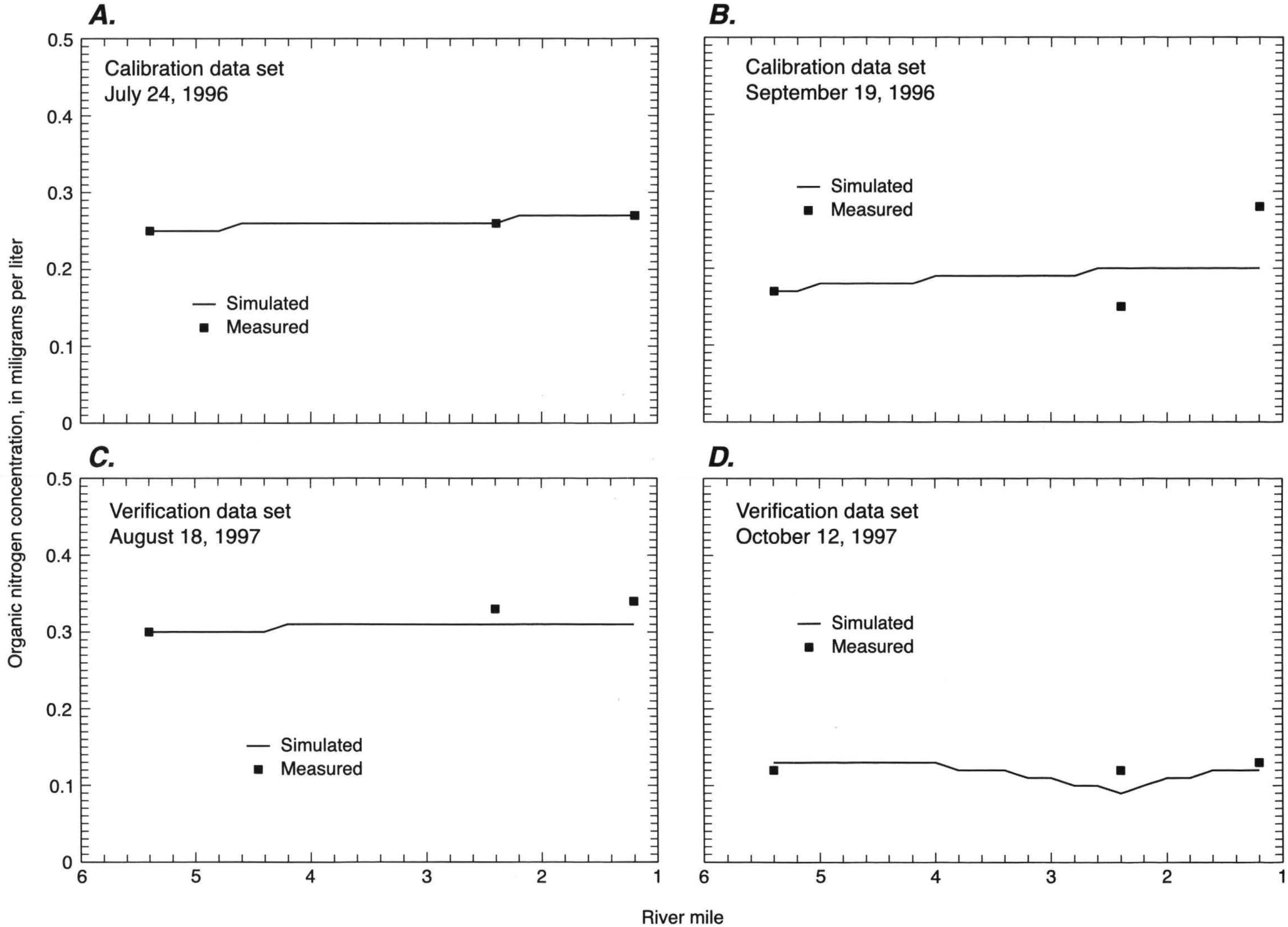


Figure 16. Simulated and measured concentrations of organic nitrogen for calibration (July 24 and September 19, 1996) and verification (August 18 and October 12, 1997) data sets, Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

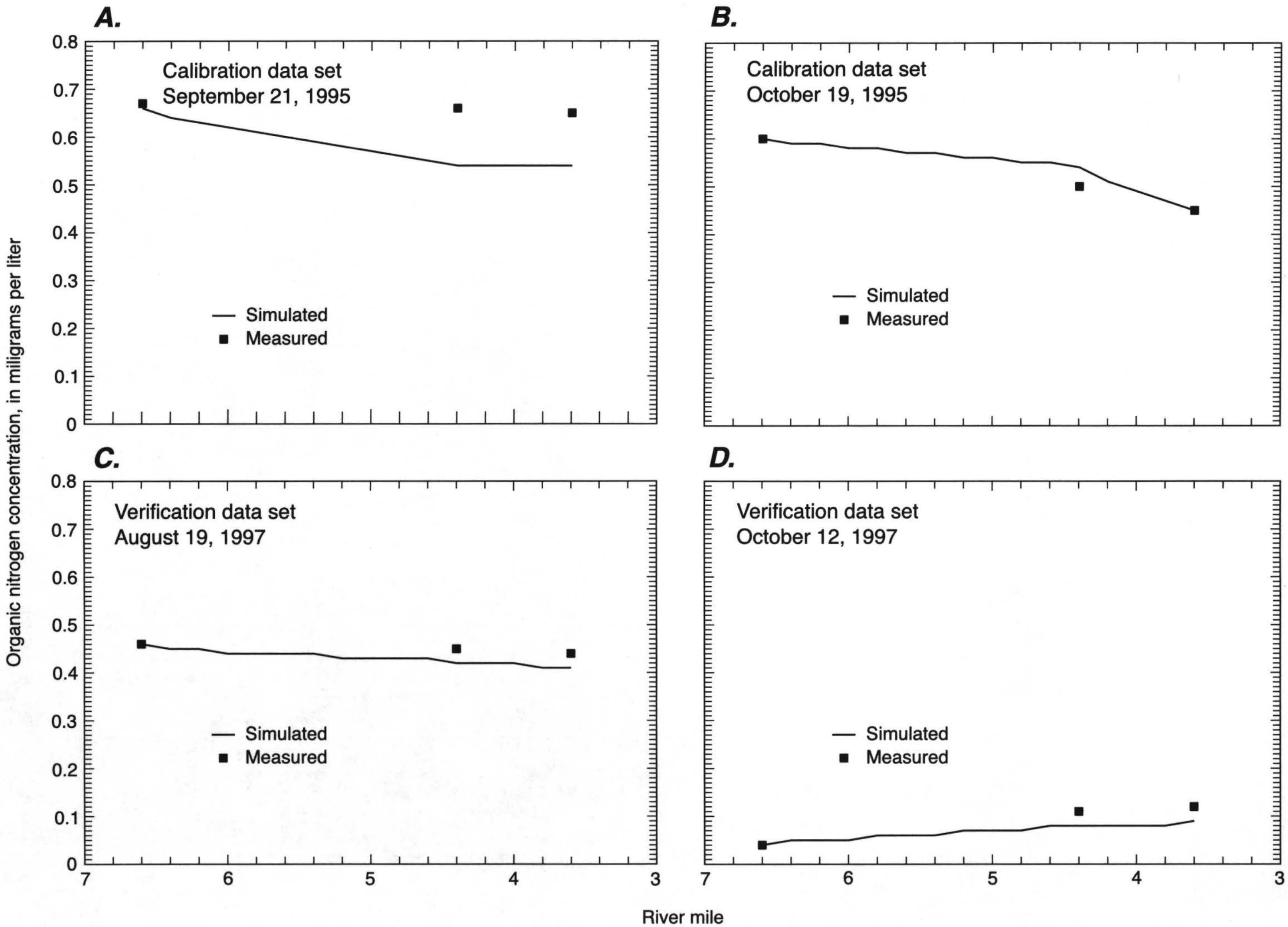


Figure 17. Simulated and measured concentrations of organic nitrogen for calibration (September 21 and October 19, 1995) and verification (August 19 and October 12, 1997) data sets, South Fork Beargrass Creek reach, Jefferson County, Kentucky.

