EFFECTS OF COMBINED-SEWER OVERFLOWS AND URBAN RUNOFF ON THE WATER QUALITY OF FALL CREEK, INDIANAPOLIS, INDIANA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 94-4066

Prepared in cooperation with the

INDIANAPOLIS DEPARTMENT OF PUBLIC WORKS

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1995

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BRUCE BABBITT, Secretary

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) as follows:

°F = 1.8 x °C + 32

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 the United States and Canada, formerly called Sea Level Datum of 1929.

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

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

Volumes of water-quality samples are given in liters (L) and milliliters (mL).

Other abbreviations used in this report:

AWT	advanced waste treatment
CBOD	carbonaceous biochemical oxygen demand
COD	chemical oxygen demand
DPW	(Indianapolis) Department of Public Works

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ABSTRACT

In 1986, the U.S. Geological Survey and the Indianapolis Department of Public Works began a study to evaluate the effects of combined-sewer overflows and urban runoff discharging to Fall Creek on the White River. This report describes the effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek during summer 1987 by comparing the water quality during base flow with that during storm runoff and by comparing water quality in the urbanized area with that in the less urbanized area upstream from the combined-sewer overflows. Data were collected at three streamflow-gaging stations located upstream from, downstream from, and in the middle of 27 combined-sewer overflows on Fall Creek. The most downstream station also was immediately downstream from the discharge of filter backwash from a water-treatment plant for public supply.

Specific conductance and concentrations of major ions and dissolved solids in base flow increased downstream in response to surface-water withdrawn for public supply, ground-water inflow, and the discharge of filter backwash. Concentrations of dissolved oxygen were least in the reach of Fall Creek in the middle of the combined-sewer overflows where black sludge deposits covered the stream bottom. Concentrations of nitrate plus nitrite and ammonia steadily increased downstream, whereas concentrations of organic nitrogen, phosphorus, and orthophosphate only increased at the most downstream station. Nearly all concentrations of chromium, copper, lead, nickel, and zinc at the upstream and middle stations were less than the detection limit of 10 micrograms per liter. Detectable concentrations of these metals and high concentrations of suspended solids in base-flow samples at the most downstream station were caused by the discharges from the water-treatment plant.

Concentrations of dissolved oxygen measured at the station in the middle of the combined-sewer overflows were less than the Indiana minimum ambient water-quality standard of 4.0 milligrams per liter during all storms. Concentrations of ammonia, oxygen demand, copper, lead, zinc, and fecal coliform bacteria at the stations downstream from the combined-sewer overflows were much higher in storm runoff than in base flow. Increased concentrations of oxygen demand in runoff probably were caused by combined-sewer overflows, urban runoff, and the resuspension of organic material deposited on the streambed. Some of the increased concentrations of lead, zinc, and probably copper can be attributed to the discharge and resuspension of filter backwash.

INTRODUCTION

Approximately 40 mi^2 of Indianapolis is served by combined sewers that discharge primarily to the White River and its tributaries (Fall Creek, Pogues Run, Pleasant Run, and Eagle Creek) through 129 combined-sewer overflows (Howard Needles Tammen & Bergendoff, 1983, p. 1-1). About 35 percent (14 mi^2) of this area discharges to Fall Creek through 28 combined-sewer overflows.

The Indianapolis Department of Public Works (DPW) is investigating measures to control the degradation of water quality caused by combined-sewer overflows and urban runoff. Information on the quantity of contaminants contributed by combined-sewer overflows and urban runoff to a major urban tributary and the effects on water quality would help assess problems associated with combined-sewer overflows and urban runoff.

In 1986, the U.S. Geological Survey and the Indianapolis Department of Public Works began a cooperative study to evaluate the effect of combined-sewer overflows and urban runoff to Fall Creek on the water quality of the White River. The objectives of the study were to (1) describe the effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek, (2) estimate the load (mass) of contaminants contributed by combined-sewer overflows and urban runoff during the summer low-flow season, and (3) assess the relative effect of contaminants discharged to Fall Creek on the White River by comparing the load of contaminants discharged to Fall Creek by combined-sewer overflows and urban runoff to the load of contaminants discharged to the White River by municipal wastewater-treatment plants.

Purpose and Scope

This report describes the effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek in and near Indianapolis during summer 1987. In addition, the report presents the hydrologic, water-quality, and quality-assurance data collected for the study.

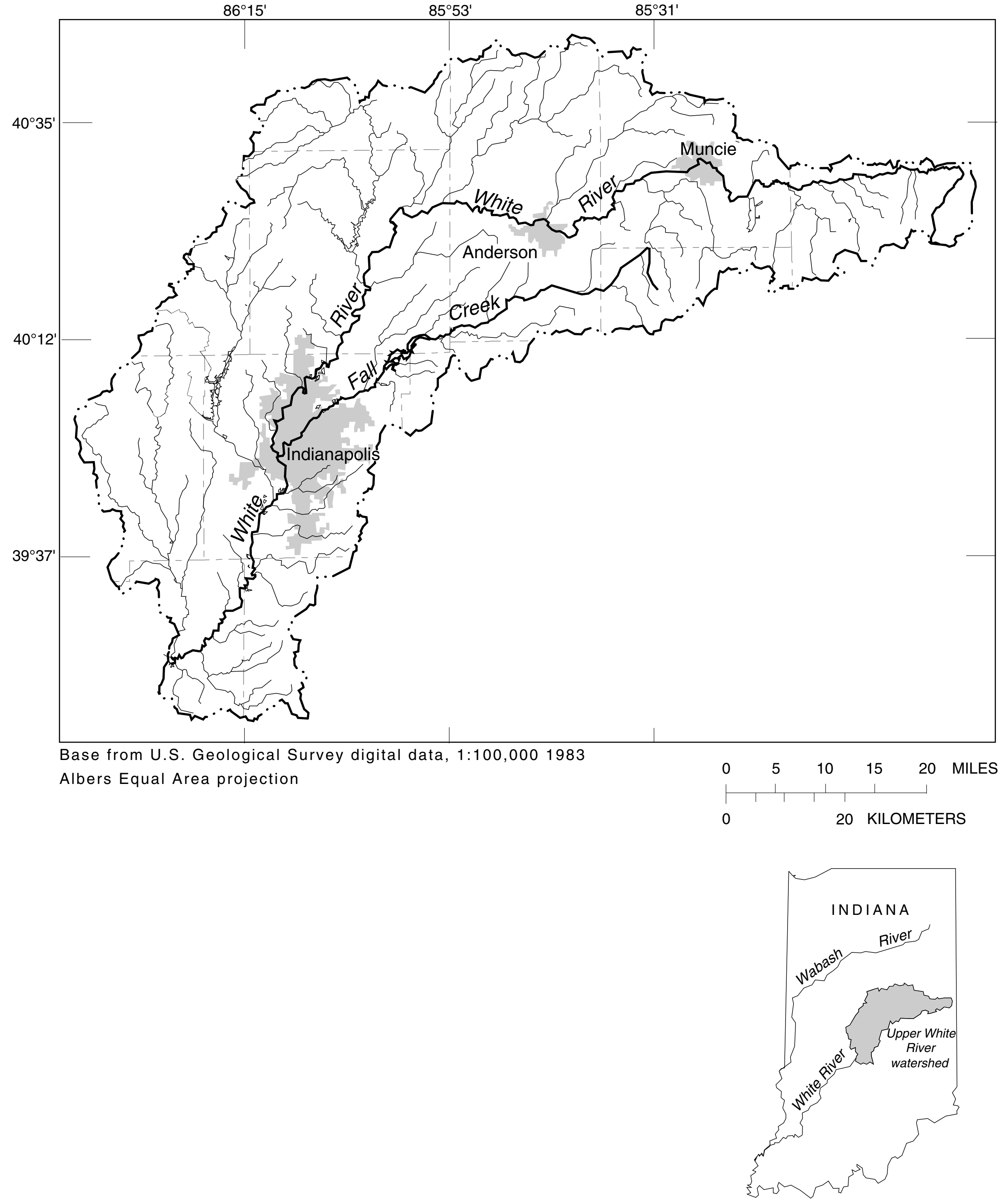
Three water-quality monitoring stations were established at three streamflow-gaging stations on Fall Creek. The streamflow-gaging stations were upstream from, in the center of, and downstream from the combined-sewer overflows and highly urbanized area of Indianapolis. Water-quality samples were collected four to six times during base flow and multiple times during storm runoff from six storms. Multiple runoff samples were composited to a single sample that represented the mean water quality during the period of storm runoff. Water samples also were collected from selected effluent sources, and measurements of water quality were made in the field at several sites during two synoptic surveys. Various types of water samples were analyzed as part of a quality-assurance program.

Methods used to collect, process, and compute hydrologic and water-quality data are described. Methods used to assess data quality are described and quality-assurance data are presented and assessed. Precipitation and streamflow data collected during the study period are compared to long-term normal precipitation and streamflow. Measurements of base flow and water withdrawals and returns were analyzed to determine the components of streamflow for an extended base-flow period during October 1987.

The effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek were determined by comparing the water quality during base flow to the water quality during storm runoff. In addition, water quality during runoff in the urbanized area was compared with water quality in the less urbanized area upstream from the combined-sewer overflows. Water-quality data are presented in tables to facilitate detailed comparisons and in graphs to facilitate interpretations.

Previous Studies

The upper White River drains almost 2,500 mi^2 of predominantly agricultural land in east-central Indiana (fig. 1). Muncie, Anderson, and Indianapolis are the major urban areas in the watershed. Parts of each urban area are served by combined sewers, and each city discharges treated



Base from U.S. Geological Survey digital data, 1:100,000 1983
Albers Equal Area projection

Figure 1. The upper White River watershed in east-central Indiana.

wastewater to the White River. Shampine (1975, p. 64) assessed the water quality of the upper White River and concluded that the most severe water-quality problems occurred in the Indianapolis area. Oxygen-demanding wastes discharged by the Indianapolis sewage-treatment plant decreased dissolved-oxygen concentrations at least 28 mi downstream from the plant (Shampine, 1975, p. 36, 64).

The City of Indianapolis has implemented a variety of studies to determine the effects of city-owned wastewater-treatment plants and the sewer system on the water quality of the White River. In 1975, Indianapolis authorized a study to locate and inventory combined-sewer overflows; 129 combined-sewer overflows were identified. In 1978, 124 of the combined-sewer overflows were instrumented to monitor overflow frequency and duration (Howard Needles Tammen & Bergendoff, 1983, p. 2-3, 3-9).

In 1980, a study to assess the effect of combined-sewer overflows on the water quality of the White River was done by Howard Needles Tammen & Bergendoff (1983, appendix J). Storm loads of contaminants from selected combined-sewer overflows were estimated, but the data are inadequate for estimating the total quantity of contaminants discharged to receiving streams, either for a single storm or for the critical summer low-flow period. Simulation of the effect of combined-sewer overflows on dissolved-oxygen concentration indicated that combined-sewer overflows could cause large reaches of the White River to have concentrations of dissolved oxygen less than the Indiana standard of 4.0 mg/L (Howard Needles Tammen & Bergendoff, 1983, p. 7–30).

In 1981, the U.S. Geological Survey began a series of cooperative studies on the water quality of the White River with the Indianapolis Department of Public Works. The first study began in 1981 as an assessment of the hydrologic effects of enlarging and improving the Indianapolis sewage-treatment plants. The two plants were upgraded to advanced wastewater treatment (AWT), including oxygen nitrification and ozone disinfection, and became operational in 1983. In 1982, a study to analyze data from the City’s fixed-station ambient water-quality monitoring network began. Dramatic improvements in base-flow water quality after AWT was implemented were indicated by analysis of wastewater effluent and fixed-station water-quality data (Crawford and Wangsness, 1991a, 1991b), data collected during four summer low-flow water-quality surveys (D.J. Wangsness, U.S. Geological Survey, written commun., 1987), and biological monitoring data (Crawford and others, 1992).

In 1985, the U.S. Geological Survey and the Indianapolis Department of Public Works began a study to determine the frequency and duration of low dissolved-oxygen concentrations (those less than 4.0 mg/L) associated with periods of base flow and storm runoff during the summers of 1986 and 1987. Continuous flowthrough water-quality monitors were installed on the White River in and downstream from Indianapolis and on Fall Creek in Indianapolis near the confluence with the White River. Low concentrations of dissolved oxygen were measured during 12 periods at the downstream station on the White River and 5 periods at the station on Fall Creek (Martin and Craig, 1990, p. 44-45). All of the low concentrations of dissolved oxygen occurred during periods of storm runoff; consequently, likely causes of the low concentrations of dissolved oxygen were combined-sewer overflows and urban runoff from Indianapolis. Although this study provided information on the effects of storm runoff on dissolved oxygen, the sources and quantities of contaminants discharged to the White River or Fall Creek during storms were not identified.

Study Area

Fall Creek drains 318 mi^2 in east-central Indiana and flows from its headwaters in northwestern Henry County to its confluence with the White River in Indianapolis, approximately 60 mi to the southwest (figs. 1, 2). Fall Creek is a highly complex, urban and rural hydrologic system that includes an instream water-supply reservoir, several low-head dams, water withdrawal for public supply, a variety of point-source discharges, stormwater and combined-sewer overflows, and interbasin water transfer into the basin as a result of aqueduct overflow.

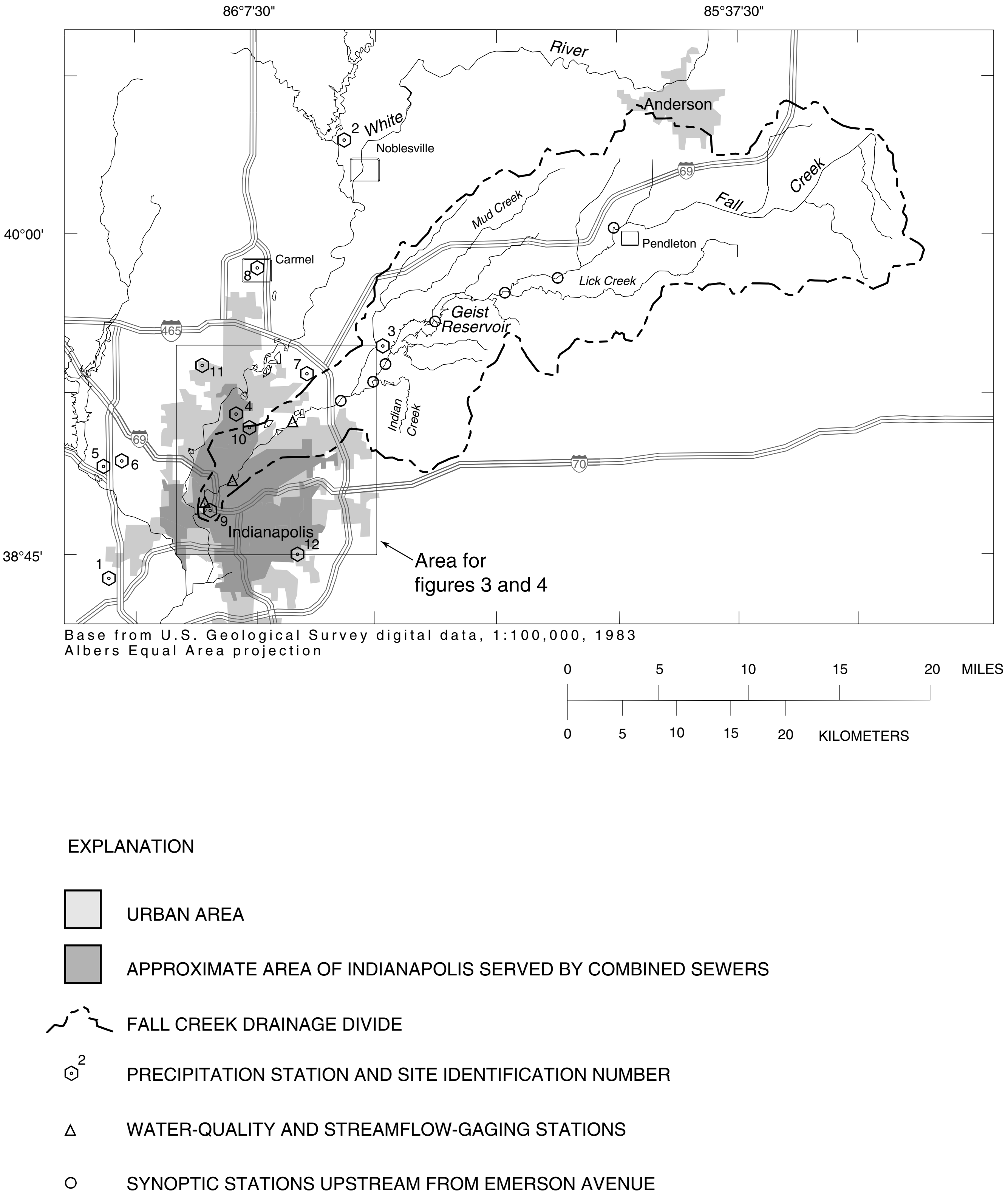


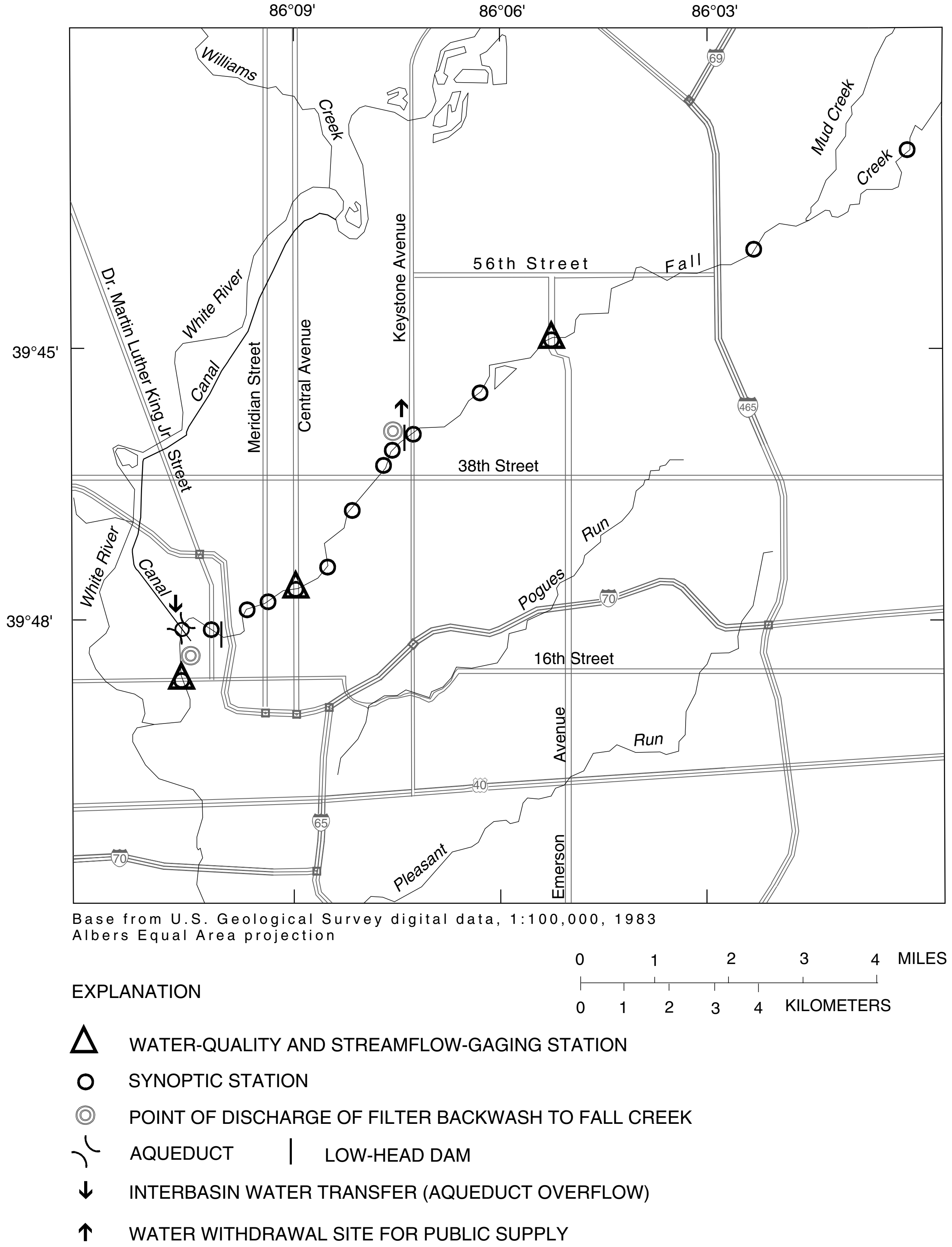
Figure 2. Locations of selected hydrologic and cultural features and data-collection stations in and near Fall Creek watershed, Indianapolis, Ind.

Central Indiana has a humid continental climate that is affected by polar and gulf air masses. Interaction of the air masses causes daily and seasonal variations in weather. Summers are hot and humid, and winters are cold. Normal annual precipitation at the Indianapolis International Airport climatological station is 39.12 in. (National Oceanic and Atmospheric Administration, 1986, p. 3), approximately one-third of which runs off as streamflow (Crawford and Mansue, 1988, fig. 5). Precipitation is fairly evenly distributed throughout the year, and summer precipitation is usually sufficient to meet agricultural needs (Hosteter, 1978, p. 1-2). July is the warmest month; normal (1951–80) maximum temperature is 85.2°F, and normal minimum temperature is 64.9°F (National Oceanic and Atmospheric Administration, 1986, p. 3). January is the coolest month; normal maximum temperature is 34.2°F, and normal minimum temperature is 17.8°F.

The Fall Creek watershed is in the Tipton Till Plain Physiographic Province, a flat to gently rolling glacial till plain (Schneider, 1966, p. 41, 49). The major soil associations in the watershed are the Miami-Crosby silt loams association on the uplands and the soils of the alluvial terraces and flood plains (Ulrich, 1966, p. 66-73, 88-89). In the downstream parts of the watershed in Marion and Hamilton Counties, the four mapped associations are the Crosby-Brookston, the Miami-Crosby, the Fox-Ockley, and the Shoals-Genesee (Hosteter, 1978, p. 3-4, general soil map; Sturm and Gilbert, 1978, p. 2-6, general soil map). The Crosby-Brookston association consists of deep, somewhat poorly to very poorly drained soils that have formed in a thin layer of loess or silty till on nearly level uplands. These soils are used mainly for farming; corn and soybeans are the principal crops. Wetness is the major use limitation. The Miami-Crosby association consists of deep, well-drained to somewhat poorly drained soils that have formed in a thin layer of loess or silty till on gently sloping to moderately steep hillsides and knolls. These soils are used mainly for parks, subdivisions, and farming. Erosion and wetness are the major use limitations. The Fox-Ockley association consists of moderately deep, well-drained soils that have formed in sand and gravel on generally level terraces and outwash plains. In Marion County, these soils are used mainly for urban development. In Hamilton County, these soils are used for cultivated crops—mostly corn, wheat, and soybeans. These soils are well suited to urban uses and are only moderately limited by erosion and wetness. The Shoals-Genesee association consists of deep, well-drained to poorly drained soils that have formed in loamy alluvium on nearly level flood plains. Use of these soils is severely limited by flooding.

Agriculture is the predominant land use in the watershed. The major cultivated crops are corn, soybeans, and winter wheat. Pasture and woodlots are on some of the steeply sloping land and in some of the flood plains. Swine and beef production also are important agricultural activities. Urban land use predominates in the downstream part of the watershed in Marion County. Urban land use includes industrial, commercial, transportation, and residential land uses. The density of urban land use and the intensity of urban development increases downstream along Fall Creek. Much of the flood plain upstream from Emerson Avenue (fig. 3) is parkland used for recreation, although residential development is occurring. Formerly rural and agricultural land near Mud Creek and Geist Reservoir is being developed rapidly for residential and commercial land uses.

Bedrock in the Fall Creek watershed is primarily limestone of Silurian and Devonian age that dips to the southwest. Surficial deposits are sandy, silty till on the uplands and outwash sand and gravel with some alluvial deposits in the flood plain (Herring, 1976, p. 5, fig. 2). Unconsolidated deposits range from less than 50 to more than 300 ft in thickness. The thickest deposits are in the uppermost headwaters of Fall Creek and immediately downstream from the dam at Geist Reservoir, whereas the thinnest deposits are upstream from the reservoir (Gray, 1983). Well yields in the part of the watershed in Marion County range from 300 to



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Albers Equal Area projection

Figure 3. Locations of selected hydrologic features and data-collection stations on Fall Creek in Indianapolis, Ind.

more than 500 gal/min, 0 to 150 gal/min, and 50 to 250 gal/min for wells properly installed in outwash, till, and limestone, respectively (Herring, 1976, figs. 7, 8). Maps of the water table in the most downstream segment of the outwash aquifer in Marion County show that Fall Creek is a gaining stream (water typically flows from the aquifer to the stream) (Meyer, 1979, fig. 5; Smith, 1983, fig. 7). Herring (1976, p. 21) found that water from both the outwash aquifer and the limestone aquifer discharges to Fall Creek in the vicinity of 71st Street.

The major hydrologic feature on Fall Creek is Geist Reservoir, a water-supply reservoir for Indianapolis (fig. 2). Fall Creek drains an area of 318 mi^2, of which drainage from 215 mi^2 must pass through Geist Reservoir (Hoggatt, 1975, p. 142-143). The dam is at river mile 17.6 and impounds water approximately 7 mi upstream. Normal storage capacity is 21,180 acre-feet and normal surface area is 1,800 acres (Ruddy and Hitt, 1990, p. 100). Typical widths of Geist Reservoir range from 0.25 to 0.5 mi. The major tributaries to Fall Creek—Mud Creek, Lick Creek, and Indian Creek—drain 43.1, 38.2, and 25.6 mi^2, respectively. Mud Creek and Indian Creek join Fall Creek downstream from Geist Reservoir at river miles 13.5 and 15.5, respectively. Lick Creek joins Fall Creek upstream from the reservoir.

Most of the hydrologic and water-quality data were collected during the study from three streamflow-gaging stations downstream from Geist Reservoir. These stations were at Emerson Avenue, Central Avenue, and 16th Street (at river miles 9.2, 3.8, and 1.3, respectively); drainage areas above the stations were 298, 312, and 317 mi^2, respectively (fig. 3). Water flowing over the spillway or released from Geist Reservoir flows freely past the Emerson Avenue gaging station until it reaches a low-head dam at Keystone Avenue (river mile 6.4) where water is impounded for withdrawal and treatment for public-water supply. Immediately downstream from the dam, wastewater (filter backwash) from the water-treatment plant is discharged to Fall Creek. Water flowing over the dam at Keystone Avenue flows in a deeply incised channel, through a series of pools and riffles, and past the Central Avenue gaging station until it reaches a low-head dam at Dr. Martin Luther King Jr. Street (river mile 2.4). Water is impounded upstream approximately 1 mi to Meridian Street.

Water flowing over the dam at Dr. Martin Luther King Jr. Street flows into another impounded reach of Fall Creek that extends from the dam to a large rocky riffle at the base of the aqueduct (river mile 1.8, fig. 3). The aqueduct is part of a canal that transports water for public supply from the White River, over Fall Creek, and delivers it to a water-treatment plant near 16th Street. Some of the canal water overflows the aqueduct, effectively transferring water from the White River to Fall Creek. Water in Fall Creek flows freely from the aqueduct downstream to the 16th Street gaging station, where it flows into backwater from a low-head dam on the White River. Filter backwash from the water-treatment plant near 16th Street is discharged to Fall Creek approximately 500 ft upstream from 16th Street.

Approximately 14 mi^2 of Indianapolis is served by combined sewers that discharge during storm runoff to Fall Creek through 28 combined-sewer overflows (fig. 4). Most of the area served by combined sewers is in the older central part of Indianapolis. At least one of the overflows had been constructed before 1900. Many of the combined sewer overflows are visible from the streambank, but some overflows are submerged or incorporated into the base of bridges. The overflows differ greatly in size and range from 2 to 12 ft in diameter. The size of the overflow generally corresponds to the size of area served by the combined sewer. Drainage areas of the combined-sewer overflows that discharge to Fall Creek range from 12 to 3,093 acres (Howard Needles Tammen & Bergendoff, 1983, p. C-2, C-3). The most upstream combined-sewer overflow discharges to Fall Creek at 39th Street. Black sludge deposits are found on the streambed downstream from 39th Street and correspond to the reach of Fall Creek that receives discharge from combined-sewer overflows.

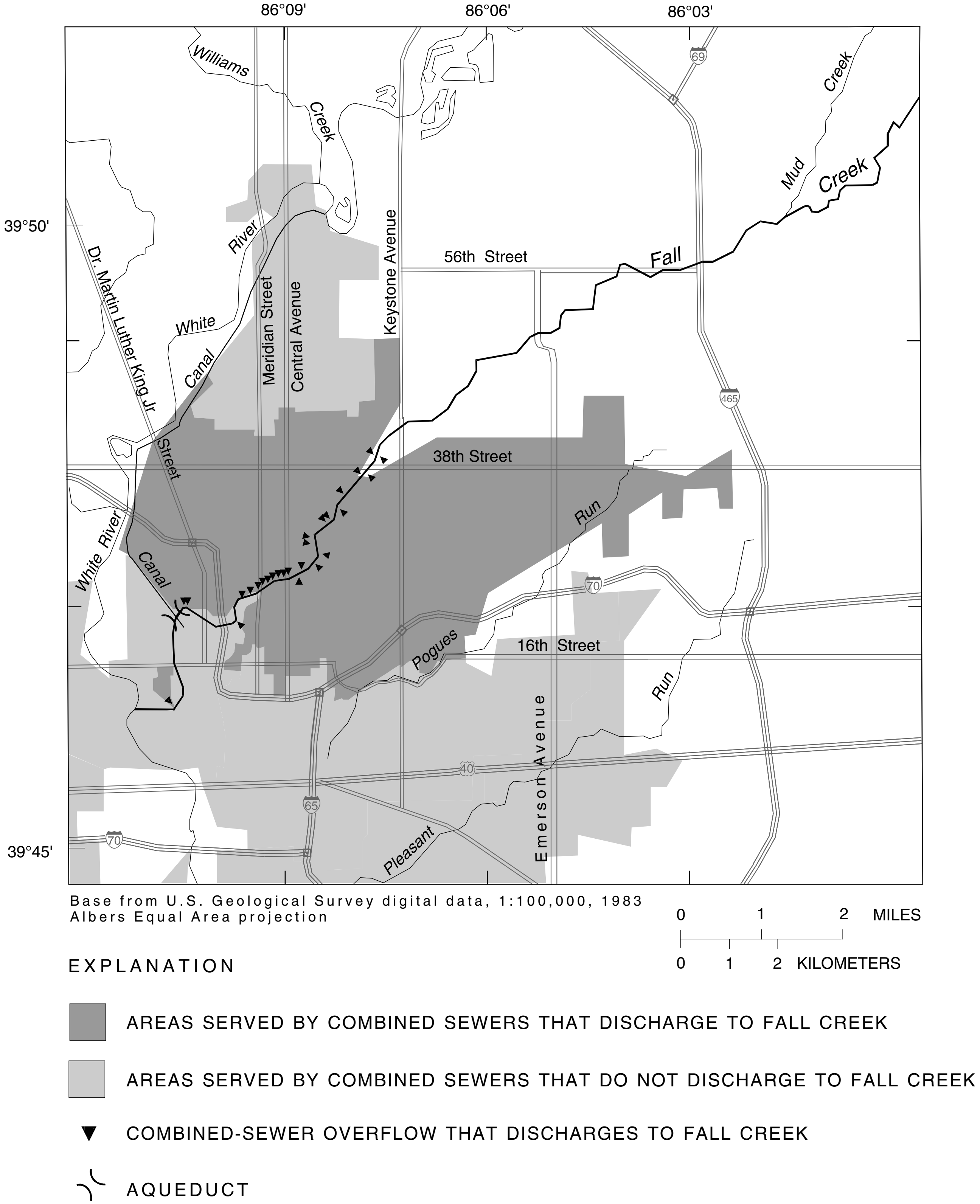


Figure 4. Locations of combined-sewer overflows that discharge to Fall Creek, Indianapolis, Ind. (Drainage areas modified from Howard Needles Tammen & Bergendoff, 1983, fig. 3,4).

A reconnaissance of Fall Creek downstream from 63rd Street revealed a variety of pipes, culverts, and overflow structures. Many of the discharge structures were large storm-sewer overflows or culverts that discharged runoff from streets and bridges. All of the combined-sewer overflows on Fall Creek and the discharge of filter backwash by the two water-treatment plants are permitted discharges for the National Pollutant Discharge Elimination System (NPDES). In addition, several dischargers have received permits to discharge noncontact cooling water to Fall Creek. Most of the cooling-water discharges are downstream from 16th Street.

Acknowledgments

The author thanks the many people who assisted in the study. Vasiliki Keramida, Indianapolis Department of Public Works, was instrumental in planning the study. Charles Crawford, U.S. Geological Survey, Indianapolis, Ind., wrote the water-quality compositing program. John Barr and Kim Cussen, Indianapolis Department of Public Works, helped plan and provide the laboratory analytical services. John Curran and the forecasting staff of the National Weather Service provided spontaneous weather forecasts upon request. Cynthia Wagner and Joseph Ketterman, Marion County Health Department, assisted in identifying combined-sewer overflows on Fall Creek. Tim Bumgardner, Indianapolis Water Company, provided data on water withdrawals and filter-backwash discharges and access to the aqueduct.

METHODS OF INVESTIGATION

The study was designed to investigate the effects of combined-sewer overflows and urban runoff on Fall Creek and to estimate the load (mass) of contaminants discharged during the low-flow period of mid-July to mid-October. This period was selected because streamflow usually is at the lowest rate of the year and provides the least amount of dilution for contaminants discharged to Fall Creek. Biota are most susceptible to low concentrations of dissolved oxygen during this period because of the decreased rate of streamflow for dilution and the warm summer temperatures that decrease the solubility of dissolved oxygen and increase the rates of reactions that consume oxygen. A 90-day period was selected to help ensure that several runoff events would be sampled. The 90-day period studied was July 22, 1987, to October 19, 1987. This period began and ended during base flow and included seven storms (referred to herein as “storms 1–7”) that produced runoff in the Indianapolis area, six of which were sampled for water-quality analysis.