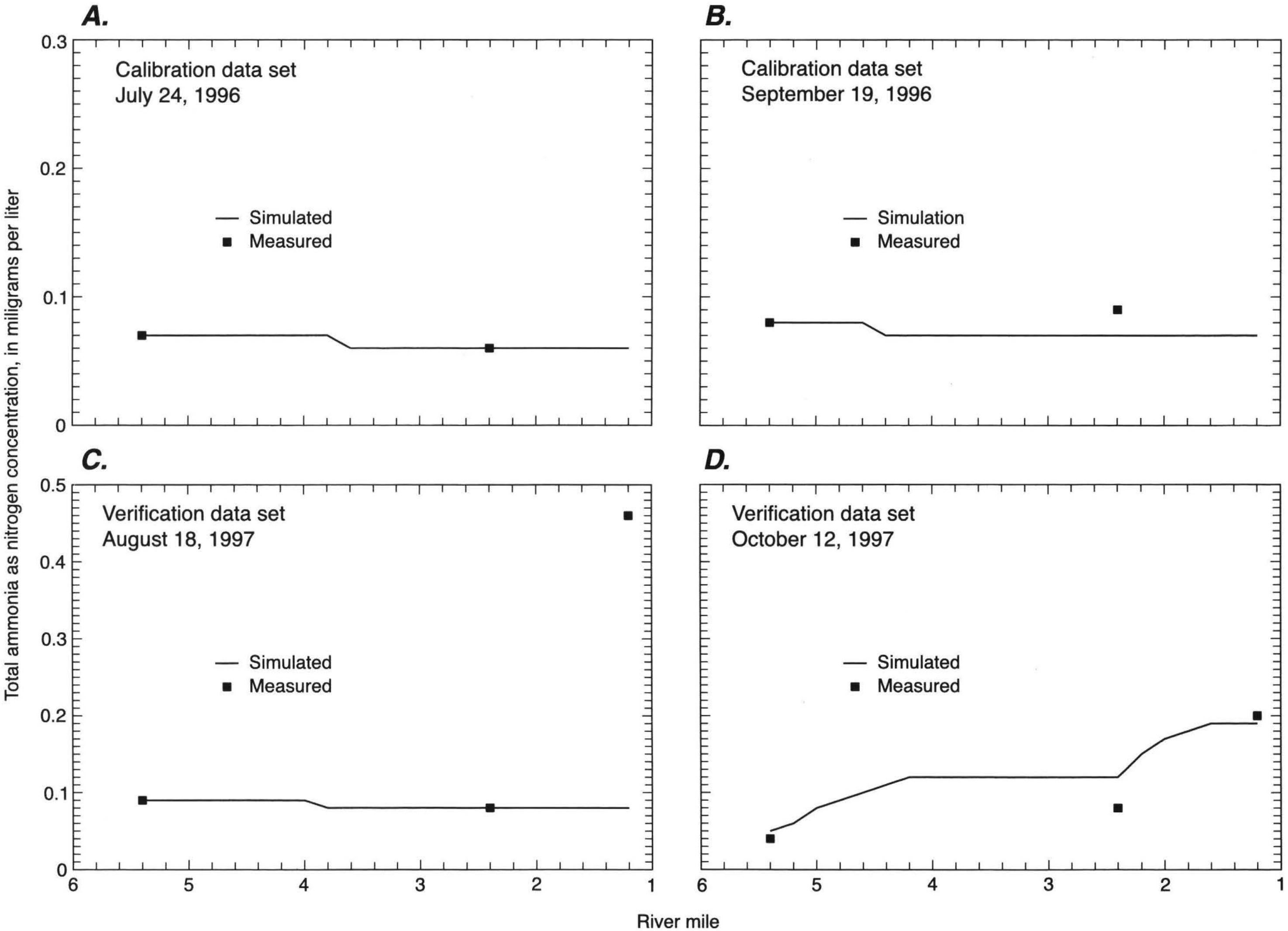


Figure 18. Simulated and measured concentrations of total ammonia as nitrogen for calibration (July 24 and September 19, 1996) and verification (August 18 and October 12, 1997) data sets, Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

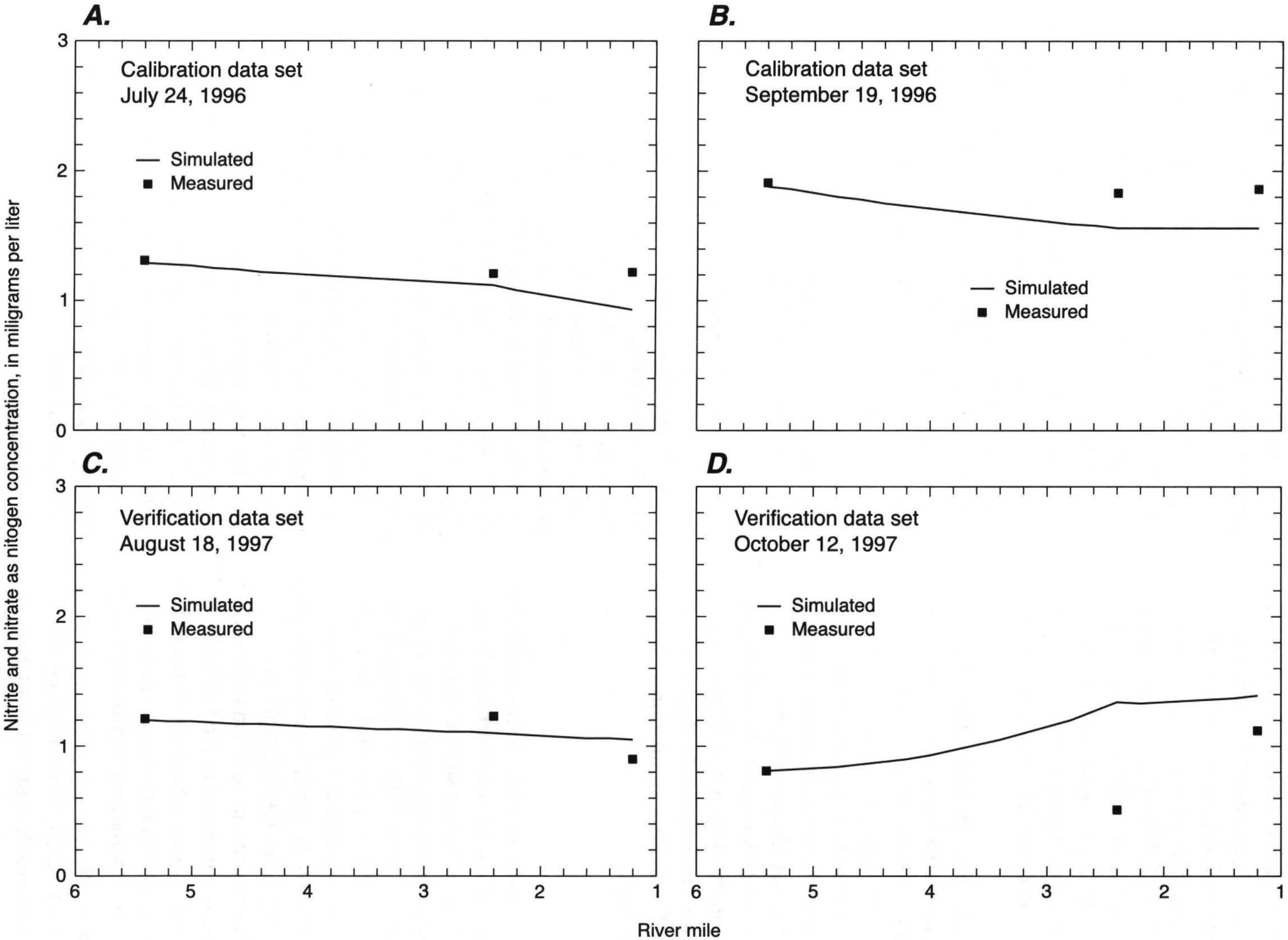


Figure 20. Simulated and measured concentrations of nitrite plus nitrate as nitrogen for calibration (July 24 and September 19, 1996) and verification (August 18 and October 12, 1997) data sets, Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

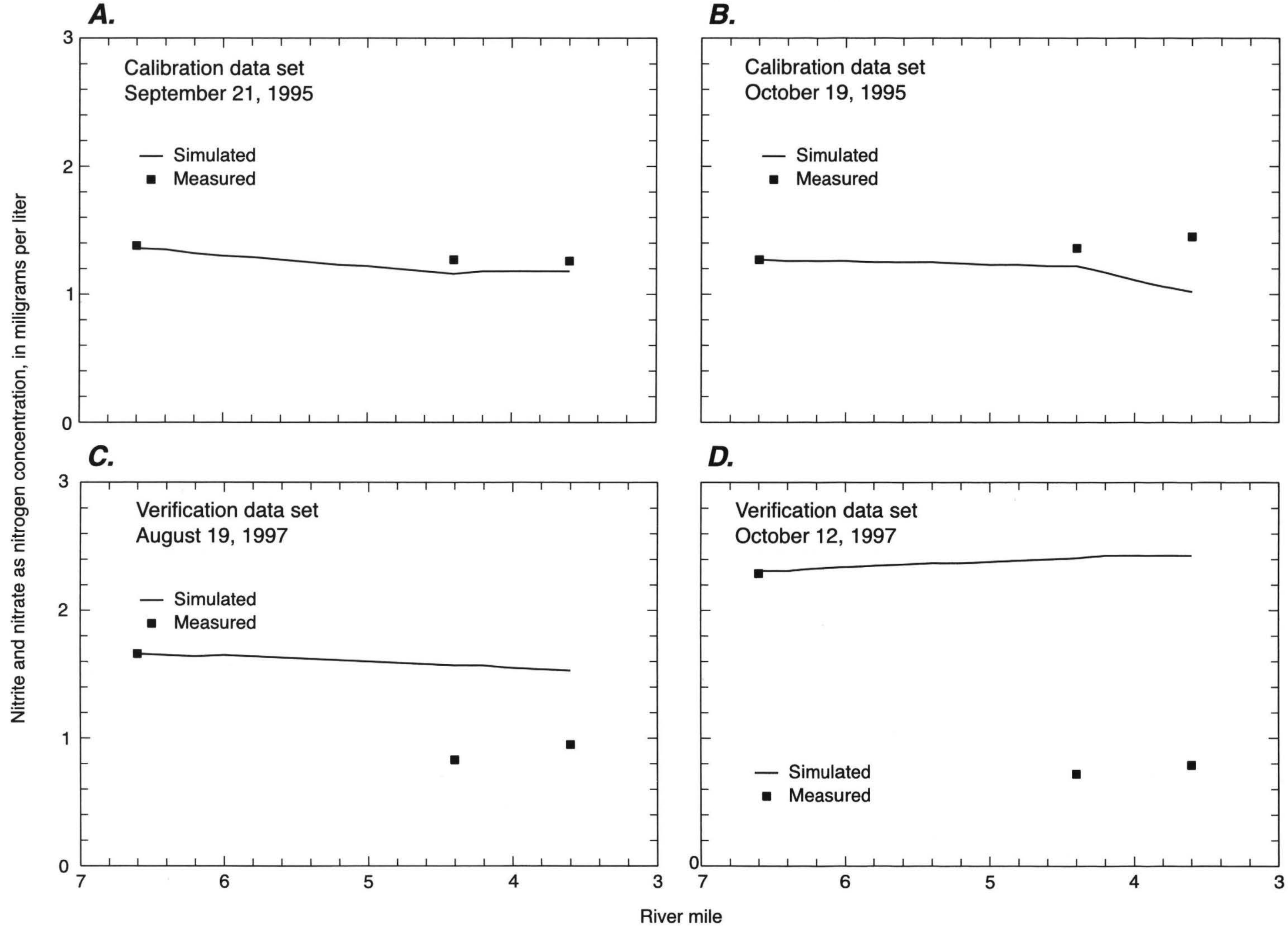


Figure 21. Simulated and measured concentrations of nitrite plus nitrate as nitrogen for calibration (September 21 and October 19, 1995) and verification (August 19 and October 12, 1997) data sets, South Fork Beargrass Creek reach, Jefferson County, Kentucky.

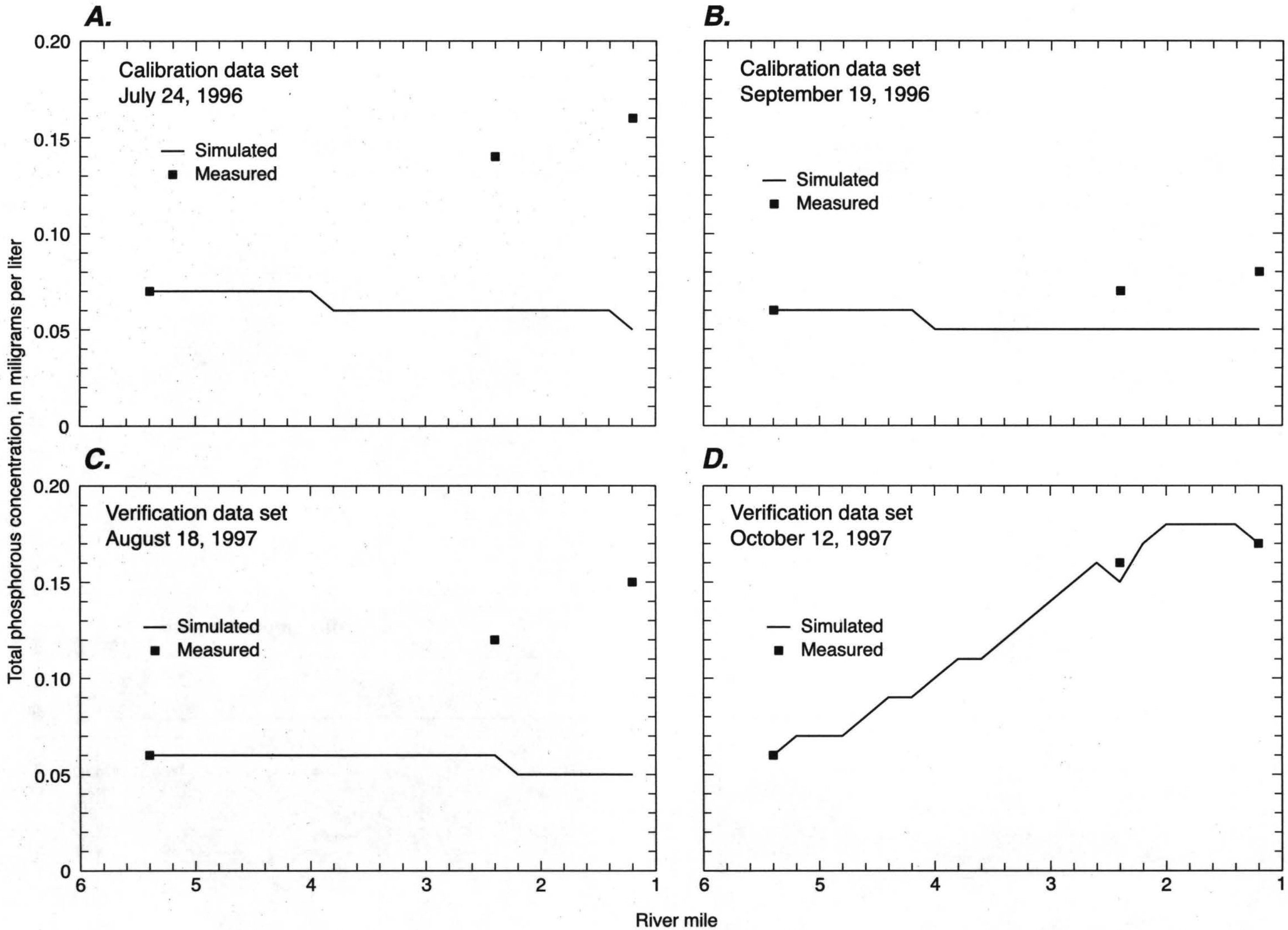


Figure 22. Simulated and measured concentrations of total phosphorus for calibration (July 24 and September 19, 1996) and verification (August 18 and October 12, 1997) data sets, Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