Selection of Data-Collection Sites

Fall Creek was surveyed by canoe on June 23, 1987, from 56th Street to 16th Street and on June 30, 1987, from Keystone Avenue to 16th Street. The purpose of the reconnaissance was to investigate the physical conditions of Fall Creek, especially hydraulic characteristics, and to map the locations of combined-sewer overflows, storm sewers, and other outfalls. Fall Creek also was surveyed by foot on July 1, 1989, at selected sites from Keystone Avenue to 16th Street during an intense thunderstorm to observe and photograph the stream and overflowing sewers during storm runoff.

Three stations were selected for streamflow measurement and intensive water-quality sampling, primarily on the basis of hydraulics and the locations of combined-sewer overflows (figs. 3, 4). Fall Creek at Millersville (station 00352500, referred to as “Emerson Avenue”) and Fall Creek at 16th Street at Indianapolis (station 03352875, referred to as “16th Street”) were streamflow-gaging stations already in the Indiana streamflow network. Fall Creek at Central Avenue at Indianapolis (station 03352850, referred to as “Central Avenue”) was established for this study.

Emerson Avenue is upstream from all Fall Creek combined-sewer overflows and receives urban and rural runoff and water released from Geist Reservoir. Central Avenue is in the center of the combined-sewer-overflow area; 15 combined-sewer overflows are upstream from Central Avenue, and 13 are downstream. The station at 16th Street is downstream from 27 of 28 combined-sewer overflows on Fall Creek, downstream from the overflow at the aqueduct, and immediately downstream from the filter backwash (figs. 3, 4). All of the stations are on free-flowing reaches of Fall Creek. Water-quality samples also were collected from the aqueduct overflow and from the filter backwash upstream from 16th Street.

Two synoptic water-quality surveys were done as part of the study. A base-flow synoptic survey was done on September 24, 1987, at 20 sites on Fall Creek. Water-quality characteristics were measured in the field from bridges across Fall Creek from Pendleton to 16th Street. A high-flow synoptic survey was done on September 29, 1987, during storm runoff (storm 6) at eight bridges from Emerson Avenue to 16th Street.

Measurement of Stage and Computation of Streamflow

A continuous record of streamflow at each station was computed by applying a stage-streamflow rating curve to a stage record obtained at 5-min (Emerson Avenue and Central Avenue) or 15-min (16th Street) intervals. The stage of Fall Creek was measured by a float (Emerson Avenue and Central Avenue) or a pressure-sensing device called a manometer (16th Street) and was digitally recorded on paper tape. The stage-streamflow rating curves were developed by a graphical analysis of current-meter streamflow measurements made at various stages.

The rate of canal overflow at the aqueduct on August 19, 1987, was measured directly at the overflow spillway. The rate of canal overflow at the aqueduct on September 23, 1987, was calculated as the difference in discharge of the canal measured upstream and downstream from the aqueduct. Methods used to measure and compute streamflow and discharge are given in Rantz and others (1982a, 1982b).

Measurement of Precipitation

Daily precipitation was measured by the National Weather Service at the Indianapolis International Airport climatological station (National Oceanic and Atmospheric Administration, 1987) and by various observers in the Indianapolis area. Observers measured precipitation with nonrecording, volumetric rain gages—typically an acrylic, cylindrical storage gage with a 3-in.-diameter opening. Observers read the rain gages between 0600 and 0900. Precipitation measured by the National Weather Service was read at midnight (2400 hours).

Water-Quality Samples and Measurements

Depth-integrated water-quality samples were collected from the downstream sides of bridges at five verticals in the cross section of the stream by use of the equal-discharge-increment method (Guy and Norman, 1970, p. 31-32). Each vertical represented 20 percent of the streamflow. Samples were collected at the centroid of the streamflow increment, approximately at the 10th, 30th, 50th, 70th, and 90th percentiles of the cumulative streamflow. Locations of the sampling verticals at various stages (streamflows) were determined early in the study by analysis of streamflow-measurement notes made to define the stage-streamflow rating curves. Depths at the sampling verticals typically ranged from 1 to 6 ft.

Water-quality samples were collected during storms by use of a US D–74AL–TM sampler suspended from a bridge crane equipped with a cable-and-reel assembly (Edwards and Glysson, 1988, p. 13). Water-quality samples were collected during base flow by use of a US DH–S–48–TM sampler suspended from a handline (Edwards and Glysson, 1988, p. 11). Both of the samplers were painted with epoxy and equipped with nylon nozzles and silicon rubber gaskets suitable for the collection of samples to be analyzed for trace metals.

Samplers were lowered and raised through the water column at a uniform rate to ensure the collection of a depth-integrated sample. The amount of water collected at each vertical depended on the type of sample being collected. During storms, most of the samples collected were composited in the District laboratory by use of a time-and-flow weighting technique. Approximately 3,600 mL of sample were needed and approximately 720 mL of water were collected at each vertical. Samples from each vertical were poured through a polyethylene funnel into a single 1-gal polyethylene sample container. Base-flow samples and selected storm samples were not composited. Storm samples that were not composited were collected near the end of a period of storm runoff, after earlier storm samples had been composited and processed. Storm samples that were not composited are termed “individual” sample types in tables 8 and 11. Approximately 7.2 L of sample were needed for base-flow and individual storm samples. Each of the five verticals was sampled twice, and the samples were combined in two 1-gal containers. Three base-flow samples were split as part of the quality-assurance program; consequently, approximately 14.4 L of water were needed for each of these samples. Sample containers were labeled with the site, date, and midpoint sample-collection time and stage and stored at 4°C in an ice-water bath in coolers while awaiting transport to the U.S. Geological Survey laboratory in Indianapolis. Samplers, funnels, and sample containers were field rinsed with sample water immediately before collecting samples from the first vertical.

Samples for the analyses of fecal coliform bacteria were collected in a sterile 300-mL (BOD) bottle secured to a weighted sampler suspended from a handline. The sampler was lowered approximately 1 ft below the surface of the water at the center of flow and allowed to fill. The bottle was removed from the sampler, and a small volume of sample was poured off to allow the sample to be mixed easily before analysis. The bottle was sealed with a sterile ground-glass stopper and plastic cap; labeled with the site, date, and time; and stored at 4°C in an ice-water bath in coolers while awaiting transport to the DPW laboratory. Dechlorinating agents were not used. Fecal coliform samples were picked up and driven to the DPW laboratory by DPW personnel at 3-hour intervals. The maximum holding time for fecal coliform samples was about 4 hours.

Water temperature, pH, dissolved-oxygen concentration, and specific conductance were made with a Hydrolab model 4041 multiparameter field meter; a Hydrolab model 2000 datasonde; or a continuous, flowthrough water-quality monitor. Saturation concentrations of dissolved oxygen were calculated as presented in Bowie and others (1985, p. 91, eq. 3-5). The Hydrolab field meter was used for all base-flow measurements, all synoptic measurements, and all storm measurements at Emerson Avenue and Central Avenue. For base-flow and synoptic measurements, water quality was measured at approximately the 25th, 50th, and 75th percentiles of the cumulative cross-sectional streamflow, at 1.5- to 2-ft depth, and the measurements averaged. For storm measurements, water quality was measured at approximately the center of flow, at 0.5- to 2-ft depth.

The field meter was calibrated onsite (for storm and high-flow synoptic measurements) or in the laboratory (for base-flow and base-flow synoptic measurements) according to the manufacturer’s instructions. Calibration was checked at the end of the day (for base-flow and base-flow synoptic measurements) or every 12 to 16 hours (during storm and high-flow synoptic measurements). If calibration checks were not within the limits specified by Gordon and Katzenbach (1983, p. 76-79), the field meter was recalibrated (for the particular parameter that differed) and a prorated correction, based on the time since the last calibration, was applied to the data (Gordon and Katzenbach, 1983, p. 89-93). In general, the field meters held calibration, and few corrections were applied.

Hydrolab model 2000 datasondes were used in addition to field meters for storm measurements at Emerson Avenue and Central Avenue during storms 1 and 2. The datasondes have the capability of recording water-quality measurements, and their utility in measuring storm runoff was investigated. Two datasondes, calibrated in the laboratory according to the manufacturer's instructions, were placed in the center of flow next to the field meters at each site. Data from the datasondes were compared with data from the field meters, and data from the datasonde that best agreed with the field meter is presented in this report. Data from the datasondes are used in this report because the frequency of measurement with the datasonde was greater than that with the field meter and provided more detailed information on water quality during storm runoff. Use of the datasondes was discontinued after storm 2 because of the long time required for calibration and other operational difficulties.

A continuous, flowthrough water-quality monitor was used for all storm measurements at 16th Street. Characteristics and use of the monitor are discussed in Gordon and Katzenbach (1983) and in Martin and Craig (1990, p. 14-27).

During storms, water-quality samples were collected at approximately every 0.2-ft change in stage or at approximately 4- to 6-hour intervals when the stage was changing slowly. Water-quality measurements were made with field meters during collection of every water-quality sample or more frequently. Water-quality measurements were made with the datasondes at 30-min intervals and with the continuous monitor at 15-min intervals.

Fecal coliform samples were collected after every water-quality sample for the first two storms and after every other water-quality sample for the remaining storms. The large number of fecal coliform samples collected during the first two storms exceeded the capacity of the DPW laboratory for prompt analyses.

A depth-integrated water-quality sample was collected from the spillway of the canal overflow at the aqueduct on October 15, 1987, by use of the equal-width-increment, equal-transit-rate method (Guy and Norman, 1970, p. 32-33). The sample was collected by use of a US DH–48–TM sampler suspended from a wading rod (Edwards and Glysson, 1988, p. 10-11). Water-quality measurements were made by use of a Hydrolab model 4041 multiparameter field meter in the canal immediately upstream from the spillway at 0.5 ft depth.

A grab water-quality sample was collected from the outfall of the filter backwash near 16th Street on August 27, 1989, by submersing two field-rinsed, 1-gal polyethylene sample containers in the effluent. Grab water-quality samples also were collected at Central Avenue and at 16th Street, as part of the quality-assurance program, from the center of flow by use of a plastic bucket suspended from a handline. Sample water was poured through a funnel into two 1-gal containers, which were then labeled and stored in coolers at 4°C. The sample containers, funnel, and bucket were field rinsed immediately before sample collection.

Sample Processing, Compositing, Preservation, and Analysis

Base-flow, individual storm, canal-overflow, and filter-backwash samples were taken to the laboratory and stored in darkness at 4°C in a walk-in refrigerator. The maximum holding time before processing and preservation for these samples was 6 hours. Samples were shaken and poured into a clean, deionized-water-rinsed, 8-L polyethylene churn splitter and were thoroughly mixed. While the sample was being mixed in the churn, five 1-L polyethylene bottles and one 500-mL glass bottle were filled with raw sample water. The remaining sample was filtered through a 0.45-μm-pore-size filter made of cellulose triacetate into a 1-L polyethylene bottle. The order in which the samples were processed and the order the bottles were filled were randomized, except that the filtered sample always was done last. The bottles were labeled with the date and an alphanumeric code that uniquely identified the sample and the types of chemical analyses to be performed for each bottle.

A time-and-flow weighting technique was used to composite most of the water-quality samples collected during periods of storm runoff. This technique was used because the cost of individually analyzing the many storm samples was prohibitively expensive. Storm samples to be composited were taken to the laboratory and stored in darkness at 4°C. The maximum holding time before processing and preservation for these samples was 36 hours. Storm samples consisted of one 1-gal container for each sampling time. Samples were shaken and poured into a clean, deionized-water-rinsed, 4-L polyethylene churn splitter and thoroughly mixed. The sample volume drawn off for use in the storm-runoff composite sample was calculated as follows (R.J. Pickering, U.S. Geological Survey, written commun., 1980):

$$v_i = (q_i t_i)/(\Sigma q_i t_i) \times VT\ , \qquad (1)$$

where

v_i is volume of the storm sample collected at time i added to the composite sample (L),
q_i is instantaneous streamflow at the mid-point time of sample collection (ft^3/s),
t_i is time interval (min, equal to one-half the time since the previous sample plus one-half the time to the next sample; the time interval for the first sample is from the start of the storm runoff to one-half the time to the second sample, the time interval for the last sample is from the end of the storm runoff to one-half the time to the next-to-last sample),
Σ is summation operator, and
VT is volume of composite sample required (7.5 L).

Samples were composited in an 8-L polyethylene churn splitter and thoroughly mixed. Seven bottles were filled with sample water in the same manner as that used for the base-flow samples.

Two of the 1-L bottles containing unfiltered sample water were preserved with concentrated sulfuric acid (2 mL each) and were used for the determination of chemical oxygen demand, nitrate plus nitrite, ammonia, organic nitrogen, and phosphorus. Two of the 1-L bottles containing unfiltered sample water were preserved with concentrated nitric acid (2 mL each) and were used for the determination of arsenic, mercury, selenium, aluminum, barium, cadmium, chromium, copper, iron, lead, nickel, and zinc. The remaining 1-L bottle containing unfiltered sample water contained no preservative and was used for the determination of total solids and carbonaceous biochemical oxygen demand. The 500-mL bottle containing raw sample water was preserved with 2.5 mL of concentrated sulfuric acid and was used for the determination of oil and grease. The 1-L bottle containing filtered sample water had no preservative added and was used for the determination of alkalinity, sulfate, chloride, dissolved solids, and orthophosphate. Samples were placed on ice in coolers and were driven to the DPW laboratory for analysis.

All chemical and biological analyses were done by the Indianapolis DPW laboratory. Alkalinity, chloride, total solids, carbonaceous biochemical oxygen demand, chemical oxygen demand, oil and grease, ammonia, phosphorus, and fecal coliform bacteria were analyzed according to the methods given in American Public Health Association and others (1985). Organic nitrogen, arsenic, mercury, selenium, aluminum, barium, cadmium, chromium, copper, iron, lead, nickel, and zinc were analyzed according to the methods given in U.S. Environmental Protection Agency (1983). Nitrate plus nitrite and orthophosphate were analyzed according to the methods given in Technicon Industrial Systems (1973a, 1973b). Sulfate was analyzed according to the method given in Skougstad and others (1979, p. 501-504). Dissolved solids were analyzed according to the method given in American Public Health Association and others (1981).

Chemical analyses for “dissolved” constituents—alkalinity, sulfate, chloride, dissolved solids, and orthophosphate—were done on water samples that were filtered through a 0.45-µm-pore-size filter and are operationally defined as dissolved (U.S. Environmental Protection Agency, 1983, p. xiv, METALS–4; Fishman and Friedman, 1989, p. 4). Chemical analyses for “total” constituents—total solids, carbonaceous biochemical oxygen demand, chemical oxygen demand, nitrate plus nitrite, ammonia, organic nitrogen, phosphorus, arsenic, mercury, and selenium—were done on unfiltered water samples (whole-water samples that contain water and suspended sediment). These analytical methods determine more than 95 percent of the constituent present in the unfiltered sample (Fishman and Friedman, 1989, p. 4, 50-51). Chemical analyses for “total recoverable” constituents—oil and grease, aluminum, barium, cadmium, chromium, copper, iron, lead, nickel, and zinc—were done on unfiltered water samples. The analytical methods (which required a dilute-acid digestion of the water and suspended sediment for the metals or extraction with an organic solvent for oil and grease) may not completely digest or extract the sample and may not determine more than 95 percent of the constituent present, hence the term “recoverable” (U.S. Environmental Protection Agency, 1983, p. METALS–2-5; Fishman and Friedman, 1989, p. 4, 50-51). Detection limits for the analytical methods used in this study are given in the last row of table 1. Concentrations less than the detection limit were plotted as one-half the detection limit in figure 13.

Calculation of Event-Mean Concentration

Event-mean concentration is the flow-weighted average concentration of a constituent during a period of storm runoff (Fisher and Katz, 1988, p. 6). Most of the water-quality samples collected during storm runoff were composited by use of a time-and-flow weighting technique. The number of water samples collected during storm runoff at a site ranged from 3 to 27. When possible, all of the samples for a single period of runoff were composited by use of the weighting technique. Where this could be done, analytical results for the composite sample are the event-mean concentrations. Often, however, several composite samples or a composite sample and an individual sample were required to adequately sample the period of runoff and not exceed the 36-hour holding time for compositing samples. Where this procedure was required, the mass of the constituent in the part of the runoff the sample represented was calculated by multiplying the analytical result (concentration) by the runoff volume. Constituent masses were summed for all runoff samples for that period of runoff. Runoff volumes corresponding to the runoff samples also were summed for that period of runoff. Event-mean concentration was calculated as the total constituent mass divided by the total runoff volume. Concentrations less than the detection limits were assigned one-half the detection limit for the purposes of calculating event-mean concentration. The mean concentration of split samples was used to calculate event-mean concentrations. Event-mean concentrations were not adjusted to remove the base-flow contribution to constituent mass or runoff volume.

Quality Assurance

Approximately 25 percent of the samples analyzed for this study were for quality assurance. Quality-assurance samples consisted of deionized-water blanks, standard reference water samples, and two types of split samples (one type for assessing analytical precision, another for assessing the effect of holding time before sample processing). Deionized water was placed in eight quality-assured 1-L polyethylene bottles obtained from the U.S. Geological Survey Water Quality Laboratory in Arvada, Colo., and two 1-gal polyethylene bottles obtained from a distributor in Indianapolis. Deionized-water blanks were stored in darkness at 4°C for 24 hours at the laboratory, then processed, preserved, and analyzed in the same manner as base-flow samples. The purpose of analyzing the deionized-water blanks was to determine if analyses obtained from the 1-gal bottles to be used for field sampling were different from those obtained from the quality-assured 1-L bottles normally used by the U.S. Geological Survey. Also, the deionized-water blanks were used to determine if contamination had occurred during sample processing, preservation, transport, or analysis. Nearly all constituents and properties were below detection limits for the deionized-water blanks (table 1). Detectable concentrations of carbonaceous biochemical oxygen demand and chemical oxygen demand in both types of bottles, and barium and iron in the 1-L bottles, were measured in the blank samples (table 1).

Table 1. Water-quality analyses for quality-assurance samples

[i.d., identification; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degree Celsius; mg/L, milligrams per liter; n.a., not applicable; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; n.d., not determined; <, less than; SRWS, standard reference water sample; hold, split sample held 48 hours before processing; hr, hour; sd., standard deviation; --, no data]

Site	Sample i.d.	Sample type	Date	Time[1]	Streamflow (ft^3/s) (00061)[2]	Specific conductance (µS/cm) (00095)[2]	pH (00400)[2]	Water temperature (°C) (00010)[2]	Dissolved oxygen (mg/L) (00300)[2]
n.a.	Liter poly[3]	Deionized water[3]	7-16-97	n.a.	n.a.	n.d.	n.d.	n.d.	n.d.
n.a.	Gallon poly[3]	Deionized water[3]	7-16-87	n.a.	n.a.	n.d.	n.d.	n.d.	n.d.
Central	Storm 2	Grab[4]	7-31-87	0830	214	411	7.7	25.6	7.1
Central	Storm 2	Grab 48-hr hold[4]	7-31-87	0830	214	411	7.7	25.6	7.1
Central	Base flow 2	Grab[4]	8-11-87	1320	35	600	7.8	24.1	7.9
Central	Base flow 2	Grab 48-hr hold[4]	8-11-87	1320	35	600	7.8	24.1	7.9
16th Street	Storm 6	Grab[4]	9-30-87	0910	50	827	7.8	18.3	6.6
16th Street	Storm 6	Grab 48-hr hold[4]	9-30-87	0910	50	827	7.8	18.3	6.6
n.a.	SRWS[5]	M98 or T97	10-15-87	n.a.	n.a.	n.d.	n.d.	n.d.	n.d.
n.a.	Mean, sd.	All labs	n.a.	n.a.	n.a.	514, 19	8.31, 0.13	n.d.	n.d.
n.a.	SRWS[5]	T99	10-15-87	n.a.	n.a.	n.d.	n.d.	n.d.	n.d.
n.a.	Mean, sd.	All labs	n.a.	n.a.	n.a.	n.d.	n.d.	n.d.	n.d.
n.a.	n.a.	Detection limit[6]	n.a.	n.a.	n.a.	n.d.	n.d.	n.d.	n.d.

Table 1. Water-quality analyses for quality-assurance samples—Continued

Site	Sample i.d.	Dissolved alkalinity (mg/L as $CaCO_3$) (29801)[2]	Dissolved sulfate (mg/L) (00945)[2]	Dissolved chloride (mg/L) (00940)[2]	Dissolved solids (mg/L) (00515)[2]	Total solids (mg/L) (00500)[2]	Suspended solids[8] (mg/L)	Total 20-day carbonaceous biochemical oxygen demand (mg/L) (80087)[2]	Total chemical oxygen demand (mg/L) (00340)[2]	Total recoverable oil and grease (mg/L) (00556)[2]
n.a.	Liter poly[3]	<1	<1	--	<10	<10	<10	2	2	<1
n.a.	Gallon poly[3]	<1	<1	<1	<10	<10	<10	1	2	<1
Central	Storm 2	128	30	23	270	293	23	3	23	<1
Central	Storm 2 hold[4]	124	31	23	263	315	52	[7]16	23	<1
Central	Base flow 2	200	51	39	364	404	40	4	12	2
Central	Base flow 2 hold[4]	194	51	39	371	399	28	3	11	2
16th Street	Storm 6	254	71	64	494	566	72	4	17	1
16th Street	Storm 6 hold[4]	256	71	64	497	557	60	4	18	1
n.a.	SRWS[5]	172	42	32	311	n.d.	n.d.	n.d.	n.d.	n.d.
n.a.	Mean, sd.	179, 5	41.5, 3.8	32.5, 2.9	309, 19	n.d.	n.d.	n.d.	n.d.	n.d.
n.a.	SRWS[5]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
n.a.	Mean, sd.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
n.a.	Detection limit[6]	1	1	1	10	10	n.d.	1	1	1

Table 1. Water-quality analyses for quality-assurance samples—Continued

Site	Sample i.d.	Total nitrate plus nitrite (mg/L as N) (00630)[2]	Total ammonia (mg/L as N) (00610)[2]	Total organic nitrogen (mg/L) (00605)[2]	Total phosphorus (mg/L) (00665)[2]	Dissolved orthophosphate (mg/L as P) (00671)[2]	Total arsenic (µg/L) (01002)[2]	Total mercury (µg/L) (71900)[2]	Total selenium (µg/L) (01147)[2]
n.a.	Liter poly[3]	<0.005	<0.01	<0.01	<0.01	<0.01	<1	<0.2	<1
n.a.	Gallon poly[3]	<.005	<.01	<.01	<.01	<.01	<1	<.2	<1
Central	Storm 2	.35	.15	1.08	.20	<.01	2	<.2	<1
Central	Storm 2 hold[4]	.35	.08	1.20	.18	<.01	2	<.2	<1
Central	Base flow 2	.28	.08	.72	.07	<.01	2	<.2	<1
Central	Base flow 2 hold[4]	.28	.10	.78	.07	<.01	2	<.2	<1
16th Street	Storm 6	.96	.14	1.08	.49	.07	2	<.2	<1
16th Street	Storm 6 hold[4]	1.03	.30	.96	.38	.08	3	<.2	<1
n.a.	SRWS[5]	n.d.	n.d.	n.d.	n.d.	.03	14	.9	36
n.a.	Mean, sd.	n.d.	n.d.	n.d.	0.04, 0.01	0.03, 0.01	11.3, 1.5	0.9, 0.2	15.9, 3.4
n.a.	SRWS[5]	n.d.	n.d.	n.d.	n.d.	n.d.	6	.2	11
n.a.	Mean, sd.	n.d.	n.d.	n.d.	n.d.	n.d.	5.8, 1.9	n.d.	9.8, 3.4
n.a.	Detection limit[6]	.005	.01	.01	.01	.01	1	.2	1

Table 1. Water-quality analyses for quality-assurance samples—Continued

Site	Sample i.d.	Total recoverable aluminum (µg/L) (01105)[2]	Total recoverable barium (µg/L) (01007)[2]	Total recoverable cadmium (µg/L) (01027)[2]	Total recoverable chromium (µg/L) (01034)[2]	Total recoverable copper (µg/L) (01042)[2]	Total recoverable iron (µg/L) (01045)[2]	Total recoverable lead (µg/L) (01051)[2]	Total recoverable nickel (µg/L) (01067)[2]	Total recoverable zinc (µg/L) (01092)[2]
n.a.	Liter poly[3]	<10	30	<10	<10	<10	10	<10	<10	<10
n.a.	Gallon poly[3]	<10	<10	<10	<10	<10	<10	<10	<10	<10
Central	Storm 2	960	90	<10	<10	10	1,490	<10	<10	10
Central	Storm 2 hold[4]	860	50	<10	<10	10	1,190	<10	<10	10
Central	Base flow 2	190	80	<10	<10	<10	340	<10	<10	<10
Central	Base flow 2 hold[4]	170	80	<10	<10	<10	330	<10	<10	<10
16th Street	Storm 6	1,780	50	<10	<10	<10	1,130	<10	<10	10
16th Street	Storm 6 hold[4]	1,780	140	<10	<10	<10	1,130	<10	10	10
n.a.	SRWS[5]	110	220	10	30	20	120	20	<10	150
n.a.	Mean, sd.	126, 42	98, 12	16.3, 2.3	26.0, 4.3	16.8, 2.5	100, 9	15.0, 3.7	15.2, 5.8	153, 10
n.a.	SRWS[5]	140	<10	<10	<10	30	130	<10	<10	30
n.a.	Mean, sd.	86, 31.4	25.1, 10.2	4.7, 1.5	16.3, 6.5	27.9, 4.6	137, 29	4.7, 3.4	5, n.d.	36.0, 7.3
n.a.	Detection limit[6]	10	10	10	10	10	10	10	10	10

[1] Midpoint time of grab sample collection.

[2] WATSTORE (U.S. Geological Survey) and STORET (U.S. Environmental Protection Agency) parameter code.

[3] Quality-assured, 1-liter polyethylene sample bottles obtained from U.S. Geological Survey National Water Quality Laboratory in Arvada, Colo. One-gallon polyethylene bottles obtained from a distributor in Indianapolis. Deionized water was stored in the liter and gallon bottles for 24 hours at 4°C, then processed and sent to the laboratory.

[4] Grab samples were split with a cone splitter. One split was immediately processed and sent to the laboratory. The second split was stored in a gallon bottle for 48 hours at 4°C, then processed and sent to the laboratory.

[5] Standard reference water samples (SRWS) obtained from the U.S. Geological Survey National Water Quality Laboratory. Mean and standard deviation were calculated from analyses from 21–66 laboratories that participate in the U.S. Geological Survey Analytical Evaluation Program (Victor J. Janzer, National Water Quality Laboratory, written commun., 1987).

[6] Limit of detection for the methods used by the Indianapolis Department of Public Works Laboratory.

[7] Nitrification was not inhibited in this sample. Reported concentrations were adjusted for oxidizable nitrogen.

[8] Suspended solids were calculated as the difference between total solids and dissolved solids.

The DPW laboratory participates in the U.S. Geological Survey's Standard Reference Water Sample program (Schroder and others, 1980; Janzer, 1985, p. 331). Water samples are sent to numerous laboratories throughout the Nation for the analysis of a variety of constituents and properties. On the basis of these analyses, the most probable values (means) of the constituent concentrations are calculated. Individual analyses within 0.5 standard deviations of the most probable value are rated excellent, within 1.0 standard deviations are rated good, within 1.5 are rated satisfactory, within 2.0 are rated questionable, and greater than 2.0 are rated poor. Ratings for individual constituents are averaged and overall ratings for major constituents, trace constituents, and nutrients are calculated. Overall ratings for the DPW laboratory were consistently good or satisfactory. Additional quality-assurance information for the DPW laboratory is given in Bobay (1988, p. 9-12) and in Duwelius and Greeman (1989, p. 9-12).

Standard reference water samples for major constituents (M98) and trace constituents (T97 and T99) were obtained from the U.S. Geological Survey and submitted to the DPW laboratory labeled as regular base-flow samples (blind quality-assurance samples). Standard reference water samples were mailed to the District laboratory in Teflon bottles and were poured directly into sample bottles that had been rinsed with the reference water. Standard reference water samples were neither split nor filtered but were preserved in the same manner as regular base-flow samples. The purpose of analyzing the standard reference water samples was to assess analytical accuracy by comparing analyses produced by the DPW laboratory with the most probable values calculated from analyses produced by a large number of laboratories. Ratings for individual constituents, according to the standard-deviation criteria given above, were excellent to good for major constituents and were excellent to poor for trace constituents (table 1).

Split samples are a pair of identical samples. Four composite storm samples and three base-flow samples were split and submitted for analysis as part of the quality-assurance program. The purpose of analyzing these split samples was to assess analytical precision—assuming no contamination or other differences caused by sample processing, preservation, or transport. Analytical results for these samples are given in tables of environmental data (tables 8, 11) rather than in the table of quality-assurance data (table 1). Average (mean) concentrations of split samples were used for calculations and interpretations of water quality. Concentrations less than the detection limits were assigned one-half the detection limit for the purposes of calculating mean concentration.

Storm samples were split by doubling the volume of composite sample required (VT=15L, eq. 1) and placing one-half of the volume of the storm sample added to the composite sample (v_i, eq. 1) in one 8-L churn and the remaining one-half in a second 8-L churn. Each split was processed and preserved in the same manner as a non-split composite storm sample. Each base-flow sample to be split consisted of four 1-gal containers. Each container was shaken and rapidly poured through an acrylic cone splitter (R.J. Pickering, U.S. Geological Survey, written commun., 1980), which split the sample into two 8-L churn splitters. Each split was processed and preserved in the same manner as a nonsplit base-flow sample.

Three grab water-quality samples were collected at Central Avenue and 16th Street and split as part of the quality-assurance program to investigate the effects of holding time prior to sample processing and preservation on the analytical results. Each grab sample to be split consisted of four 1-gal containers. Each container was shaken and rapidly poured through a cone splitter which split the sample into an 8-L churn splitter and two 1-gal sample containers that were rinsed with deionized water. The split in the churn splitter was processed and preserved in the same manner as a nonsplit base-flow sample. The split in the two 1-gal sample containers was stored in darkness at 4°C for 48 hours, then processed and preserved in the same manner as a nonsplit base-flow sample. Analytical results for the split samples that were immediately processed and for the split samples that were held for 48 hours before processing are given in table 1.

Analytical precision and the effect of holding time before sample processing were assessed by calculating statistics of the log difference (expressed in log percent) between split samples. Log difference, which expresses the relative difference between split samples with respect to their logarithmic mean, is the only symmetric, additive, and normed measure of relative difference (Tornqvist and others, 1985, p. 43, 44):

$$ln(y/x) = (y-x)/L(x,y) \ , \qquad (2)$$

where

$ln(y/x)$ is log difference between split samples (unitless),

x is concentration in the first split sample (mass/volume),

y is concentration in the second split sample (mass/volume), and

$L(x,y)$ is logarithmic mean (base e) of x and y (mass/volume).

The logarithmic mean is less than the arithmetic mean but greater than the geometric mean.

Log difference was used instead of arithmetic difference because of the property of additivity, which is preferred for statistical summaries. In addition, log difference is not limited to a maximum difference of 200 percent as is arithmetic difference and, therefore, is a better measure of relative difference between split samples with large differences in concentration. Log difference is easily calculated as the natural logarithm of the concentration of the second split sample divided by concentration of the first split sample:

$$ln(y/x) \ , \qquad (3)$$

where

ln is logarithm (base e), and x and y are as previously defined.

Log difference used in the tables and text is expressed in log percent and is calculated as the log difference multiplied by 100 percent (Tornqvist and others, 1985, p. 45). The absolute values of the log differences were calculated for split samples used to assess analytical precision (table 2). Absolute value was used because the direction of change was not of interest. Absolute values of the log difference were not calculated for split samples used to assess the effect of holding time before sample processing (table 3). Absolute value was not used because the direction of change was of interest. For the purposes of this analysis, concentrations less than the detection limit were assigned one-half the detection limit. Detection limits are given in the last row of table 1.

The most precise analytical determinations (mean and standard deviation of log differences equal to or less than 4.6 log percent) were for alkalinity, sulfate, chloride, dissolved solids, total solids, nitrate plus nitrite, arsenic, aluminum, and iron (table 2). The most imprecise determinations (mean log differences greater than 47 log percent and the standard deviation of log differences greater than 65 percent) were for organic nitrogen, oil and grease, and barium. All concentrations of mercury, selenium, and cadmium, and many of chromium and nickel were less than the detection limits (tables 8, 11); high precision (small log differences) for these constituents is a result of the many nondetections.

The effect of holding water samples for 48 hours before processing did not seem to bias the analytical results. None of the 25 water-quality constituents exhibited a consistent increase or decrease in concentration for all pairs of split samples (median, minimum, and maximum concentration difference between split samples, table 3). For parameters with measurable differences in concentration for at least two of the three pairs of split samples, only phosphorus, aluminum, and iron showed a consistent direction of change (a decreased concentration in the split sample held for 48 hours, table 3). Concentration differences (and log differences) between split samples for these three constituents, however, were similar in magnitude to those observed for split samples used to assess analytical precision (table 2) and probably do not indicate a bias that can be attributed to holding time.