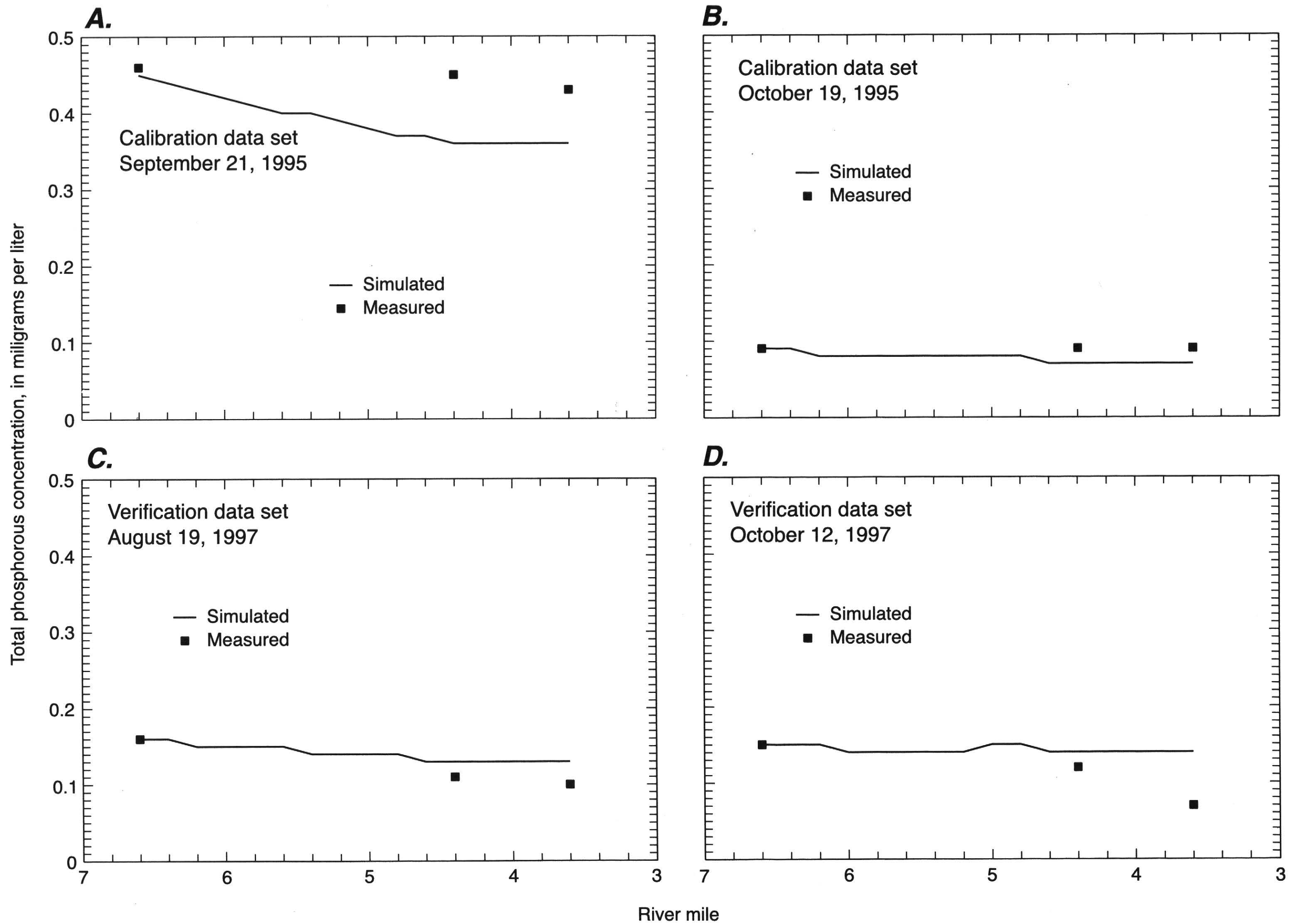


Figure 23. Simulated and measured concentrations of total phosphorus for calibration (September 21 and October 19, 1995) and verification (August 19 and October 12, 1997) data sets, South Fork Beargrass Creek reach, Jefferson County, Kentucky.

each sampling period where continuous records were available (including the calibration data set), the delta was determined as the maximum minus the minimum DO concentration for that day at the three monitoring sites. Reach-averaged values were used for delta. The reaeration rate was determined using the measured streamflow for the sampling period and the relations shown in table 6. The number of daylight hours for each sampling period was obtained from the Department of Geology and Geography, Western Kentucky University, Bowling Green, Kentucky (Glen Conner, State Climatologist, written commun., 1998).

The assumption that the DO deficit does not vary spatially and, therefore, the DO deficit mass balance can be described by:

$$P = R - K_2\bar{D} \ , \qquad (11)$$

where

- P is the primary production because of algal photosynthesis, in milligrams per liter;
- R is the respiration, in milligrams per liter per day;
- K_2 is the reaeration-rate coefficient, in day^{-1}; and
- $\bar{D}$ is the average daily oxygen deficit, in milligrams per liter.

The average daily oxygen deficit ($\bar{D}$) is estimated as the saturation concentration minus the daily mean DO concentration (which also was determined from the continuous record). From equation 11, respiration then can be determined. Daily net photosynthesis minus respiration was determined from each of the calibration data sets and resulted in a range of from -0.5 to 1.1 mg/L oxygen.

For the model simulations, chlorophyll *a* concentration was set at 50 mg/L. This concentration is the default value given by Brown and Barnwell (1987), and the recommended range is 35 to 65 mg/L (Thomann and Mueller, 1987, p. 436). Recommended values (Brown and Barnwell, 1987) were assigned to rate coefficients for both the Middle Fork and South Fork reaches as follows: the ratio of chlorophyll *a* to algal biomass (α_0) was set to 80 micrograms (µg) chlorophyll *a* per milligram (mg) algae; the fraction of algal biomass that is nitrogen (α_1) was set to 0.085 mg nitrogen/mg algae; the fraction of algal biomass that is phosphorus (α_2) was set to 1.14 mg phosphorus/mg algae; oxygen production per unit of algal growth (α_3) was set to 1.6 mg O_2/mg algae; oxygen uptake per unit of algae respired (α_3) was set to 1.95 mg O_2/mg algae; algal respiration rate (ρ) was set to 0.30 day^{-1}; maximum algal growth rate (u_{max}) was set to 2.5 day^{-1}; and the algal settling rate (σ_1) was set to 0.5 ft/d. Data input to the model also included the reach average longitude and latitude, dust-attenuation coefficient, wet-bulb and dry-bulb air temperature, atmospheric pressure, daily solar radiation, wind speed, and cloud cover. Evaporation coefficients used were selected from Brown and Barnell (1987). Atmospheric pressure was measured at the time of the sampling. Cloud cover was set on the basis of information collected during the sampling, and the value was adjusted to account for tree canopy cover along the stream. Daily solar radiation and wind speed were not measured during the sampling but values (digital data) for Louisville, Kentucky, were obtained from the Midwest Climate Information Center (Illinois State Water Survey, Champaign, Illinois).

Concentrations obtained from the simulations using the calibration data sets ranged from 0 to 0.72 mg/L oxygen for the net photosynthesis minus respiration. These concentrations were deemed reasonable relative to the results of the delta method and were used to represent the daily net value.

Dissolved Oxygen

The daily mean DO concentration, not the actual instantaneous DO concentration, was chosen as the target value for the simulations. This choice was made for several reasons; the most important reason was to make the model more robust with respect to identifying the major factors affecting DO concentrations. The calibration data sets had accompanying continuous record. The daily maximum, minimum, and mean DO concentrations and the measured values are shown in figures 24 and 25. The verification data sets did not have accompanying continuous record. Because water-quality determinations were made at different times throughout the mid-morning and early-afternoon, it was necessary to normalize the instantaneous DO concentrations by making an estimate of the daily mean DO concentration. The first step was to determine the time of day the DO measurement was made. The next step was to define from the daily record, the percent difference from the daily mean of values associated with the time of day that the measurements were made. Finally, the instantaneous DO concentrations determined during August 18, August 19, and October 12, 1997 (used as verification data), were adjusted by that percentage, and the adjusted values

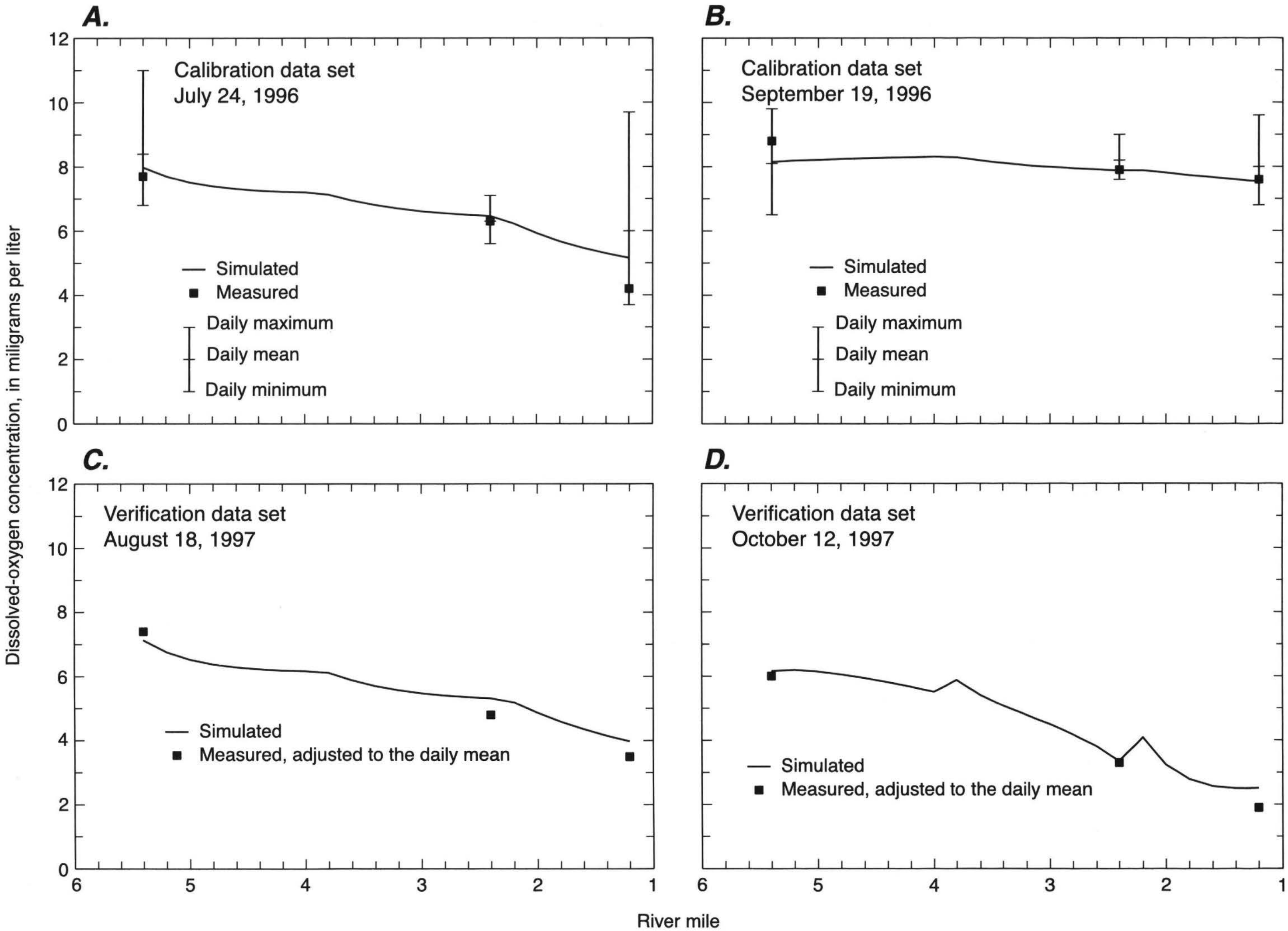


Figure 24. Simulated and measured concentrations of dissolved oxygen for calibration (July 24 and September 19, 1996) and verification (August 18 and October 12, 1997) data sets, Middle Fork Beargrass Creek reach, Jefferson County, Kentucky.

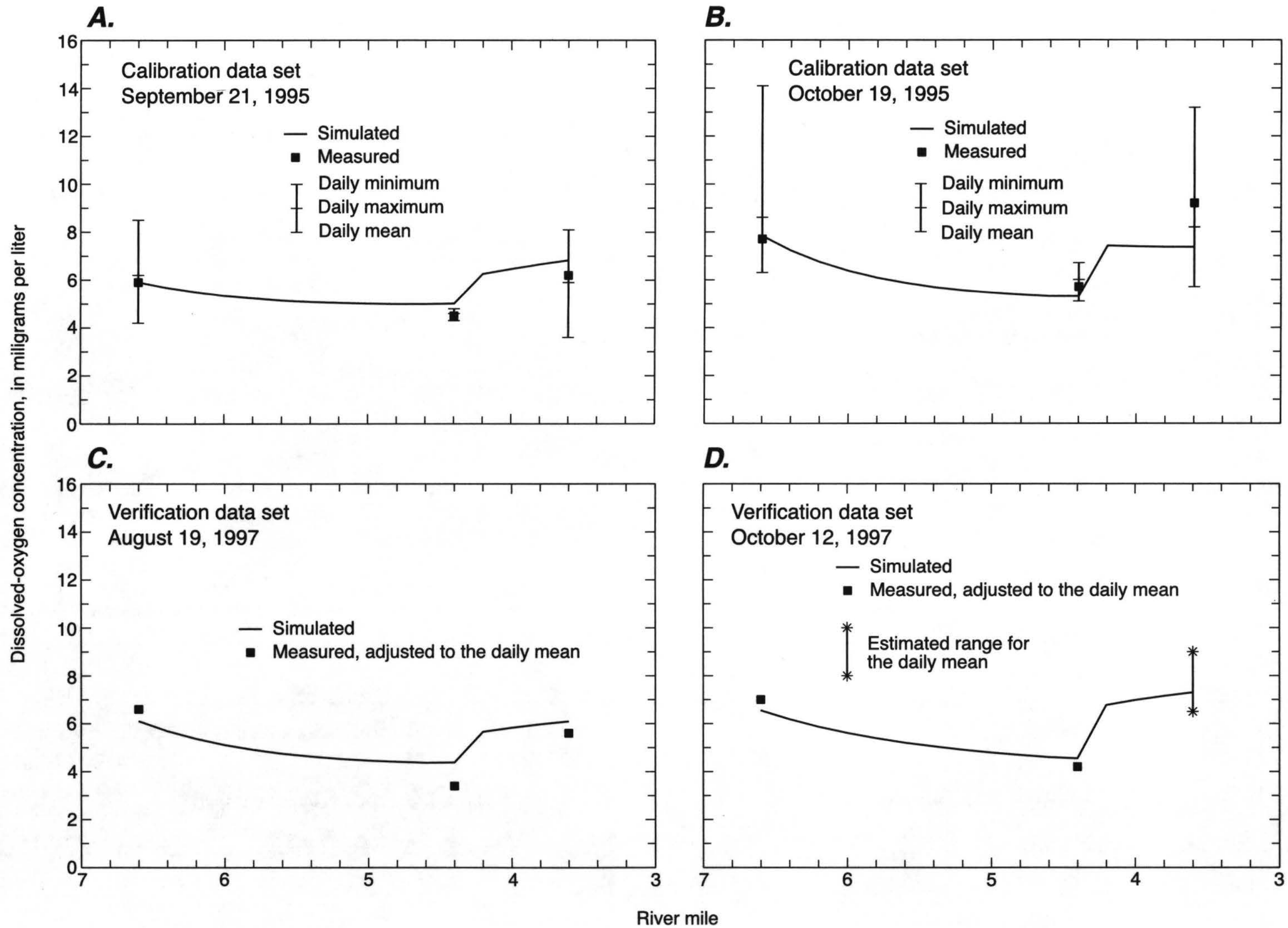


Figure 25. Simulated and measured concentrations of dissolved oxygen for calibration (September 21 and October 19, 1995) and verification (August 19 and October 12, 1997) data sets, South Fork Beargrass Creek reach, Jefferson County, Kentucky.

are shown on the verification graphs in figures 24 and 25.