Table 2. Statistical analysis of split quality-assurance samples used to assess analytical precision

[CBOD, carbonaceous biochemical oxygen demand; COD, chemical oxygen demand; mg/L, milligram per liter; µg/L, microgram per liter]

Water-quality characteristic (units)	Number of split samples[1]	Mean concentration of split samples [2, 3]			Absolute difference between split samples			Absolute log difference (log percent)[4]				
		Median	Minimum	Maximum	Median	Minimum	Maximum	Mean	Median	Minimum	Maximum	Standard deviation
Dissolved:												
Alkalinity (mg/L)	7	213	138	277	2	0	9	1.4	1.0	0.0	4.0	1.5
Sulfate (mg/L)	7	56	37	75	0	0	2	1.0	.0	.0	3.1	1.3
Chloride (mg/L)	7	46	29	85	0	0	2	1.2	.0	.0	4.0	1.6
Solids (mg/L)	7	411	298	573	15	2	24	3.1	3.1	.5	5.7	2.3
Orthophosphate (mg/L)	7	.03	.005	.29	.00	.00	.05	11.6	.0	.0	81.1	30.7
Suspended:												
Solids[5] (mg/L)	7	75	18	193	19	3	45	22.5	22.7	14.8	36.1	7.2
Total:												
Solids (mg/L)	7	469	401	661	16	0	41	3.0	3.4	.0	6.2	2.3
20-day CBOD (mg/L)	7	7	2	12	1	0	6	30.7	15.4	.0	109.9	40.8
COD (mg/L)	6	32	21	43	1	0	9	7.0	4.2	.0	21.3	7.6
Nitrate plus nitrite (mg/L)	6	.50	.33	.77	.01	.00	.05	3.5	1.5	.0	11.1	4.6
Ammonia (mg/L)	6	.30	.07	.71	.03	.01	.08	17.4	12.0	1.7	47.0	16.7
Organic nitrogen (mg/L)	6	1.18	.87	2.45	.63	.02	1.55	79.8	42.3	1.2	290.3	111.6

Table 2. Statistical analysis of split quality-assurance samples used to assess analytical precision—Continued

Water-quality characteristic (units)	Number of split samples[1]	Mean concentration of split samples [2, 3]			Absolute difference between split samples			Absolute log difference (log percent)[4]				
		Median	Minimum	Maximum	Median	Minimum	Maximum	Mean	Median	Minimum	Maximum	Standard deviation
Phosphorus (mg/L)	6	.56	.20	1.34	.02	.00	.36	14.6	1.8	.0	59.8	24.0
Arsenic (µg/L)	6	4	1	10	0	0	0	.0	.0	.0	.0	.0
Mercury (µg/L)	6	.1	.1	.1	0	0	0	.0	.0	.0	.0	.0
Selenium (µg/L)	6	.5	.5	.5	0	0	0	.0	.0	.0	.0	.0
Total recoverable:												
Oil and grease (mg/L)	7	2	1	3	1	0	3	80.9	69.3	.0	179.2	67.3
Aluminum (µg/L)	6	2,850	190	11,470	30	10	300	4.1	3.1	.3	11.0	4.3
Barium (µg/L)	6	90	40	120	20	0	50	47.1	23.7	.0	179.2	65.7
Cadmium (µg/L)	6	5	5	5	0	0	0	.0	.0	.0	.0	.0
Chromium (µg/L)	6	5	5	20	0	0	5	11.6	.0	.0	69.3	28.3
Copper (µg/L)	6	20	10	30	0	0	10	11.6	.0	.0	69.3	28.3
Iron (µg/L)	6	2,640	310	3,630	60	0	250	3.9	2.7	.0	9.9	4.0
Lead (µg/L)	6	20	5	20	5	0	10	34.7	34.7	.0	69.3	38.0
Nickel (µg/L)	6	5	5	10	0	0	0	.0	.0	.0	.0	.0
Zinc (µg/L)	6	30	10	40	0	0	10	11.6	.0	.0	69.3	28.3

[1] Split samples are a pair of theoretically identical samples.

[2] Concentrations less than the detection limit were assigned one-half the detection limit for this analysis. Detection limits are given in the last row of table 1.

[3] Statistics were rounded to the same number of significant figures as analytical measurements of the same magnitude.

[4] Absolute log difference is the absolute value of the difference between a pair of split samples divided by the logarithmic mean of the pair of split samples multiplied by 100 percent (Tornqvist and others, 1985, p. 44–45). It is used in this context to summarize the relative precision of chemical analyses.

[5] Suspended solids were calculated as the difference between total solids and dissolved solids.

Table 3. Statistical analysis of split quality-assurance samples used to assess the effect of holding samples at 4°C for 48 hours before processing and preservation

[CBOD, carbonaceous biochemical oxygen demand; COD, chemical oxygen demand; mg/L, milligram per liter; µg/L, microgram per liter]

Water-quality characteristic (units)	Number of split samples[1]	Mean concentration of split samples [2, 3]			Concentration difference between split samples[4]			Log difference (log percent)[4, 5]				
		Median	Minimum	Maximum	Median	Minimum	Maximum	Mean	Median	Minimum	Maximum	Standard Deviation
Dissolved:												
Alkalinity (mg/L)	3	197	126	255	4	–2	6	1.8	3.0	–0.8	3.2	2.2
Sulfate (mg/L)	3	51	31	71	0	–1	0	–1.1	.0	–3.3	.0	1.9
Chloride (mg/L)	3	39	23	64	0	0	0	.0	.0	.0	.0	.0
Solids (mg/L)	3	368	267	496	–3	–7	7	.0	–.6	–1.9	2.6	2.3
Orthophosphate (mg/L)	3	.005	.005	.08	.00	–.01	.00	–4.5	.0	–13.4	.0	7.7
Suspended:												
Solids[6] (mg/L)	3	38	34	66	12	–29	12	–9.2	18.2	–81.6	35.7	63.3
Total:												
Solids (mg/L)	3	402	304	562	5	–22	9	–1.5	1.2	–7.2	1.6	5.0
20-day CBOD (mg/L)	3	4	4	10	0	–13	1	–46.2	.0	–167.4	28.8	105.9
COD (mg/L)	3	18	12	23	0	–1	1	1.0	.0	–5.7	8.7	7.3
Nitrate plus nitrite (mg/L)	3	.35	.28	1.00	.00	–.07	.00	–2.3	.0	–7.0	.0	4.1
Ammonia (mg/L)	3	.12	.09	.22	–.02	–.16	.07	–11.9	–22.3	–76.2	62.9	70.1
Organic nitrogen (mg/L)	3	1.02	.75	1.14	–.06	–.12	.12	–2.3	–8.0	–10.5	11.8	12.2
Phosphorus (mg/L)005	3	.19	.07	.44	.02	.00	.11	12.0	10.5	.0	25.4	12.8

Table 3. Statistical analysis of split quality-assurance samples used to assess the effect of holding samples at 4°C for 48 hours before processing and preservation—Continued

Water-quality characteristic (units)	Number of split samples[1]	Mean concentration of split samples [2, 3]			Concentration difference between split samples[4]			Log difference (log percent)[4, 5]				
		Median	Minimum	Maximum	Median	Minimum	Maximum	Mean	Median	Minimum	Maximum	Standard Deviation
Arsenic (ug/L)	3	2	2	3	0	–1	0	–13.5	.0	–40.5	.0	23.4
Mercury (µg/L)	3	.1	.1	.1	.0	.0	.0	.0	.0	.0	.0	.0
Selenium (µg/L)	3	.5	.5	.5	.0	.0	.0	.0	.0	.0	.0	.0
Total recoverable:												
Oil and grease (mg/L)	3	1	1	2	0	0	0	.0	.0	.0	.0	.0
Aluminum (µg/L)	3	910	180	1,780	20	0	100	7.4	11.0	.0	11.1	6.4
Barium (µg/L)	3	80	70	100	0	–90	40	–14.7	.0	–103.0	58.8	81.9
Cadmium (ug/L)	3	5	5	5	0	0	0	.0	.0	.0	.0	.0
Chromium (µg/L)	3	5	5	5	0	0	0	.0	.0	.0	.0	.0
Copper (µg/L)	3	5	5	10	0	0	0	.0	.0	.0	.0	.0
Iron (µg/L)	3	1,130	340	1,340	10	0	300	8.5	3.0	.0	22.5	12.2
Lead (µg/L)	3	5	5	5	0	0	0	.0	.0	.0	.0	.0
Nickel (µg/L)	3	5	5	7.5	0	–5	0	–23.1	.0	–69.3	.0	40.0
Zinc (µg/L)	3	10	5	10	0	0	0	.0	.0	.0	.0	.0

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[1] Split samples are a pair of theoretically identical samples. One split was processed immediately, whereas the other was held 48 hours at 4°C before processing to investigate the effect of holding time on chemical analysis.

[2] Concentrations less than the detection limit were assigned one-half the detection limit for this analysis. Detection limits are given in the last row of table 1.

[3] Statistics were rounded to the same number of significant figures as analytical measurements of the same magnitude.

[4] Concentration differences were calculated as the immediately processed sample minus the held sample. Positive differences indicate higher concentrations in the immediately processed sample, whereas negative differences indicate higher concentrations in the held sample.

[5] Log difference is the difference between a pair of split samples divided by the logarithmic mean of that pair of split samples multiplied by 100 percent (Tornqvist and others, 1985, p.44–45). It is used in this context to summarize the relative changes attributed to holding samples prior to processing. Positive log difference indicates higher concentrations in the immediately processed sample, whereas negative log difference indicates higher concentrations in the held sample.

[6] Suspended solids were calculated as the difference between total solids and dissolved solids.

HYDROLOGIC CONDITIONS

Differences in the amounts of precipitation and streamflow can profoundly influence water quality. Knowledge of the hydrologic conditions during which water-quality samples were collected is critical for interpreting water-quality data and is needed to place interpretations and conclusions in a historical context. Precipitation and streamflow were far below normal during the study—unusually extreme conditions for the summer low-flow period.

Precipitation

Normal annual precipitation at the Indianapolis International Airport climatological station is 39.12 in., one-third of which falls during July through October (National Oceanic and Atmospheric Administration, 1986, p. 3). Normal monthly precipitation is 4.32 in. for July, 3.46 in. for August, 2.74 in. for September, and 2.51 in. for October. Precipitation at the Indianapolis International Airport climatological station (station 1, table 4 and fig. 2) was substantially below normal during the study period (July 22–October 19, 1987). Monthly precipitation for July was 213 percent of normal; for August, 25 percent of normal; for September, 51 percent of normal; and for October, 54 percent of normal. Although July was much wetter than normal, more than 82 percent of the precipitation fell in the first half of the month, before the study period (table 4a).

Monthly precipitation measured by observers in the Indianapolis area generally was in agreement with that measured at the Indianapolis International Airport by the National Weather Service and shows the small amount of rain that fell in and near Indianapolis during the study period (tables 4a–4d and fig. 2). Daily precipitation was highly variable among stations on some dates (for example, July 26–31, table 4a). Spatially variable, high-intensity precipitation is characteristic of summer thunderstorms that cause localized heavy rain.

Seven storms produced runoff in the Indianapolis area during the study period. Water-quality samples were collected during runoff from six of these storms. The six sampled storms and periods of storm runoff were July 26–28 (storm 1), July 29–August 3 (storm 2), August 26–27 (storm 3), September 10–13 (storm 4), September 16–17 (storm 5), and September 29–30 (storm 6). The unsampled storm on August 17 (table 4b) was similar in volume of precipitation to storms 5 and 6. All of the storms except storm 4 were characterized as moderate-intensity, short-duration storms. Storm 4 was a low-intensity, long-duration storm. Storms 1 and 2 included multiple periods of intense precipitation, whereas storms 3, 5, and 6 included only one period of intense precipitation. Precipitation for each of the storms, based on all precipitation stations in and near the watershed is as follows:

	Precipitation, in inches		
Storm	Minimum	Median	Maximum
1	0.28	0.83	1.41
2	.04	.66	1.59
3	.07	.25	.61
4	.09	.20	.67
5	.10	.36	.55
6	.36	.45	.50

Although the median amount of precipitation for some of the storms was small, all storms caused at least some of the combined sewers to overflow.

Streamflow

Historic streamflow information has been summarized for the Emerson Avenue gaging station for the 42-year period 1944–85 (Arvin, 1989, p. 470-476). Streamflow during this period was regulated by Geist Reservoir. Compared with historic streamflow, monthly mean streamflow during July and August (1987) was near or above normal, whereas streamflow during September and October (1987) was well below normal. Monthly mean streamflow for October 1987 (42 ft^3/s, table 5) was the second lowest of record. Only the monthly mean for October 1944 (38 ft^3/s) was lower. Most of the high streamflow in July occurred before the beginning of the study period.

Table 4a. Daily precipitation at selected stations in and near Indianapolis, July 1987

[T, trace; --, no data]

Day	Daily precipitation[1], in inches, at given precipitation station[2]											
	1	2	3	4	5	6	7	8	9	10	11	12
1	5.09	0.00	0.57	0.91	0.92	1.29	0.80	0.84	--	0.79	--	1.52
2	.01	.84	2.17	2.02	1.76	2.50	1.98	1.33	--	1.11	--	4.16
3	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
4	.02	.00	.04	.08	.08	.11	.00	.43	--	.17	--	.00
5	.01	.00	.00	.00	T	T	.10	.00	--	T	--	.00
6	.97	.40	.47	.51	.48	.51	.38	.43	--	.48	--	.00
7	.00	.15	.20	.28	.13	.15	.34	.11	--	.23	--	.23
8	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
9	.04	.00	.00	.00	.00	.29	.00	.00	--	.00	--	.00
10	.00	.22	T	.00	.33	.00	.01	.22	--	T	--	.03
11	.01	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
12	.82	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
13	.50	.21	.93	1.07	.55	1.06	.62	.81	--	.83	--	.98
14	.00	.80	.94	.53	.69	.69	.51	1.16	--	.71	--	.64
15	.10	.00	.00	T	.00	.00	.00	.00	--	.00	--	.00
16	.00	.38	.11	.09	.06	.06	.06	.26	--	.10	--	.05
17	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
18	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
19	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
20	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
21	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
22	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
23	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	--	.00
24	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	--	.00
25	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	--	.00
26	.62	.00	.00	.00	T	.00	.00	.00	.00	.00	--	.00
27	.58	.36	1.24	.18	.02	.05	.48	.52	.10	.34	.20	.56
28	T	.10	.17	.84	.26	.57	.00	.19	.54	.75	1.10	.38
29	.36	.00	.00	.00	.38	.00	.00	.00	.00	.00	.00	.00
30	.04	.32	.87	.23	.00	.25	1.02	1.05	.32	.30	.00	.66
31	.05	.11	.12	.06	T	.03	.49	.00	.77	.00	.25	.26
Total	9.22	3.89	7.83	6.80	5.66	7.56	6.79	7.35	--	5.81	--	9.47

[1] Daily precipitation was measured in the morning between 0600 and 0900 hours, except at station 1 which was measured at midnight (2400 hours).

[2] Locations of precipitation stations are shown in figure 2.

Table 4b. Daily precipitation at selected stations in and near Indianapolis, August 1987

[T, trace; --, no data]

	Daily precipitation[1], in inches, at given precipitation station[2]											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.05
2	T	.26	.11	.15	.00	.00	.00	.16	.00	.10	.00	.00
3	T	.00	.00	.00	.04	.19	.08	.00	.06	.22	.20	.02
4	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
5	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
6	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
7	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
8	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
9	.07	.20	.06	.05	.13	.15	.04	.21	.07	T	.05	.04
10	.00	T	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
11	.00	.00	.00	T	.00	.00	.00	.00	.00	.00	.00	.00
12	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
13	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
14	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
15	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
16	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
17	.32	.13	.17	.57	.28	.46	.22	.28	.15	.38	--	.08
18	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
19	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
20	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
21	.03	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
22	.00	.08	.04	.05	.00	.07	.05	.07	.03	T	.00	T
23	.00	.05	.00	.00	.00	.00	.00	.00	.10	.00	.00	T
24	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
25	.11	.00	.00	.01	T	T	.00	.00	.01	.00	T	.00
26	.24	.94	.52	.16	.15	.16	.15	.73	.08	.19	.20	.15
27	.04	.61	.26	.19	.07	.09	.24	--	.24	.29	.10	.30
28	.03	.18	.06	.07	.03	.03	.05	--	.02	.10	T	.08
29	.00	.00	.00	.00	.00	.00	.00	--	.00	.00	.00	.00
30	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
31	.01	.03	.00	.00	.01	.04	T	.00	.01	T	T	T
Total	.86	2.48	1.22	1.26	.71	1.19	.83	--	.79	1.28	--	.72

[1] Daily precipitation was measured in the morning between 0600 and 0900 hours, except at station 1 which was measured at midnight (2400 hours).

[2] Locations of precipitation stations are shown in figure 2.

Table 4c. Daily precipitation at selected stations in and near Indianapolis, September 1987

[T, trace; --, no data]

	Daily precipitation[1], in inches, at given precipitation station[2]											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0.00	0.00	0.00	0.00	T	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	.00	.00	.00	.00	0.00	.00	.00	.00	--	.00	.00	.00
3	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00	.00
4	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00	.00
5	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00	.00
6	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00	.00
7	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00	.00
8	.00	.00	.00	.03	.00	.00	.00	.00	--	T	.00	.00
9	.00	T	T	.00	.00	T	.00	.00	--	.00	.00	T
10	.00	.00	.00	.00	T	.00	.00	.00	--	.00	.00	.00
11	.04	.12	.16	.18	.64	.15	.16	.23	--	.18	.08	.07
12	.20	.04	.01	.02	.01	.06	.03	.06	--	--	.01	.05
13	.00	.15	.00	.00	.02	.02	.00	.00	--	--	.00	.00
14	.00	.00	.00	.00	.00	.00	.00	.00	--	--	.00	.00
15	.34	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00
16	.06	.04	.05	.10	.19	.00	.08	.18	.10	--	.10	.24
17	.28	.40	.15	.55	.40	.45	.40	.31	--	--	.10	.22
18	.00	.03	.02	.01	.02	.05	.02	.06	--	--	.00	.00
19	.00	.00	.00	.01	T	.00	.00	.00	--	--	.00	.00
20	.00	.00	.00	.00	.00	.00	.00	.00	--	--	.00	.00
21	.00	.00	.00	T	.00	.00	.00	.00	--	--	.00	.00
22	.02	.05	T	.03	.01	.01	.01	.00	--	--	.00	.00
23	.00	.00	.11	.01	.00	.00	.00	.00	--	--	.00	.00
24	.00	.00	.00	.00	.00	.00	.00	.00	--	--	.00	.00
25	.00	.00	.00	.00	.00	.00	.00	.00	--	--	.00	.00
26	.00	.00	.00	.00	.00	.00	.00	.00	--	--	.00	.00
27	.00	.00	.00	.00	.00	.00	.00	.00	--	--	.00	.00
28	.00	.00	.00	.00	.00	.00	.00	.00	--	--	.00	.00
29	.47	.49	.20	.44	.49	.37	.02	.40	--	--	.50	.39
30	.00	.00	.16	.00	.00	.08	.40	.00	--	--	.00	T
Total	1.41	1.32	.86	1.38	1.78	1.19	1.12	1.24	--	--	.79	.97

[1] Daily precipitation was measured in the morning between 0600 and 0900 hours, except at station 1 which was measured at midnight (2400 hours).

[2] Locations of precipitation stations are shown in figure 2.

Table 4d. Daily precipitation at selected stations in and near Indianapolis, October 1987

[T, trace; --, no data]

	Daily precipitation[1], in inches, at given precipitation station[2]											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0.00	0.03	0.00	T	0.00	T	0.00	0.00	0.00	--	0.00	0.00
2	.00	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00
3	.00	.00	.00	.00	.01	.00	.00	.00	.00	--	.00	T
4	.00	.00	.00	.00	.00	.00	.00	.00	.00	--	.00	.00
5	.03	.00	.00	T	.00	.00	.00	.08	.00	--	.10	.00
6	.02	.03	.09	.08	.09	.08	.12	.00	.03	--	.10	T
7	.00	.09	.08	.08	.05	.07	.12	.00	.02	--	.07	T
8	.00	.00	.00	.01	T	T	--	.00	.00	--	.00	.00
9	.01	.18	.05	.04	.03	.02	--	.00	.00	--	.03	.01
10	.33	.00	T	.10	.11	.00	--	.00	.29	--	.03	T
11	.00	.30	.44	.26	.27	.00	--	.42	--	--	.30	.32
12	.00	.00	T	.00	.00	.00	--	.00	--	--	.00	.00
13	.00	.00	.00	.00	.00	.00	--	.00	--	--	.00	.00
14	.00	.00	.00	.00	.00	.00	--	.00	--	--	.00	.00
15	.00	.00	.00	.00	.00	.00	--	.00	--	--	.00	.00
16	.00	.00	.00	.00	.00	.00	--	.00	--	--	.00	.00
17	.02	.10	.08	.08	.08	.10	--	.09	--	--	.20	.06
18	.00	.00	.00	T	.00	.00	--	.00	--	--	--	.00
19	.00	.00	.00	.00	.00	.00	--	.00	--	--	--	.00
20	.03	.03	.05	.05	.05	.00	--	.00	--	--	--	.00
21	.00	.05	.01	.01	.00	.00	--	.00	--	--	--	.02
22	.01	.00	.00	T	.02	.00	--	.00	--	--	--	.00
23	.00	.00	.03	.02	.03	.00	--	.00	--	--	--	.00
24	.19	.02	.04	.01	.15	.38	--	.32	--	--	--	.03
25	.00	.34	.23	.23	.13	.00	--	.00	--	--	--	.17
26	.53	.00	.00	.00	.01	.00	--	.00	--	--	--	.00
27	.19	.85	.95	.84	.70	.74	--	.80	--	--	--	.84
28	.00	.00	.00	T	.00	.00	--	.00	--	--	--	.00
29	.00	.00	.00	.00	.00	.00	--	.00	--	--	--	.00
30	.00	.00	.00	.00	.00	.00	--	.00	--	--	--	.00
31	.00	.00	.00	.00	.00	.00	--	.00	--	--	--	T
Total	1.36	2.02	2.05	1.81	1.73	1.39	--	1.71	--	--	--	1.45

[1] Daily precipitation was measured in the morning between 0600 and 090 hours, except at station 1 which was measured at midnight (2400 hours).

[2] Locations of precipitation stations are shown in figure 2.

Table 5. Daily mean streamflow at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, July through October 1987

	Daily mean streamflow (cubic feet per second)					
	July			August		
Day	Emerson Avenue	Central Avenue	16th Street	Emerson Avenue	Central Avenue	16th Street
1	475	904	815	167	137	178
2	1,180	910	1,070	168	133	161
3	1,340	1,060	1,310	164	131	163
4	861	655	916	217	158	195
5	521	413	535	201	158	205
6	381	310	396	142	115	141
7	327	255	315	106	78	102
8	248	193	241	86	60	87
9	184	148	177	74	52	83
10	146	121	127	74	41	66
11	126	102	100	70	36	66
12	108	114	113	59	26	57
13	336	269	491	56	20	42
14	800	565	625	73	34	60
15	649	487	607	59	21	48
16	410	322	404	61	23	45
17	269	210	277	63	36	61
18	194	153	213	60	22	45
19	151	123	176	62	21	47
20	121	93	130	61	22	42
21	101	74	110	60	23	47
22	88	55	98	60	25	44
23	79	48	96	60	27	40
24	70	38	93	60	22	36
25	66	36	91	60	24	37
26	65	40	97	63	37	44
27	117	118	175	64	31	59
28	109	84	114	56	25	48
29	81	54	84	57	20	33
30	308	241	241	62	26	39
31	257	212	224	56	20	40
Mean	328	271	337	86	52	76
Median	194	153	213	62	27	48
Minimum	65	36	84	56	20	33
Maximum	1,340	1,060	1,310	217	158	205

Table 5. Daily mean streamflow at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, July through October 1987—Continued

Day	Daily mean streamflow (cubic feet per second)					
	September			October		
	Emerson Avenue	Central Avenue	16th Street	Emerson Avenue	Central Avenue	16th Street
1	64	24	43	40	22	51
2	57	16	23	38	16	29
3	59	18	19	39	14	26
4	62	18	26	39	14	25
5	71	28	39	39	14	24
6	70	27	36	39	16	27
7	70	27	41	40	15	43
8	69	24	28	40	14	32
9	67	27	35	40	14	31
10	59	17	29	41	15	35
11	73	31	46	43	20	36
12	71	34	54	40	16	33
13	69	32	52	40	15	32
14	69	27	40	40	15	35
15	67	27	50	40	14	31
16	58	25	59	41	15	29
17	57	36	57	42	19	35
18	55	22	39	41	22	48
19	48	19	32	41	19	42
20	46	14	24	42	18	51
21	49	16	26	43	16	33
22	53	17	26	43	13	30
23	53	17	33	44	18	30
24	52	17	30	45	22	33
25	52	17	24	46	23	37
26	51	15	35	45	20	34
27	50	15	27	66	69	97
28	50	16	25	46	29	53
29	55	30	54	40	21	51
30	52	22	46	38	18	52
31				38	18	59
Mean	59	23	37	42	19	39
Median	58	22	35	40	16	34
Minimum	46	14	19	38	13	24
Maximum	73	36	59	66	69	97

The highest daily mean streamflow measured at Emerson Avenue during the study period was 308 ft^3/s on July 30 (table 5). Daily mean streamflow of this magnitude is exceeded approximately 26 percent of the time (Arvin, 1989, p. 473). The lowest daily mean streamflow measured at Emerson Avenue during the study period was 38 ft^3/s on October 2. Daily mean streamflow of this magnitude is exceeded approximately 99 percent of the time. Most of the daily mean streamflows measured during the study period were less than 71 ft^3/s, a rate exceeded approximately 75 percent of the time. Daily mean streamflow at Emerson Avenue was at or less than the 7-day, 10-year low flow—39 ft^3/s (Stewart, 1983, p. 121)—for 7 days in October 1987 (table 5).

Base Flow

During base flow, streamflow at Emerson Avenue was greater than that downstream at Central Avenue or 16th Street (fig. 5, table 5) and showed the effect of water withdrawn for public supply at Keystone Avenue (fig. 3). The median streamflow measured at Emerson Avenue during October was 40 ft^3/s (table 5), and the median rate of water withdrawn for public-water supply downstream at Keystone Avenue during October was 35 ft^3/s (table 6). Other surface-water inflows were assumed to be negligible during this month of extreme low flows; therefore, the median streamflow downstream from Keystone Avenue at Central Avenue during October was expected to be 5 ft^3/s (40 ft^3/s – 35 ft^3/s, table 5). The measured median streamflow at Central Avenue during October was 16 ft^3/s. The difference between the expected and measured rates indicates that 69 percent (11 ft^3/s) of the base-flow streamflow at Central Avenue during October was contributed by ground-water seepage in the reach between Emerson Avenue and Central Avenue. Most of the ground-water inflow likely occurred between Keystone Avenue and Central Avenue, where the stream is deeply incised in the flood plain. The median rate of backwash effluent discharged to Fall Creek immediately downstream from Keystone Avenue during October was 0.17 ft^3/s (table 6) and constituted only a minor part (1 percent) of the streamflow measured at Central Avenue during October.

The median rate of streamflow measured at 16th Street during October was 34 ft^3/s (table 5). The increase in the median rate of streamflow during October from Central Avenue to 16th Street was 18 ft^3/s (34 ft^3/s – 16 ft^3/s, table 5), and can be attributed to three sources: aqueduct overflow, ground-water inflow, and backwash effluent. Most of the increase can be attributed to overflow from the aqueduct approximately 0.5 mi upstream from 16th Street (fig. 3).

The amount of water that overflowed the aqueduct into Fall Creek varied during the study but was not continuously measured. The rate of overflow did not appear to increase during storm runoff, but it did increase with increased rates of flow in the canal needed to meet greater demand for public supply. The rate of overflow estimated on August 18 was 22 ft^3/s (table 5). The rate of aqueduct overflow measured on August 19 at the spillway was 24 ft^3/s. The water-supply utility installed boards in the spillway of the aqueduct on or about August 23 to reduce the amount of aqueduct overflow. The rate of aqueduct overflow measured on September 23 as the difference of canal-flow measurements made upstream and downstream from the aqueduct was 16 ft^3/s. The rate of overflow estimated on October 15 was 7 ft^3/s. The rate of overflow measured on July 21, 1977, was 25 ft^3/s (Meyer, 1979, p. 10).

On the basis of the limited information collected during the study period, the median rate of overflow before August 23 was estimated to be 23 ft^3/s, and the median rate of overflow on and after August 23 was estimated to be 12 ft^3/s. On the basis of these estimates, aqueduct overflow constituted approximately 35 percent of the streamflow measured at 16th Street during October.

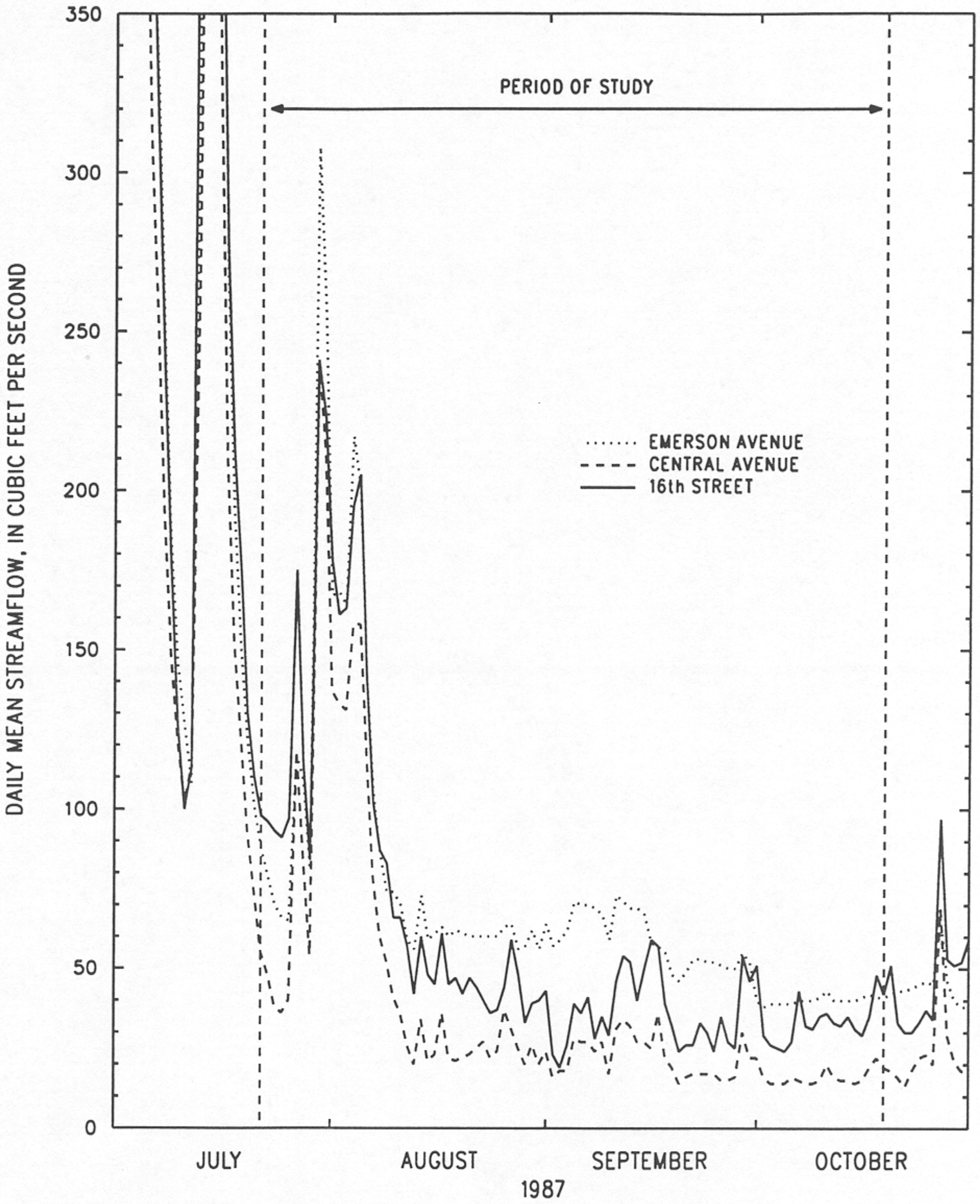

Figure 5. Daily mean streamflow at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, July through October 1987. (Daily mean streamflows greater than 350 cubic feet per second are not shown.)

Table 6. Daily mean water withdrawal from Fall Creek at Keystone Avenue and daily mean discharge of filter backwash to Fall Creek at Keystone Avenue and at 16th Street, July through October 1987

[Data from Tim Bumgardner, Indianapolis Water Company, written commun., September 1988]

	Daily mean rate of water withdrawal or discharge of filter backwash[1] (cubic feet per second)					
	July			August		
	Water withdrawal at Keystone Avenue	Filter backwash at		Water withdrawal at Keystone Avenue	Filter backwash at	
Day		Keystone Avenue	16th Street		Keystone Avenue	16th Street
1	52	0.23	0.11	54	0.60	1.02
2	55	.32	.22	55	.40	.60
3	53	.39	.25	60	.51	2.12
4	47	.23	.79	60	.59	.88
5	41	.05	2.94	56	.59	.26
6	50	.06	.28	56	.46	.85
7	52	.19	.34	61	.43	1.78
8	57	.36	.71	53	.50	1.19
9	53	.19	.48	48	.23	.00
10	51	.28	1.72	58	.48	.85
11	56	.28	1.02	60	.39	.90
12	56	.25	1.24	61	.79	1.07
13	56	.23	.54	65	.73	1.13
14	56	.39	.11	63	.57	.82
15	50	.31	.26	68	.50	1.02
16	50	.36	.00	66	.63	1.04
17	52	.22	.53	61	.56	1.25
18	54	.45	1.73	60	.65	1.33
19	51	.36	1.19	65	.42	.68
20	58	.48	1.14	65	.70	2.10
21	61	.43	.15	57	.39	1.07
22	63	.50	.56	59	.59	1.32
23	62	.48	1.83	57	.37	1.78
24	65	.45	1.10	57	.57	1.55
25	60	.56	.46	52	.45	.36
26	58	.32	.80	52	.26	.00
27	57	.29	.91	53	.40	.88
28	58	.26	2.86	50	.34	.19
29	59	.26	1.24	52	.28	.93
30	55	.26	.03	50	.31	1.44
31	58	.25	.96	56	.45	.62
Mean	55	.31	.86	58	.49	1.00
Median	56	.29	.71	57	.48	1.02
Minimum	41	.05	.00	48	.23	.00
Maximum	65	.56	2.94	68	.79	2.12

Table 6. Daily mean water withdrawal from Fall Creek at Keystone Avenue and daily mean discharge of filter backwash to Fall Creek at Keystone Avenue and at 16th Street, July through October 1987—Continued

Day	Daily mean rate of water withdrawal or discharge of filter backwash[1] (cubic feet per second)					
	September			October		
	Water withdrawal at Keystone Avenue	Filter backwash at Keystone Avenue	Filter backwash at 16th Street	Water withdrawal at Keystone Avenue	Filter backwash at Keystone Avenue	Filter backwash at 16th Street
1	61	0.84	0.00	36	0.11	0.93
2	57	.06	.67	36	.06	.02
3	65	.76	.53	36	.23	.34
4	65	.43	1.64	34	.14	.54
5	64	.87	.85	35	.11	.42
6	58	.36	.82	36	.43	.34
7	60	.40	.09	32	.14	.51
8	61	.26	.00	33	.03	1.18
9	62	.23	.65	34	.17	.50
10	68	.39	3.48	35	.11	.60
11	58	.26	.34	32	.08	.29
12	55	.23	.19	33	.20	.48
13	55	.28	1.32	35	.08	.71
14	60	.12	1.67	36	.11	.80
15	57	.34	1.73	36	.17	.79
16	47	.11	1.28	37	.15	.00
17	47	.23	.60	35	.29	.80
18	47	.08	.50	34	.19	.00
19	48	.23	.60	36	.22	.85
20	47	.15	.09	37	.12	3.42
21	48	.34	1.75	36	.36	.80
22	51	.34	.08	36	.14	.00
23	50	.14	1.02	36	.28	.00
24	49	.15	.28	34	.29	.43
25	50	.28	.26	33	.17	.00
26	51	.26	.29	34	.53	.31
27	55	.28	.50	34	.29	3.06
28	55	.25	1.01	34	.32	.77
29	50	.22	.63	33	.12	.00
30	42	.19	1.39	34	.29	1.13
31				33	.34	2.82
Mean	55	.30	.81	35	.20	.74
Median	55	.26	.62	35	.17	.51
Minimum	42	.06	.00	32	.03	.00
Maximum	68	.87	3.48	37	.53	3.42

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[1] Water withdrawn from Fall Creek approximately 100 ft downstream from Keystone Avenue. Filter backwash discharged to Fall Creek approximately 500 ft downstream from Keystone Avenue and approximately 300 ft upstream from 16th Street.