The final step in calibrating the model to simulate DO concentration for the July 24 and September 19, 1996, data sets on the Middle Fork Beargrass Creek reach was to adjust the SOD rate for each of the subreaches. The SOD rate was adjusted rather than the reaeration-rate coefficient (K_2) because the measured SOD rates are point values that may not represent reach averages, whereas K_2 measurements are reach averages. A value of SOD of 0.25 g $O_2/(ft^2/d)$ was used initially for all three subreaches in the model simulations for the calibration data sets. The resulting simulated DO concentrations indicated good agreement with the measured daily mean concentrations (fig. 24). The simulation for the August 18, 1997, verification data set indicated good agreement with measured concentrations, but the October 12, 1997, simulation indicated poor agreement with a DO concentration of zero at the two downstream sites. The calibration water-quality determinations (July 24 and September 19, 1996) were made at streamflow values of 6.5 and 10.1 ft^3/s, respectively. The verification water-quality determinations (August 18 and October 12, 1997) were made at streamflow values of 4.9 and 0.30 ft^3/s, respectively. Subsequent simulations using different SOD rates were made for these four data sets and for the four additional data sets included in table 2. Concentrations of selected constituents for the four additional data sets had to be estimated on the basis of available data. The trials indicated that the SOD rate needed to be adjusted and appeared to be correlated with the value of streamflow at the time of the water-quality determination. The adjusted SOD rates corresponding to selected values of streamflow are presented in table 8.

The 0.25 g $O_2/(ft^2/d)$ for the SOD rate is 92 percent greater than the largest measured value at any Middle Fork site. The resulting simulation for the October 12, 1997, data set using SOD rates of 0.08, 0.06, and 0.03 g $O_2/(ft^2/d)$ for the upstream, middle, and downstream subreaches (fig. 2), respectively, indicates good agreement between simulated and measured concentrations (fig. 24). In addition, changes in SOD rates for the water-quality determinations made when streamflow was less than about 3.0 ft^3/s resulted in appreciable changes in DO concentrations.

For the Middle Fork reach, these results indicate that SOD rate may be related to flow, or flow as a surrogate of the time since the last rain that would have caused the CSO's to discharge effluent to the stream. These CSO discharges to the stream system are episodic. The physical basis for this result is that storm runoff could increase deposits of organic material immediately after the storm during periods of higher base flow. This increase of organic material would result in initially high SOD rates. Extended base-flow periods would result in decreasing streamflow, and because no new effluent is delivered to the stream during the period, the SOD rate would likewise decrease. This result implies that the SOD rate is a function of time since the last effluent discharge (temporal variability). A measurement of the SOD rate was made on August 26, 1996, and the resulting value was very low at 0.02 g $O_2/(ft^2/d)$. The streamflow for this measurement was 0.90 ft^3/s. The measurement may indicate that the SOD rate is changing with time for the Middle Fork reach. However, for the August 26, 1996, measurement, the initial DO concentrations in the SOD chamber were low, and the measurement was considered suspect because the difference in the initial DO concentration and the ending DO concentration also was small. This measurement also indicates the inherent difficulty involved in making reliable in-place SOD measurements during base-flow conditions at certain stream locations where DO concentrations are low (less than about 3.0 mg/L).

It is unlikely, however, that SOD rates decrease by such a large magnitude over a limited period of time such as several weeks. A more plausible explanation is related to the manner in which the DO consumption by SOD is simulated in the model. The ratio of the SOD rate to depth is used in QUAL2E model simulation to compute the DO consumption by SOD (Brown and Barnwell, 1987). This computation is probably an oversimplification of the processes affecting SOD in a stream environment. For the Middle Fork simulations, the depth would vary with streamflow as shown by the relations given in table 4 and figure 11. With decreasing streamflow, the depth also would decrease, thus increasing the effect of the SOD rate on the depletion of oxygen in the mass balance of DO concentration. In the typical application of the QUAL2E model, approximation accuracy of SOD simulation is not important because variations in streamflow among calibration, verification, and simulation are relatively small. In the case of the Middle Fork Beargrass Creek reach, an order of magnitude range in discharge is considered, and the SOD approximation error becomes detectable.

Table 8. Streamflow and sediment-oxygen-demand rates used in QUAL2E model simulations for Middle Fork Beargrass Creek reach, Jefferson County, Kentucky, 1996–97

[ft^3/s, cubic foot per second; g $O_2/(ft^2/d)$, grams of oxygen per square foot per day; >, greater than]

Streamflow (ft^3/s)	Sediment-oxygen-demand rate [g $O_2/(ft^2/d)$]		
	Upper subreach	Middle subreach	Lower subreach
>3.0	0.25	0.25	0.25
1.5	.23	.21	.16
1.0	.20	.18	.14
.5	.14	.10	.04
.3	.08	.06	.03

To compensate for possible SOD approximation errors, the SOD rates in the model need to be decreased so that the simulated DO concentrations matched the daily mean DO concentrations. In addition, the SOD rate for the water-quality determinations with the lowest streamflow need to be decreased in the downstream direction. This also probably is because of depth; that is because the depth relations in table 4 indicate that the coefficient and exponent values for the depth relations increase in the downstream direction. To compensate for this increase, the SOD rate had to be lowered in the downstream direction for the determinations made when extremely low streamflow values were present.

It is apparent that the inclusion of the SOD rate only as a function of depth in the DO mass balance equation may be an oversimplification. These results also may have implications for the use of a calibrated QUAL2E model based on high base-flow conditions for the purpose of simulating DO concentrations for extremely low base-flow conditions, such as the $7Q_{10}$.

The daily mean DO concentration, not the instantaneous DO concentration, was chosen as the target value for the South Fork reach simulations as was done for the Middle Fork simulations. Again, this mean concentration was used primarily to make the model more robust with respect to identifying the major factors affecting DO concentrations. The calibration data sets had accompanying continuous record. The daily maximum, daily minimum, and mean daily DO concentrations and the measured concentrations are shown in figure 25. The verification data sets did not have accompanying continuous record, and because these determinations (table 3) were made at different times throughout the mid-morning and early afternoon, it was necessary to normalize these values by making an estimate of the daily mean DO concentration. The instantaneous concentrations determined during August 19 and October 12, 1997, and used as verification data sets were adjusted as was done for the Middle Fork reach, and the adjusted concentrations are shown by the verification data sets in figure 25. A range of values was assigned for the mean daily DO concentration at the Winter Avenue site for October 12, 1997 (indicated by the bracket in figure 25). The measurement was made at 1230, a time at which the corresponding DO concentration was, in general, substantially greater than the mean value for the continuous-record data collected at the site.

The final step in calibrating the model to simulate DO concentrations for September 21 and October 19, 1995, on the South Fork Beargrass Creek reach was to adjust the SOD rate for each of the subreaches. A value of 0.23 g $O_2/(ft^2/d)$ was used for the upstream subreach, and a value of 0.12 g $O_2/(ft^2/d)$ was used for the downstream subreach. These values correspond well to the measured values of SOD made during the study period. The results of the calibration and verification are shown in figure 25. The calibration data sets generally indicate good agreement between simulated and measured concentrations. The large increase in the simulated DO concentration at river mile 4.4 results from the large increase in the reaeration-rate coefficient at the point where the concrete channel begins. The increase actually may be slightly more, but it is reduced because of the proration of the reaeration from the lower rate to the higher rate. The verification data sets generally indicate good agreement, although the August 19, 1997, data set indicates a slight over-simulation as does the September 21, 1995, data set used for calibration. These determinations were made at a streamflow of between 4.0 and 5.1 ft^3/s. The October 12, 1997, simulation indicates generally good agreement at the Eastern Parkway site and is in the estimated range of the daily mean value of DO concentration (fig. 25*D*). The measured concentration at the Winter Avenue site was 13.5 mg/L and was made at 1230, close to the time of day when maximum DO concentrations were present at the site when the continuous record was collected. The results are similar to those indicated for the October 19, 1995, simulation. These two water-quality determinations were made at a streamflow rate ranging from 1.7 to 2.4 ft^3/s.