The median discharge rate of filter backwash effluent to Fall Creek immediately upstream from 16th Street during October was 0.51 ft^3/s (table 6). This relatively minor source combined with the aqueduct overflow (total approximately 12.5 ft^3/s) leaves the balance of the increased streamflow from Central Avenue to 16th Street during October—approximately 5.5 ft^3/s—as ground-water inflow (18 ft^3/s – 12.5 ft^3/s).

The median rate of ground-water inflow into Fall Creek from Emerson Avenue to 16th Street during October was approximately 16.5 ft^3/s (the sum of ground-water inflow from both reaches, 11 ft^3/s + 5.5 ft^3/s) which constituted about 48.5 percent of the median rate of streamflow measured at 16th Street during October. The sum of the components of streamflow at 16th Street (35 percent aqueduct overflow, 48.5 percent ground-water seepage, 1.5 percent backwash effluent discharged upstream from 16th Street, and 0.5 percent backwash effluent discharged upstream from Central Avenue) shows that only about 14.5 percent of the streamflow measured at 16th Street during October was streamflow that originated in Fall Creek upstream from Emerson Avenue.

Storm Runoff

Hydrographs for storms 1 through 6 are shown in figures 6–11. Storm runoff for storms 3, 5, and 6 exhibited single, well-defined peaks at Central Avenue (figs. 8, 10, 11). Streamflow at Central Avenue increased rapidly in response to precipitation and decreased rapidly after precipitation had ceased. This pattern of runoff is typical for urban streams. Urbanization reduces infiltration of precipitation, and surface runoff rapidly is conveyed to streams. Because infiltration is reduced, subsurface flow is reduced and streamflow quickly returns to base flow. Streamflow at 16th Street increased and decreased less rapidly than streamflow at Central Avenue in response to precipitation from small storms (storms 3, 5, and 6). Although land upstream from 16th Street is urbanized, the increased times from rise to peak and from peak to base flow probably is caused by storage in the channel between Central Avenue and 16th Street. A low-head dam in this reach impedes storm runoff at low streamflows and slowly releases it as the impoundment fills. Streamflow increased little or not at all in response to precipitation at Emerson Avenue, which indicates that storm runoff occurred primarily in the downstream, urbanized part of the watershed (figs. 8, 10, 11).

Runoff during storms 1 and 2 occurred as multiple, well-defined peaks at Central Avenue and 16th Street and at Emerson Avenue during storm 2 (figs. 6, 7). Streamflow increased little in response to precipitation at Emerson Avenue during storm 1, which indicates that storm runoff occurred primarily in the downstream, urbanized part of the watershed. Streamflow increased markedly in response to precipitation at Emerson Avenue during storm 2, which indicates that much of the storm runoff occurred in the upstream, rural part of the watershed. Streamflow increased rapidly at Central Avenue and 16th Street at approximately 0900 on July 30 in response to precipitation, and the initial peaks at these stations preceded the peak at Emerson Avenue. This pattern of initial peak streamflows indicates that storm runoff also occurred in the downstream, urbanized part of the watershed and that initial peak streamflows at Central Avenue and 16th Street at approximately 1000 on July 30 were caused by urban runoff and combined-sewer overflows and not the downstream movement of water that ran off upstream from Emerson Avenue (fig. 7). Subsequent peak streamflows at Central Avenue and 16th Street at approximately midnight on July 30 were caused by the downstream movement of water measured at Emerson Avenue at approximately 2100 on July 30 and not by runoff from the urbanized part of the watershed.

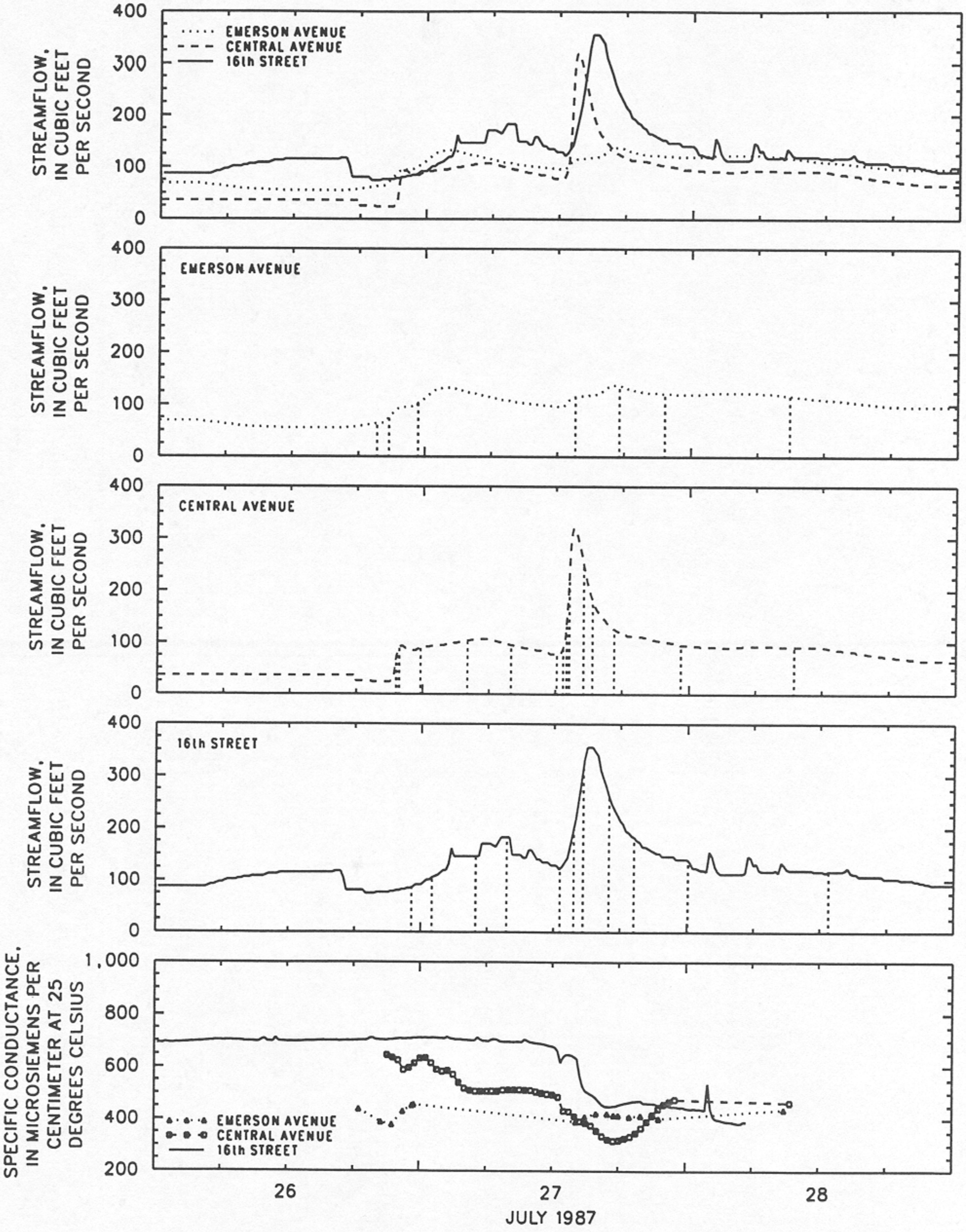

Figure 6. Streamflow and water quality in Fall Creek during storm 1, July 26–28, 1987. (Vertical dashed lines show times when water samples were collected.)

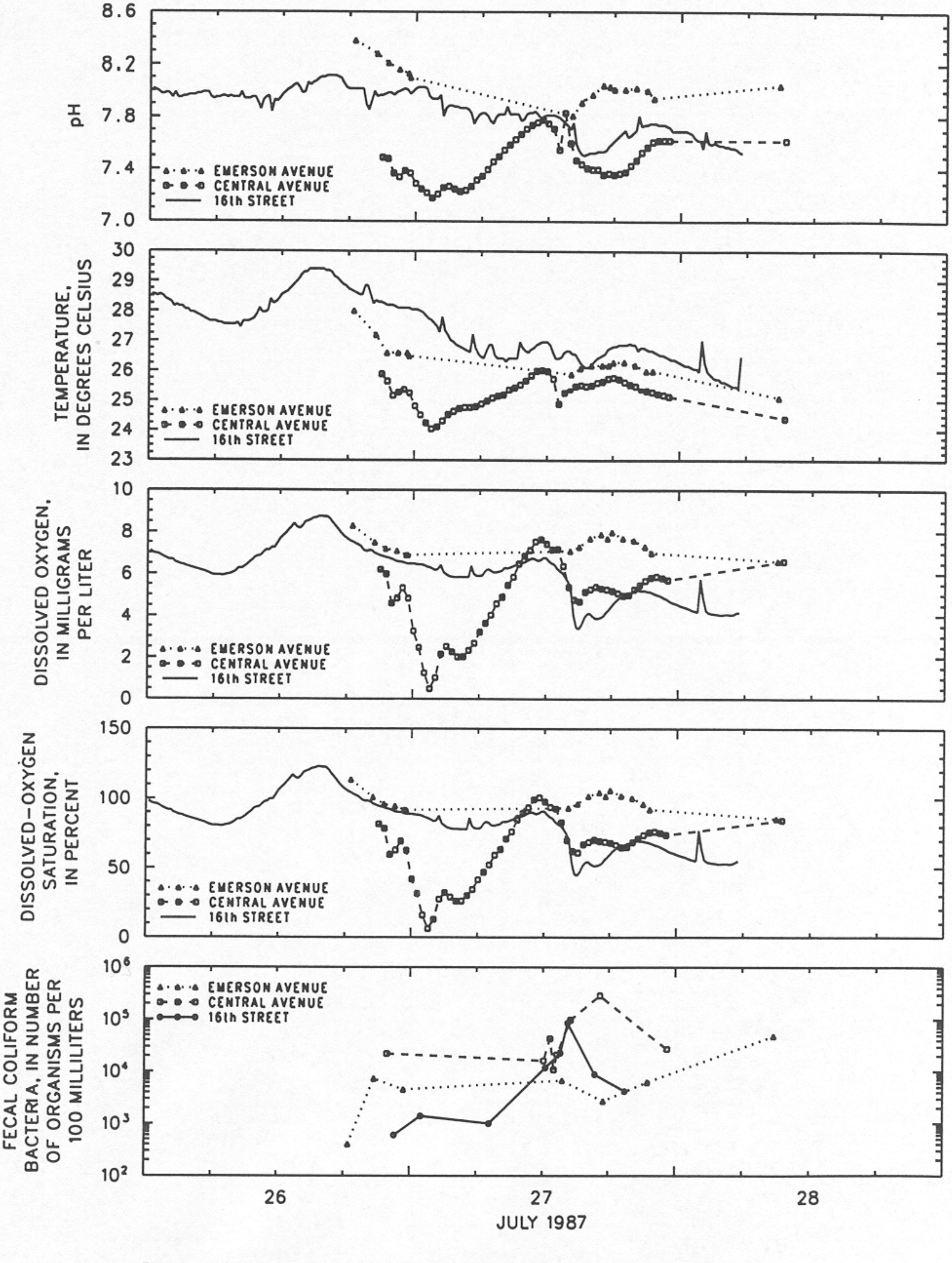

Figure 6. Streamflow and water quality in Fall Creek during storm 1, July 26–28, 1987. -- Continued.

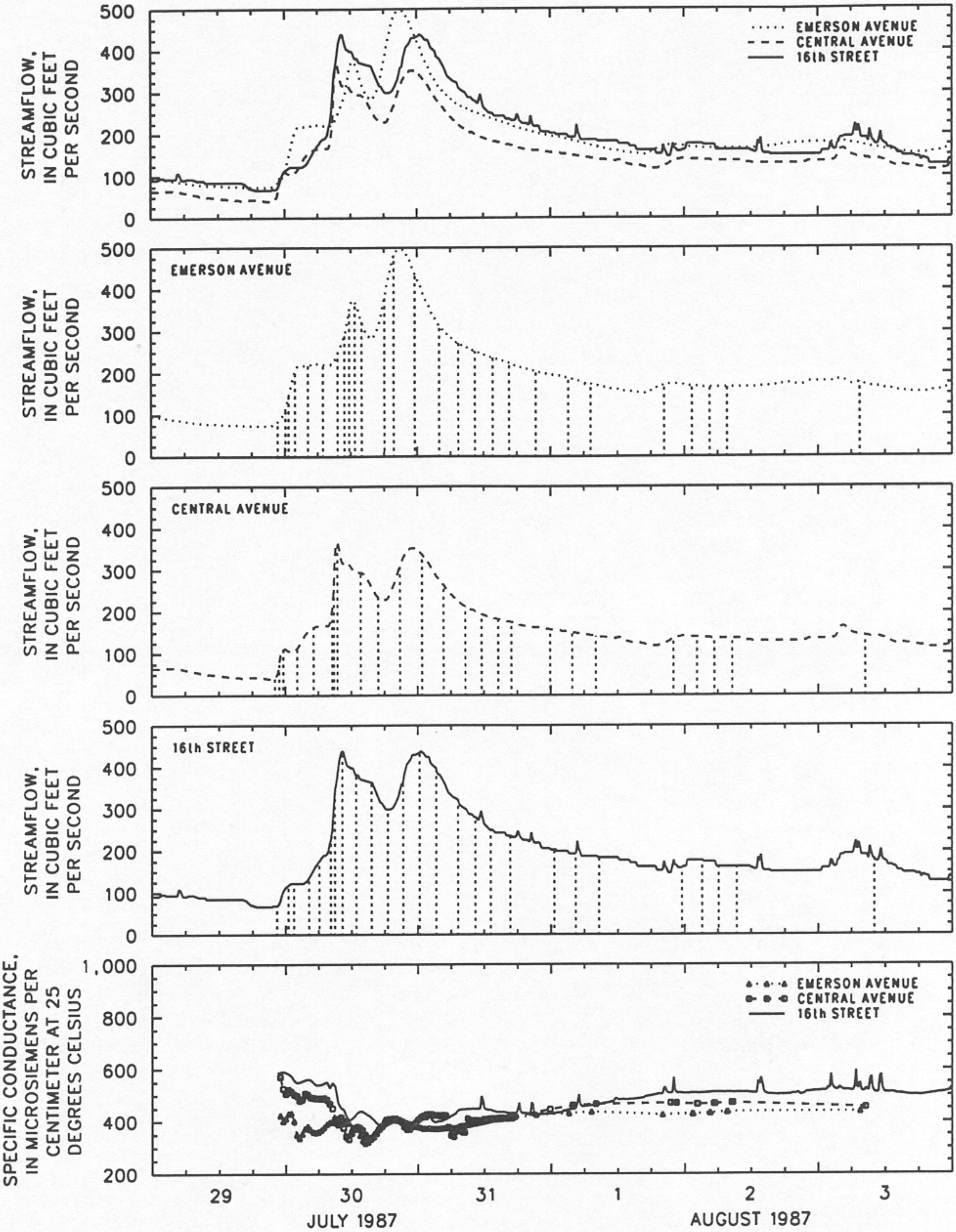

Figure 7. Streamflow and water quality in Fall Creek during storm 2, July 29–August 3, 1987. (Vertical dashed lines show times when water samples were collected.)

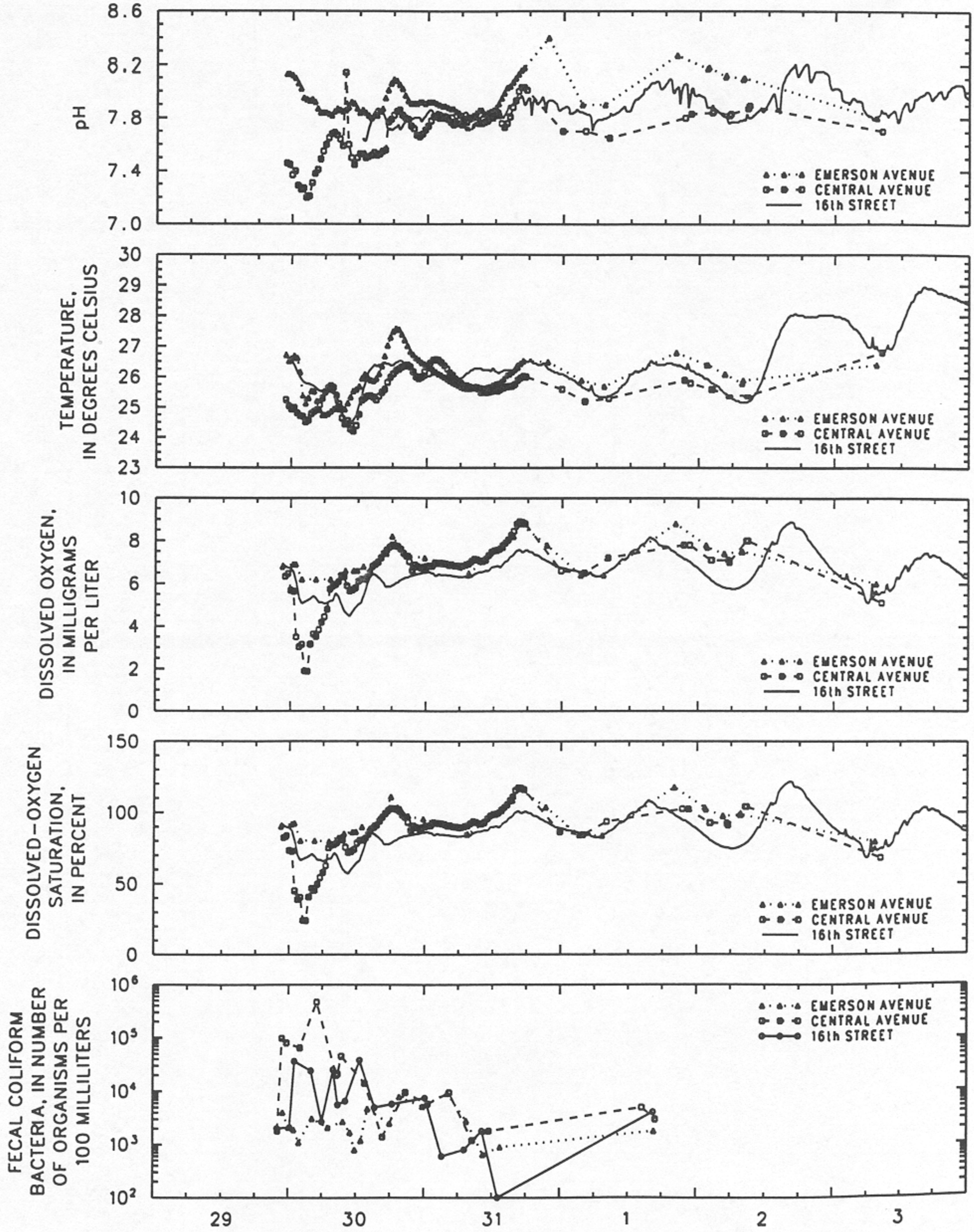

Figure 7. Streamflow and water quality in Fall Creek during storm 2, July 29–August 3, 1987. -- Continued.

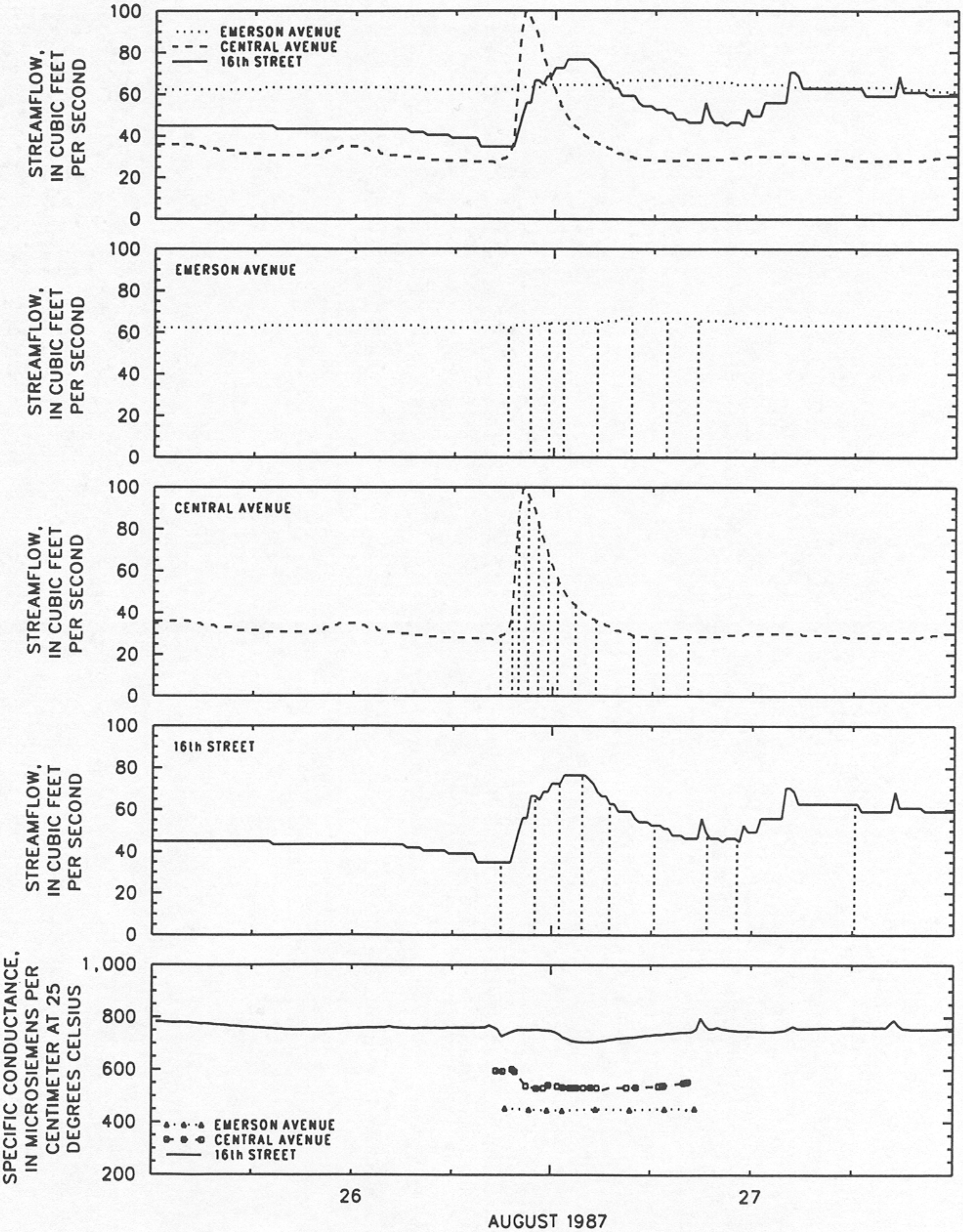

Figure 8. Streamflow and water quality in Fall Creek during storm 3, August 26–27, 1987. (Vertical dashed lines show times when water samples were collected.)

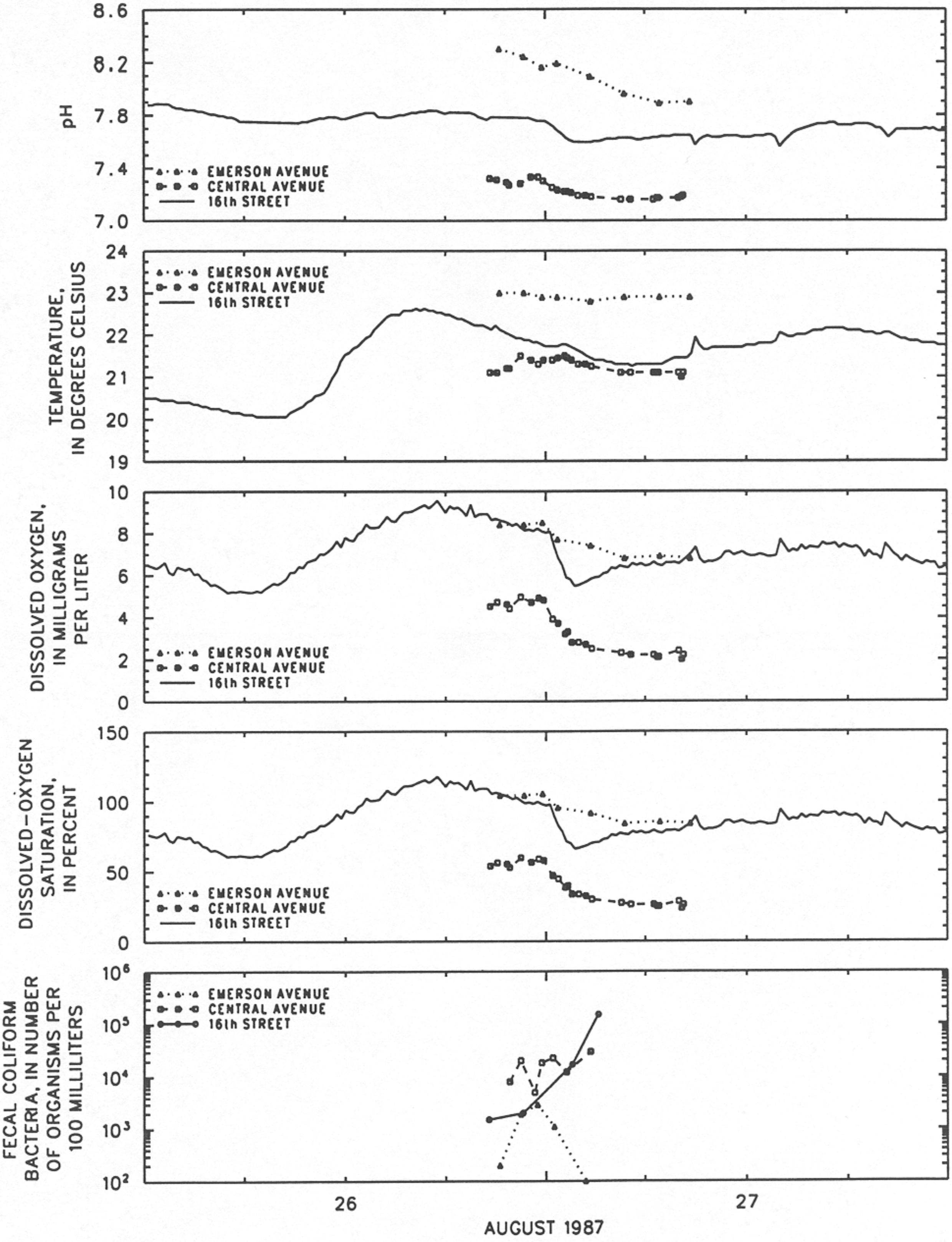

Figure 8. Streamflow and water quality in Fall Creek during storm 3, August 26-27, 1987. -- Continued.

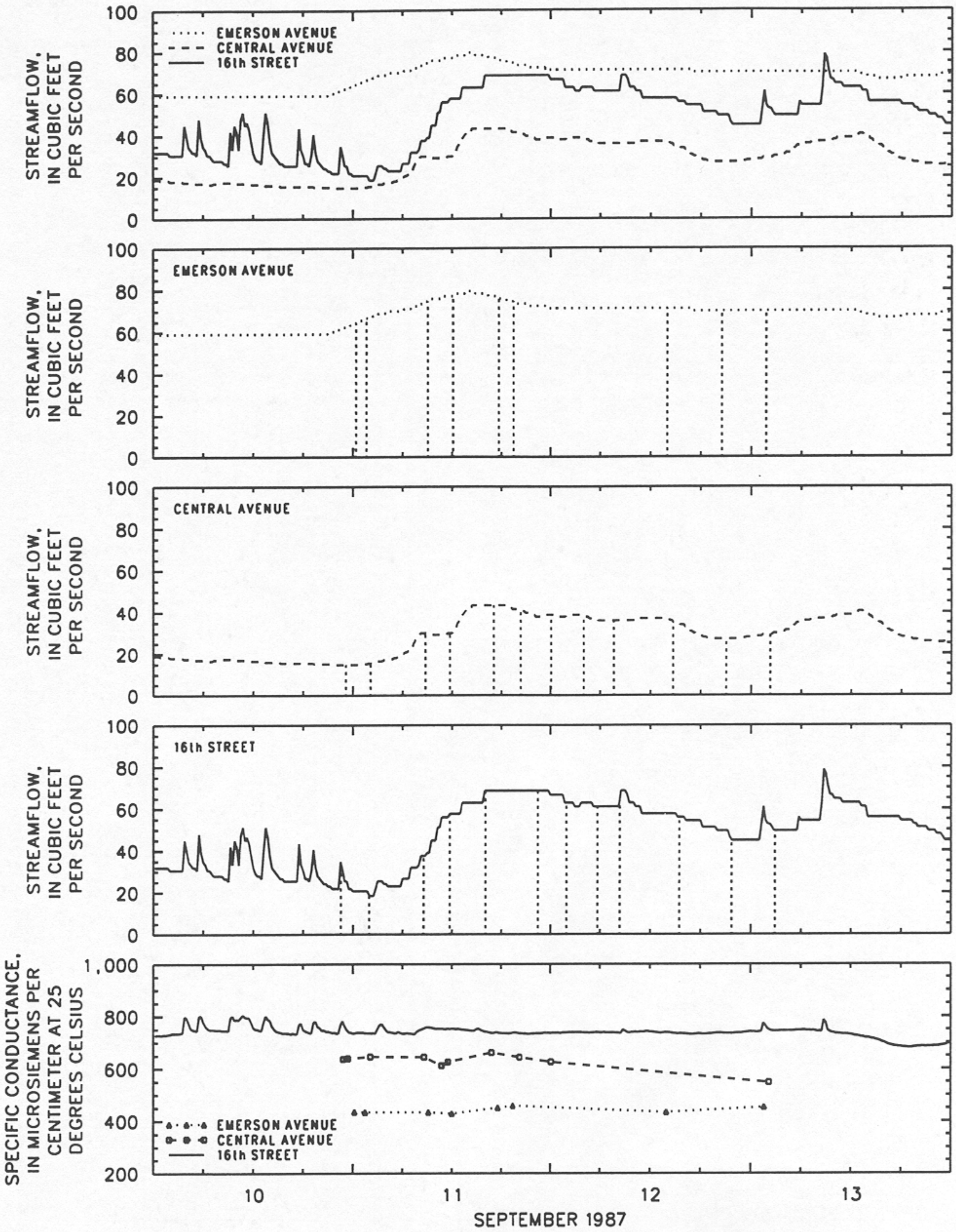

Figure 9. Streamflow and water quality in Fall Creek during storm 4, September 10–13, 1987. (Vertical dashed lines show times when water samples were collected.)

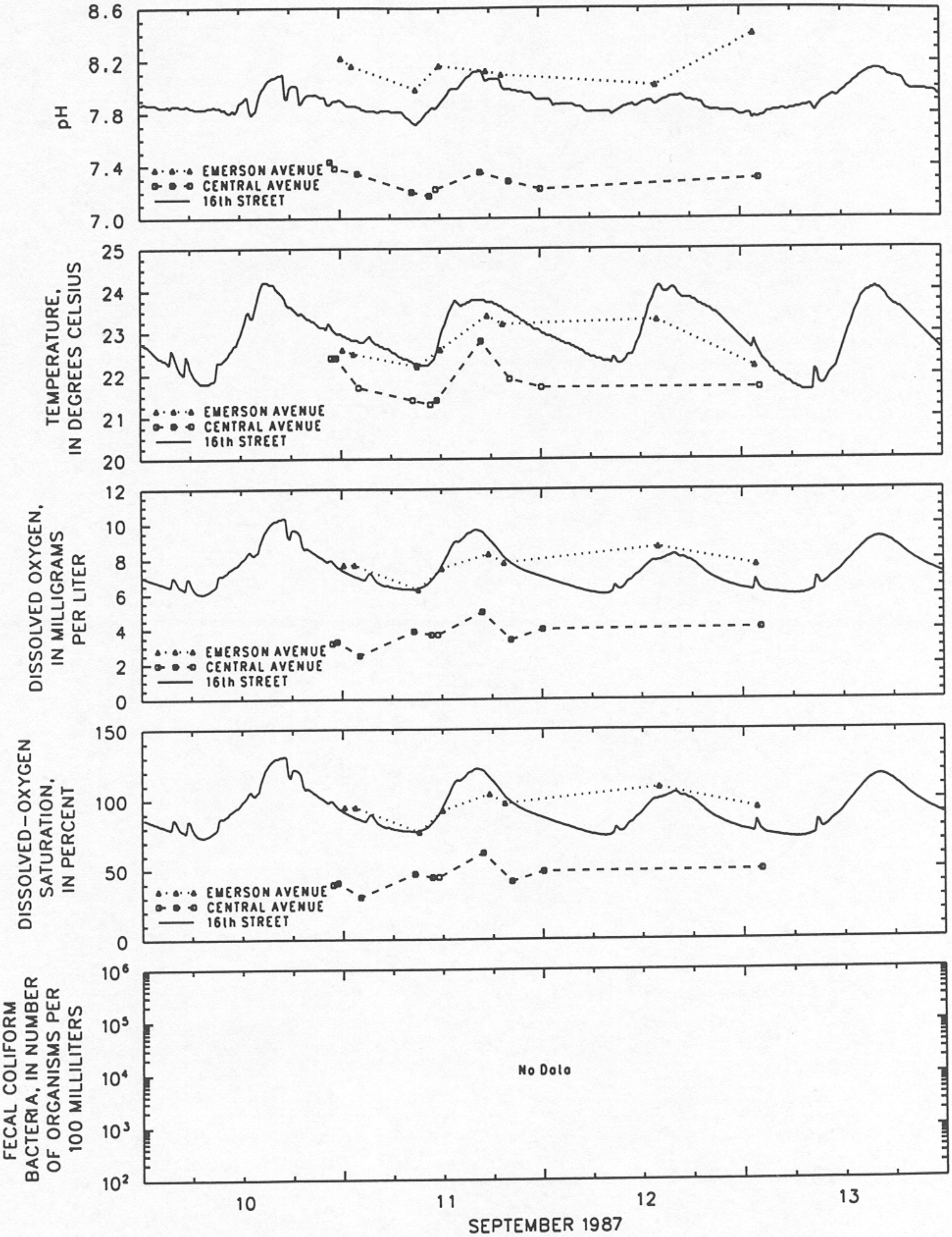

Figure 9. Streamflow and water quality in Fall Creek during storm 4, September 10-13, 1987. -- Continued.

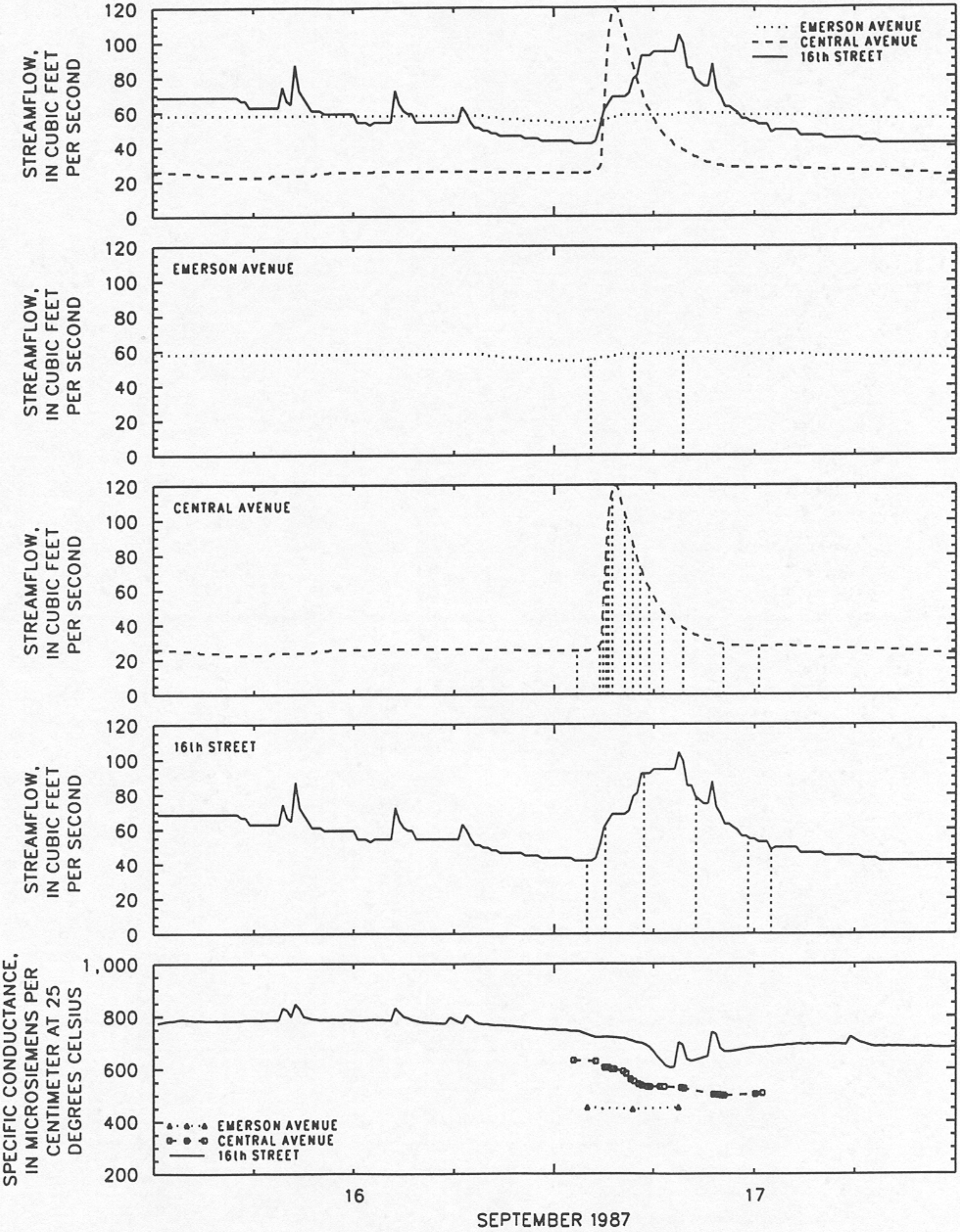

Figure 10. Streamflow and water quality in Fall Creek during storm 5, September 16–17, 1987. (Vertical dashed lines show times when water samples were collected.)

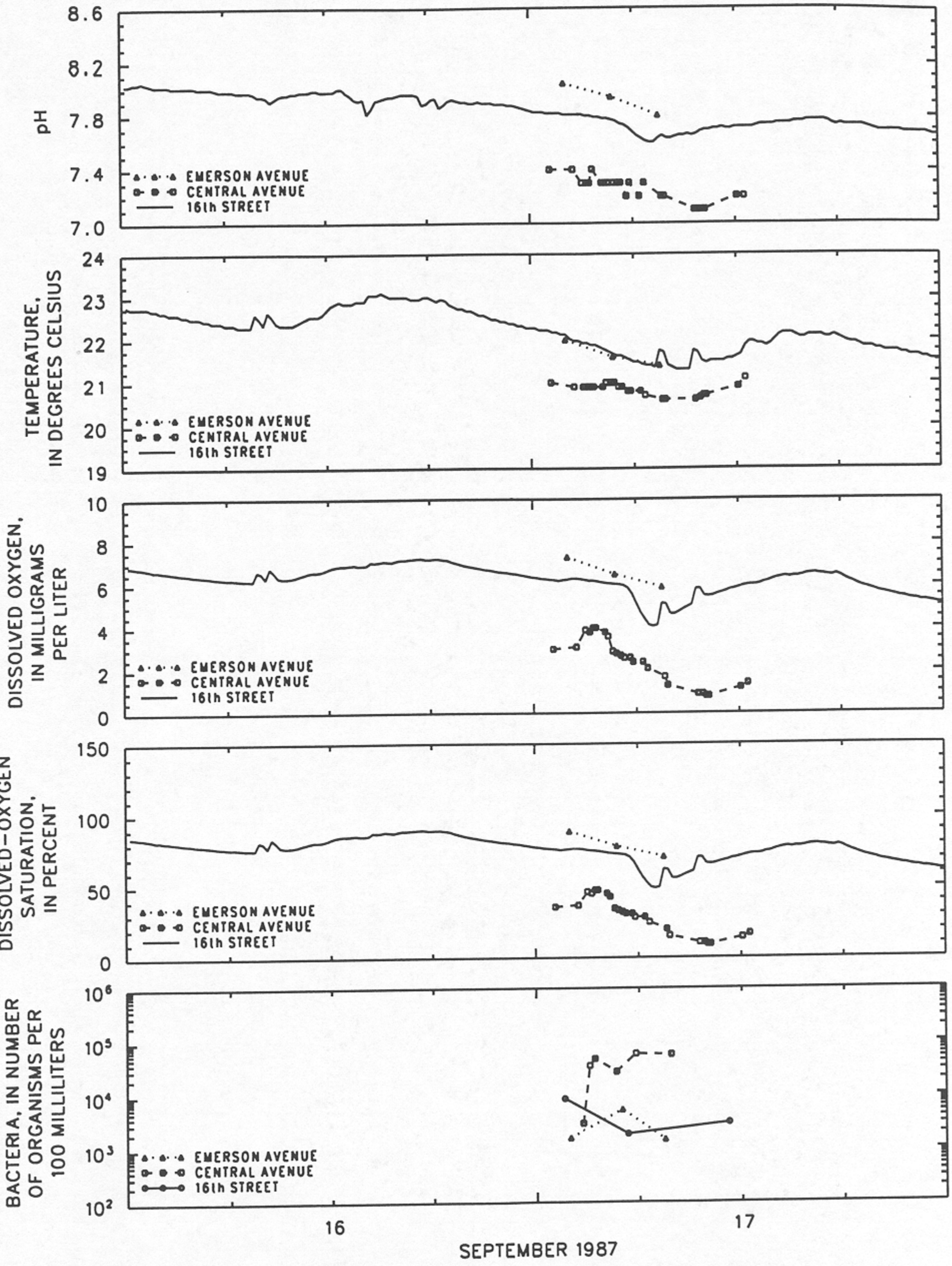

Figure 10. Streamflow and water quality in Fall Creek during storm 5, September 16-17, 1987. -- Continued.

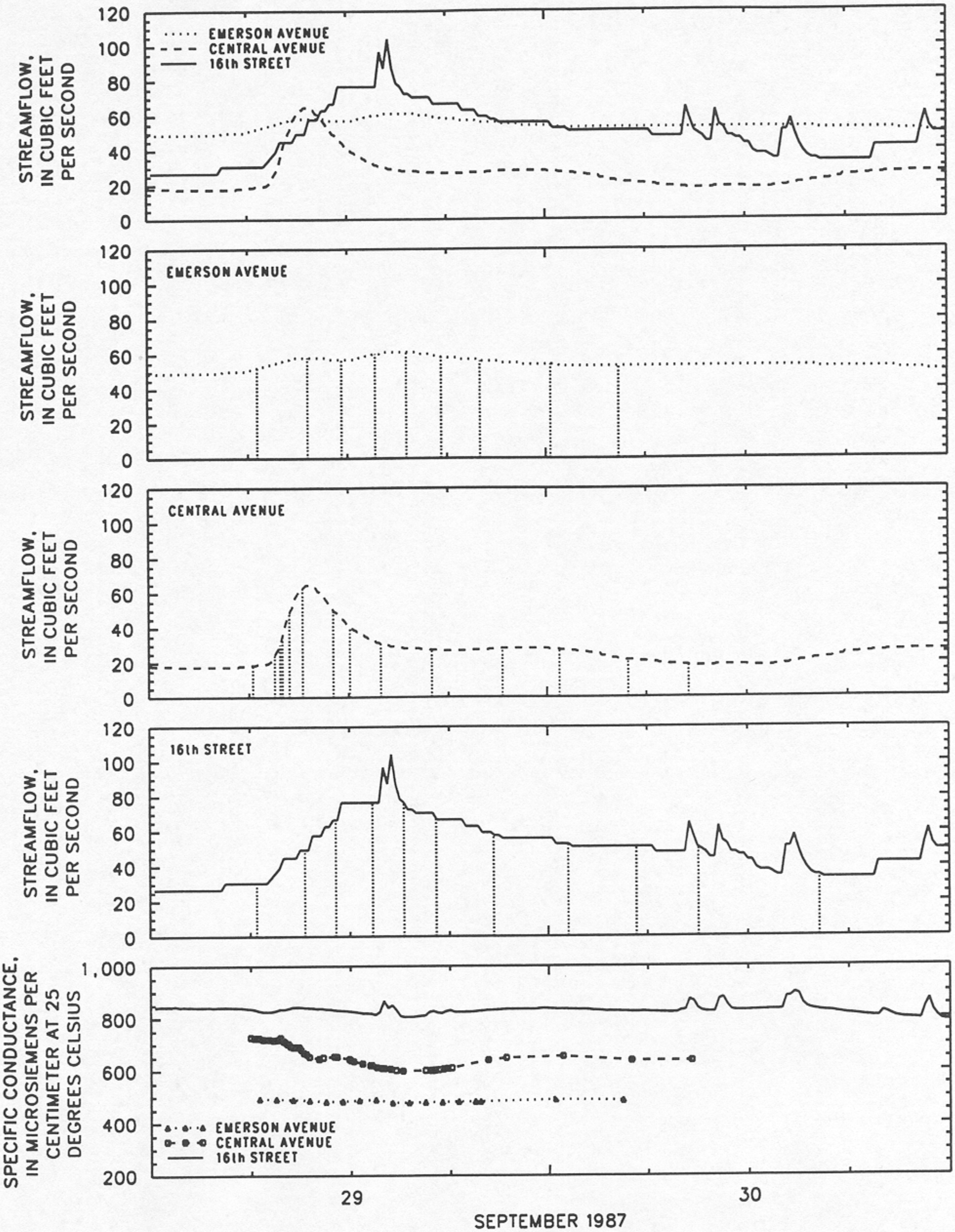

Figure 11. Streamflow and water quality in Fall Creek during storm 6, September 29–30, 1987. (Vertical dashed lines show times when water samples were collected.)

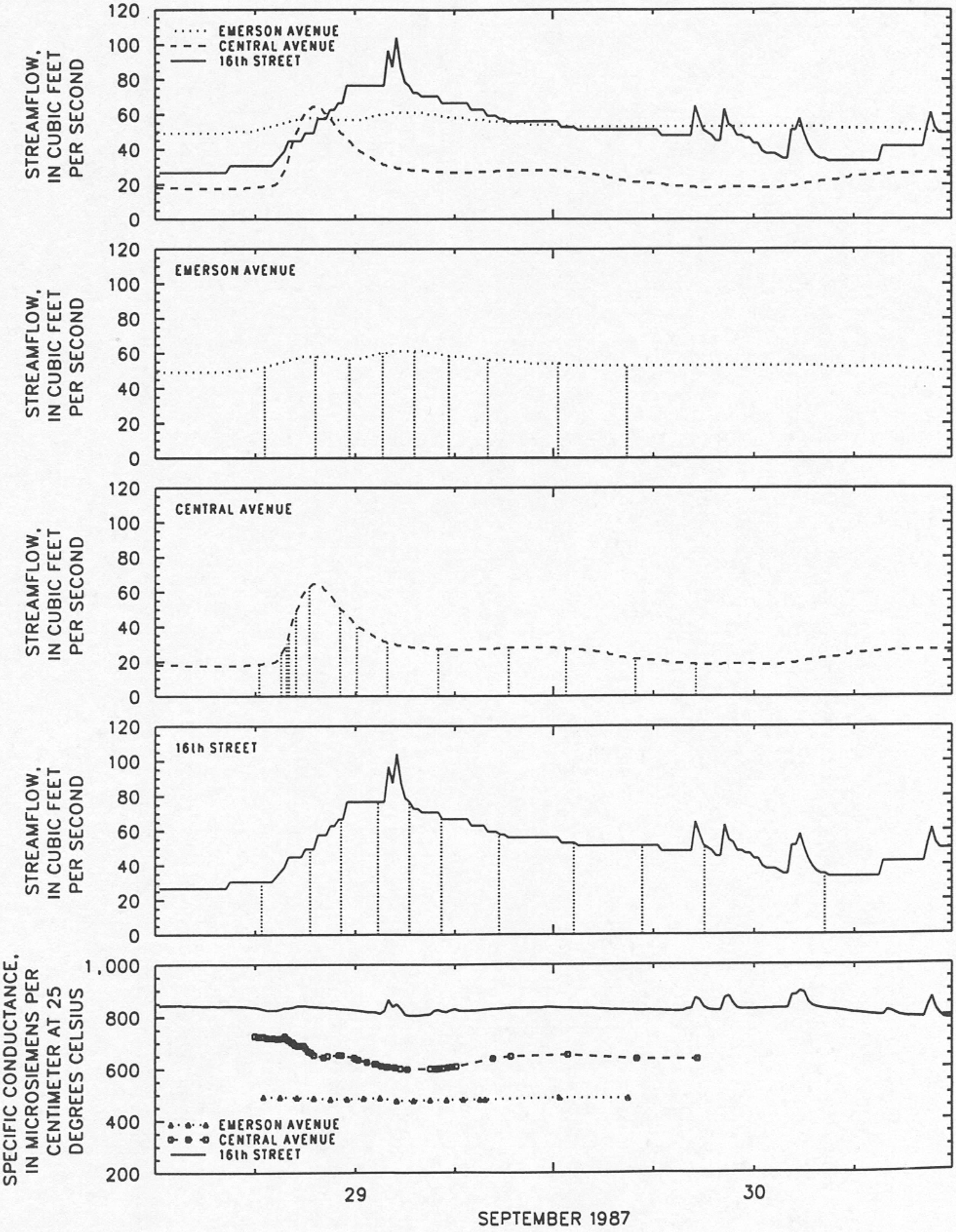

Figure 11. Streamflow and water quality in Fall Creek during storm 6, September 29–30, 1987. (Vertical dashed lines show times when water samples were collected.)-- Continued.

Runoff during storm 4 did not occur as well-defined peaks (fig. 9) primarily because precipitation was of low intensity and long duration. Streamflow increased at all three stations but relatively more at 16th Street than at Central Avenue or Emerson Avenue. This pattern of streamflow increase indicates that a significant part of the storm runoff occurred in the urbanized part of the watershed between Central Avenue and 16th Street.

In-channel storage did not seem to affect the rates of increase or decrease of runoff at 16th Street during storms 1, 2, and 4. The large magnitude of the runoff during storms 1 and 2 seemed to exceed the storage capacity of the impoundment, and rates of rise and fall of the hydrograph at 16th Street were similar to those at Central Avenue (figs. 6, 7). Runoff during the low-intensity, long-duration storm (storm 4) was not noticeably detained in the impoundment (fig. 9).

Storm runoff for the unsampled storm (August 17) was most similar to storm 6 (fig. 11) in terms of hydrograph shape and the relations of peak flow rates and runoff volumes among the three stations. Although the peak flow rates were similar, volumes of runoff were greater for the unsampled storm than for storm 6.

Water Withdrawals and Returns

Water is withdrawn from Fall Creek at Keystone Avenue and treated for public-water supply (fig. 3). The median rates of water withdrawal were 56 ft^3/s during July through September and 35 ft^3/s during October (table 6). Decreased rates of withdrawal during October reflect decreased demand for water as temperatures cool during autumn. Water withdrawal ranged from 32 to 68 ft^3/s during the study period. A comparison of daily mean streamflow at Emerson Avenue (table 5) and daily mean water withdrawal at Keystone Avenue (table 6) shows that on several days during August and September, more water was withdrawn at Keystone Avenue for water supply than flowed past the Emerson Avenue gaging station approximately 2 mi upstream. Measurement error could be the cause of the discrepancy, but a more likely reason is that sufficient water is impounded at Keystone Avenue to allow rates of withdrawal to exceed rates of supply for short periods of time. Ground-water inflow between Emerson Avenue and Keystone Avenue also may increase the amount of water available for withdrawal.

During periods of base flow, instantaneous streamflow at Central Avenue varied in gradual, cyclical, daily fluctuations of approximately 5 to 15 ft^3/s. The maximum streamflow usually occurred during midday, and the minimum usually occurred at midnight (although base flow on some days did not fluctuate at all or the maximum streamflow occurred at night). These fluctuations probably were the result of variation in the rate of water withdrawn at Keystone Avenue and the travel time from Keystone Avenue to Central Avenue, although the discharge of filter backwash or unknown withdrawals or returns between Emerson Avenue and Central Avenue might also contribute to fluctuations in base flow. Daily fluctuations in base flow also occurred at 16th Street.

Water used to backwash filters used in the treatment of municipal drinking water is discharged into Fall Creek at two locations: approximately 500 ft downstream of the water intakes at Keystone Avenue and approximately 300 ft upstream from the 16th Street gaging station. The backwash effluent is composed of water used to backwash the filters, suspended sediment removed from treated drinking water, aluminum hydroxide floc—a result of the use of alum (aluminum sulfate) as a coagulant for treating drinking water—and other materials. The source of the water discharged downstream from Keystone Avenue is water from Fall Creek that is withdrawn at Keystone Avenue. The source of the water discharged upstream from 16th Street is water from the canal that is withdrawn from the White River north of Kessler Avenue (fig. 3).

The discharge of filter backwash is sporadic and of short duration (typically ranging from less than 1 to 3 hours). The instantaneous streamflow record at 16th Street shows abrupt increases and decreases in streamflow ranging from 5 to 30 ft^3/s (typically 20 ft^3/s) that were attributed to the discharge of filter backwash (figs. 6–11). Abrupt changes in streamflow at Central Avenue caused by the discharge of filter backwash were not observed in the streamflow record. Typically, filter backwash was discharged several times per day; the number of discharges per day during the study period ranged from 0 to 10. More than twice as much backwash effluent is discharged upstream from 16th Street than downstream from Keystone Avenue (table 6). Daily mean rates of backwash discharge ranged from 0.03 to 0.87 ft^3/s at Keystone and from 0.00 to 3.48 ft^3/s at 16th Street and were much more variable at 16th Street.

EFFECTS OF COMBINED-SEWER OVERFLOWS AND URBAN RUNOFF ON FALL CREEK

The effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek were determined by comparing water quality of base flow with water quality of storm runoff. In addition, water quality during storm runoff in the urbanized area was compared with water quality in the less urbanized area upstream from the combined-sewer overflows.

Water Quality of Base Flow

The water quality of base flow was characterized by measurements made in the field during a base-flow synoptic survey and by chemical and biological analyses of water samples.

Synoptic Survey

A synoptic, base-flow water-quality survey was done of Fall Creek on September 24, 1987. Field-measured water-quality characteristics (specific conductance, pH, water temperature, and dissolved-oxygen concentration) were measured at 20 stations from Pendleton to 16th Street (figs. 2, 3, 12, table 7). The synoptic survey was done to determine longitudinal changes in water quality and to identify reaches of Fall Creek having low concentrations of dissolved oxygen.

On the basis of water-quality data collected during the synoptic survey, three distinct reaches were identified. The upstream reach extended from Pendleton to Geist Reservoir (river miles 34.5-26.1, table 7, fig. 2) and was characterized by water quality typical of base flow, which primarily consists of ground-water inflow. Specific conductance ranged from 734 to 792 µS/cm, pH ranged from 8.1 to 8.3, water temperature ranged from 17.8 to 19.4°C, and dissolved oxygen ranged from 8.3 to 9.8 mg/L (table 7).

The middle reach consists of Geist Reservoir and the stations downstream to and including Keystone Avenue (river miles 20.8-6.4, table 7, figs. 2, 3). Water quality in this reach was affected by water that was stored in the reservoir and released downstream for public-water supply. Water in the reservoir was composed of storm runoff, base flow, ground-water inflow, and precipitation that fell directly upon the reservoir. Because the reservoir contains storm runoff and precipitation, the reservoir water was much less mineralized (more dilute, lower concentrations of dissolved solids) than the base flow of the upstream reach. Consequently, specific conductance in the middle reach (467-500 µS/cm) was much less than that in the upstream reach (table 7, fig. 12). Except for the measurement at the causeway, measurements of pH and dissolved oxygen in the middle reach were similar to those in the upstream reach. Greater concentrations of dissolved oxygen and a greater pH at the causeway probably were caused by photosynthesis by plankton in the upper water layer (epilimnion) of the reservoir. The warmest water was measured in the reservoir at the causeway (21.3°C, table 7). Water released from the reservoir cooled as it flowed downstream until it joined warmer water in the impoundment upstream from Keystone Avenue. Water released from Geist Reservoir generally was warmer than that of base flow upstream from Geist.

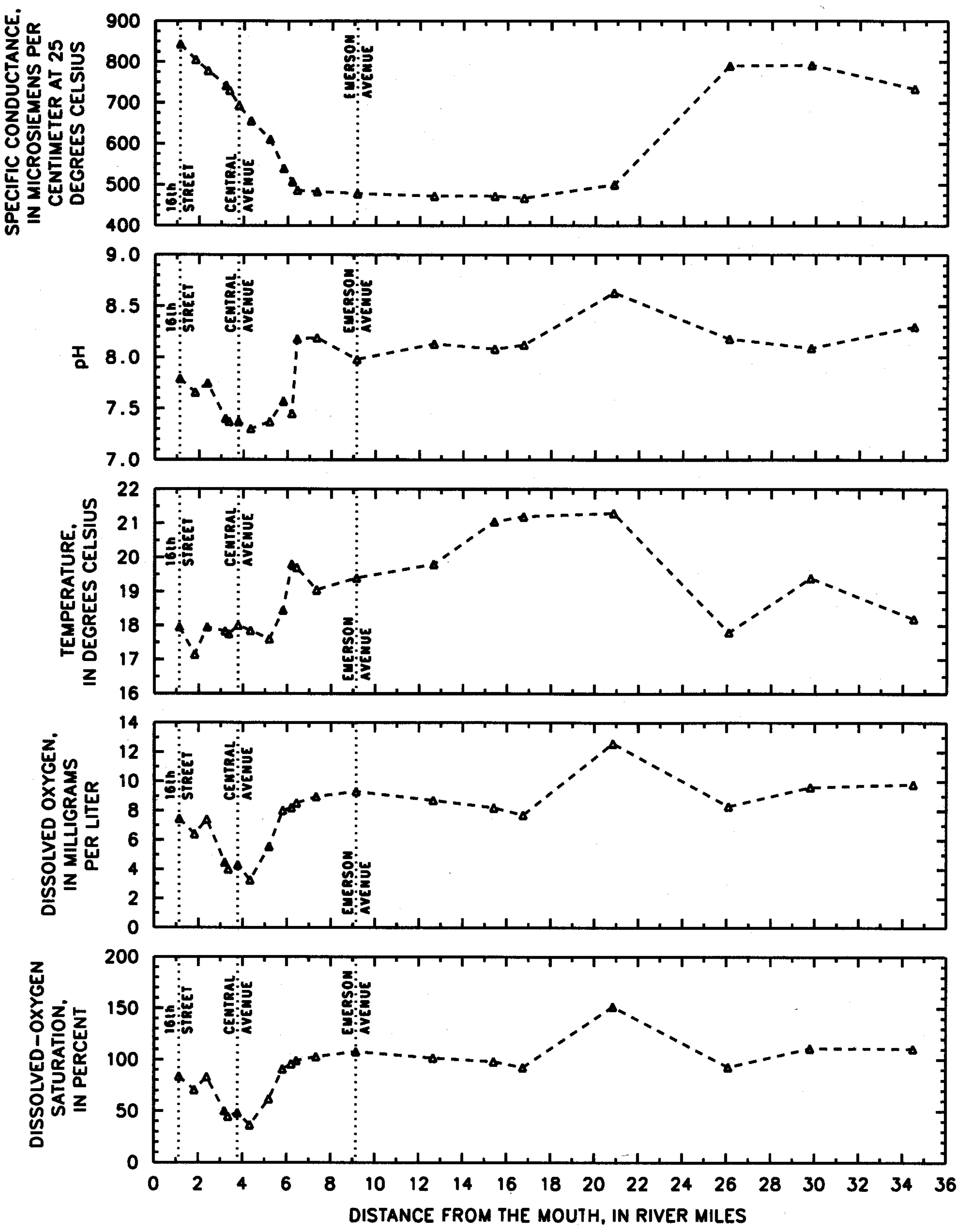

Figure 12. Longitudinal plots of water quality in Fall Creek during base flow, September 24, 1987. (Sampling sites are described in table 7 and shown in figs. 2 and 3.)

Table 7. Water-quality sampling stations and measurements for the base-flow synoptic survey, Fall Creek, September 24, 1987

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degree Celsius; mi, mile; mg/L, milligrams per liter; --, no data]

Reach of Fall Creek and sampling station[1]	River mile (mi)	Time	Streamflow (ft^3/s)	Specific conductance (µS/cm)	pH	Water temperature (°C)	Dissolved oxygen (mg/L)
Downstream reach							
16th Street	1.3	1018	30	843	7.8	17.9	7.4
Aqueduct	1.8	1049	--	805	7.7	17.1	6.4
Dr. Martin Luther King Jr. Street	2.4	1105	--	778	7.7	17.9	7.4
Capitol Avenue	3.2	1120	--	742	7.4	17.8	4.5
Meridian Street	3.3	1137	--	730	7.4	17.7	4.0
Central Avenue	3.8	1228	17	693	7.4	18.0	4.3
30th Street	4.3	1241	--	656	7.3	17.8	3.2
Monon Railroad bridge	5.2	1318	--	610	7.4	17.6	5.5
39th Street	5.8	1300	--	539	7.6	18.4	8.0
Norfolk & Western Railroad bridge	6.2	1348	--	507	7.4	19.8	8.2
Middle reach							
Keystone Avenue	6.4	1412	--	486	8.2	19.7	8.5
46th Street	7.3	1424	--	483	8.2	19.0	8.9
Emerson Avenue	9.2	1435	52	478	8.0	19.4	9.3
63rd Street	12.7	1540	--	472	8.1	19.8	8.7
71st Street	15.4	1557	--	472	8.1	21.0	8.2
79th Street	16.7	1607	--	467	8.1	21.2	7.7
Geist Reservoir causeway	20.8	1620	--	500	8.6	21.3	12.6
Upstream reach							
Fortville gaging station	26.1	1651	31	790	8.2	17.8	8.3
Madison County Road 750 West	29.8	1704	--	792	8.1	19.4	9.6
Pendleton (State Road 38)	34.5	1720	--	734	8.3	18.2	9.8

[1] Locations of synoptic sampling stations are shown in figures 2 and 3. Reach of Fall Creek is described in the text.

The third, downstream reach of Fall Creek extended from the Norfolk & Western Railroad bridge, downstream from the discharge of filter backwash near Keystone Avenue, to 16th Street (river miles 6.2-1.3, table 7, fig. 3). Specific conductance increased dramatically in this reach and measurements of pH and dissolved oxygen were much lower than those at other stations in the synoptic survey (fig. 12). The change in specific conductance in the downstream reach was rapid and systematic, an increase from 507 to 843 µS/cm (table 7). The increase in specific conductance downstream from the point where water is withdrawn at Keystone Avenue probably was caused by the inflow of highly mineralized ground water. Discharge of filter backwash or aqueduct overflow also could have increased specific conductance downstream, but the gradual, systematic increase in specific conductance indicates that the inflow of ground water probably is the primary cause of increased specific conductance.

The lowest concentrations of dissolved oxygen (3.2-5.5 mg/L, table 7) were measured at five stations between river miles 5.2 and 3.2 and correspond to the first occurrences of combined-sewer overflows (figs. 3, 4, 12). Extensive areas of black sludge deposits having a septic odor characterized the stream bed in this reach. Sources of these deposits probably are combined-sewer overflows, which begin at 39th Street. Sediment oxygen demand, caused by the biochemical oxidation of organic wastes in the sludge, probably decreased dissolved oxygen in this reach. Concentrations of dissolved oxygen increased at sites downstream from the low-head dam at Dr. Martin Luther King Jr. Street (table 7). Several factors probably caused the increased concentrations of dissolved oxygen: mixing with water high in dissolved oxygen produced by photosynthesis of plankton in the impoundments upstream and downstream from the dam; reaeration, especially as water flowed over the dam; overflow of highly oxygenated water from the aqueduct; and discharge of highly oxygenated filter backwash.

Low pH in the downstream reach probably was caused by the inflow of low-pH ground water, discharge of filter backwash, and biochemical oxidation of organic wastes (Martin and Craig, 1990, fig. 16, p. 34-35). Low temperatures in the downstream reach probably resulted from shading by streambank vegetation and the inflow of cool ground water. Measurements of temperature, dissolved oxygen, and pH in the downstream reach could have been greater than those actually determined if the measurements had been made later in the day when the effects of solar radiation and photosynthesis were more pronounced. The author, however, expects that the principal water-quality interpretations would not change.

Chemical, Physical, and Biologic Characteristics

Base-flow water-quality samples were collected at Emerson Avenue, Central Avenue, and 16th Street four times during the study period. Samples also were collected from the filter backwash upstream from 16th Street, from the overflow from the aqueduct, and at 16th Street during and after the discharge of filter backwash (fig. 3). Constituents and properties determined include field-measured characteristics (specific conductance, pH, water temperature, and dissolved oxygen), major anions (alkalinity, sulfate, and chloride), gross measures (dissolved and total solids, 20-day carbonaceous biochemical oxygen demand, chemical oxygen demand, and oil and grease), nutrients (nitrate plus nitrite, ammonia, organic nitrogen, phosphorus, and orthophosphate), metals and trace elements (arsenic, mercury, selenium, aluminum, barium, cadmium, chromium, copper, iron, lead, nickel, and zinc) (table 8), and fecal coliform bacteria (table 9). Some of the base-flow water-quality samples were split for the quality-assurance program. The mean concentration of the pair of split samples is used for all interpretations of water quality.