The variability of the SOD rate with streamflow was not observed for the South Fork water-quality determinations, but no determinations were made for flows less than 1.7 ft^3/s. The change in depth for the range in streamflow was not as great as that for the Middle Fork reach. The downstream subreach was assigned a lower SOD rate. The higher measured value at the Trevilian Way site may be the result of effluent discharged to the stream from the leaking sewer line observed at the time of the measurement. Another factor, although less plausible, may be the unique hydraulic characteristics of the two subreaches. The upstream subreach is a natural channel consisting of pools and riffles, and the downstream subreach consists of generally smooth concrete. During storms, when the CSO's are flowing, effluent discharge from CSO's would tend to settle more readily in the natural channel. Effluent discharged to the concrete section would tend to be moved more readily out of the subreach, and settling of the materials would be less likely. Even when high base flows are present, velocities in the concrete section would be substantially higher than those in the natural channel (see table 4 for the coefficients and exponents used to estimate velocity as a function of streamflow). This is indicated by the value of Manning's roughness coefficient for the two subreaches (table 5), although this value has less applicability when considering low flows. The roughness coefficient for the downstream subreach was determined as 0.023, which is within the range of literature values for rough concrete. The value for the upstream subreach was 0.360, which probably has limited physical meaning except that the value indicates that the mean velocity in the pool-and-riffle environment is substantially less than in the concrete section for the same streamflow.

Model Limitations

Probably the most important limitation in the use of water-quality models is in the application of a calibrated model to streamflow values defined by frequency analysis, such as the $7Q_{10}$, that may be substantially smaller than the flows for which the model was calibrated and verified. Flow values and other pertinent constituent values for which QUAL2E was calibrated and verified are given in tables 2 and 3 for the Middle Fork and South Fork reaches, respectively.

For the Middle Fork reach, the October 12, 1997, water-quality determination was made when flow at the Old Cannons Lane site was at the $7Q_{10}$ value. For the South Fork reach, flow for the October 12, 1997, determination at the Trevilian Way site was not particularly low (2.4 ft^3/s). The lowest flow for which a water-quality determination was made on the South Fork was 1.7 ft^3/s for October 19, 1995, which is well above even the $7Q_2$ value of 0.26 ft^3/s. No correlation of streamflow values was observed in a comparison of daily mean streamflows between the Old Cannons Lane and Trevilian Way sites. The only physical explanation for this increase is the leaking sewer line upstream of the Trevilian Way site on the South Fork; however, no information was collected upstream from this site to confirm that the flow may have been augmented. Because SOD rates had to be adjusted on the basis of flow for the Middle Fork simulations, no attempt was made to conduct simulations for the South Fork for theoretical low flow, such as the $7Q_2$.

Simulation of Reduced Sediment-Oxygen Demand

SOD is one of the major factors affecting DO concentrations in the model simulations for the Middle Fork and South Fork reaches. SOD probably is affected to some degree by CSO contributions, although other processes contribute to SOD including the decomposition of organic material that collects on the stream bottom. The reaeration-rate coefficient was not adjusted because it is assumed to be a stable relation that cannot be modified unless the stream channel is physically altered.

From the results of the simulations for the Middle Fork reach (table 9), reducing the SOD rate by 50 percent results in an increase in the DO concentration from 7 to 82 percent at the Scenic Loop site and from 11 to 132 percent at the Lexington Road site for the flow conditions present during periodic water-quality determinations. The largest increases at the two sites (82 and 132 percent, respectively) occurred on October 12, 1997, at a streamflow of 0.30 ft^3/s. The large increase at the Lexington Road site indicates that the SOD rate has a substantial effect on the DO concentration.

From the results of the simulations for the South Fork reach (table 10), reducing the SOD rate by 50 percent results in an increase in the DO concentration from 22 to 48 percent for the Eastern Parkway site and from 10 to 14 percent for the Winter Avenue site. The increases in DO concentration are smaller than for the Middle Fork sites, probably because the streamflow for the South Fork reach did not attain extremely low rates. The smaller decrease in DO concentration at the Winter Avenue site (as compared with

Table 9. Dissolved-oxygen concentrations from QUAL2E model simulations of calibration and verification data sets, Middle Fork Beargrass Creek subreaches, Jefferson County, Kentucky, for selected sediment-oxygen-demand rates

[g $O_2/(ft^2/d)$, grams of oxygen per square foot per day; mg/L, milligrams per liter]

Date (month/day/year)	Sediment-oxygen-demand rate [g $O_2/(ft^2/d)$]: Upper subreach (fig. 2)	Middle subreach (fig. 2)	Lower subreach (fig. 2)	Simulated dissolved-oxygen concentration (mg/L): Cannons Lane site (fig. 2)	Scenic Loop site (fig. 2)	Lexington Road site (fig. 2)
07/24/96	0.25	0.25	0.25	7.98	6.46	5.16
	.13	.13	.13	8.22	7.43	6.34
	.01	.01	.01	8.45	8.41	7.51
09/19/96	.25	.25	.25	8.67	7.92	7.59
	.13	.13	.13	8.79	8.50	8.41
	.01	.01	.01	8.91	9.08	9.24
08/19/97	.25	.25	.25	7.13	5.32	3.98
	.13	.13	.13	7.48	6.65	5.86
	.01	.01	.01	7.83	7.98	7.74
10/12/97	.08	.06	.03	5.73	3.35	2.51
	.04	.03	.01	6.97	6.10	5.82
	.01	.01	.01	7.57	7.94	5.90

Table 10. Dissolved-oxygen concentrations from QUAL2E model simulations of calibration and verification data sets, South Fork Beargrass Creek subreaches, Jefferson County, Kentucky, for selected sediment-oxygen-demand rates

[g $O_2/(ft^2/d)$, grams of oxygen per square foot per day; mg/L, milligrams per liter]

Date (month/day/year)	Sediment-oxygen-demand rate [g $O_2/(ft^2/d)$]: Upper subreach (fig. 3)	Lower subreach (fig. 3)	Simulated dissolved-oxygen concentration (mg/L): Trevilian Way site (fig. 3)	Eastern Parkway site (fig. 3)	Winter Avenue site (fig. 3)
09/21/95	0.23	0.12	5.90	5.02	6.83
	.13	.06	6.20	6.40	7.61
	.01	.01	6.49	7.78	8.36
10/19/95	.23	.12	7.83	5.31	7.37
	.13	.06	8.29	7.32	8.11
	.01	.01	8.76	9.33	8.82
08/19/97	.23	.12	6.10	4.38	6.09
	.13	.06	6.44	6.03	6.94
	.01	.01	6.78	7.68	7.76
10/12/97	.23	.12	6.55	4.55	7.30
	.13	.06	6.97	6.75	8.18
	.01	.01	7.38	8.95	9.01

the increase at the Eastern Parkway site) indicates that SOD has less effect than does reaeration.

No attempt was made to conduct simulations for extremely low base-flow conditions for the South Fork reach because of the uncertainty in the low-flow statistics for the South Fork reach and because of the modification to the SOD rates that was required for the calibration of the Middle Fork data sets when streamflow reached extremely low levels.

PROCESSES AFFECTING DISSOLVED-OXYGEN CONCENTRATIONS IN MIDDLE FORK AND SOUTH FORK BEARGRASS CREEK REACHES

Output from the model simulations for the calibration and verification data sets indicates that the major processes affecting DO concentration in the Middle Fork and South Fork reaches are reaeration and SOD. Other processes include BOD decay, nitrification, and net photosynthesis minus respiration. DO concentrations for each of the components of the DO mass balance are shown in table 11 for each of the data sets. The concentrations shown are taken directly from the QUAL2E output and are the range in DO concentrations in milligrams per liter per day. As indicated by the values in the table, reaeration and SOD have the largest effect on DO concentration in the mass balance by at least an order of magnitude when compared to the other factors affecting DO concentration on a per day basis.

As stated in previous sections, streamflow is also a major component of the QUAL2E model because streamflow is used in relations to determine velocity, depth, and reaeration-rate coefficient. Depth is also used in determination of the consumption of oxygen from SOD. The determination of these different elements at various streamflow levels appears to be warranted because of the need to define those relations that are based on streamflow.