Table 8. Water-quality analyses for samples collected during periods of base flow

[i.d., identification; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degree Celsius; mg/L, milligrams per liter; n.d., not determined; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; --, no data; <, less than; ss, split sample]

Site	Sample i.d.	Sample type	Date	Time[1]	Streamflow (ft^3/s) (00061)[2]	Specific conductance (µs/cm) (00095)[2]	pH (00400)[2]	Water temperature (°C) (00010)[2]	Dissolved oxygen (mg/L) (00300)[2]
Emerson	Base flow 1	Individual	7-22-87	1245	85	465	8.4	26.8	8.8
Central	Base flow 1	Individual	7-22-87	1110	55	565	8.0	25.9	8.4
16th Street	Base flow 1	Individual ss[3]	7-22-87	0900	102	624	8.0	26.4	7.4
16th Street	Base flow 1	Individual ss[3]	7-22-87	0900	102	624	8.0	26.4	7.4
Emerson	Base flow 2	Individual	8-11-87	1415	67	467	8.2	24.9	8.6
Central	Base flow 2	Individual	8-11-87	1300	36	600	7.7	23.9	7.8
16th Street	Base flow 2	Individual ss[3]	8-11-87	1045	73	686	7.9	24.2	7.7
16th Street	Base flow 2	Individual ss[3]	8-11-87	1045	73	686	7.9	24.2	7.7
Emerson	Base flow 3	Individual	8-21-87	1200	60	n.d.	n.d.	n.d.	n.d.
Central	Base flow 3	Individual	8-21-87	1130	21	682	7.3	22.4	3.9
16th Street	Base flow 3	Individual	8-21-87	1300	48	760	7.8	24.8	5.6
Water Company outfall	Filter backwash	Grab	8-27-87	1230	[4]15	n.d.	n.d.	n.d.	n.d.
Emerson	Base flow 4	Individual	9-16-87	1800	58	n.d.	n.d.	n.d.	n.d.
Central	Base flow 4	Individual	9-16-87	1620	26	617	7.5	22.1	5.2
16th Street	Base flow 4	Individual	9-16-87	1805	54	789	7.9	23.0	7.2
16th Street	During backwash	Individual	10-15-87	1015	45	841	7.6	12.1	9.3
16th Street	After backwash	Individual	10-15-87	1205	29	827	7.8	13.1	9.2
Aqueduct	Overflow	Individual ss[3]	10-15-87	1115	[4]7	930	8.2	11.7	9.7
Aqueduct	Overflow	Individual ss[3]	10-15-87	1115	[4]7	930	8.2	11.7	9.7

Table 8. Water-quality analyses for samples collected during periods of base flow—Continued

Site	Sample i.d.	Dissolved alkalinity (mg/L as $CaCO_3$) (29801)[2]	Dissolved sulfate (mg/L) (00945)[2]	Dissolved chloride (mg/L) (00940)[2]	Dissolved solids (mg/L) (00515)[2]	Total solids (mg/L) (00500)[2]	Suspended solids[6] (mg/L)	Total 20-day carbonaceous biochemical oxygen demand (mg/L) (80087)[2]	Total chemical oxygen demand (mg/L) (00340)[2]	Total recoverable oil and grease (mg/L) (00556)[2]
Emerson	Base flow 1	164	36	28	307	319	12	4	18	<1
Central	Base flow 1	195	47	35	385	386	1	3	17	1
16th Street	Base flow 1 ss[3]	210	50	39	435	477	42	6	20	<1
16th Street	Base flow 1 ss[3]	216	49	39	411	461	50	7	21	2
Emerson	Base flow 2	162	36	28	--	327	--	<1	15	2
Central	Base flow 2	202	51	39	363	424	61	<1	15	2
16th Street	Base flow 2 ss[3]	220	56	51	422	560	138	3	32	2
16th Street	Base flow 2 ss[3]	220	55	49	400	560	160	1	32	2
Emerson	Base flow 3	159	35	28	280	325	45	2	6	2
Central	Base flow 3	226	61	45	422	449	27	2	6	1
16th Street	Base flow 3	238	66	57	473	688	215	9	23	1
Water Company outfall	Filter backwash	244	87	86	553	823	270	16	63	2
Emerson	Base flow 4	159	36	28	285	310	25	4	14	2
Central	Base flow 4	198	55	38	383	402	19	4	14	5
16th Street	Base flow 4	237	66	60	485	539	54	8	22	3
16th Street	During backwash	260	74	70	501	616	115	2	19	2
16th Street	After backwash	256	72	67	490	570	80	3	17	<1
Aqueduct	Overflow ss[3]	278	75	85	564	628	64	3	14	3
Aqueduct	Overflow ss[3]	276	75	85	582	633	51	3	n.d.	<1

Table 8. Water-quality analyses for samples collected during periods of base flow—Continued

Site	Sample i.d.	Total nitrate plus nitrite (mg/L as N) (00630)[2]	Total ammonia (mg/L as N) (00610)[2]	Total organic nitrogen (mg/L) (00605)[2]	Total phosphorus (mg/L) (00665)[2]	Dissolved orthophosphate (mg/L as P) (00671)[2]	Total arsenic (µg/L) (01002)[2]	Total mercury (µg/L) (71900)[2]	Total selenium (µg/L) (01147)[2]
Emerson	Base flow 1	0.16	0.10	0.78	0.10	<0.01	2	<0.2	<1
Central	Base flow 1	.30	.09	.92	.08	<.01	1	<.2	<1
16th Street	Base flow 1 ss[3]	.77	.10	1.00	.20	.01	2	<.2	<1
16th Street	Base flow 1 ss[3]	.77	.13	.98	.20	.01	2	<.2	<1
Emerson	Base flow 2	.11	<.01	.45	.09	.02	2	<.2	<1
Central	Base flow 2	.28	.08	.79	.08	.02	2	<.2	<1
16th Street	Base flow 2 ss[3]	.59	.08	1.84	.63	.03	4	<.2	<1
16th Street	Base flow 2 ss[3]	.59	.05	.67	.63	.03	4	<.2	<1
Emerson	Base flow 3	.10	<.01	.91	.90	<.01	2	<.2	<1
Central	Base flow 3	.32	.14	.50	.40	<.01	1	<.2	<1
16th Street	Base flow 3	.42	.48	2.53	1.14	.02	10	<.2	<1
Water Company outfall	Filter backwash	1.31	.47	2.45	3.30	.17	2	<.2	<1
Emerson	Base flow 4	.13	.05	.64	.08	<.01	1	<.2	<1
Central	Base flow 4	.33	.18	.95	.05	<.01	1	<.2	<1
16th Street	Base flow 4	.88	.28	.96	.31	.05	2	<.2	<1
16th Street	During backwash	1.34	.22	.86	.27	.05	6	<.2	<1
16th Street	After backwash	1.16	.20	.66	.09	.05	3	<.2	<1
Aqueduct	Overflow ss[3]	2.40	.10	[5].07	.46	.29	3	<.2	<1
Aqueduct	Overflow ss[3]	n.d.	n.d.	n.d.	n.d.	.29	n.d.	n.d.	n.d.

Table 8. Water-quality analyses for samples collected during periods of base flow—Continued

Site	Sample i.d.	Total recoverable aluminum (μg/L) (01105)[2]	Total recoverable barium (μg/L) (01007)[2]	Total recoverable cadmium (μg/L) (01027)[2]	Total recoverable chromium (μg/L) (01034)[2]	Total recoverable copper (μg/L) (01042)[2]	Total recoverable iron (μg/L) (01045)[2]	Total recoverable lead (μg/L) (01051)[2]	Total recoverable nickel (μg/L) (01067)[2]	Total recoverable zinc (μg/L) (01092)[2]
Emerson	Base flow 1	190	30	<10	<10	<10	400	<10	<10	<10
Central	Base flow 1	400	110	<10	<10	<10	300	<10	<10	<10
16th Street	Base flow 1 ss[3]	1,270	100	<10	<10	10	1,220	10	<10	10
16th Street	Base flow 1 ss[3]	1,260	140	<10	<10	10	1,250	<10	<10	10
Emerson	Base flow 2	130	50	<10	<10	<10	430	<10	<10	<10
Central	Base flow 2	200	60	<10	<10	10	330	<10	<10	<10
16th Street	Base flow 2 ss[3]	5,000	80	<10	<10	20	2,660	20	<10	20
16th Street	Base flow 2 ss[3]	4,700	100	<10	<10	20	2,410	10	<10	20
Emerson	Base flow 3	190	40	<10	<10	<10	410	<10	<10	<10
Central	Base flow 3	110	60	<10	<10	10	230	<10	<10	<10
16th Street	Base flow 3	12,690	140	<10	20	30	3,880	20	10	30
Water Company outfall	Filter backwash	27,240	160	<10	30	40	4,250	30	30	40
Emerson	Base flow 4	100	60	<10	<10	<10	370	<10	<10	<10
Central	Base flow 4	130	100	<10	<10	<10	290	<10	<10	<10
16th Street	Base flow 4	890	60	<10	<10	<10	940	<10	<10	10
16th Street	During backwash	6,360	90	<10	<10	10	1,570	<10	<10	20
16th Street	After backwash	1,900	120	<10	<10	<10	970	<10	<10	10
Aqueduct	Overflow ss[3]	700	50	<10	<10	<10	970	<10	<10	20
Aqueduct	Overflow ss[3]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

[1] Midpoint time of sample collection.

[2] WATSTORE (U.S. Geological Survey) and STORET (U.S. Environmental Protection Agency) parameter code.

[3] A split sample (ss) is one of a pair of identical samples used to assess analytical precision. The mean of the pair of split samples was used for all calculations and interpretations.

[4] Estimated.

[5] Anomalous concentration. Not used in analysis of base-flow water quality.

[6] Suspended solids were calculated as the difference between total solids and dissolved solids.

Table 9. Concentrations of fecal coliform bacteria during periods of base flow
[col/100 mL, colonies per 100 milliliters; >, greater than; <, less than]

	Sampling station					
	Emerson Avenue		Central Avenue		16th Street	
Date	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]
Base flow 1						
7-22-87	1300	>667	1325	237	1350	>1,000
					1351	>2,000
Base flow 2						
8-12-87	1045	300	1111	500	1132	<100
	1046	100	1112	400	1133	100
Base flow 3						
8-21-87	1055	2,000	1200	200	1030	12,800
	1230	100	1300	200	1225	7,800

[1] WATSTORE (U.S. Geological Survey) and STORET (U.S. Environmental Protection Agency) parameter code.

Specific Conductance, Dissolved Oxygen, Temperature, and pH

Water quality of base flow measured at Emerson Avenue, Central Avenue, and 16th Street generally was similar to water-quality patterns measured during the base-flow synoptic survey (tables 7, 8, fig. 12). Specific conductance increased downstream, and pH was greatest at Emerson Avenue and least at Central Avenue (table 8). Concentrations of dissolved oxygen were greatest at Emerson Avenue (8.8 mg/L and 8.6 mg/L) and least at 16th Street for the first two base-flow samples (7.4 and 7.7 mg/L). Concentrations of dissolved oxygen were least at Central Avenue for the last two base-flow samples (3.9 and 5.2 mg/L). Streamflow was greater during the first two base-flow samples than during the last two (table 8). The lower streamflows probably contributed to the low concentrations of dissolved oxygen measured at Central Avenue by increasing the influence of sediment oxygen demand. At low rates of flow, water can be more thoroughly deoxygenated by sediments because the volume of water (and therefore the mass of oxygen available to satisfy the sediment oxygen demand) is much less than that at higher rates of flow.

Water overflowing the aqueduct had the highest specific conductance (930 µS/cm) and one of the highest values of pH (8.2) and dissolved oxygen (9.7 mg/L) during base flow (tables 7, 8). Previous studies have shown that specific conductance, pH, and dissolved-oxygen concentration in the White River upstream from the intake to the canal (and, presumably, in the canal) typically were greater than those in Fall Creek at 16th Street during base flow (Martin and Craig, 1990, tables 5, 6, 7, 20, 21, 22). Therefore, increased specific conductance, pH, and dissolved-oxygen concentration downstream from the aqueduct can be attributed, at least partially, to the overflow from the aqueduct.

Different rates of base flow had little effect on specific conductance, pH, or concentrations of dissolved oxygen at Emerson Avenue. The quality of water released from the reservoir varied little with changes in release (tables 7, 8); however, different rates of base flow had a large effect on water quality at Central Avenue and 16th Street. Specific conductance generally increased as streamflow decreased, whereas pH and dissolved oxygen generally decreased as streamflow decreased. At low streamflows, the effects of ground-water discharge, sediment oxygen demand, low-head dams, filter backwash, and aqueduct overflow were the most pronounced.

Major Anions

Concentrations of alkalinity (predominantly bicarbonate), sulfate, and chloride steadily increased downstream (fig. 13) as a result of surface-water withdrawals, the inflow of mineralized ground water, aqueduct overflow, and the discharge of filter backwash. Concentrations were least variable at Emerson Avenue and were most variable at 16th Street (fig. 13). The aqueduct overflow and filter backwash had relatively high concentrations of anions and contributed to increased and variable concentrations at 16th Street.

Dissolved and Total Solids, Chemical Oxygen Demand, Carbonaceous Biochemical Oxygen Demand, and Oil and Grease

Concentrations of dissolved and total solids steadily increased downstream in a pattern similar to that of specific conductance and the major anions (fig. 13). The aqueduct overflow had the highest concentration of dissolved solids (573 mg/L) and the filter backwash had the highest concentration of total solids (823 mg/L). Concentrations of suspended solids were calculated as the difference between total solids and dissolved solids (table 8) and ranged from 12 to 45 mg/L at Emerson Avenue, from 1 to 61 mg/L at Central Avenue, and from 42 to 215 mg/L at 16th Street. Suspended solids, expressed as a proportion of total solids, ranged from 0.3 to 32.8 percent. The highest concentration and proportion of suspended solids was measured in the sample of filter backwash (270 mg/L, 32.8 percent). Of the base-flow samples collected at the three streamflow-gaging stations on a given day, the Central Avenue sample had the lowest concentration and proportion of suspended solids, whereas the 16th Street sample had the highest concentration and proportion. This pattern indicates that filter backwash had little effect on the concentration of suspended solids at Central Avenue during base flow but had a pronounced effect at 16th Street. The decrease in suspended-solids concentration between Emerson Avenue and Central Avenue probably can be attributed to the settling out of non-backwash-associated suspended solids in the impoundment at Keystone Avenue and to inflow of ground water that is low in suspended solids. Suspended solids in the aqueduct overflow and in Fall Creek at Emerson Avenue and Central Avenue probably were composed of sediment and plankton, whereas suspended solids in the filter backwash and at 16th Street also contained large amounts of aluminum hydroxide floc.

Chemical oxygen demand (COD) and 20-day carbonaceous biochemical oxygen demand (CBOD) exhibited similar patterns of water quality among stations during base flow (fig. 13). Concentrations of CBOD and COD measured at Emerson Avenue were nearly identical to those measured at Central Avenue, whereas those at 16th Street were approximately two times greater (table 8). Concentrations of CBOD at Emerson Avenue and Central Avenue ranged from <1 to 4 mg/L but ranged from 2 to 9 mg/L at 16th Street. Concentrations of COD ranged from 6 to 18 mg/L at Emerson Avenue and from 6 to 17 mg/L at Central Avenue, but they ranged from 17 to 32 mg/L at 16th Street. Concentrations of CBOD and COD in the aqueduct overflow were similar to those measured upstream at Emerson Avenue and Central Avenue. Concentrations of CBOD and COD in the filter backwash were the highest measured (16 and 63 mg/L, respectively). The discharge of filter backwash caused the increased concentrations of CBOD and COD at 16th Street.

Except for one measurement of 5 mg/L at Central Avenue, concentrations of oil and grease ranged from <1 to 3 mg/L (table 8). In view of the poor measurement precision for oil and grease (mean log difference 80.9 percent, table 2), water-quality patterns or differences among sites were not discernible (fig. 13).

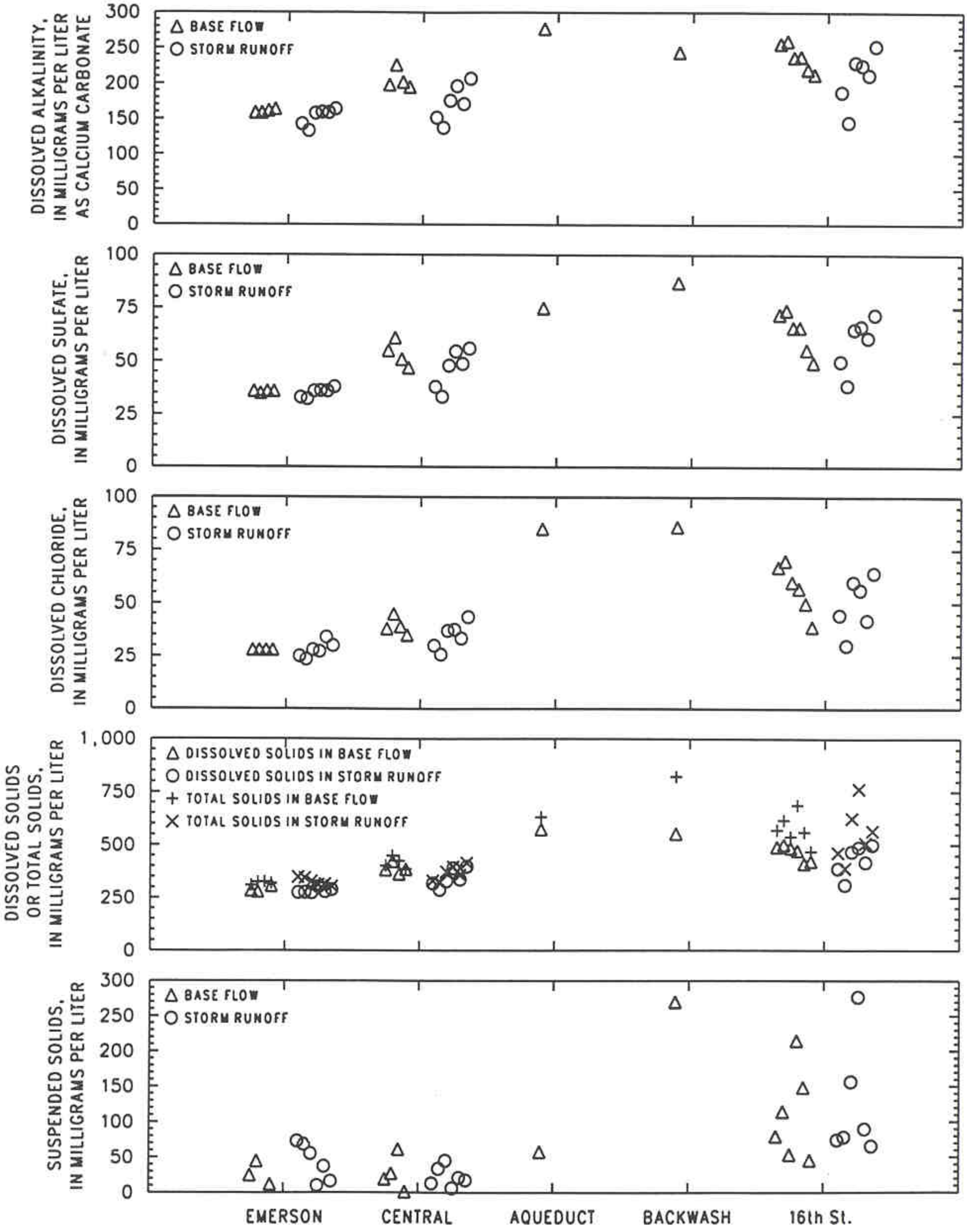

Figure 13. Water-quality constituents measured during base flow and event-mean concentrations of water-quality constituents measured during storm runoff at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, and water-quality constituents measured in the aqueduct overflow and filter backwash.

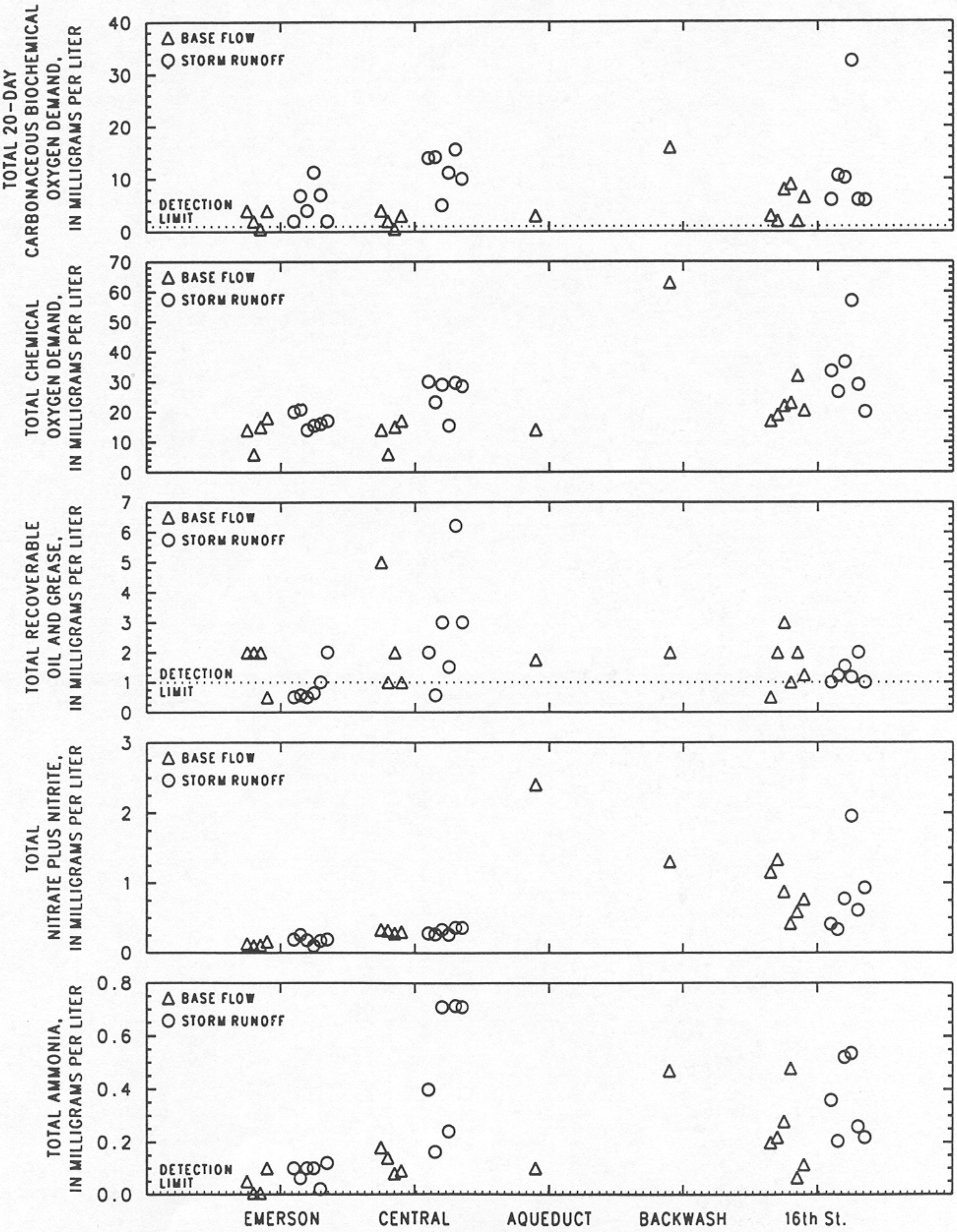

Figure 13. Water-quality constituents measured during base flow and event-mean concentrations of water-quality constituents measured during storm runoff at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, and water-quality constituents measured in the aqueduct overflow and filter backwash. -- Continued.

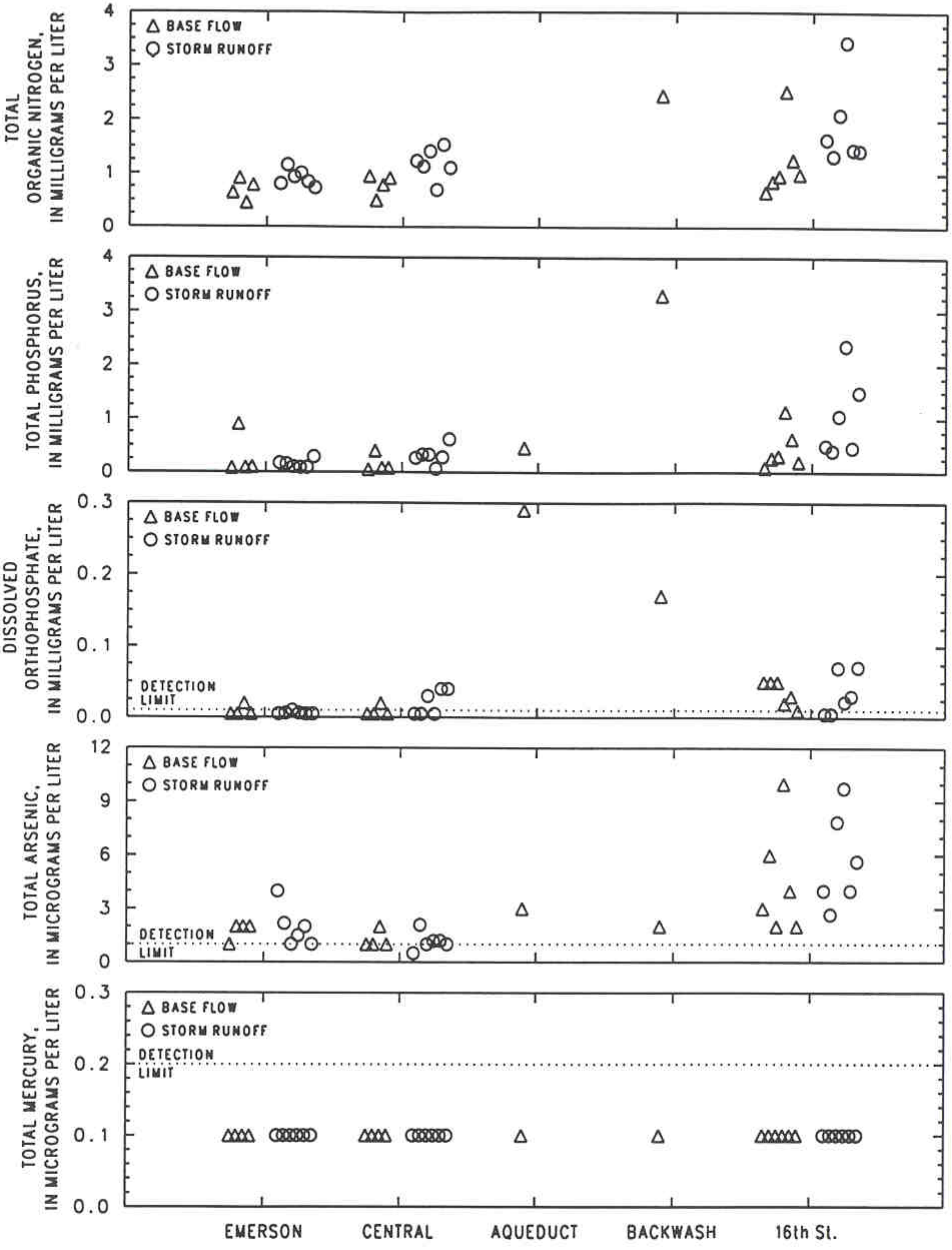

Figure 13. Water-quality constituents measured during base flow and event-mean concentrations of water-quality constituents measured during storm runoff at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, and water-quality constituents measured in the aqueduct overflow and filter backwash. -- Continued.

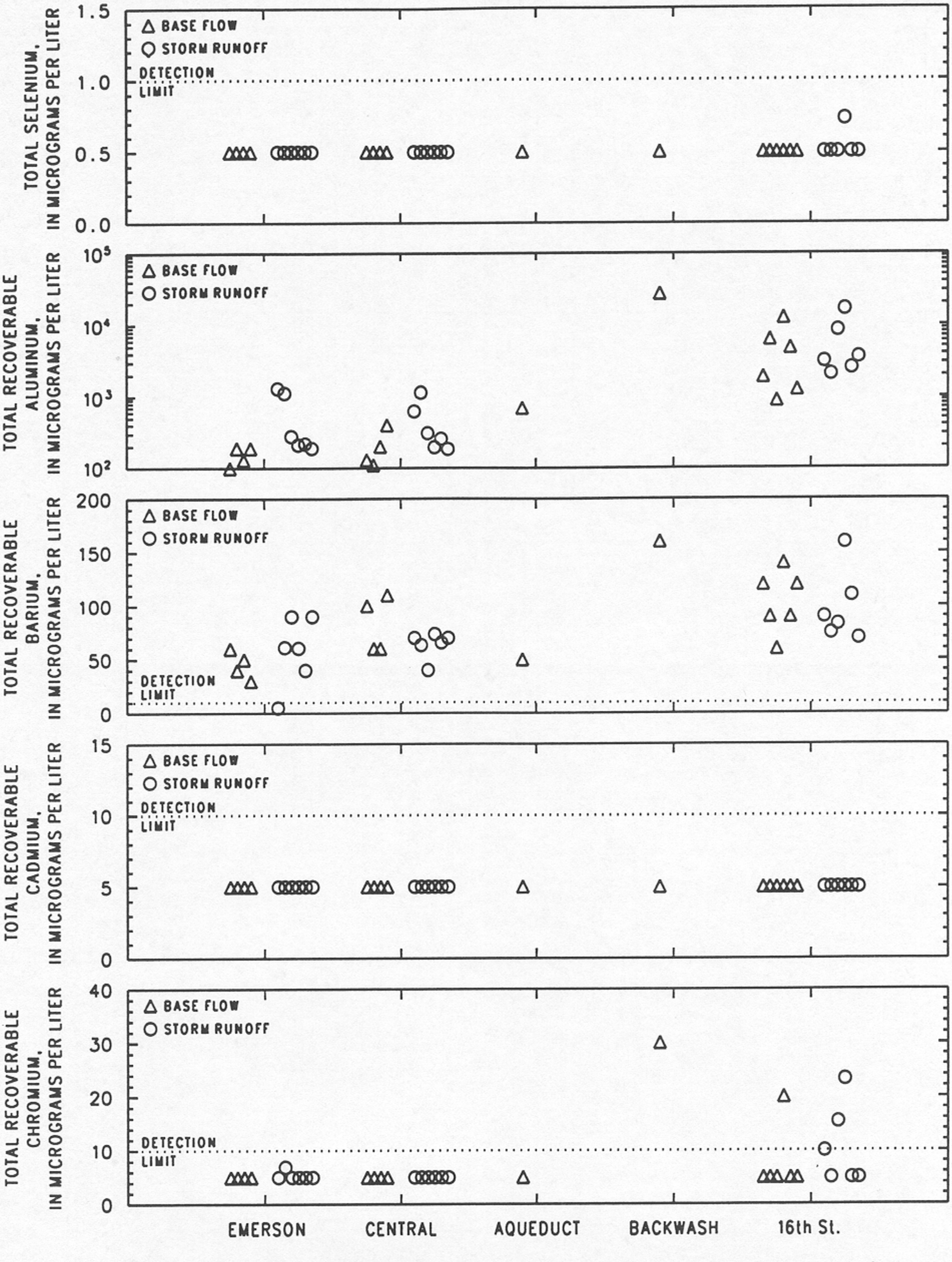

Figure 13. Water-quality constituents measured during base flow and event-mean concentrations of water-quality constituents measured during storm runoff at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, and water-quality constituents measured in the aqueduct overflow and filter backwash. -- Continued.

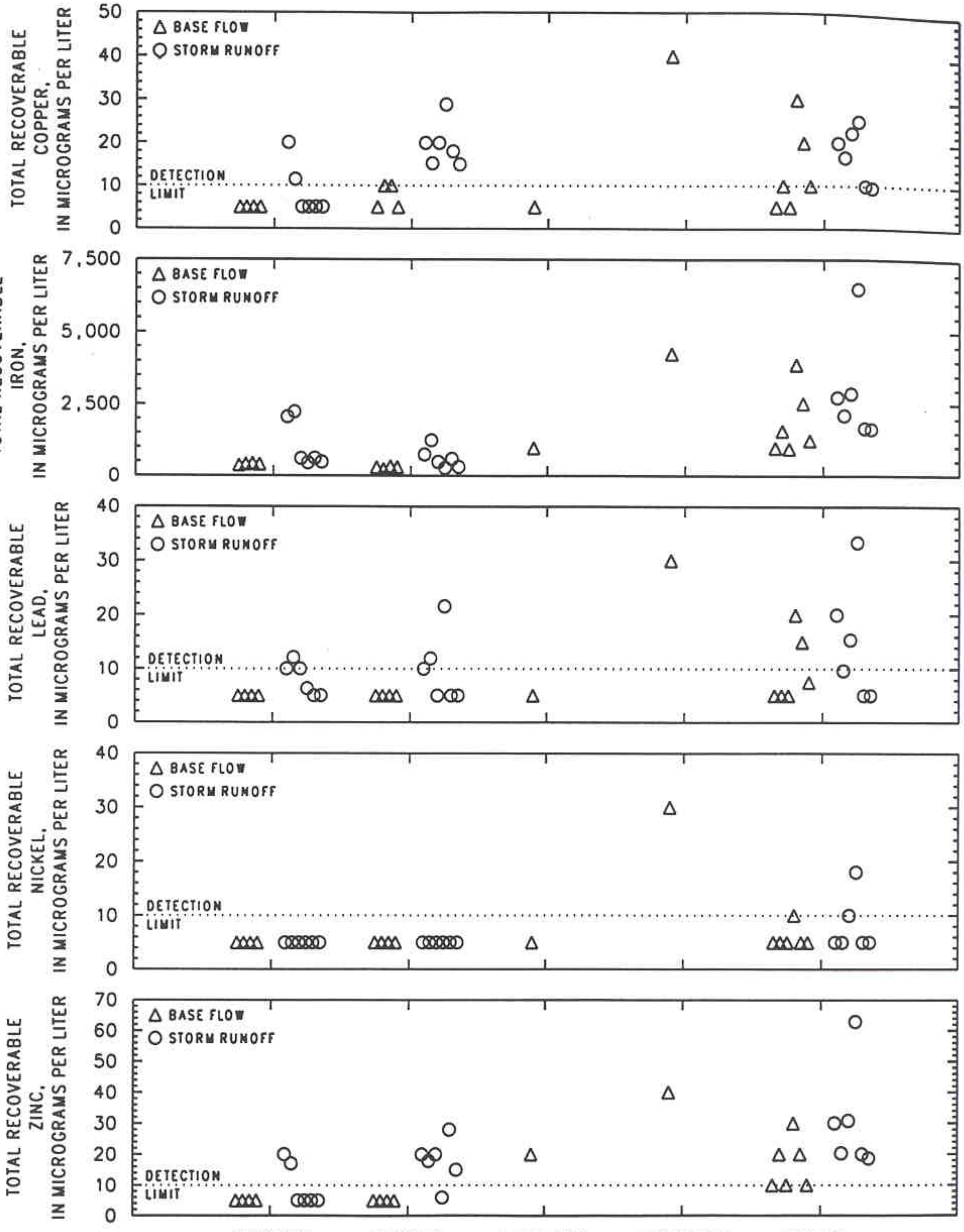

Figure 13. Water-quality constituents measured during base flow and event-mean concentrations of water-quality constituents measured during storm runoff at Fall Creek at Emerson Avenue, Central Avenue, and 16th Street, and water-quality constituents measured in the aqueduct overflow and filter backwash. -- Continued.

Nutrients

Concentrations of nutrients in base flow in Fall Creek exhibited two distinct water-quality patterns. Concentrations of nitrate plus nitrite and ammonia steadily increased downstream, whereas concentrations of organic nitrogen, phosphorus, and orthophosphate increased at 16th Street only (fig. 13).

Concentrations of nitrate plus nitrite approximately doubled at each downstream station and ranged from 0.10 to 0.16 mg/L at Emerson Avenue, from 0.28 to 0.33 mg/L at Central Avenue, and from 0.42 to 1.34 mg/L at 16th Street (table 8). Concentrations of ammonia generally were less than concentrations of nitrate plus nitrite and ranged from <0.10 to 0.10 mg/L at Emerson Avenue, from 0.08 to 0.18 mg/L at Central Avenue, and from 0.07 to 0.48 at 16th Street. A sample of the aqueduct overflow had the greatest concentration of nitrate plus nitrite (2.40 mg/L), whereas a sample at 16th Street had the greatest concentration of ammonia (0.48 mg/L). Ground-water inflow and (or) decomposition and mineralization of nitrogen-containing organic material deposited on the streambed could explain the steady downstream increase in nitrate plus nitrite and ammonia. Increased and highly variable concentrations of nitrate plus nitrite and ammonia at 16th Street were caused, in part, by filter backwash and aqueduct overflow.

Concentrations of organic nitrogen, phosphorus, and orthophosphate measured at Emerson Avenue were similar to those measured at Central Avenue, but higher concentrations were measured at 16th Street (table 8). Orthophosphate was detected only once in samples collected from Emerson Avenue and Central Avenue but was detected in all samples collected from 16th Street. High concentrations of organic nitrogen (2.45 mg/L) and phosphorus (3.30 mg/L) were detected in the filter backwash. High concentrations of orthophosphate were detected in the aqueduct overflow (0.29 mg/L) and the filter backwash (0.17 mg/L). Increased concentrations of organic nitrogen and phosphorus were caused by filter backwash, whereas increased concentrations of orthophosphate were caused by aqueduct overflow and filter backwash.

Trace Elements

Concentrations of mercury, selenium, and cadmium were less than the detection limits (table 1) in all base-flow samples (table 8). Except for two detectable concentrations of copper at Central Avenue and detectable zinc in the aqueduct overflow, all concentrations of chromium, copper, lead, nickel, and zinc were less than the detection limit (10 µg/L) for base-flow samples collected at Emerson Avenue, Central Avenue, and the aqueduct overflow. Filter backwash had the highest concentrations of chromium (30 µg/L), copper (40 µg/L), lead (30 µg/L), nickel (30 µg/L), and zinc (40 µg/L). Detectable concentrations of these metals in base-flow samples from 16th Street were caused by the discharge of filter backwash (table 8, fig. 13).

Concentrations of aluminum and barium steadily increased downstream, whereas concentrations of arsenic and iron were greater at Emerson Avenue than at Central Avenue (fig. 13). Concentrations of all four constituents were greatest at 16th Street.

Concentrations of aluminum ranged from 100 to 190 µg/L at Emerson Avenue, from 110 to 400 µg/L at Central Avenue, and from 890 to 12,690 µg/L at 16th Street (table 8). Increased concentrations of aluminum at 16th Street were caused by the discharge of aluminum hydroxide floc (in the filter backwash) from the drinking-water-treatment process. Filter backwash had the highest concentration of aluminum (27,240 µg/L). Given that the filter backwash contained 270 mg/L of suspended solids, and assuming little dissolved aluminum, the solids discharged as filter backwash were approximately 10 percent aluminum.

Solubility of aluminum at neutral pH is low (Hem, 1985, p. 73); consequently, the increased concentration of aluminum at Central Avenue probably was not caused by ground-water inflow. Aluminum and iron are major components of suspended solids. It is unlikely, however, that suspended solids were the cause of increased concentrations of aluminum at Central Avenue because concentrations of suspended solids and iron were relatively low at this site (fig. 13, table 8). Increased concentrations of aluminum at Central Avenue could have been caused by the discharge of filter backwash upstream from Central Avenue. Although the concentration of suspended solids was low at Central Avenue, filter backwash contains high concentrations of aluminum; thus, even relatively small amounts of this type of suspended solids could increase concentrations of aluminum. Some evidence for this hypothesis is found by calculation of the aluminum/iron ratios for the base-flow samples by use of data given in table 8. The ratios ranged from 0.27 to 0.48 at Emerson Avenue, 0.45 to 1.33 at Central Avenue, and 0.95 to 4.05 at 16th Street, showing relative aluminum enrichment downstream. The aluminum/iron ratio for the filter backwash was 6.41 and the ratio for the aqueduct overflow was 0.72.

Concentrations of iron ranged from 370 to 430 μg/L at Emerson Avenue, from 230 to 330 μg/L at Central Avenue, and from 940 to 3,880 μg/L at 16th Street (table 8). Decreased concentrations of iron at Central Avenue may have been caused by the deposition of suspended sediment in the impoundment upstream from Keystone Avenue. The maximum concentration of iron was in the filter backwash (4,250 μg/L). Because alum is added to raw water to remove suspended solids, and because iron is a principal chemical component of suspended sediment removed by alum, the discharge of filter backwash was primarily responsible for the increased concentrations of iron at 16th Street.

Concentrations of barium ranged from 30 to 60 μg/L at Emerson Avenue, from 60 to 110 μg/L at Central Avenue, and from 60 to 140 μg/L at 16th Street (table 8). Increased concentrations of barium at Central Avenue and 16th Street may have been caused by the inflow of ground water. The maximum concentration of barium was in the filter backwash (160 μg/L). The discharge of filter backwash contributed to the increased concentrations of barium at 16th Street.

Concentrations of arsenic ranged from 1 to 2 μg/L at Emerson Avenue and at Central Avenue but were generally greater at Emerson Avenue (table 8). Concentrations of arsenic at 16th Street ranged from 2 to 10 μg/L. The cause of the increased concentrations of arsenic at 16th Street could not be explained on the basis of data collected during this study. Increased concentrations at 16th Street could not be attributed to the discharge of filter backwash because the concentration of arsenic in the backwash was only 2 μg/L. Ground-water inflow probably is not the cause of increased concentrations of arsenic because increased concentrations were not measured at Central Avenue where base flow is composed largely of ground-water inflow.

Fecal Coliform Bacteria

Concentrations of fecal coliform bacteria during base flow generally were lowest at Central Avenue and highest at 16th Street. Concentrations of fecal coliform bacteria ranged from 100 to 2,000 col/100 mL at Emerson Avenue, from 200 to 500 col/100 mL at Central Avenue, and from <100 to 12,800 col/100 mL at 16th Street (table 9). Concentrations of bacteria at 16th Street might have been higher than those measured because a dechlorinating reagent was not added to the samples, and the filter backwash probably contained chlorine.

Water Quality of Storm Runoff and Comparisons with Water Quality of Base Flow

The water quality of storm runoff was characterized by measurements made in the field during a storm-runoff synoptic survey and by chemical and biological analyses of water samples.

Synoptic Survey

A synoptic water-quality survey of the downstream reach of Fall Creek was done during a period of storm runoff (storm 6) on September 29, 1987—5 days after the base-flow synoptic survey. Measurements of water quality were made in the field at eight stations from Emerson Avenue to 16th Street (figs. 3, 14, table 10) to determine longitudinal changes in water quality in the urbanized area of Indianapolis that could be attributed to storm runoff. Most of the runoff generated by this small storm occurred downstream from Emerson Avenue, and water quality was measured after the peak during decreasing streamflow (fig. 11).

In general, water-quality patterns observed during the storm-runoff synoptic survey were similar to those observed during the base-flow synoptic survey (figs. 12, 14). Streamflow was greater during the storm-runoff survey, especially at the most downstream stations. Specific conductance increased dramatically in the downstream reach as it did during the base-flow survey, but specific conductance was lower because runoff typically is more dilute (contains lower concentrations of ions and dissolved material) than base flow. Water temperature during the storm-runoff survey was 2°C higher than that during the base-flow survey, probably because of warmer air temperatures on the day of and the day preceding the storm-runoff survey. Concentrations of dissolved oxygen were similar to those during the base-flow survey except that dissolved-oxygen concentration at Central Avenue was 1.0 mg/L (table 10), 3.3 mg/L less than during the base-flow survey (table 7). The decreased concentration of dissolved oxygen probably was caused by (1) the consumption of oxygen by oxygen-demanding materials from combined-sewer overflows, urban runoff, and the resuspension of sediment that had accumulated on the streambed; and (2) the inflow of anoxic water from combined-sewer overflows.

Table 10. Water-quality sampling stations and measurements for the storm-runoff synoptic survey, storm 6, Fall Creek, September 29, 1987

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degree Celsius; mi, mile; mg/L, milligrams per liter; --, no data]

Sampling station on Fall Creek[1]	River mile (mi)	Time	Streamflow (ft^3/s)	Specific conductance (µS/cm)	pH	Water temperature (°C)	Dissolved oxygen (mg/L)
16th Street	1.3	1700	71	827	7.9	20.3	7.5
Dr. Martin Luther King Jr. Street	2.4	1612	--	749	7.8	19.9	7.2
Capitol Avenue	3.2	1602	--	686	7.5	20.1	5.3
Central Avenue	3.8	1649	29	601	7.3	20.4	1.0
30th Street	4.3	1820	--	636	7.3	19.3	2.4
Monon Railroad bridge	5.2	1545	--	575	7.6	19.4	5.6
39th Street	5.8	1530	--	523	7.7	20.6	8.2
Emerson Avenue	9.2	1630	70	480	8.3	20.1	9.1

[1] Locations of synoptic sampling stations are shown in figure 3.

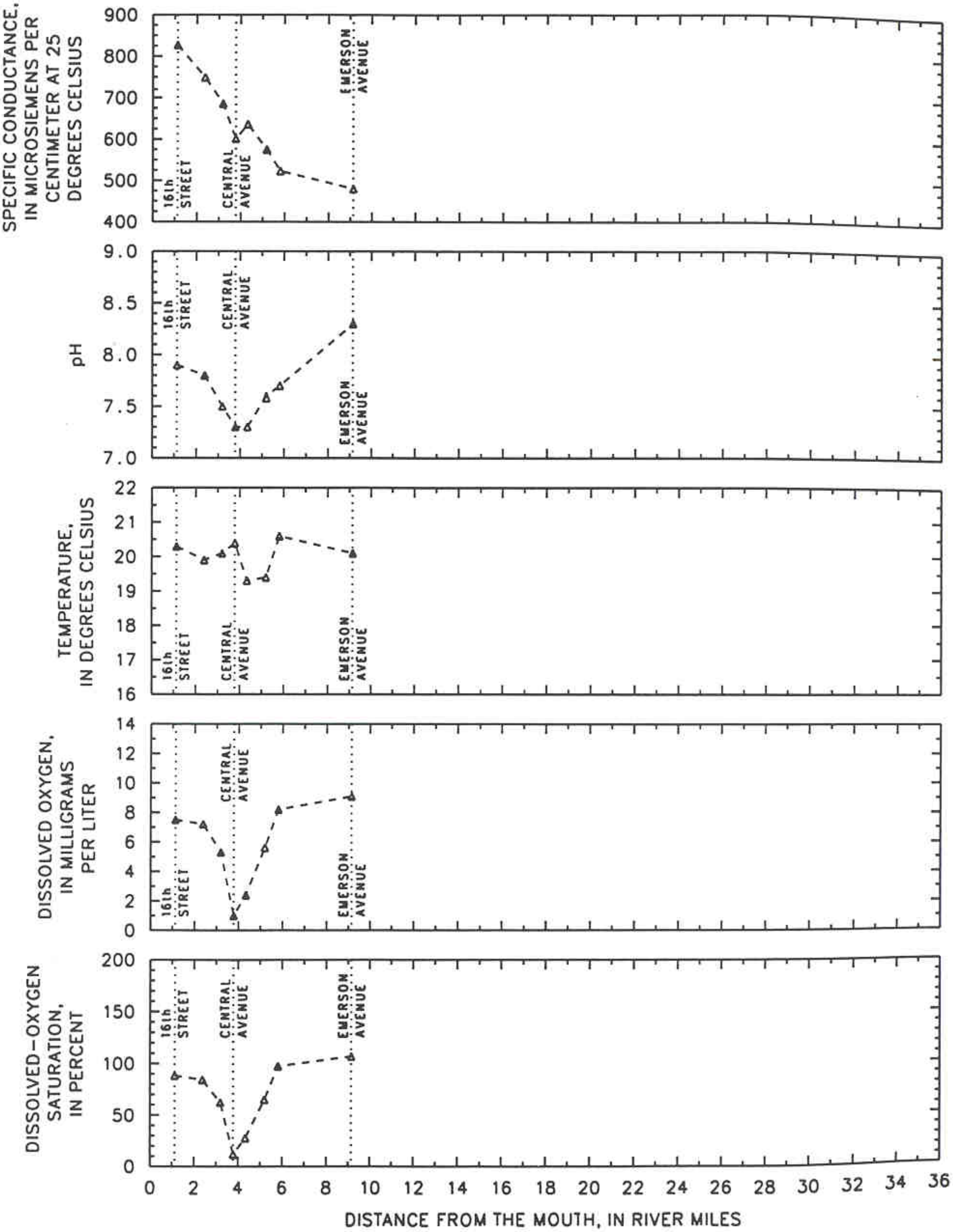

Figure 14. Longitudinal plots of water quality in Fall Creek during storm runoff, September 29, 1987. (Sampling sites are described in table 10 and shown in fig. 3.)

Chemical, Physical, and Biologic Characteristics

Multiple water-quality samples were collected over the hydrograph during six periods of storm runoff at Emerson Avenue, Central Avenue, and 16th Street (fig. 3). Most of the samples were composited by use of a flow and time weighting technique. For some storms, several composite (or individual) water-quality samples were required to characterize the period of storm runoff. Constituents and properties determined include field-measured characteristics, major anions, gross measures, nutrients, metals and trace elements (table 11), and fecal coliform bacteria (table 12). Analytical results for these samples, including samples split to assess analytical precision for the quality-assurance program, are reported in tables 11 and 12.

Analytical results reported in table 11 and continuous records of streamflow were used to mathematically calculate an event-mean concentration for each constituent for each storm (table 13, fig. 13). For split samples, the average (mean) concentration was used in the calculations. Event-mean concentration is used in this report to represent the streamflow-weighted average concentration during the period of storm runoff (runoff load divided by runoff volume). Concentrations less than the detection limit were assigned concentrations one-half the detection limit for the purpose of calculating event-mean concentration. Event-mean concentrations were used for all water-quality interpretations.

Specific Conductance, Dissolved Oxygen, Temperature, and pH

Patterns of water quality measured in the field at Emerson Avenue, Central Avenue, and 16th Street during base flow immediately before rainfall or runoff generally were the same as those measured during the base-flow and storm-runoff synoptic surveys. Specific conductance was least at Emerson Avenue and greatest at 16th Street, pH and concentrations of dissolved oxygen were greatest at Emerson Avenue and least at Central Avenue, and water temperature was least at Central Avenue (figs. 6–11). These water-quality patterns were maintained during storm runoff for the four storms characterized by low rates of storm runoff (storms 3–6, figs. 8–11). More complex water-quality patterns were exhibited during storm runoff for the two storms characterized by high rates of storm runoff (storms 1–2, figs. 6–7).

In general, specific conductance, pH, water temperature, and concentrations of dissolved oxygen were lower during storm runoff than during base flow (figs. 6–11). Specific conductance decreased because rainfall and surface runoff typically contain lower concentrations of ions (ions increase electrical conductance) than does base flow. Values of pH decreased during storm runoff because rainfall is acidic. Concentrations of dissolved oxygen decreased probably because oxygen was consumed by oxygen-demanding materials from combined-sewer overflows, urban runoff, and resuspended sediment and because of the discharge of anoxic water from combined-sewer overflows.

High rates of storm runoff seemed to affect field-measured water quality to a greater degree than did low rates of runoff. Characteristics of storm runoff and its effect on dissolved oxygen, pH, water temperature, and specific conductance are discussed in Martin and Craig (1990, p. 17, 27–41).

Concentrations of dissolved oxygen measured at Central Avenue were less than the Indiana minimum ambient water-quality standard of 4.0 mg/L during all storms (figs. 6–11). For storms that occurred during low base-flow rates, concentrations of dissolved oxygen at Central Avenue were near or less than 4.0 mg/L before rainfall or runoff. During storm runoff, concentrations of dissolved oxygen decreased further (figs. 8–11).

Table 11. Water-quality analyses for samples collected during periods of storm runoff

[i.d., identification number; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degree Celsius; mg/L, milligrams per liter; n.a., not applicable; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; µg/L, micrograms per liter; --, no data; <, less than; ≥, greater than or equal to; ss, split sample]

Site	Sample i.d.[1]	Sample type	First sample[2]		Last sample[3]		Streamflow[4] (ft^3/s)	Specific conductance[4] (µS/cm)	pH [4]	Water temperature (°C)	Dissolved oxygen[4] (mg/L)
			Date	Time	Date	Time					
Emerson	Storm 1	Composite	7-26-87	1940	7-28-87	0855	63–138	380–457	7.8–8.4	25.1–28.0	6.6–8.3
Central	Storm 1	Composite	7-26-87	2135	7-28-87	0930	72–320	319–637	7.2–7.8	24.1–26.0	.5–7.7
16th Street	Storm 1	Composite ss[5]	7-26-87	2310	7-28-87	1248	85–356	384–716	7.5–8.0	25.4–28.1	3.4–6.8
16th Street	Storm 1	Composite ss[5]	7-26-87	2310	7-28-87	1248	85–356	384–716	7.5–8.0	25.4–28.1	3.4–6.8
Emerson	Storm 2a	Composite	7-29-87	2242	7-31-87	0359	83–495	318–433	7.8–8.1	24.7–27.6	6.2–8.2
Central	Storm 2a	Composite	7-29-87	2206	7-31-87	0440	41–367	333–571	7.2–8.1	24.2–26.4	1.9–7.8
16th Street	Storm 2a	Composite ss[5]	7-29-87	2225	7-31-87	0318	69–439	368–591	7.6–7.9	24.3–26.7	4.5–7.0
16th Street	Storm 2a	Composite ss[5]	7-29-87	2225	7-31-87	0318	69–439	368–591	7.6–7.9	24.3–26.7	4.5–7.0
Emerson	Storm 2b	Composite	7-31-87	0725	8-01-87	0714	173–271	377–437	7.8–8.4	25.6–26.6	6.4–8.8
Central	Storm 2b	Composite	7-31-87	0838	8-01-87	0807	141–212	359–466	7.7–8.0	25.2–26.0	6.5–8.9
16th Street	Storm 2b	Composite	7-31-87	0715	8-01-87	0838	183–323	422–502	7.7–8.0	25.3–26.5	6.3–7.6
Emerson	Storm 2c	Composite	8-01-87	2021	8-02-87	0741	166–173	426–438	8.1–8.3	25.8–26.8	7.4–8.8
Central	Storm 2c	Composite	8-01-87	2157	8-02-87	0834	136–141	466–472	7.8–7.9	25.4–25.9	7.0–8.0
16th Street	Storm 2c	Composite	8-01-87	2330	8-02-87	0924	159–177	508–512	7.8–8.0	25.2–26.1	5.7–6.8
Emerson	Storm 2d	Individual	8-03-87	0730	n.a.	n.a.	175	438	7.8	26.4	6.0
Central	Storm 2d	Individual	8-03-87	0827	n.a.	n.a.	141	454	7.7	26.8	5.1
16th Street	Storm 2d	Individual	8-03-87	1003	n.a.	n.a.	180	513	7.8	26.9	5.7
Emerson	Storm 3	Composite	8-26-87	2114	8-27-87	0838	62– 67	446–454	7.9–8.3	22.8–23.0	6.8–8.5
Central	Storm 3	Composite	8-26-87	2050	8-27-87	0808	28– 99	530–602	7.2–7.3	21.0–21.5	2.0–5.0
16th Street	Storm 3a	Composite ss[5]	8-26-87	2055	8-27-87	1107	35– 77	706–798	7.6–7.8	21.2–22.2	5.5–8.7
16th Street	Storm 3a	Composite ss[5]	8-26-87	2055	8-27-87	1107	35– 77	706–798	7.6–7.8	21.2–22.2	5.5–8.7
16th Street	Storm 3b	Individual	8-27-87	1807	n.a.	n.a.	63	762	7.7	22.1	7.3

Table 11. Water-quality analyses for samples collected during periods of storm runoff—Continued

Site	Sample i.d.[1]	Sample type	First sample[2]		Last sample[3]		Streamflow[4] (ft^3/s)	Specific conductance[4] (μS/cm)	pH [4]	Water temperature (°C)	Dissolved oxygen[4] (mg/L)
			Date	Time	Date	Time					
Emerson	Storm 4a	Composite	9-11-87	0023	9-11-87	1207	64– 78	429–435	8.0–8.2	22.2–22.6	6.3–7.7
Central	Storm 4a	Composite	9-10-87	2308	9-11-87	1143	15– 30	612–646	7.2–7.4	21.3–22.4	2.5–3.9
16th Street	Storm 4a	Composite	9-10-87	2232	9-11-87	1144	18– 58	732–782	7.7–7.9	22.2–23.2	6.3–7.9
Emerson	Storm 4b	Composite	9-11-87	1742	9-11-87	1930	75– 76	451–459	8.1–8.1	23.2–23.4	7.8–8.3
Central	Storm 4b	Composite	9-11-87	1704	9-12-87	0738	36– 43	626–662	7.2–7.4	21.7–22.8	3.4–5.0
16th Street	Storm 4b	Composite	9-11-87	1606	9-12-87	0822	61– 69	733–742	7.8–8.1	22.2–23.8	6.0–9.7
Emerson	Storm 4c	Composite	9-12-87	1358	9-13-87	0145	70– 71	434–454	8.0–8.4	22.2–23.3	7.7–8.7
Central	Storm 4c	Composite	9-12-87	1440	9-13-87	0215	27– 35	548	7.3	21.7	4.1
16th Street	Storm 4c	Composite	9-12-87	1528	9-13-87	0252	45– 61	732–774	7.8–7.9	22.3–24.1	6.1–8.3
Emerson	Storm 5	Composite	9-17-87	0213	9-17-87	0745	55– 59	448–455	7.8–8.0	21.4–22.0	5.9–7.3
Central	Storm 5a	Composite	9-17-87	0122	9-17-87	1009	24–120	499–634	7.1–7.4	20.6–21.0	.8–4.0
16th Street	Storm 5	Composite	9-17-87	0158	9-17-87	1300	4–104	606–739	7.6–7.8	21.3–22.1	4.1–6.3
Central	Storm 5b	Individual	9-17-87	1215	n.a.	n.a.	28	506	7.2	21.0	1.3
Emerson	Storm 6	Composite	9-29-87	0634	9-30-87	0425	52– 61	478–493	7.8–8.3	18.3–20.3	6.8–9.3
Central	Storm 6	Composite ss[5]	9-29-87	0614	9-30-87	0832	18– 65	599–726	7.3–7.6	17.3–20.4	.5–2.9
Central	Storm 6	Composite ss[5]	9-29-87	0614	9-30-87	0832	18– 65	599–726	7.3–7.6	17.3–20.4	.5–2.9
16th Street	Storm 6a	Composite	9-29-87	0623	9-30-87	0903	31–104	805–871	7.7–7.9	18.3–20.6	6.3–7.6
16th Street	Storm 6b	Individual	9-30-87	1615	n.a.	n.a.	35	828	7.9	19.8	7.8

Table 11. Water-quality analyses for samples collected during periods of storm runoff—Continued

Site	Sample i.d.[1]	Dissolved alkalinity (mg/L as $CaCO_3$)	Dissolved sulfate (mg/L)	Dissolved chloride (mg/L)	Dissolved solids (mg/L)	Total solids (mg/L)	Suspended solids[9] (mg/L)	Total 20-day carbonaceous oxygen demand (mg/L)	Total chemical oxygen demand (mg/L)	Total recoverable oil and grease (mg/L)
Emerson	Storm 1	143	33	25	275	348	73	2	20	<1
Central	Storm 1	152	38	30	318	331	13	14	30	2
16th Street	Storm 1 ss[5]	188	50	45	387	471	84	6	33	<1
16th Street	Storm 1 ss[5]	188	50	44	389	454	65	6	34	1
Emerson	Storm 2a	123	30	23	263	379	116	4	24	<1
Central	Storm 2a	128	30	25	285	330	45	≥ 22	29	<1
16th Street	Storm 2a ss[5]	139	37	29	290	412	122	14	30	1
16th Street	Storm 2a ss[5]	137	37	29	305	390	85	8	33	2
Emerson	Storm 2b	131	32	23	289	317	28	<1	20	<1
Central	Storm 2b	130	32	24	285	298	13	<1	18	<1
16th Street	Storm 2b	139	36	29	298	381	83	3	27	<1
Emerson	Storm 2c	142	35	24	293	339	46	[6]16	18	<1
Central	Storm 2c	152	38	28	291	344	53	[6]18	20	<1
16th Street	Storm 2c	152	43	32	358	404	46	[6]17	23	2
Emerson	Storm 2d	155	35	25	260	307	47	[6]13	18	1
Central	Storm 2d	158	38	28	295	308	13	[6]12	21	1
16th Street	Storm 2d	170	43	33	304	353	49	[6]17	18	1
Emerson	Storm 3	158	36	28	273	328	55	4	14	<1
Central	Storm 3	176	48	37	328	373	45	5	29	3
16th Street	Storm 3a ss[5]	222	64	59	466	681	215	14	38	3
16th Street	Storm 3a ss[5]	231	66	59	470	640	170	10	47	1
16th Street	Storm 3b	237	65	62	468	544	76	6	23	<1

Table 11. Water-quality analyses for samples collected during periods of storm runoff—Continued

Site	Sample i.d.[1]	Dissolved alkalinity (mg/L as $CaCO_3$)	Dissolved sulfate (mg/L)	Dissolved chloride (mg/L)	Dissolved solids (mg/L)	Total solids (mg/L)	Suspended solids[9] (mg/L)	Total 20-day carbonaceous oxygen demand (mg/L)	Total chemical oxygen demand (mg/L)	Total recoverable oil and grease (mg/L)
Emerson	Storm 4a	160	36	27	293	317	24	11	15	1
Central	Storm 4a	208	60	41	417	429	12	12	17	1
16th Street	Storm 4a	224	66	59	515	1,223	708	62	90	3
Emerson	Storm 4b	158	37	28	307	316	9	10	17	<1
Central	Storm 4b	202	57	39	413	413	0	11	15	<1
16th Street	Storm 4b	224	66	57	485	761	276	32	65	1
Emerson	Storm 4c	160	36	27	303	306	3	12	15	<1
Central	Storm 4c	184	49	34	349	360	11	11	15	3
16th Street	Storm 4c	228	67	54	478	549	71	19	31	<1
Emerson	Storm 5	159	36	34	278	315	37	7	16	1
Central	Storm 5a	176	50	34	344	368	24	16	30	7
16th Street	Storm 5	212	61	42	418	508	90	6	29	2
Central	Storm 5b	152	44	31	305	314	9	14	28	3
Emerson	Storm 6	164	38	30	288	304	16	2	17	2
Central	Storm 6 ss[5]	208	56	44	395	411	16	10	28	3
Central	Storm 6 ss[5]	206	56	43	399	418	19	10	29	3
16th Street	Storm 6a	252	72	64	499	567	68	6	20	1
16th Street	Storm 6b	258	70	66	507	547	40	5	20	1

Table 11. Water-quality analyses for samples collected during periods of storm runoff—Continued

Site	Sample i.d.[1]	Total nitrate plus nitrite (mg/L as N)	Total ammonia (mg/L as N)	Total organic nitrogen (mg/L)	Total phosphorus (mg/L)	Dissolved orthophosphate (mg/L as P)	Total arsenic (µg/L)	Total mercury (µg/L)	Total selenium (µg/L)
Emerson	Storm 1	0.19	0.10	0.80	0.17	<0.01	4	<0.2	<1
Central	Storm 1	.28	.40	1.24	.27	<.01	<1	<.2	<1
16th Street	Storm 1 ss[5]	.41	.35	[7] .09	.49	<.01	4	<.2	<1
16th Street	Storm 1 ss[5]	.41	.37	1.64	.50	<.01	4	<.2	<1
Emerson	Storm 2a	.27	.05	1.16	.17	<.01	3	<.2	<1
Central	Storm 2a	.27	.26	1.15	.60	<.01	3	<.2	<1
16th Street	Storm 2a ss[5]	.32	.25	1.14	.44	<.01	3	<.2	<1
16th Street	Storm 2a ss[5]	.33	.22	2.47	.56	<.01	3	<.2	<1
Emerson	Storm 2b	.29	.07	1.21	.16	<.01	2	<.2	<1
Central	Storm 2b	.34	.08	1.12	.17	<.01	2	<.2	<1
16th Street	Storm 2b	.39	.16	1.18	.44	<.01	3	<.2	<1
Emerson	Storm 2c	.18	.05	1.09	.14	<.01	1	<.2	<1
Central	Storm 2c	.21	.14	1.13	.14	<.01	<1	<.2	<1
16th Street	Storm 2c	.33	.22	.97	.28	<.01	2	<.2	<1
Emerson	Storm 2d	.26	.10	1.12	.12	.01	2	<.2	<1
Central	Storm 2d	.21	.08	1.15	.15	<.01	2	<.2	<1
16th Street	Storm 2d	.24	.20	.92	.23	<.01	2	<.2	<1
Emerson	Storm 3	.18	.10	.93	.10	.01	1	<.2	<1
Central	Storm 3	.33	.71	1.42	.33	.03	1	<.2	<1
16th Street	Storm 3a ss[5]	.69	.59	2.43	1.35	.04	10	<.2	<1
16th Street	Storm 3a ss[5]	.74	.58	2.46	1.33	.09	10	<.2	<1
16th Street	Storm 3b	.91	.38	1.32	.39	.08	3	<.2	<1

Table 11. Water-quality analyses for samples collected during periods of storm runoff—Continued

Site	Sample i.d.[1]	Total nitrate plus nitrite (mg/L as N)	Total ammonia (mg/L as N)	Total organic nitrogen (mg/L)	Total phosphorus (mg/L)	Dissolved orthophosphate (mg/L as P)	Total arsenic (μg/L)	Total mercury (μg/L)	Total selenium (μg/L)
Emerson	Storm 4a	.09	.09	.88	.09	.01	2	<.2	<1
Central	Storm 4a	.35	.35	.75	.09	<.01	2	<.2	<1
16th Street	Storm 4a	.62	.85	7.08	6.76	.03	31	<.2	<1
Emerson	Storm 4b	.13	.11	.83	.08	<.01	2	<.2	<1
Central	Storm 4b	.26	.27	.67	.05	<.01	1	<.2	<1
16th Street	Storm 4b	3.60	.54	3.45	2.06	.02	9	<.2	1
Emerson	Storm 4c	.09	.10	1.14	.09	<.01	1	<.2	<1
Central	Storm 4c	.22	.15	.70	.08	<.01	1	<.2	<1
16th Street	Storm 4c	.54	.38	1.69	.62	.02	<1	<.2	<1
Emerson	Storm 5	.17	.02	.84	.09	<.01	2	<.2	<1
Central	Storm 5a	.36	.74	1.58	.29	.04	1	<.2	<1
16th Street	Storm 5	.61	.26	1.45	.46	.03	4	<.2	<1
Central	Storm 5b	.37	.61	1.38	.25	.04	2	<.2	<1
Emerson	Storm 6	.19	.12	.73	.29	<.01	1	<.2	<1
Central	Storm 6 ss[5]	.38	.67	1.07	.44	.04	1	<.2	<1
Central	Storm 6 ss[5]	.34	.75	1.15	.80	.04	1	<.2	<1
16th Street	Storm 6a	.97	.21	1.47	1.60	.07	6	<.2	<1
16th Street	Storm 6b	[8] --	.31	1.03	.30	.08	2	<.2	<1

Table 11. Water-quality analyses for samples collected during periods of storm runoff—Continued

Site	Sample i.d.[1]	Total recoverable aluminum (µg/L)	Total recoverable barium (µg/L)	Total recoverable cadmium (µg/L)	Total recoverable chromium (µg/L)	Total recoverable copper (µg/L)	Total recoverable iron (µg/L)	Total recoverable lead (µg/L)	Total recoverable nickel (µg/L)	Total recoverable zinc (µg/L)
Emerson	Storm 1	1,310	<10	<10	<10	20	2,060	10	<10	20
Central	Storm 1	630	70	<10	<10	20	740	10	<10	20
16th Street	Storm 1 ss[5]	3,130	80	<10	10	20	2,700	20	<10	30
16th Street	Storm 1 ss[5]	3,150	100	<10	<10	20	2,780	20	<10	30
Emerson	Storm 2a	2,050	80	<10	10	10	4,070	20	<10	30
Central	Storm 2a	2,190	80	<10	<10	20	2,070	20	<10	30
16th Street	Storm 2a ss[5]	2,690	60	<10	<10	20	2,840	10	<10	30
16th Street	Storm 2a ss[5]	2,410	10	<10	<10	20	2,630	20	<10	30
Emerson	Storm 2b	770	60	<10	<10	10	1,380	10	<10	10
Central	Storm 2b	710	40	<10	<10	10	960	<10	<10	10
16th Street	Storm 2b	2,810	70	<10	<10	20	2,660	<10	<10	20
Emerson	Storm 2c	390	30	<10	<10	20	820	<10	<10	10
Central	Storm 2c	380	70	<10	<10	20	510	10	<10	10
16th Street	Storm 2c	940	90	<10	<10	10	1,040	10	<10	10
Emerson	Storm 2d	390	60	<10	<10	<10	930	<10	<10	<10
Central	Storm 2d	220	50	<10	<10	<10	470	<10	<10	10
16th Street	Storm 2d	830	50	<10	<10	10	790	<10	<10	10
Emerson	Storm 3	280	90	<10	<10	<10	600	10	<10	<10
Central	Storm 3	310	40	<10	<10	20	480	<10	<10	20
16th Street	Storm 3a ss[5]	11,490	70	<10	20	30	3,620	20	10	40
16th Street	Storm 3a ss[5]	11,450	90	<10	20	30	3,630	20	10	40
16th Street	Storm 3b	1,890	90	<10	<10	<10	1,160	<10	10	10

Table 11. Water-quality analyses for samples collected during periods of storm runoff—Continued

Site	Sample i.d.[1]	Total recoverable aluminum (μg/L)	Total recoverable barium (μg/L)	Total recoverable cadmium (μg/L)	Total recoverable chromium (μg/L)	Total recoverable copper (μg/L)	Total recoverable iron (μg/L)	Total recoverable lead (μg/L)	Total recoverable nickel (μg/L)	Total recoverable zinc (μg/L)
Emerson	Storm 4a	230	30	<10	<10	<10	460	10	<10	<10
Central	Storm 4a	160	30	<10	<10	<10	300	<10	<10	10
16th Street	Storm 4a	44,800	240	<10	70	70	15,150	70	40	160
Emerson	Storm 4b	220	30	<10	<10	<10	420	<10	<10	<10
Central	Storm 4b	200	70	<10	<10	<10	270	<10	<10	<10
16th Street	Storm 4b	15,990	160	<10	20	20	6,800	30	20	60
Emerson	Storm 4c	200	90	<10	<10	<10	460	<10	<10	<10
Central	Storm 4c	210	10	<10	<10	70	260	50	<10	<10
16th Street	Storm 4c	4,210	120	<10	<10	10	1,930	20	<10	20
Emerson	Storm 5	220	40	<10	<10	<10	610	<10	<10	<10
Central	Storm 5a	300	50	<10	<10	20	650	<10	<10	30
16th Street	Storm 5	2,540	110	<10	<10	10	1,660	<10	<10	20
Central	Storm 5b	90	130	<10	<10	10	330	<10	<10	20
Emerson	Storm 6	190	90	<10	<10	<10	480	<10	<10	<10
Central	Storm 6 ss[5]	190	70	<10	<10	10	310	<10	<10	20
Central	Storm 6 ss[5]	180	70	<10	<10	20	310	<10	<10	10
16th Street	Storm 6a	3,860	70	<10	<10	10	1,710	<10	<10	20
16th Street	Storm 6b	1,110	70	<10	<10	<10	770	<10	<10	<10

[1] The suffixes a, b, c, and d indicate that more than one composite sample was needed to represent the storm hydrograph.
[2] Midpoint time of sample collection for the first sample collected for a composite sample or the only sample collected for an individual sample.
[3] Midpoint time of sample collection for the last sample collected for a composite sample.
[4] Range of field measurements observed for a composite sample or the field measurements observed for an individual sample.
[5] A split sample (ss) is one of a pair of theoretically identical samples used to assess analytical precision. The mean concentration was used for all calculations and interpretations.
[6] Nitrification was not inhibited in these samples. Reported concentrations were adjusted for oxidizable nitrogen.
[7] Anomalous concentration. Not used to calculate event-mean concentration.
[8] Median storm-runoff concentration at this site (0.54 mg/L) used to calculate event-mean concentration.
[9] Suspended solids were calculated as the difference between total solids and dissolved solids.