Table 11. Range in dissolved-oxygen concentration, in milligrams per liter per day, of mass balance from output of QUAL2E model simulations for calibration and verification data sets, Middle Fork and South Fork Beargrass Creek reaches, Jefferson County, Kentucky

[BOD, carbonaceous biochemical-oxygen demand; SOD, sediment oxygen demand; Net P-R, net photosynthesis minus respiration; NH_3, total ammonia; NO_2, nitrite]

Date (month/day/year) and location (figs. 2 and 3)	Reaeration	BOD	SOD	Net P-R	NH_3	NO_2
		Middle Fork Beargrass Creek reach				
07/24/96						
Upper subreach	4.89	-0.04	-5.23	0.14	-0.02	-0.01
Middle subreach	3.74	-.06	-4.23	.14	-.02	-.01
Lower subreach	2.30	-.07	-2.32	.07	-.02	-.01
09/19/96						
Upper subreach	3.74	-.03	-2.53	.04	.01	.01
Middle subreach	2.47	-.03	-1.93	.03	.01	.01
Lower subreach	1.02	-.03	-1.21	.02	.01	.01
08/19/97						
Upper subreach	6.95	-.07	-8.53	.19	-.05	-.02
Middle subreach	6.80	-.08	-6.80	.18	-.05	-.02
Lower subreach	2.70	-.06	-3.26	.09	-.03	-.01
10/12/97						
Upper subreach	4.52	-.04	-4.31	.03	-.06	-.02
Middle subreach	2.48	0	-2.32	0	-.08	-.03
Lower subreach	1.40	-.06	-1.09	0	-.11	-.04
		South Fork Beargrass Creek reach				
09/21/95						
Upper subreach	8.30	-.54	-6.96	.68	-.28	-.12
Lower subreach	1.02	-.01	-.26	.01	-.02	0
10/19/95						
Upper subreach	11.7	-.27	-12.3	.43	-.36	-.17
Lower subreach	1.61	0	-.41	0	-.01	0
08/19/97						
Upper subreach	8.59	-.64	-8.53	1.01	.53	-.15
Lower subreach	1.15	-.01	-.33	.02	.03	0
10/12/97						
Upper subreach	12.8	-.93	-12.8	.90	-.58	-.17
Lower subreach	1.42	-.01	-.68	.01	-.03	-.01

SUMMARY

Many streams along the Ohio River in urban areas are affected by inputs from combined-sewer outfalls (CSO's). This is the case for the downstream reaches of Middle Fork and South Fork Beargrass Creeks. A cooperative study was conducted by the USGS and MSD to define the major processes affecting DO concentrations in these reaches. Continuous DO monitoring, periodic chemical water-quality determinations, and simulations using the QUAL2E computer model were done.

Modeling results indicate that streamflow, reaeration, and SOD are the processes that have the most effect on the net production and depletion of DO in the downstream reaches of Middle Fork and South Fork Beargrass Creeks. Oxygen production by photosynthesis results in large variability in DO concentrations throughout the day, but supersaturated conditions that occur at the upstream and downstream ends of each reach appear to be offset by respiration. The modeling was targeted to simulate daily mean DO concentrations to provide a robust model and to incorporate the net daily effect of photosynthesis and respiration on DO concentration.

Analysis of the results for the Middle Fork reach indicated that the model simulation of the consumption of oxygen by SOD is strongly affected by streamflow. This effect is probably because the oxygen consumption by SOD is defined as the SOD rate divided by the water depth. For the QUAL2E modeling approach used in this study, depth is determined from streamflow. As streamflow decreases, depth also decreases, and the consumption of DO by SOD increases if the value of the SOD rate is held constant. For the water-quality determinations with streamflow values less than 3.0 ft^3/s (the lowest observed during the period of continuous DO data collection), the SOD rate used in the model for the Middle Fork simulations had to be reduced in each subreach to obtain simulated DO concentrations close to targeted values at the two downstream monitoring sites. It is probably unrealistic to conclude that the SOD rate decreased substantially in the span of a few weeks as a result of no CSO discharges to the stream. The inclusion of the SOD rate as a function of depth only in the DO mass balance equation used in the QUAL2E model may be an oversimplification. These results also may have implications for the use of a calibrated QUAL2E model based on high base-flow conditions for the purpose of simulating DO concentrations for extremely low base-flow conditions, as might be present for the $7Q_{10}$ flow. Additional study of SOD rates at locations throughout the Middle Fork reach may be warranted. Because the Middle Fork simulation indicated decreasing SOD rate with time, better definition of SOD rates, both spatially and temporally throughout the reach, may provide additional information on the mechanics of SOD in this reach.

Reaeration also appears to have an appreciable effect on DO concentrations in the Middle Fork reach. Equations available in the literature to estimate the reaeration-rate coefficient provide reasonable estimates for certain stream conditions or types but provide poor estimates for others. Determining the reaeration-rate coefficient through direct measurement for at least one base-flow condition will provide insight as to which equation(s) might provide adequate estimates. Measurements made during low and high base-flow conditions would allow for the determination of a relation between streamflow and the reaeration-rate coefficient.

Nitrogen, ammonia, and BOD also affect DO concentrations in the Middle Fork reach but to a lesser extent than streamflow, the reaeration-rate coefficient, and the SOD rate. For the period studied, the concentrations of nitrogen, ammonia, and BOD were low; ammonia and BOD levels increased in the downstream direction. No physical evidence was apparent to account for the increase in concentration, and no leaking CSO's were observed in the reach.

The increase in BOD could be the result of algae expiring in the sample bottle. This expiration of algae could account for the increase in measured concentrations, particularly at the Lexington Road site. The increase in BOD and ammonia concentrations in the downstream direction also could be the result of leaking sewer lines near the stream. The materials from the leaking sewer lines could be transported to the stream along with base flow.

Lowering the SOD rates by 50 percent in the model simulations resulted in an increase in DO concentrations from 7 to 82 percent at the Scenic Loop site and from 11 to 132 percent at the Lexington Road site. The most substantial increases occurred on October 12, 1997, when streamflow was 0.30 ft^3/s.

The South Fork reach model analyses required no decrease in SOD rate for decreased streamflow conditions; however, during the study period, base-flow conditions did not reach extremely low levels. Streamflows did not correlate well between the Middle Fork and South Fork reaches during base-flow conditions. For October 12, 1997, when concurrent samples were collected at both Middle Fork and South Fork sites, streamflow at the Middle Fork at Old Cannons Lane site reached the $7Q_{10}$ value of 0.30 ft^3/s, whereas the South Fork at Trevilian Way site remained at a streamflow of 2.4 ft^3/s, well above the $7Q_2$ value of 0.26 ft^3/s. This indicates that base-flow conditions in the South Fork reach probably were being augmented, possibly through leaking sewer lines, in the upstream part of the reach. The possibility of a leaking sewer line was evident during the October 12, 1997, water-quality determination when a mat of effluent was observed approximately 1,200 ft upstream from the Trevilian Way site. Fecal-coliform counts at the Trevilian Way site on August 19 and October 12, 1997, were 22,400 and 4,200 colonies per 100 milliliters of sample, respectively. The fecal coliform counts at the two downstream sites were substantially lower, ranging from 110 to 370 colonies per 100 milliliters of sample. Also, the SOD rate measured at the Trevilian Way site on October 12, 1997, was the highest obtained at any site during the study period.

An extremely low base-flow condition was not simulated for the South Fork reach for two reasons. The first reason is the uncertainty evident in the low-flow statistics for the South Fork reach, and the second is the variability in the SOD rate needed to match the simulated and measured daily mean DO concentrations for the Middle Fork simulations.

As with the Middle Fork reach, reaeration also appears to have a substantial effect on DO concentrations in the South Fork reach. This result was evident from the model output for the simulations. The higher reaeration-rate coefficient for the downstream subreach appears to be the reason that minimum concentrations at the Winter Avenue site did not reach extremely low levels during the nighttime hours.

Nitrogen, ammonia, and BOD also affected DO concentrations for the South Fork reach; however, as was observed for the Middle Fork reach, concentrations of nitrogen, ammonia, and BOD were low throughout the reach.

Lowering the SOD rates by 50 percent in the model simulations resulted in an increase in DO concentrations from 27 to 48 percent at the Eastern Parkway site and from 11 to 14 percent at the Winter Avenue site. The increases are smaller than those reported for the Middle Fork sites, probably because extremely low-flow conditions were not present during any of the water-quality determinations.

A better understanding of SOD in channels affected by episodic inputs of effluent to a stream reach is needed. In such stream systems, the temporal and spatial variability of SOD needs to be better defined.

Continuous record of DO concentrations collected at three sites on each stream reach during the summer indicated generally decreasing values of DO in the downstream direction. The data also indicated DO concentrations less than the State water-quality standard for minimum in-stream DO concentrations for instantaneous and daily mean values.

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