Table 12. Concentrations of fecal coliform bacteria during periods of storm runoff

[col/100 mL, colonies per 100 milliliters; >, greater than; <, less than]

	Sampling station					
	Emerson Avenue		Central Avenue		16th Street	
Date	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]
Storm 1						
7-26-87	1825	400	2155	22,000	2235	600
	2045	7,300	2355	>20,000		
	2325	4,500				
7-27-87	1346	6,700	0730	>20,000	0100	1,400
	1732	2,700	1205	16,100	0710	1,000
	2132	6,200	1240	43,000	1215	11,800
			1300	10,800	1336	22,800
			1316	21,000	1415	86,000
			1430	98,400	1645	8,800
			1721	288,000	1930	4,200
			2316	27,000		
7-28-87	0847	48,000				
Storm 2						
7-29-87	2302	4,000	2205	1,800	2200	2,000
			2251	97,600		
			2340	80,000		
7-30-87	0005	2,100	0202	64,800	0015	2,100
	0020	2,100	0500	470,000	0105	36,400
	0100	1,900	0835	20,000	0400	24,100
	0155	1,100	0849	21,000	0600	2,700
	0415	3,100	0927	45,200	0800	25,200
	0705	2,100	1333	14,200	0850	5,600
	0945	2,700	1643	1,400	1010	6,600
	1100	1,700	2046	9,600	1240	38,100
	1150	800			1520	5,000
	1255	1,200			1825	5,800
	1405	4,700				
	1800	2,500				
	1942	7,900				
	2345	5,200				

Table 12. Concentrations of fecal coliform bacteria during periods of storm runoff—Continued

	Sampling station					
	Emerson Avenue		Central Avenue		16th Street	
Date	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]	Time	Fecal coliform bacteria (col/100 mL) (31625)[1]
Storm 2 continued						
7-31-87	0407	9,200	0040	5,800	0010	7,500
	0730	2,800	0429	9,400	0311	600
	1026	650	0833	1,200	0708	800
	1330	900	1131	1,800	1015	1,800
					1305	<100
8-1-87	1636	1,800	1429	5,000	1628	4,100
			1650	3,000		
Storm 3						
8-26-87	2114	200	2150	8,000	2035	1,500
	2230	1,900	2230	20,200	2238	2,000
	2330	2,900	2320	5,000		
			2345	18,300		
8-27-87	0030	1,100	0025	22,600	0136	17,000
	0225	<100	0115	12,200	0311	152,000
			0243	29,800		
Storm 5						
9-17-87	0200	1,600	0244	3,000	0140	8,700
	0500	5,400	0307	35,600	0520	1,900
	0730	1,500	0325	48,000	1115	3,100
			0440	27,600		
			0548	59,400		
			0752	57,600		
Storm 6						
9-29-87	1130	4,500	1210	69,600	1105	500
	1530	2,000	1330	53,400	1510	32,000
	1920	1,400	1625	223,200	2035	9,800
			2018	58,400		
9-30-87	0805	1,200	0830	26,000	0857	150

[1] WATSTORE (U.S. Geological Survey) and STORET (U.S. Environmental Protection Agency) parameter code.

Table 13. Event-mean concentrations of constituents during periods of storm runoff

[mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; N, nitrogen; P, phosphorus; n.a., not applicable; µg/L, micrograms per liter]

Site	Storm	Dissolved alkalinity (mg/L as $CaCO_3$)	Dissolved sulfate (mg/L)	Dissolved chloride (mg/L)	Dissolved solids (mg/L)	Total solids (mg/L)	Suspended solids[2] (mg/L)	Total 20-day carbonaceous biochemical oxygen demand (mg/L)	Total chemical oxygen demand (mg/L)	Total recoverable oil and grease (mg/L)
Emerson	Storm 1	143.0	33.0	25.0	275.0	348.0	73.0	2.0	20.0	0.50
Central	Storm 1	152.0	38.0	30.0	318.0	331.0	13.0	14.0	30.0	2.0
16th Street	Storm 1	188.0	50.0	44.5	388.0	462.5	74.5	6.0	33.5	1.0
Emerson	Storm 2	133.5	32.3	23.5	275.9	344.2	68.3	6.8	20.8	.57
Central	Storm 2	137.7	33.3	25.8	287.6	321.4	33.8	14.2	23.2	.57
16th Street	Storm 2	145.4	38.7	30.1	310.6	389.2	78.6	10.6	26.6	1.2
Emerson	Storm 3	158.0	36.0	28.0	273.0	328.0	55.0	4.0	14.0	.50
Central	Storm 3	176.0	48.0	37.0	328.0	373.0	45.0	5.0	29.0	3.0
16th Street	Storm 3	229.7	65.0	59.9	468.0	624.9	156.9	10.2	36.5	1.5
Emerson	Storm 4	159.6	36.2	27.2	301.2	311.2	10.0	11.3	15.5	.63
Central	Storm 4	196.5	54.6	37.5	390.2	396.5	6.3	11.2	15.4	1.5
16th Street	Storm 4	225.5	66.4	56.3	487.7	764.5	276.8	32.5	56.9	1.2
Emerson	Storm 5	159.0	36.0	34.0	278.0	315.0	37.0	7.0	16.0	1.0
Central	Storm 5	171.3	48.8	33.4	336.3	357.4	21.1	15.6	29.6	6.2
16th Street	Storm 5	212.0	61.0	42.0	418.0	508.0	90.0	6.0	29.0	2.0
Emerson	Storm 6	164.0	38.0	30.0	288.0	304.0	16.0	2.0	17.0	2.0
Central	Storm 6	207.0	56.0	43.5	397.0	414.5	17.5	10.0	28.5	3.0
16th Street	Storm 6	252.5	71.8	64.2	499.7	565.2	65.5	5.9	20.0	1.0
Detection limit[1]		1	1	1	10	10	n.a.	1	1	1

Table 13. Event-mean concentrations of constituents during periods of storm runoff—Continued

Site	Storm	Total nitrate plus nitrite (mg/L as N)	Total ammonia (mg/L as N)	Total organic nitrogen (mg/L)	Total phosphorus (mg/L)	Dissolved orthophosphate (mg/L as P)	Total arsenic (µg/L)	Total mercury (µg/L)	Total selenium (µg/L)
Emerson	Storm 1	0.190	0.100	0.800	0.170	0.005	4.0	0.10	0.50
Central	Storm 1	.280	.400	1.240	.270	.005	.50	.10	.50
16th Street	Storm 1	.410	.360	1.640	.495	.005	4.0	.10	.50
Emerson	Storm 2	.255	.062	1.153	.154	.006	2.2	.10	.50
Central	Storm 2	.267	.163	1.138	.331	.005	2.1	.10	.50
16th Street	Storm 2	.334	.205	1.332	.402	.005	2.7	.10	.50
Emerson	Storm 3	.180	.100	.930	.100	.010	1.0	.10	.50
Central	Storm 3	.330	.710	1.420	.330	.030	1.0	.10	.50
16th Street	Storm 3	.775	.522	2.101	1.049	.070	7.9	.10	.50
Emerson	Storm 4	.099	.100	1.001	.088	.006	1.5	.10	.50
Central	Storm 4	.262	.241	.696	.069	.005	1.2	.10	.50
16th Street	Storm 4	1.956	.536	3.443	2.358	.022	9.8	.10	.73
Emerson	Storm 5	.170	.020	.840	.090	.005	2.0	.10	.50
Central	Storm 5	.362	.714	1.541	.282	.040	1.2	.10	.50
16th Street	Storm 5	.610	.260	1.450	.460	.030	4.0	.10	.50
Emerson	Storm 6	.190	.120	.730	.290	.005	1.0	.10	.50
Central	Storm 6	.360	.710	1.110	.620	.040	1.0	.10	.50
16th Street	Storm 6	.932	.219	1.431	1.486	.071	5.6	.10	.50
Detection limit[1]		.005	.01	.01	.01	.01	1	.2	1

Table 13. Event-mean concentrations of constituents during periods of storm runoff—Continued

Site	Storm	Total recoverable aluminum (µg/L)	Total recoverable barium (µg/L)	Total recoverable cadmium (µg/L)	Total recoverable chromium (µg/L)	Total recoverable copper (µg/L)	Total recoverable iron (µg/L)	Total recoverable lead (µg/L)	Total recoverable nickel (µg/L)	Total recoverable zinc (µg/L)
Emerson	Storm 1	1,310	5.0	5.0	5.0	20	2,060	10	5.0	20
Central	Storm 1	630	70	5.0	5.0	20	740	10	5.0	20
16th Street	Storm 1	3,140	90	5.0	10	20	2,740	20	5.0	30
Emerson	Storm 2	1,130	61	5.0	6.9	11	2,235	12	5.0	17
Central	Storm 2	1,156	63	5.0	5.0	15	1,236	12	5.0	18
16th Street	Storm 2	2,076	75	5.0	5.0	17	2,113	9.7	5.0	20
Emerson	Storm 3	280	90	5.0	5.0	5.0	600	10	5.0	5.0
Central	Storm 3	310	40	5.0	5.0	20	480	5.0	5.0	20
16th Street	Storm 3	8,539	83	5.0	15	22	2,871	15	10	31
Emerson	Storm 4	212	61	5.0	5.0	5.0	451	6.3	5.0	5.0
Central	Storm 4	196	74	5.0	5.0	29	272	22	5.0	6.0
16th Street	Storm 4	16,730	159	5.0	23	25	6,482	33	18	63
Emerson	Storm 5	220	40	5.0	5.0	5.0	610	5.0	5.0	5.0
Central	Storm 5	259	66	5.0	5.0	18	587	5.0	5.0	28
16th Street	Storm 5	2,540	110	5.0	5.0	10	1,660	5.0	5.0	20
Emerson	Storm 6	190	90	5.0	5.0	5.0	480	5.0	5.0	5.0
Central	Storm 6	185	70	5.0	5.0	15	310	5.0	5.0	15
16th Street	Storm 6	3,619	70	5.0	5.0	9.6	1,628	5.0	5.0	19
Detection limit[1]		10	10	10	10	10	10	10	10	10

[1] Concentrations less than the detection limit were assigned concentrations one-half the detection limit for the calculation of event-mean concentration. Event-mean concentrations are reported to one additional significant figure than analytical measurements of the same magnitude.

[2] Suspended solids were calculated as the difference between total solids and dissolved solids.

Durations of concentrations of dissolved oxygen less than 4.0 mg/L at Central Avenue during storm runoff ranged from approximately 4 hours during storm 2 (fig. 7) to more than 24 hours during storm 6 (fig. 11). Minimum concentrations of dissolved oxygen at Central Avenue during storm runoff were 0.5, 1.9, 2.0, 2.5, 0.8, and 0.5 mg/L during storms 1–6, respectively (table 11). Concentrations of dissolved oxygen at 16th Street were less than 4.0 mg/L for approximately 1 hour during storm 1 (minimum 3.4 mg/L, fig. 6). The minimum concentration of dissolved oxygen at Emerson Avenue during storm runoff was 5.9 mg/L (table 11).

Major Anions

Concentrations of alkalinity, sulfate, and chloride measured in storm runoff increased downstream (fig. 13). The pattern of increase was similar to that measured in base flow, but the concentrations were somewhat less in storm runoff because of dilution by precipitation and runoff. Similarly, event-mean concentrations measured during the storms characterized by high rates of storm runoff (storms 1 and 2) were less than those measured during the storms characterized by low rates of storm runoff (storms 3–6, table 13).

Dissolved and Total Solids, Chemical Oxygen Demand, Carbonaceous Biochemical Oxygen Demand, and Oil and Grease

Concentrations of dissolved solids and total solids measured in storm runoff increased downstream in a pattern similar to that in base flow (fig. 13). Concentrations of dissolved solids measured at Emerson Avenue and 16th Street in storm runoff were similar to those measured in base flow, but those measured at Central Avenue were less than those measured in base flow. The water quality of base flow at Central Avenue is strongly influenced by ground-water inflow. Precipitation and surface runoff caused a discernible decrease in the concentration of dissolved solids at Central Avenue, a decrease that did not occur at the sites that were less influenced by ground-water inflow. Concentrations of total solids were predominantly controlled by concentrations of dissolved solids and, consequently, exhibited similar water-quality patterns (fig. 13). Concentrations of total solids in storm runoff at Emerson Avenue were slightly greater than those in base flow, indicating increased concentrations of suspended solids at this site that generally were not measured at Central Avenue or 16th Street.

Event-mean concentrations of suspended solids (calculated as the difference between total solids and dissolved solids, table 13) ranged from 10 to 73 mg/L at Emerson Avenue, from 6.3 to 45 mg/L at Central Avenue, and from 65.5 to 276.8 mg/L at 16th Street. As with base flow, storm runoff at Central Avenue had the lowest concentration and proportion of suspended solids whereas storm runoff at 16th Street had the highest (fig. 13). The lack of a discernible increase in suspended-solids concentration in storm runoff at 16th Street probably can be attributed to the large amounts of suspended solids discharged as filter backwash during base flow. Low concentrations and the lack of an increase in suspended-solids concentration in storm runoff at Central Avenue may be attributed to sedimentation in the impoundment at Keystone Avenue.

The highest concentrations of suspended solids and total solids in storm runoff at Emerson Avenue were measured during the two storms characterized by high rates of runoff (storms 1 and 2), whereas the highest concentrations of dissolved solids, suspended solids, and total solids at Central Avenue and 16th Street occurred during the four storms characterized by low rates of runoff (storms 3–6, table 13). High rates of runoff caused increased concentrations of suspended solids at Emerson Avenue, probably attributable to upstream erosion. High concentrations of suspended solids were not measured downstream (fig. 13). High rates of runoff decreased concentrations of dissolved solids at Central Avenue and 16th Street probably because base flow at these sites was composed largely of ground-water inflow (and aqueduct overflow at 16th Street) that had much higher concentrations of dissolved solids than did surface runoff. High rates of runoff had a negligible effect on the concentration of dissolved solids at Emerson Avenue because water released from Geist Reservoir probably had concentrations of dissolved solids that were similar to those in surface runoff.

Concentrations of CBOD in storm runoff generally were higher than those in base flow (fig. 13) and ranged from 2 to 11.3 mg/L at Emerson Avenue, from 5 to 15.6 mg/L at Central Avenue, and from 5.9 to 32.5 mg/L at 16th Street (table 13). Generally, the highest concentrations of CBOD and the most discernible increases compared to base flow occurred at Central Avenue. Concentrations of COD in storm runoff also were higher than those in base flow and ranged from 14 to 20.8 mg/L at Emerson Avenue, from 15.4 to 30 mg/L at Central Avenue, and from 20 to 56.9 mg/L at 16th Street. Concentrations of CBOD and COD were similar at Emerson and Central Avenues in base flow but were much higher at Central Avenue than at Emerson Avenue in storm runoff (fig 13). Increased concentrations of these measures of oxygen demand in runoff at Central Avenue probably were caused by combined-sewer overflows, urban runoff, and the resuspension of organic material deposited on the streambed.

Concentrations of oil and grease ranged from 0.5 to 2 mg/L at Emerson Avenue, from 0.57 to 6.2 mg/L at Central Avenue, and from 1 to 2 mg/L at 16th Street (table 13). Concentrations of oil and grease in storm runoff were similar to those in base flow, except at Central Avenue where concentrations in storm runoff were somewhat higher (fig. 13).

Nutrients

Concentrations of nutrients in storm runoff increased downstream and, for all nutrients except nitrate plus nitrite, were higher than those in base flow. Concentrations of nitrate plus nitrite in runoff at Central Avenue and 16th Street were similar to those in base flow; at Emerson Avenue, however, concentrations were slightly higher compared with those in base flow (fig. 13).

Event-mean concentrations of ammonia ranged from 0.02 to 0.12 mg/L at Emerson Avenue, from 0.163 to 0.714 mg/L at Central Avenue, and from 0.205 to 0.536 mg/L at 16th Street (table 13). Concentrations of ammonia at Central Avenue were much higher in runoff than in base flow, whereas concentrations of ammonia at 16th Street and Emerson Avenue were only slightly higher than those in base flow (fig. 13). The minimum concentration of ammonia in storm runoff at Central Avenue was twice as high as that in base flow, and the maximum concentration in runoff was four times as high as that in base flow. The increase in ammonia at Central Avenue probably was caused by combined-sewer overflows and, most likely to a lesser degree, by urban runoff.

Event-mean concentrations of organic nitrogen, phosphorus, and orthophosphate were least at Emerson Avenue, intermediate at Central Avenue, and greatest at 16th Street (fig. 13). During base flow, however, concentrations of organic nitrogen, phosphorus, and orthophosphate at Emerson and Central Avenues were similar. Except for orthophosphate at Emerson Avenue, concentrations of organic nitrogen, phosphorus, and orthophosphate in storm runoff were higher than those in base flow, particularly at Central Avenue and 16th Street. Increased concentrations of organic nitrogen, phosphorus, and orthophosphate in storm runoff, particularly in the reach between Emerson and Central Avenues, probably were caused by combined-sewer overflows and urban runoff.

Trace Elements

As with all base-flow samples, all storm-runoff samples for mercury, selenium, and cadmium (except for one detection of selenium at the detection limit at 16th Street) were less than the detection limits (table 11).

As with base-flow samples, chromium and nickel were detected only at 16th Street (except for one detection of chromium at the detection limit at Emerson Avenue, table 11). Detectable concentrations of chromium and nickel in runoff at 16th Street were associated with high concentrations of aluminum and iron (table 11). Concentrations of chromium and nickel in runoff at 16th Street were higher than those in base flow (fig. 13) and were attributed to the discharge of filter backwash and the probable resuspension of settled flocculent from the streambed in the reach of Fall Creek between 16th Street and the discharge point for filter backwash. Because these metals were not detected in storm runoff at Central Avenue, urban runoff and combined-sewer overflows seemed to have little effect on concentrations of chromium and nickel.

Concentrations of copper, lead, and zinc in storm runoff were much higher than those in base flow (fig. 13). Event-mean concentrations of copper, lead, and zinc at Central Avenue and 16th Street generally were greater than those at Emerson Avenue. Copper and zinc were detected at Emerson Avenue only during storms 1 and 2, but were detected at Central Avenue and 16th Street during all six storms (tables 11, 13). Higher concentrations and more frequent detections at Central Avenue and 16th Street indicate that runoff from the highly urbanized area downstream from Emerson Avenue is a source of copper, lead, and zinc in Fall Creek. The highest concentrations of lead (33 µg/L) and zinc (63 µg/L) were associated with the highest concentrations of aluminum (16,730 µg/L) and iron (6,482 µg/L) (table 13). This association indicates that some of the increased concentrations of lead, zinc, and probably copper at 16th Street can be attributed to the discharge and resuspension of filter backwash.

Concentrations of aluminum in storm runoff generally were higher than those in base flow (fig. 13). Increased concentrations of aluminum at Emerson Avenue were caused by increased concentrations of suspended solids, probably from soil and bank erosion. Because concentrations of suspended solids at Central Avenue generally were less than those at Emerson Avenue, increased concentrations of aluminum at Central Avenue probably were caused by the discharge and resuspension of small amounts of aluminum-rich filter backwash rather than by a large increase in suspended solids caused by soil and bank erosion. Aluminum/iron ratios of storm runoff ranged from 0.36 to 0.64 at Emerson Avenue, from 0.44 to 0.94 at Central Avenue, and from 0.98 to 2.97 at 16th Street (calculated from data in table 13) and indicate aluminum enrichment (most likely in the suspended material) downstream. Increased concentrations of aluminum in runoff at 16th Street were caused by the discharge and probable resuspension of filter backwash. In view of the large contributions of aluminum from filter backwash in base flow and storm runoff and the increased concentrations of aluminum (probably attributable to soil or bank erosion) upstream from Emerson Avenue, combined-sewer overflows and urban runoff do not discernibly affect concentrations of aluminum in Fall Creek.

Concentrations of iron in storm runoff generally were higher than those in base flow, particularly at Emerson and Central Avenues (fig. 13). Increased concentrations of iron at Central Avenue in runoff were not associated with increased concentrations of suspended solids. Because concentrations of dissolved iron in streams at neutral pH usually are low (Hem, 1985, p. 83), increased iron concentrations probably were caused by solids having high concentrations of iron. Urban runoff or the resuspension of filter backwash could have been the source of iron-rich solids. Event-mean concentrations of iron at Emerson Avenue were consistently greater than those at Central Avenue (table 13). Higher concentrations of iron in runoff at Emerson Avenue were caused by the higher concentrations of suspended solids, probably from soil or bank erosion upstream.

Urban runoff and combined-sewer overflows may have increased concentrations of iron in Fall Creek, but the increased concentrations were comparable to those caused by soil and bank erosion from rural areas upstream from Emerson Avenue.

Concentrations of arsenic in storm runoff were similar to those in base flow (fig. 13). As with base flow, concentrations of arsenic in storm runoff were much greater at 16th Street than concentrations at Emerson and Central Avenues. Urban runoff and combined-sewer overflows had little discernible effect on arsenic in Fall Creek.

Concentrations of barium in storm runoff at Emerson Avenue were greater than concentrations measured in base flow, whereas concentrations during runoff at Central Avenue and 16th Street were less than concentrations measured in base flow (fig. 13). Decreased concentrations of barium in runoff would be expected if ground-water inflow is the major source of barium and surface runoff contains low concentrations of barium. The cause of the increased concentrations of barium at Emerson Avenue in storm runoff is not known. Combined-sewer overflows and urban runoff do not seem to be a source of barium in Fall Creek.

Fecal Coliform Bacteria

Concentrations of fecal coliform bacteria in storm runoff were much greater than those in base flow (tables 9, 12). Concentrations of fecal coliform bacteria in storm runoff ranged from <100 to 48,000 col/100 mL at Emerson Avenue, from 1,200 to 470,000 col/100 mL at Central Avenue, and from <100 to 152,000 col/100 mL at 16th Street. Concentrations of fecal coliform bacteria exceeded 10,000 col/100 mL only once at Emerson Avenue but frequently exceeded this concentration at Central Avenue and 16th Street. Raw sewage in combined-sewer overflows and animal wastes in urban runoff are the major sources of fecal coliform bacteria. In general, concentrations of fecal coliform bacteria were highest at Central Avenue and lowest at Emerson Avenue and were highly variable in storm runoff (figs. 6–11). Combined-sewer overflows and urban runoff dramatically increased concentrations of fecal coliform bacteria in Fall Creek.

SUMMARY AND CONCLUSIONS

In 1986, the U.S. Geological Survey and the Indianapolis Department of Public Works began a cooperative study to evaluate the effects of combined-sewer overflows and urban runoff to Fall Creek on the water quality of the White River. This report describes the effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek in and near Indianapolis during summer 1987.

Fall Creek drains 318 mi^2 in east-central Indiana and flows approximately 60 mi to its confluence with the White River in Indianapolis. Fall Creek is a highly complex, urban and rural hydrologic system that includes an instream water-supply reservoir, several low-head dams, water withdrawal for public supply, a variety of point-source effluents, stormwater and combined-sewer overflows, and interbasin water transfer into the basin as a result of aqueduct overflow.

Most of the water-quality data collected during the study were collected from three streamflow-gaging stations on Fall Creek in Indianapolis. These stations were located at Emerson Avenue, Central Avenue, and 16th Street at river miles 9.2, 3.8, and 1.3, respectively. The Emerson Avenue station is upstream from all combined-sewer overflows and receives urban and rural runoff and water released from Geist Reservoir. The Central Avenue station is in the center of the combined-sewer-overflow area; 15 combined-sewer overflows are upstream from Central Avenue and 13 are downstream. The 16th Street station is downstream from 27 of 28 combined-sewer overflows on Fall Creek, downstream from the aqueduct overflow from the water-supply canal, and immediately downstream from the discharge of filter backwash from the water-treatment process for public supply. Water-quality samples were collected four to six times during base flow and multiple times during storm runoff during six storms. Multiple runoff samples were composited to a single sample that represented the mean water quality during the period of storm runoff. Water-quality samples also were collected from the aqueduct overflow and from the filter backwash. Most chemical analyses were done on whole-water (nonfiltered) samples and are termed “total” or “total recoverable.”

Precipitation in the Indianapolis area was about one-half of normal during the study period (July 22–October 19, 1987). Seven storms produced runoff during the study period. Water samples were collected during runoff from six of these storms. Although the median amount of precipitation for some of the storms was small, all storms caused at least some of the combined sewers to overflow.

Streamflow at the three streamflow-gaging stations is regulated by Geist Reservoir. Compared with historical streamflow, monthly mean streamflow during July and August was near or above normal, whereas streamflow during September and October was well below normal. During base flow, streamflow at Emerson Avenue was greater than that downstream at Central Avenue or 16th Street and showed the effect of water withdrawn for public supply between Emerson and Central Avenues. Approximately 69 percent of the streamflow at Central Avenue during October was contributed by ground-water seepage in the reach between Emerson Avenue and Central Avenue. The increase in streamflow from Central Avenue to 16th Street was attributed to three sources: aqueduct overflow, ground-water inflow, and filter backwash. These sources accounted for approximately 35, 48.5, and 2 percent, respectively, of the streamflow measured at 16th Street during October. Only about 14.5 percent of the streamflow measured at 16th Street during October was streamflow that originated in Fall Creek upstream from Emerson Avenue.

The effects of combined-sewer overflows and urban runoff on the water quality of Fall Creek were determined by comparing the water quality of base flow with water quality of storm runoff. In addition, water quality of runoff in the urbanized area was compared with water quality in the less urbanized area upstream from the combined-sewer overflows.

During base flow, specific conductance and concentrations of major anions and dissolved solids increased downstream in response to ground-water inflow, aqueduct overflow, and the discharge of filter backwash. Dissolved oxygen concentrations were least in the reach of Fall Creek near Central Avenue where black sludge deposits covered the stream bottom. The black deposits correspond to the areas where combined-sewer overflows discharge. Concentrations of suspended solids were least at Central Avenue and greatest at 16th Street. High concentrations of suspended solids at 16th Street were caused by the discharge of filter backwash. Concentrations of CBOD and COD measured at Emerson Avenue were nearly identical to those measured at Central Avenue, whereas those at 16th Street were approximately two times greater. Concentrations of CBOD at Emerson Avenue and Central Avenue ranged from <1 to 4 mg/L but ranged from 2 to 9 mg/L at 16th Street. Concentrations of CBOD and COD in the aqueduct overflow were similar to concentrations measured upstream at Emerson Avenue and Central Avenue, whereas concentrations in the filter backwash were the highest measured (16 and 63 mg/L, respectively). The discharge of filter backwash caused the increased concentrations of CBOD and COD during base flow at 16th Street.

During base flow, concentrations of nitrate plus nitrite and ammonia steadily increased downstream, whereas concentrations of organic nitrogen, phosphorus, and orthophosphate increased at 16th Street only. Concentrations of mercury, selenium, and cadmium were less than the detection limits (0.2, 1, and 10 μg/L, respectively) in all base-flow samples. Except for two detectable concentrations of copper at Central Avenue and detectable zinc in the aqueduct overflow, all concentrations of chromium, copper, lead, nickel, and zinc were less than the detection limit (10 µg/L) for base-flow samples collected at Emerson Avenue, Central Avenue, and the aqueduct overflow. Filter backwash had the highest concentrations of chromium (30 µg/L), copper (40 µg/L), lead (30 µg/L), nickel (30 µg/L), and zinc (40 µg/L). Detectable concentrations of these metals in base-flow samples from 16th Street were caused by the discharge of filter backwash.

Concentrations of aluminum steadily increased downstream, whereas concentrations of arsenic were greater at Emerson Avenue than at Central Avenue. Concentrations of both constituents were greatest at 16th Street. Increased concentrations of aluminum at 16th Street were caused by the discharge of aluminum hydroxide floc (in the filter backwash) from the drinking-water-treatment process. Filter backwash had the highest concentration of aluminum (27,240 µg/L). The solids discharged as filter backwash were approximately 10 percent aluminum. Concentrations of arsenic ranged from 1 to 2 µg/L at Emerson Avenue and Central Avenue, but ranged from 2 to 10 µg/L at 16th Street. Increased concentrations at 16th Street could not be attributed to the discharge of filter backwash because the concentration of arsenic in the backwash was only 2 µg/L. Ground-water inflow probably is not the cause of increased concentrations of arsenic because increased concentrations were not measured at Central Avenue, where base flow is composed largely of ground-water inflow.

Concentrations of fecal coliform bacteria in base flow generally were lowest at Central Avenue and highest at 16th Street. Concentrations of fecal coliform bacteria ranged from 100 to 2,000 col/100 mL at Emerson Avenue, from 200 to 500 col/100 mL at Central Avenue, and from <100 to 12,800 col/100 mL at 16th Street.

During storm runoff, specific conductance, pH, water temperature, and concentrations of dissolved oxygen generally decreased. Specific conductance decreased because rainfall and surface runoff typically contain lower concentrations of ions than does base flow. Because rainfall is acidic, pH decreased during storm runoff. Concentrations of dissolved oxygen decreased probably because oxygen was consumed by oxygen-demanding materials from combined-sewer overflows, urban runoff, and resuspended sediment and because of the discharge of anoxic water from combined-sewer overflows. Concentrations of dissolved oxygen measured at Central Avenue were less than the Indiana minimum ambient water-quality standard of 4.0 mg/L for all storms. For storms that occurred during low base-flow rates, concentrations of dissolved oxygen measured at Central Avenue were near or less than 4.0 mg/L before rainfall or runoff. During storm runoff, concentrations of dissolved oxygen decreased further. Durations of concentrations of dissolved oxygen less than 4.0 mg/L at Central Avenue during storm runoff ranged from approximately 4 to more than 24 hours, and minimum concentrations during storms 1 through 6 were 0.5, 1.9, 2.0, 2.5, 0.8, and 0.5 mg/L, respectively. Concentrations of dissolved oxygen at 16th Street were less than 4.0 mg/L for approximately 1 hour during storm 1 (minimum 3.4 mg/L). The minimum concentration of dissolved oxygen at Emerson Avenue during storm runoff was 5.9 mg/L.

Concentrations of CBOD in storm runoff generally were higher than those in base flow and ranged from 2 to 11.3 mg/L at Emerson Avenue, from 5 to 15.6 mg/L at Central Avenue, and from 5.9 to 32.5 mg/L at 16th Street. Generally, the highest concentrations of CBOD and most discernible increases compared to base flow occurred at Central Avenue. Concentrations of CBOD and COD were similar in base flow at Emerson and Central Avenues but were much higher in storm runoff at Central Avenue. Increased concentrations of these measures of oxygen demand in runoff at Central Avenue probably were caused by combined-sewer overflows, urban runoff, and the resuspension of organic material deposited on the streambed.

Concentrations of nutrients in storm runoff increased downstream and, for all nutrients except nitrate plus nitrite, were higher than those in base flow. Concentrations of ammonia at Central Avenue were much higher in storm runoff than in base flow, whereas concentrations of ammonia in storm runoff at 16th Street and Emerson Avenue were only slightly higher than those in base flow. The minimum concentration of ammonia in storm runoff at Central Avenue was twice as high as that in base flow, and the maximum concentration in runoff was four times as high as that in base flow. The increase in ammonia at Central Avenue probably was caused by combined-sewer overflows and, most likely to a lesser degree, by urban runoff.

As with all base-flow samples, concentrations of mercury, selenium, and cadmium in all storm-runoff samples (except for one detection of selenium at the detection limit at 16th Street) were less than the detection limits. Detectable concentrations of chromium and nickel in runoff at 16th Street were associated with the discharge of filter backwash to Fall Creek. Urban runoff and combined-sewer overflows seemed to have little effect on concentrations of chromium and nickel in Fall Creek. Concentrations of copper, lead, and zinc in storm runoff were much higher than those in base flow. Copper and zinc were detected at Emerson Avenue only during storms 1 and 2 but were detected at Central Avenue and 16th Street during all six storms. Higher concentrations and more frequent detections at Central Avenue and 16th Street indicate that runoff from the highly urbanized area downstream from Emerson Avenue is a source of copper, lead, and zinc in Fall Creek. Some of the increased concentrations of lead, zinc, and probably copper at 16th Street can be attributed to the discharge and resuspension of filter backwash.

Concentrations of fecal coliform bacteria in storm runoff were much greater than those in base flow. Concentrations of fecal coliform bacteria in storm runoff ranged from <100 to 48,000 col/100 mL at Emerson Avenue, from 1,200 to 470,000 col/100 mL at Central Avenue, and from <100 to 152,000 col/100 mL at 16th Street. Concentrations of fecal coliform bacteria in storm runoff exceeded 10,000 col/100 mL in only one sample collected at Emerson Avenue but frequently exceeded this concentration at Central Avenue and 16th Street. Combined-sewer overflows and urban runoff dramatically increased concentrations of fecal coliform bacteria in Fall Creek.

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